ALBERT-LUDWIGS
UNIVERSITÄT FREIBURG

HYDROLOGIE FREIBURG

Impacts of upstream uses on the alluvial aquifer of the Swakop River, Namibia

Vera Luisa Marx

Diplomarbeit unter Leitung von Prof. Dr. Markus Weiler

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a	coefficient for the determination of K_{hi}	-
α	fractionation factor	-
b	coefficient for the determination of K_{hi}	-
c_i	dissolved concentration	mol/l
d	Deuterium excess	-
δ	delta notation of isotopes	‰
e	slope of evaporation line	-
h	altitude	m a.s.l.
k_{Hi}	Henry constant	mol/l Pa
p_{H_2O}	water vapour pressure	Pa
p	atmospheric pressure	Pa
p_i	partial pressure	Pa
R	isotope ratio	-
S	salinity	‰
T	temperature	°C
x_i	volumetric ratio of gas in air	pptv

Abbreviations

ADE	aquifer dependent ecosystem
CAN	Central Area of Namibia
BIWAC	Bittner Water Consult
CFC	chlorofluorocarbons
CFC-11	trichlorofluoromethane
CFC-12	dichlorodifluoromethane
CFC-113	trichlorotrifluoroethane
CSIR	Council for Scientific and Industrial research
DWA	Department of Water Affairs
GIS	Geographical Information System
GMWL	Global Meteoric Water Line
IAEA	International Atomic Energy Agency
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
IRMS	Isotope Ratio Mass Spectrometer
LHU	Langer Heinrich Uranium (Pty) Ltd.
m a.s.l.	meter above sea level
NAMROM	Namibia runoff model
OMDEL	Omaruru Delta
pptv	parts per trillion by volume
RUL	Rossing Uranium Ltd.
RWL	rest water level
SF_6	sulphur hexafluoride
TDLAS	Tunable Diode Laser Absorption Spectometry
TDS	Total Dissolved Solids
VSMOV	Vienna Standard Mean Ocean Water
WSS	water supply scheme

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Abstract

In arid and semi-arid regions the population, livestock, vegetation and wildlife are highly dependent on the water resources of ephemeral streams. In order to assure effective and sustainable water management in these heavily-used and sensitive environments, thorough investigations of the hydrological system are required.

In case of the Swakop River in Namibia, water for human consumption is stored in two surface dams, built in the 1970s, and abstracted from boreholes in the alluvial aquifer. This study aims at identifying the impacts of the construction of the Swakoppoort and Von Bach Dam on the downstream groundwater quantity and quality of the alluvial aquifer.

It could be shown, on the basis of previous reports and streamflow data, that the hydrological regime of the Swakop River was significantly impacted by the construction of the two dams. The groundwater system of the alluvial aquifer which is closely linked to streamflow was characterised on the basis of a longitudinal sampling profile. On the one hand, the analysed parameters provided information on the water quality, and on the other hand they served also as indicators for the spatial and temporal distribution of groundwater recharge. The analysis of stable isotopes ^{18}O and ^{2}H showed that there is a high dependency of the lower alluvial aquifer on floods generated in the headwaters of the catchment. The ion composition of the groundwater samples provided insight into the high longitudinal variability of the groundwater quality indicating source areas of groundwater recharge. High uranium concentrations were detected in the lower catchment. It was not investigated if these high levels in the groundwater sample originate from weathering of uranium bearing rocks or from pollution of modern mining activities. With the application of the CFC age dating method, changes in the distribution of groundwater recharge along the alluvium resulting most probably from the dam construction were detected. The analysis of SF_6 revealed a high natural geogenic background in the catchment which makes it unsuitable as an age dating tool.

Furthermore, the findings of the longitudinal profile were used to identify and describe the major relevant processes associated with the groundwater system. This resulting perceptual model may serve as a basis for a detailed modeling of the alluvial

groundwater resources and thus for the determination of the water requirements for both people and the environment.

Zusammenfassung

In ariden und semi-ariden Gebieten sind Bevölkerung, Landwirtschaft und Natur extrem abhängig von Wasserressourcen ephemerer Flüsse. Daher sind gründliche hydrologische Untersuchungen notwendig, um ein effektives und nachhaltiges Wasserressourcenmanagement in diesen stark genutzten und sensitiven Umgebungen zu garantieren.

Das Wasser des ephemeren Swakops in Nambia wird für Zwecke der Wasserversorgung in zwei Dämmen, die in den 1970ern gebaut wurden, gespeichert. Zudem wird Grundwasser aus Bohrlöchern im alluvialen Aquifer entnommen. Ziel dieser Arbeit ist es, die Auswirkungen der Dammbauten auf die Quantität und Qualität des Grundwassers im alluvialen Aquifer stromabwärts zu untersuchen.

Anhand von vorhergehenden Studien und Abflussdaten konnte gezeigt werden, dass das hydrologische Regime des Swakop Rivers durch den Bau der beiden Dämme erheblich beeinflusst wurde. Das Grundwassersystem, welches im Falle ephemerer Flüssen eng mit dem Gerinneabfluss verbunden ist, wurde mit Hilfe eines Längsprofils an Grundwasserproben charakterisiert. Die analysierten Parameter gaben Informationen über die Wasserqualität und sogleich dienten sie als Indikatoren für die räumliche und zeitliche Verteilung der Grundwasserneubildung. Die Ergebnisse der stabilen Isotope ^{18}O and ^{2}H zeigten, dass die Isotopensignatur im alluvialen Aquifer des unteren Einzugsgebiets von der Isotopenzusammensetzung großer Abflussereignisse, die im Oberlauf entstehen, geprägt ist. Die Zusammensetzung der Hauptionen weist auf eine hohe Variabilität der Wasserqualität entlang des Flusslaufes hin. Des Weiteren konnten anhand der Ionenzusammensetzung Bereiche identifiziert werden, in denen verstärkt indirekte Grundwasserneubildung stattfindet oder der Zufluss aus dem Festgestein von großer Bedeutung ist. Im unteren Teil des Einzugesgebietes wurden hohe Urankonzentrationen gemessen. Es wurde jedoch nicht untersucht, ob diese hohen Werte durch Verwitterung uranhaltigen Gesteins oder durch Kontamination im Zusammenhang mit dem Uranabbau entstanden sind. Die Anwendung der FCKW-Altersdatierungsmethode zeigte, dass der Bau der Dämme höchstwahrscheinlich eine Veränderung der Grundwasserneubildungsverteilung verursachte. Die Analyse von SF_6

ergab eine hohe natürliche Hintergrundkonzentration im Swakop Einzugsgebiet, weshalb die Methode nicht zur Altersdatierung angewendet werden konnte.

Mit den Ergebnissen des Längsprofils konnten die wichtigsten hydrologischen Prozesse im Zusammenhang mit dem alluvialen Grundwassersystem identifiziert und näher beschrieben werden. Dies erlaubte die Erstellung eines schematischen Modells (Wahrnehmungsmodell) dieser Prozessen, welches als Grundlage für eine detaillierte Modellierung der alluvialen Ressourcen und somit zur Bestimmung des Wasserbedarfs von Mensch und Natur dienen kann.

1 Introduction

Namibia is one of the driest countries in sub-Saharan Africa. The climatic conditions are very harsh and thus, no perennial rivers originate from within the countries borders. Therefore, the population, livestock, vegetation and wildlife are highly dependent on the water resources of ephemeral rivers. For human consumption water is either stored in surface dams or abstracted from boreholes in the alluvial aquifer (SHANYENGANA et al., 2004). Both of these reservoirs are recharged only by seasonal flood events. Usually, surface water dams are constructed in the upper parts of the catchments where annual rainfall is high and transmission losses low. However, since these surface water bodies are extremely exposed to evaporation, water losses are enormous.

In case of the Swakop River catchment two surface water dams, Von Bach and Swakoppoort Dam, were constructed in the upper part. The stored water is essential for the drinking water supply of the Central Area of Namibia (CAN). In the middle and lower parts of the catchment the alluvial aquifer provides water to farms, mines, communities, vegetation and wildlife. Since the dam construction in the 1970s, flood water is impeded from infiltrating further downstream or flowing into the Atlantic Ocean. Hence, the hydrological regime of the Swakop River is altered with numerous consequences for all downstream users. Recently more and more people depend on the scarce water resources of the Swakop River catchment and the expanding mining sector likewise leads to a growing water demand. Thus, an exact understanding of the altered flow regime in the Swakop River catchment and the impacts on the alluvial aquifer is crucial for sustainable water resources management.

1.1 Motivation and objectives

The scarce water resources in arid and semi-arid areas are under increasing pressure due to growing populations, increasing per capita water use and irrigation. In many regions, groundwater resources are over-exploited and threatened by pollution and also surface flows are managed in unsustainable ways. Thus, effective and sustainable water management is essential which presumes thorough investigations of the hydrological system in order to identify the natural state and hence, impacts of environmental changes. This study aims at assessing the impacts of upstream uses on the alluvial aquifer of the Swakop River in Namibia.

The detailed objectives are to:

- Detect changes in the hydrological regime of the Swakop River due to environmental changes.
- Identify resulting effects on the availability and quality of groundwater in the alluvial aquifer.
- Estimate the indirect recharge of the Swakop alluvial aquifer for a defined reach of the river for different scenarios.

The focus will be set on the impact of the two surface dams on the downstream groundwater quantity and quality of the alluvial aquifer of the Swakop River.

1.2 State of the art

1.2.1 Alluvial aquifers of ephemeral rivers

Alluvial groundwater resources need to be investigated thoroughly as aquifer dependent ecosystems (ADEs) immediately react on alterations of the groundwater level. At the same time, the alluvial water resources may be readily available and thus important for water supply. Alluvial aquifers can be described as unconfined groundwater units that are hosted in horizontally discontinuous layers of sand, silt and clay deposited by a river. Their shallow depth and vicinity to the streambed leads to a tight relationship with streamflow (DE HAMER et al., 2008). Alluvial aquifers are recharged indirectly after flood events by percolation through the riverbed (DE VRIES & SIMMERS, 2002). Aspects of recharge, including mechanisms and estimation of indirect recharge, in arid and semi-arid regions are described extensively in the literature (BREDENKAMP et al., 1995; LERNER et al., 1990; SIMMERS, 1997). SCANLON et al. (2006) synthesise findings from more than 100 recharge studies from arid and semi-arid regions. The study provides comprehensive information on recharge rates which are, in the context of global change, crucial for sustainable water resources management. In numerous studies the processes of indirect recharge have been investigated in situ and in detail. During a study carried out by (DAHAN et al., 2008) on flood water infiltration and ground water recharge of a shallow alluvial aquifer, the infiltration during a flood event was continuously monitored. It is shown that infiltration rates are rather controlled by flow duration and available aquifer storage than by flood stages. Other studies which are summarised by WHEATER (2008) reach similar results. However, it is stated that complex processes, like air entrapment and clogging of surface layers, as well as heterogeneity of the alluvial material make it impossible at present to extrapolate from point studies to transmission losses from ephemeral channels at a larger scale. Other methods allow quantifying transmission losses at a larger scale by observing floods at different locations. In some cases, where deep unsaturated alluvium exists, the linear relationship between transmission losses and volume of surface flow is valid. Thereby it must be considered that transmission losses and thus groundwater recharge are limited by available storage in the alluvium. Additionally, evaporation losses have to be accounted for when studying groundwater recharge. ANDERSEN et al. (1998) showed in Botswana that evaporation losses are high when the alluvial aquifer is fully saturated while they are small once the water table drops below the surface. In this case, the first flood of the wet season was sufficient to fully recharge the underlying aquifer. Subsequent floods topped up the storage which was then depleted by evaporation. HELLWIG (1973b) found out during an experiment on water losses from alluvial aquifers that dropping the water-table in sand (mean grain size of 0.53 mm) below 0.6 m will practically prevent evaporation losses. Once infiltration has taken place, the alluvium effectively reduces evaporation as capillary effects are small due to the coarse structure of the alluvium (WHEATER, 2008). Concluding from these studies, it can be said that, besides the hydraulic conductivity of the aquifer, the flood duration and the depth to water table are highly important factors influencing indirect groundwater recharge.

1.2.2 Environmental impacts

Alluvial aquifers and thus ADEs are exposed to various environmental impacts like surface dam constructions, land-use change, groundwater abstractions and climatic change. In arid and semi-arid regions seasonal variations and climatic irregularities make the efficient use of river runoff difficult. The construction of dams offers a possibility to store surface water for times of scarcity and has been seen as a straightforward solution to water supply problems for a very long time (JACOBSON et al., 1995). However, the history of dams has shown that the benefits come along with a huge amount of environmental costs. Considerable investments have been made to alleviate the environmental impacts of dams. Concerns remain and the current state of knowledge shows that the impacts of dams on the environment are profound, multiple and mostly negative (BERKAMP et al., 2000). From a hydrological point of view, dams alter the downstream pattern of streamflow. For ephemeral streams this includes changes in flood frequency and magnitude as well as reduction in overall flow with a resultant wide range of impacts on the closely linked alluvial aquifer and the riverine ecology (BATALLA et al., 2004). Amongst others, by altering the pattern of downstream flow, dams change sediment and nutrient regimes as well as the water temperature and chemistry. In arid and semi-arid regions, the effect of dams on streamflow is especially drastic as the variability of natural flow is high (SHAFROTH et al., 2002). Besides, the reservoir storage which is required to supply a certain yield is always greater than in perennial rivers as there are longer periods of zero flow between storage replenishment. These large storage volumes capture even moderately large events and spillage is limited to the largest events (HUGHES, 2005). BERKAMP et al. (2000) review the impacts of large scale dams on ecosystems and conclude that the related processes are highly complex. Thus, it is not possible to assess the impacts of dams on downstream ecosystems by a standard or normative approach but rather on a case-by-case basis. CONSTANTZ (2003) points out that the dam problem is often viewed as a surface phenomenon, but instead, surface water and groundwater should be investigated as a single resource. Still, little is known about the vulnerability of alluvial aquifers as well as time and type of response to external impacts

2 Study area

Namibia has no perennial rivers except for the border rivers Kunene, Okavango, Zambezi and Kwando-Linyati-Chobe in the north and the Orange River in the south. The rivers within Namibia are all ephemeral, flowing only for a short period after intense rains (CHRISTELIS & STRUCKMEIER, 2001). The Swakop River is one of the largest of the country's twelve major ephemeral streams draining westwards into the Atlantic Ocean (figure 1). The catchment stretches from the sea to the east with a total area of 30 100 km^2 (JACOBSON et al., 1995).

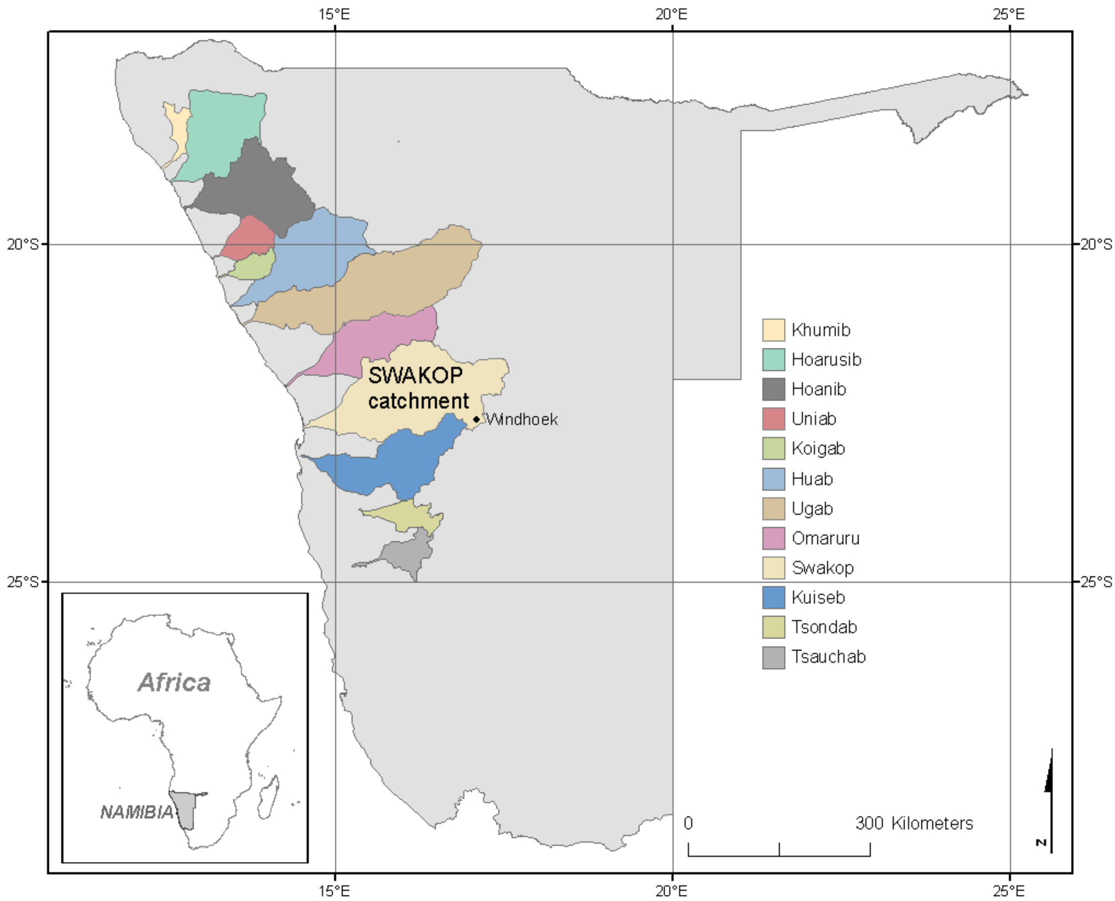


Figure 1: Location of Namibia in Africa and the country's western catchments (modified from JACOBSON et al., 1995)

Within this study, the term upper Swakop River refers to the headwaters upstream of Swakoppoort Dam, the middle Swakop River to the area around Otjimbingwe and the lower Swakop River to the reaches downstream of the Langer Heinrich Uranium (LHU) mine (figure 2). The elevation varies from 0 to about 2400 m, and numerous towns, amongst the capital Windhoek, farms and mines are situated in the Swakop River catchment. This makes it an important centre of development with a high population. The catchment has a share on three regional government areas: Erongo, Khomas and Otjozondjupa. The majority of the land is privately owned or used for farming and tourism. There is also communal land with small scale agriculture around Okahandja and Otjimbingwe as well as at the north-western fringe of the catchment. Two state-protected areas, the Namib-Naukluft Park in the lower part and the Von Bach Dam recreational resort in the upper part, contribute to the tourism potential of the catchment (JACOBSON et al., 1995). Two uranium mines, Rossing Uranium Ltd. (RUL) and LHU, as well as a gold mine (Navachab) are situated in the catchment (figure 2) providing a large number of jobs. Due to high demand on the world market, the uranium mining in the lower catchment is expanding further and the mining sector is a major contributor to Namibia's economy. It is expected that in the near future about 50 000 people will move into the Swakop River catchment, either as mine employees, work-seekers or family members. This significant increase in the population will of course have consequences for the region's water resources and their management (ELLMIES, 2008).

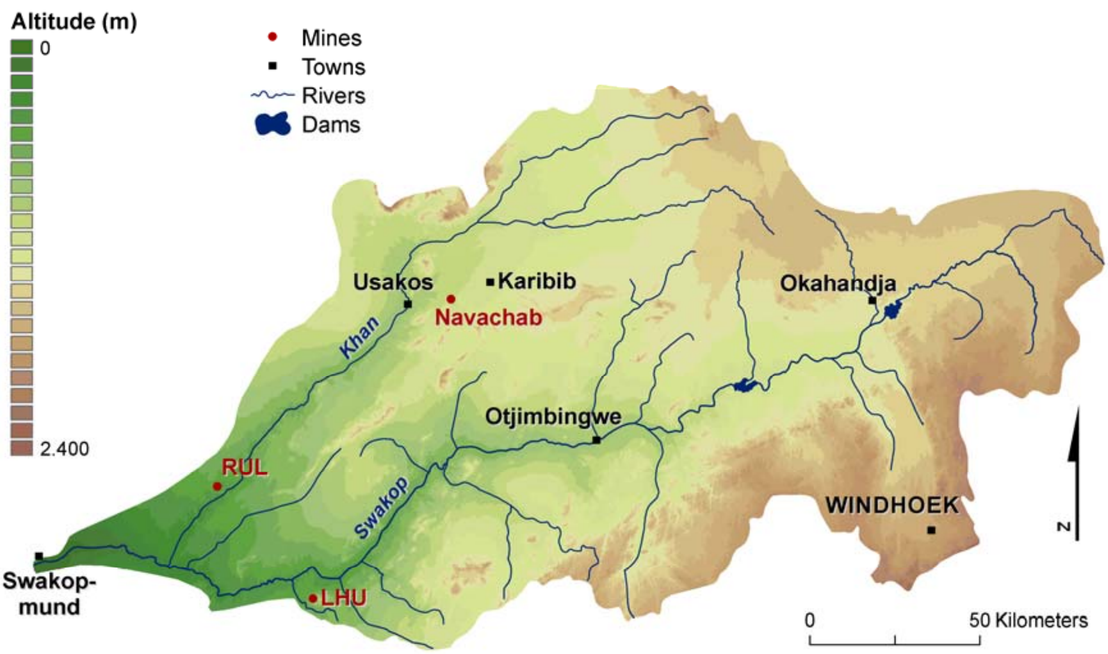


Figure 2: Elevation information, towns and mines in the Swakop River catchment (data from ATLAS OF NAMIBIA and DWA)

2.1 Climate

Namibia's climate can be characterised as dry according to the Köppen climate classification. The low annual rainfall, relatively high temperatures during the rainy season and huge evaporation losses cause an almost continuous water deficit. In the western catchments there are significant climatic differences between the coastal and the interior region which are shown for the Swakop River catchment in figure 4 (JACOBSON et al., 1995). The cold Atlantic sea water, the Benguela current, leads to an nearly permanent temperature inversion at the coast resulting in the extreme aridity of the Namib desert (CHRISTELIS & STRUCKMEIER, 2001).

The average maximum temperatures during the hottest month are 20 – 22 °C in Swakopmund while they reach 30 – 32 °C in Windhoek. The average minimum temperatures during the coldest month are 10 – 12 °C in Swakopmund and 4 – 6 °C in Windhoek (ATLAS OF NAMIBIA, 2002).

Additionally to the general scarcity of precipitation in Namibia, rainfall events are unreliable, variable and unevenly distributed in space and time which is characteristic for drylands (CHRISTELIS & STRUCKMEIER, 2001). Most of the precipitation falls on the eastern catchment mostly as showers or thunderstorms in summer between October and May. Figure 3 shows the steep rainfall gradient from East to West in the Swakop River catchment. The variability of rainfall in the Swakop catchment in general is high and it increases with aridity towards the sea. At the coast the average annual rainfall varies from 0 - 50 mm while in the interior regions it reaches up to 450 mm (ATLAS OF NAMIBIA, 2002).

In the coastal area the high moisture conditions lead to frequent fog formation. Fog precipitation can exceed three or four times the annual precipitation and hence is an important water supply for the adapted flora and fauna in the Namib desert (JACOBSON et al., 1995).

Mean annual potential evaporation especially in the middle part of the catchment reaches up to 3400 mm while at the coast it is less than 2400 mm (ATLAS OF NAMIBIA, 2002). As a consequence of these extremely high evaporation, water is rapidly lost from ecosystems and conditions are rather unfavourable for surface water storage (JACOBSON et al., 1995).

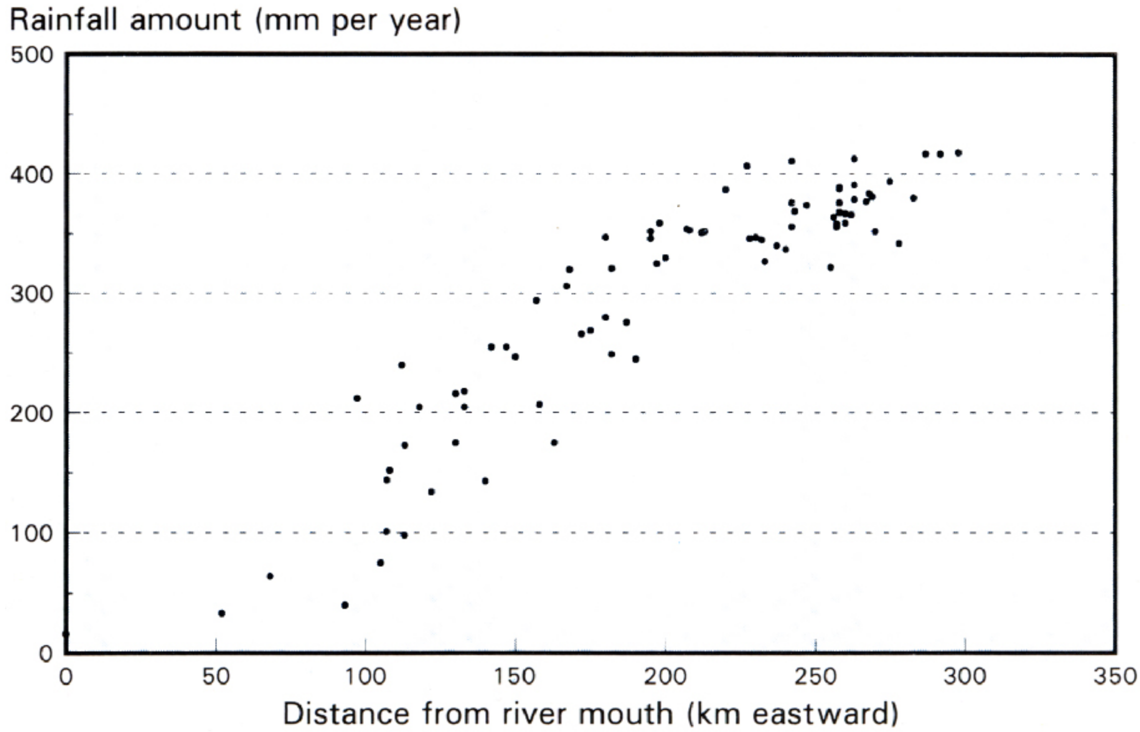


Figure 3: Distribution of average annual rainfall in the Swakop River catchment (JACOBSON et al., 1995)

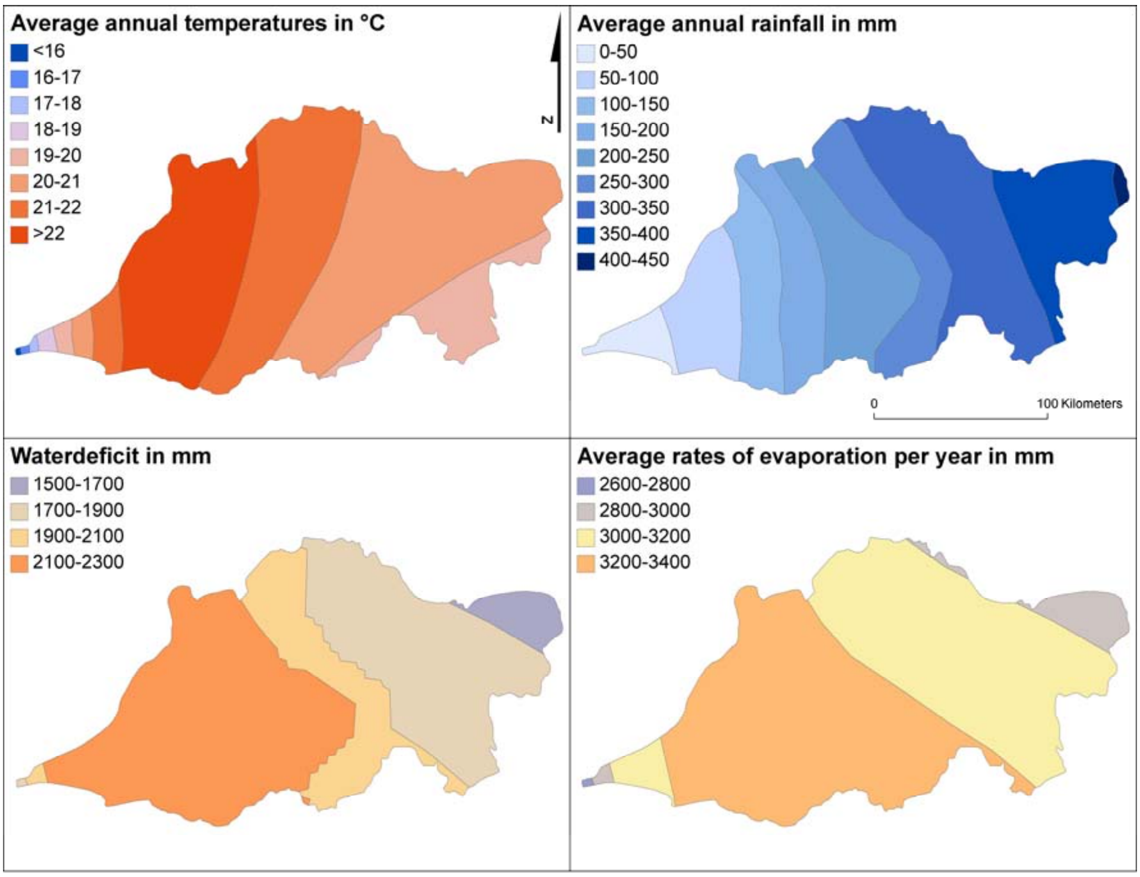


Figure 4: Climatic differences within the Swakop River catchment (data source: ATLAS OF NAMIBIA)

2.2 Geology and Geomorphology

The oldest rocks in the Swakop River catchment are thought to be nearly two billion years old belonging to the Epupa, Huab, Abbabis metamorphic complexes and can be found in the lower part of the catchment. The geology of the Swakop River catchment is dominated by the Damara Sequence, a group of rocks which are approximately 850 to 500 Ma old (JACOBSON et al., 1995). Damara granites constitute the middle parts of the Swakop River catchment. The Swakop Group of the Damara Sequence consists mainly of meta-carbonate deposits with interbedded mica and graphite schist, quartzite, mass flow deposits, lavas and iron formation which all are intensely folded and fractured to varying degrees (CHRISTELIS & STRUCKMEIER, 2001). The upper part of the catchment is characterised by schists of the Swakop Group while in the lower part schists and dolomites can be found (figure 5).

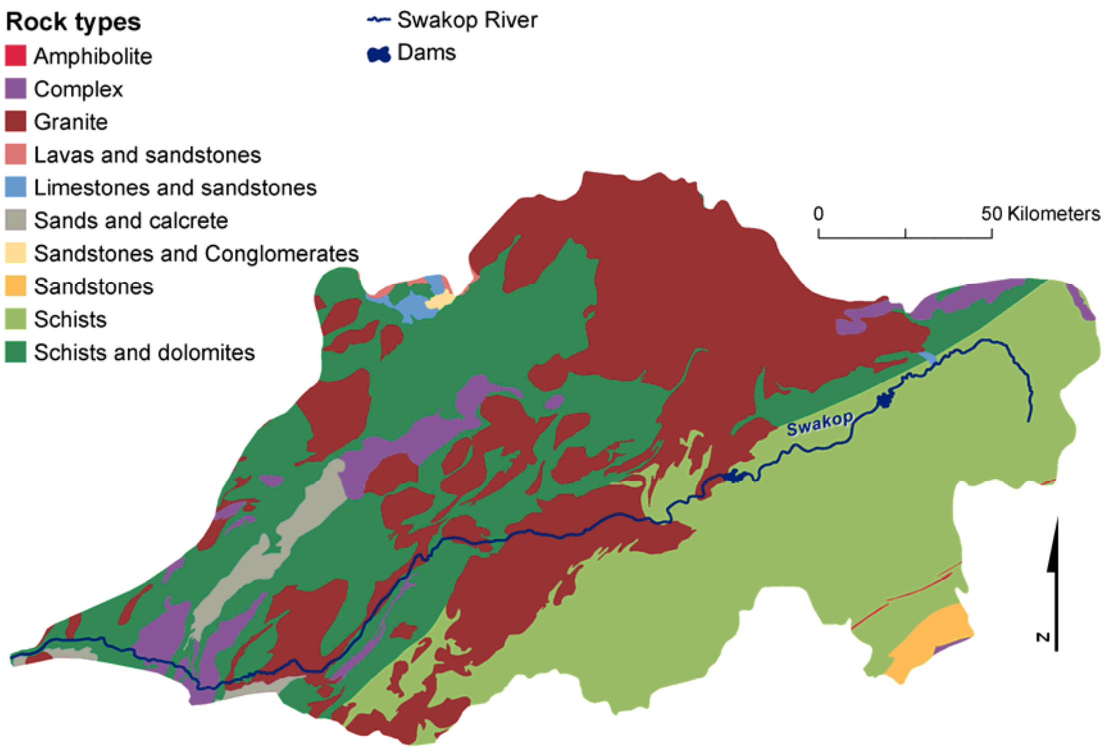


Figure 5: Rock types in the Swakop River catchment (data source: ATLAS OF NAMIBIA)

Some 650 Ma ago deformation occurred subsequent of continental collision which went along with syntectonic intrusion of serpentinites and syn- to post- tectonic granites. Uranium bearing Alaskite emerged at deep stratigraphic levels and can be found today at different sites in the Swakop River catchment providing the basis for uranium mining activities. The Damara Orogenesis was followed by the Karoo Sequence approximately 300 Ma ago which was a period of deposition and erosion. Some of the Karoo sediments were preserved under volcanic coverings. The Cretaceous to Tertiary break-up of South America and Africa resulted in volcanic activity accompanied by basaltic lava eruptions. These sheet basalts were removed by erosion almost completely. Only their feeder channels can be found as dolerite dykes throughout the Namib Desert. This volcanic period lead to partial melting of Damara metamorphites which resulted in granitic or granodioritic rocks. These granites intruded into the earth crust and later the surrounding rocks were removed by erosion. Spitzkoppe, Brandberg and the Erongo Mountains north of and in the North of the Swakop River catchment are remnants of these intrusions. The surrounding schists of the Damara Orogen have been eroded causing a gap between 21° and 23° S in Namibia's Great Escarpment which stretches along the whole country roughly parallel to the coastline.

Various phases of erosion and sedimentation followed under different climate conditions. Large volumes of sediments were deposited onto the coastal plains and shallow lagoons and marshes developed. The formation of gypsum and salt layers resulted from increased evaporation. Renewed uplifting in late tertiary caused the incision of the Swakop River in the Namib forming the so called Moon Landscape. Large proportions of the earlier deposited salt are still present today in lower layers of the alluvium. Along the Khan, Swakop and Kuiseb Rivers massive conglomerate terraces, the Oswater Conglomerate Formation, can be found in the lower reaches (CSIR, 1997). Figure 5 shows tertiary to recent deposits of sand and calcrete which cover the crystalline bedrock in lower parts of the catchment.

The catchment is divided into two main physiographic regions: the Khomas Hochland Plateau and the Central-Western Plains. Moreover, parts of the Inselbergs lie within the catchment at the north-western fringe (ATLAS OF NAMIBIA, 2002). As mentioned above, due to erosion processes the transition between the central plateau and the coastal plain is not sharply defined but rather indistinct (HÜSER et al., 2001). In adjacent catchments to the north or south where there is no gap in the Great Escarpment, the elevated interior is sharply separated from the coastal margin.

2.3 Vegetation and soils

Vegetation in the western catchments is primarily determined by variations in rainfall. According to the classification of Giess four vegetation types can be found in the Swakop River catchment: Central Namib (9 %), Semi-desert / Savanna Transition

(34 %), Thornbush Savanna (28 %) and Highland Savanna (29 %). However, this classification method does not reflect the typical vegetation patterns associated with ephemeral river courses. Soil deposition, increased soil moisture and groundwater storage lead to characteristic riparian vegetation along alluvial aquifers. River sections with extremely dense vegetation, so called riparian forests, are often referred to as linear oases as they provide food and water in arid landscapes. This vegetation is highly adapted to the climatic conditions as well as to the erratic and destructive nature of floods. The Swakop riparian vegetation (figure 6) mainly consists of *Faidherbia albida* (Ana tree), *Tamarix* (Tamarisk), *Acacia erioloba* (Camelthorn), Fig, *Euclea* and *Salvadora*. Besides *Prosopis glandulosa* (Prosopis), an alien invasive plant, largely contributes to the flora of the Swakop River. At several places where groundwater is forced to the surface by shallow bedrock, wetlands occur along the Swakop River (JACOBSON et al., 1995). In these areas high evapotranspiration losses occur, for instance at Riet, some 100 km upstream of Swakopmund (CSIR, 1997).

Figure 6: Riparian vegetation in the Namib section of the Swakop River catchment

Soils within the Swakop River catchment are generally shallow, rocky and barely developed due to arid climate conditions. The dune fields close to the coast consist of littoral sands while soils in the lower catchment in general are halomorphic. Further inland soils become calcareous and are almost unsuitable for irrigated agriculture. Along the Swakop River alluvial deposits of varying depth can be found. Sediments are transported by floods and deposited along the river course resulting in a deep soil profile of alternating layers of sand, silt, clay and gravels. Easily accessible groundwater makes these alluvial soils suitable for agriculture despite the fact that they have a high potential to salinisation. Alluvial soils are highly erosive and sensitive to compaction which reduces infiltration and thus groundwater recharge (JACOBSON et al., 1995).

2.4 Water supply sources

The relative high population density and economic development led to a huge and increasing water demand in the Central Area of Namibia (CAN) of which the Swakop River catchment is part of. The water resources are developed to their full potential and are partly overexploited. Figure 7 shows the water supply situation in the Swakop River catchment.

2.4.1 Surface water dams

In the upper part of the Swakop River catchment two surface dams, Von Bach and Swakoppoort Dam, have been constructed in 1970 and 1978, respectively. Together with a third dam located in the northern neighbouring Omatako catchment, they constitute an interconnected system contributing largely to the region's water supply. Raw water from Von Bach Dam is treated in a purification plant close by the dam and then directed to Windhoek via pipeline. This scheme is supported by raw water being transferred from Swakoppoort to Von Bach Dam. Furthermore, water is pumped to Von Bach Dam from Omatako Dam. The yield at 95 % assurance is 20 Mm^3/year for the interconnected system. If the dams are run on an individual basis, the yield is only 13 Mm^3/year which is mainly due to high evaporation losses at Swakoppoort and Omatako Dam (ENVES, 2008). Table 1 summarises the characteristics of the two major surface water dams in the Swakop River catchment.

Table 1: Characteristics of Von Bach and Swakoppoort Dam (NAMWATER, 1999)

	Von Bach	Swakoppoort
Structure	Rock fill with concrete outlet with gate	Concrete arch
Purpose	Domestic supply to Windhoek and Okahandja	Water supply to Navachab mine and Karibib; augmentation to Von Bach
Capacity	48.560 Mm^3	63.489 Mm^3
Surface area	4.884 km^2 (when full)	7.808 km^2 (when full)
Construction year	1970	1978

2.4.2 Groundwater abstraction

In the lower catchment area groundwater is supplied from the OMDEL (Omaruru Delta) water scheme via Swakopmund to the uranium mines. LHU has a permit to use 0.5 Mm³/year of alluvial groundwater of the Swakop River for dust suppression on the mining area (BITTNER, 2008).

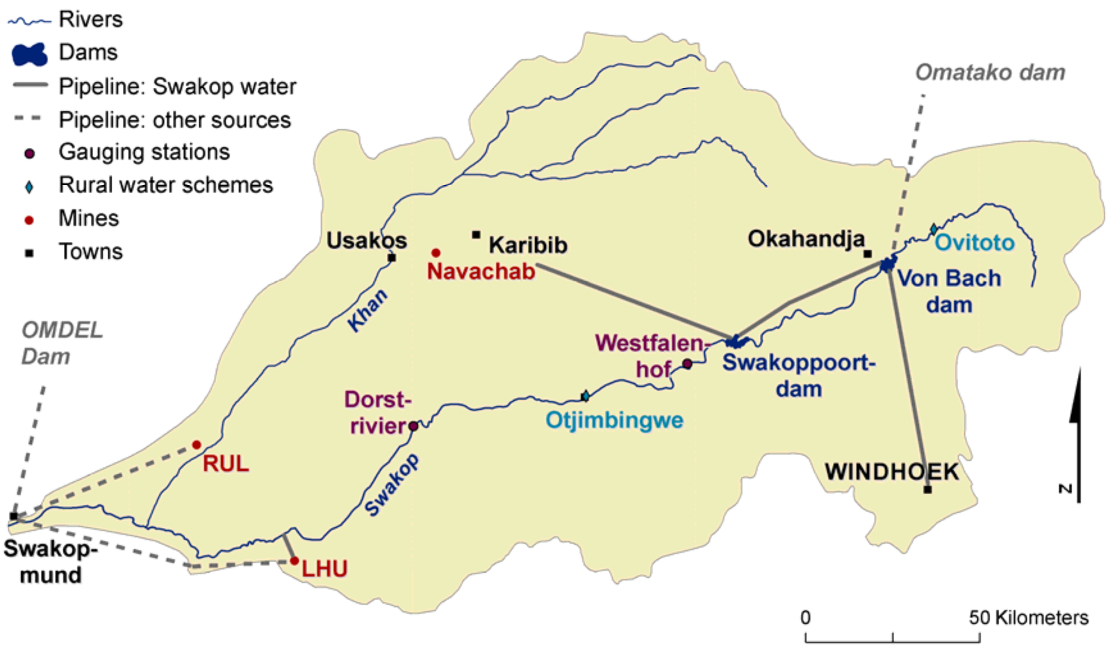


Figure 7: Water supply situation in the Swakop River catchment and schematic location of the pipelines (data source: DWA, ATLAS OF NAMIBIA)

Along the Swakop River there are two water supply schemes (WSS) based on boreholes in the alluvium. The Ovitoto WSS consists of several production boreholes and is located upstream of both dams, adjacent to the Swakop River and some 15 km from Ovitoto. It provides water to the town of Ovitoto (NAMWATER, 1999). Records of the two production boreholes (28250 and 28251) obtained from NamWater show an average abstraction rate of 0.046 Mm³/year. Another WSS is situated downstream of both dams at Otjimbingwe. It consists of 6 individual WSS, comprising of the Otjimbingwe Town WSS as well as five rural WSS (Okaruse, Karikaub, Arueis, Anawood and Huises) operated by NamWater on behalf of the Ministry of Agriculture, Water and Rural Development (NAMWATER, 1999). Production records for the period from 1990 to 1995 indicate an average abstraction of 0.17 Mm³/year (CSIR, 1997). A smallholder farming zone is located between Swakopmund and the confluence with the

Khan River. Here groundwater abstraction for farming purposes was estimated to be 0.55 Mm³/year. The groundwater stored in these lower reaches of the Swakop River is generally brackish and thus unsuitable for human consumption (CSIR, 1997).

Different options to augment the water supply situation in the CAN have been examined in the past decade. Finally it has been decided to artificially recharge the Windhoek aquifer with surplus water from the dam system. Over-abstraction has led to an underground storage facility in this aquifer where the recharged water is better protected from evaporation and can be used for the water supply of Windhoek. This will also serve as a water bank for security of supply during extreme dry periods that result in shortages of surface water (ENVES, 2008).

2.5 Previous studies and data availability

JACOBSON et al. (1995) give a profound overview on Namibia's western ephemeral streams, their catchments and resources. The book points to the relevance of these resources and to the urgent need of plans for a sustainable development in the future. "Groundwater in Namibia- an explanation to the hydrogeological map" (CHRISTELIS & STRUCKMEIER, 2001) synthesises information on groundwater related data, information and knowledge in Namibia. Several investigations on the Swakop River were conducted by the Council for Scientific and Industrial Research (CSIR) starting in the late 60s. Besides, studies on the groundwater occurrence in the lower Swakop were carried out by RUL and the Department of Water Affairs (DWA). Important information on the aquifer characteristics were obtained from pumping tests conducted by the DWA and the Geological Survey, Pretoria (DZIEMBOWSKI, 1970). HELLWIG (1971, 1973a, 1973b) carried out detailed investigations on the evaporation from wet sand including an experimental setup at Gross Barmen in the Swakop River. Furthermore, the loss of water from the Swakop River bed by evaporation and transpiration was determined using a calculation method. From infiltration experiments in the laboratory and in the bed of the Swakop River it was concluded that the formation of an impermeable silt layer during flood events is - even at high velocities - an extremely important factor for the determination of recharge (CREAR et al., 1988).

Within the Central Area Water Master Plan (CAWMP) all hydrological data on the Swakop River and several other catchments in the CAN was reviewed. The report includes the application of the rainfall-runoff model NAMROM (Namibia runoff model) (JVC, 1993). A report on the impact of a proposed recharge dam in the Khan River was compiled for RUL by the Council for Scientific and Industrial research (CSIR) in 1997. The hydrology and hydrogeology of the lower Swakop River was investigated and data on aquifer dimensions and parameters, water quality, groundwater levels, vegetation, evapotranspiration and streamflow were summarised. Furthermore, the report introduces a model which is using a yearly time-step consisting of a hydrological, hydrogeological, sediment and water quality component. The model was applied in order to assess the impact of the existing dams and the proposed Khan scheme on the lower Swakop River.

In Namibia the DWA provided access to the groundwater database (GROWAS) with data on the location of existing boreholes in the Swakop River catchment. The majority of the borehole data contains information on water chemistry and at nine monitoring boreholes in the Swakop River water level data was available. The Hydrology Division shared data on water levels and flood volumes at several gauging stations as well as time series of dam in- and outflow. Additionally, relevant GIS data of the study area was provided and reports on previous studies could be accessed in the DWA archive and library. Water quality and water level data of the boreholes at Ovitoto and Otjimbingwe was obtained from NamWater. Besides, sampling at these two WSS was supported and a general overview on the dams and the water supply situation in the catchment was given.

3 Characteristics of the ephemeral system

This chapter describes the characteristics of the streamflow and groundwater system of the ephemeral Swakop River. Changes in the natural state, which was altered by the construction of the two surface dams, are reported by locals and can be observed from existing data. This holds various consequences for the ADEs downstream.

3.1 Streamflow

The Swakop River originates in the Khomas Hochland in the east and flows westwards to the Atlantic Ocean with a total river length of 460 km. Typical for ephemeral streams, the Swakop River only flows during rainy season after intensive rainfall (JACOBSON et al., 1995). Streamflow is mostly generated in the elevated, uppermost parts of the catchment where there is sufficient precipitation. Downstream of the gauging station Dorstrivier (figure 7) a zone of depletion of flood waters starts as annual rainfall is below 150 mm and there are no significant tributaries other than the Khan River (CSIR, 1997).

Within the review of literature and data on the hydrology of the Swakop River it turned out that it is rather difficult to obtain streamflow records downstream of the dams of sufficient length and quality. This is a problem typical in arid regions as measuring of floods in ephemeral streams is complicated due to their erratic and destructive nature. In order to show the impact of the dams on the streamflow of the Swakop River, records of gauging stations located downstream of the dams are required. The streamflow records at these gauging stations, Westfalenhof and Dorstrivier, are partly incomplete and the latter has been constructed only after the dams were built. In this study, observed data at Westfalenhof were used to show the impact of the dams on the hydrological regime of the Swakop River. Figure 8 displays annual streamflow (1962-2005). A first visual assessment of the record shows that streamflow was clearly influenced by the construction of the Swakoppoort Dam in 1978. Afterwards, annual streamflow decreased to almost zero and only the spills in 1988/89 resulted in significant floods. It is important to note that from 1997 to 2000 and in 2004/05 most of the year no data was recorded at Westfalenhof and in most of all the years, data has been partly estimated. Swakoppoort Dam spilled again in 2006 and 2008. For these recent years no streamflow data from the gauging station is yet available.

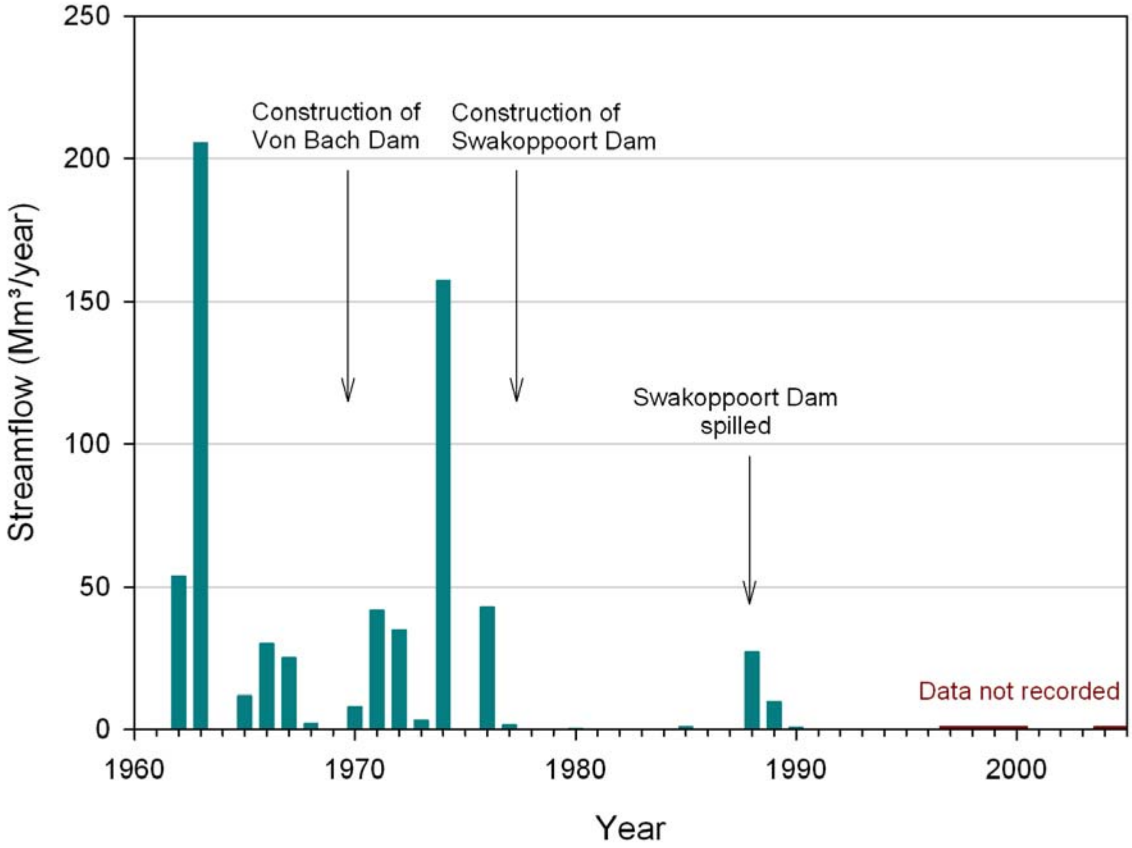


Figure 8: Annual streamflow at Westfalenhof (data source: DWA)

In this study flow duration curves (FDCs) have been constructed from the monthly record (1962-1996) at Westfalenhof according to DINGMAN (2002). Therefore, the record has been divided into three periods: before, between and after the dam construction (figure 9). In the period between 1996 and 2005 almost no data was recorded why it has not been included in the analysis. The curves describe the percentage of time that a certain streamflow volume is equalled or exceeded. It is shown that, after both dams were completed, the volume of monthly streamflow equaled or exceeded for a certain time was reduced significantly. Furthermore, maximum values decreased by one order of magnitude.

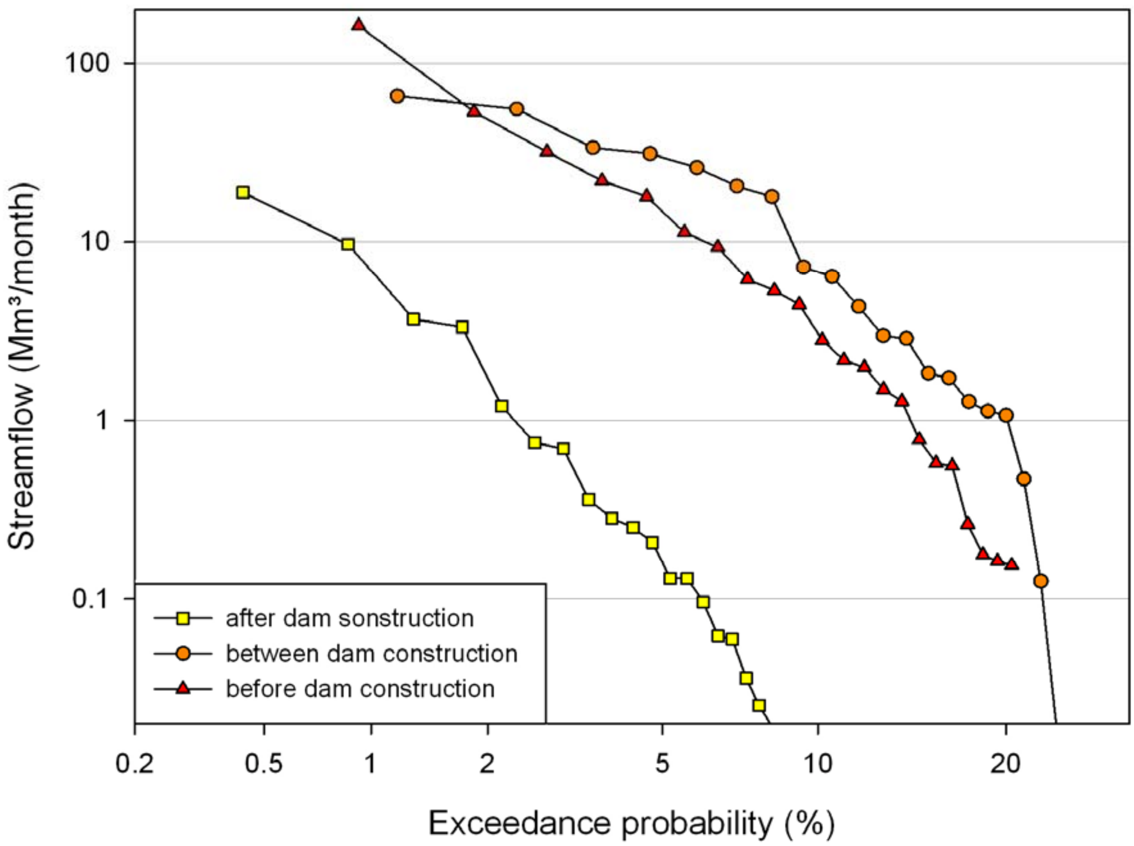


Figure 9: FDCs for monthly streamflow at Westfalenhof (data source: DWA)

In the CSIR report (1997) the modelling results indicate that the mean reduction in the volume of streamflow in the lower Swakop River is approximately 40 % since the two dams are completed. Furthermore, the contribution to streamflow from the Khan River increased from 13 to 20 %. The model is based on various simplifying assumptions and was calibrated with streamflow data based on observations and not on measurements.

Due to high uncertainties associated the streamflow data and the model approach in the CSIR report (1997), the results are regarded qualitatively rather than quantitatively. However, it is obvious that the construction of the two surface dams significantly altered the hydrological regime of the Swakop River.

3.2 Groundwater

As mentioned above, in the Swakop River catchment, streamflow is generated in the headwaters after intense rainfall. The flood moves downstream, infiltrates into the alluvium and recharges the alluvial aquifer indirectly. Figure 10 shows the monthly streamflow at Dorstrivier and the response of the water table in the alluvium to indirect recharge. The boreholes are located between 15 and 30 km downstream of the gauging station Dorstrivier. All of them show an instantaneous reaction to flood events which underlines the close interdependency of the flood regime and the alluvial aquifer.

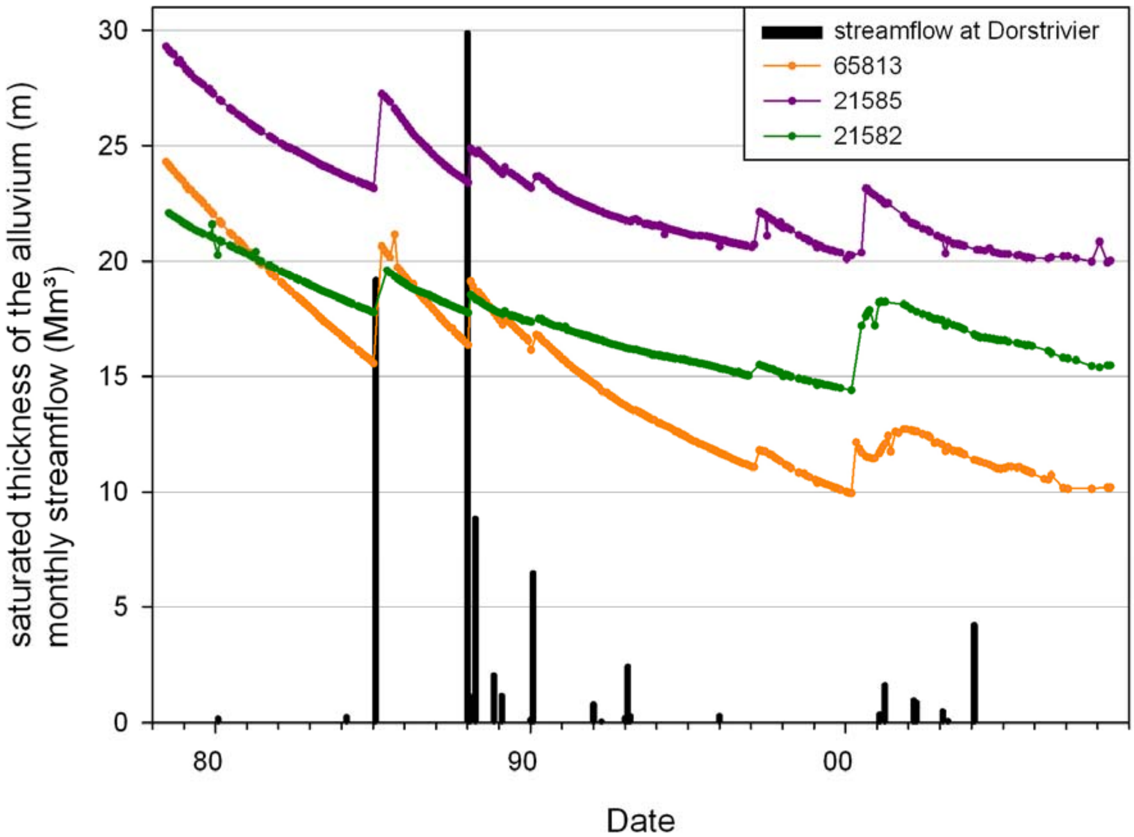


Figure 10: Monthly streamflow at Dorstrivier and groundwater level response (data source: DWA)

The flood event in February 1985 is not complete as data were lost. No data were recorded in 1996/1997, but the groundwater levels show a response of the aquifer. In this summer period, widespread rains were recorded over large parts of Namibia. The Swakop River as well as the neighbouring rivers, Kuiseb and Omaruru, were all in flood this year (1997) and the Swakop River even reached the sea. The runoff volumes have been below average and particularly poor in 1994/1995 and 1995/1996 rainy seasons (CSIR, 1997).

The water tables of the DWA monitoring boreholes shown in figure 10 dropped by 7 m (21582), 9 m (21585) and 14 m (65813) between 1978 and 2008. In the CSIR report (1997) water levels in the farming zone of the lower Swakop River have been found to continue to drop approximately 0.07 m/year

3.3 Aquifer dependent ecosystems

The ADEs of the Swakop River can serve as indicators for changes in the hydrological system. In a study recently conducted by DOUGLAS (2008) it was evidenced that the hydrological changes and the invasive species Prosopis have a negative impact on the native species and thus the health of the riparian ecosystem. The reduced floods and consequently reduced groundwater recharge in the Swakop River influence the trees with regards to mortality, die-back and recruitment. Prosopis is efficient at sourcing water and together with a reduction in groundwater recharge, the water availability for Ana Trees is being reduced (DOUGLAS, 2008). Similarly, large-scale die-back of Ana Trees along the Kuiseb River has been observed as a consequence of falling groundwater tables due to excessive abstractions near Walvis Bay (CSIR, 1997). Locals recently report an increase in die-back of Ana Trees and at the same time a spreading of the invasive species Prosopis along the Swakop River downstream of the dams. The farm Graceland is located between the two dams at the Swakop River just upstream of the confluence with the Okahandja River where streamflow is undisturbed by dams. The farmer states that the vegetation density, consisting mainly of Prosopis, is much higher in the Swakop River than in the Okahandja River (BASSINGTHWAIGHTE, 2008) (figure 11). At the farm Westfalenhof, downstream of Swakoppoort Dam, the water table was dropping rapidly after the dam construction and lots of dead Ana Trees were observed. In 2005 the borehole in the alluvium dried out and several trees were irrigated to be kept alive (REDECKER & REDECKER, 2008). In the CSIR report (1997) it is noted that in the lower Swakop River the reduced floods have promoted Prosopis and Tamarisk growth which leads to increased transpiration losses.

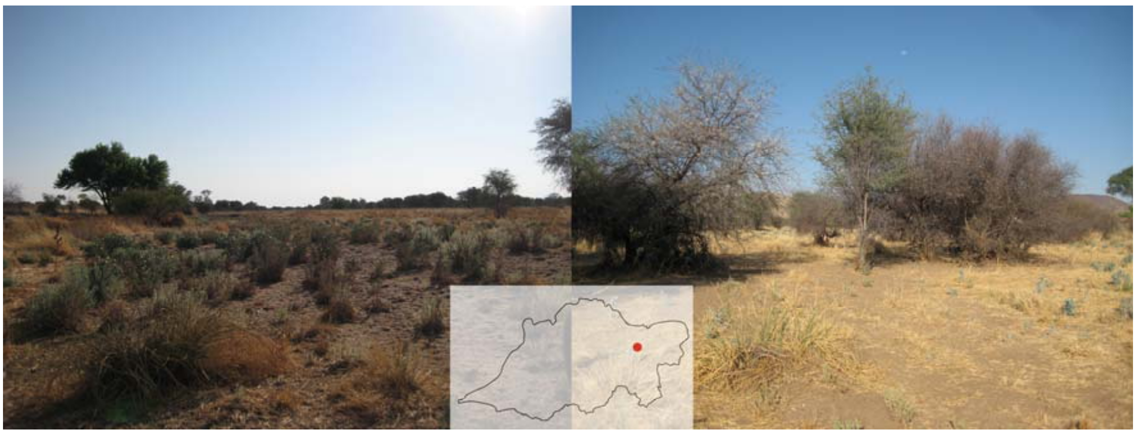


Figure 11: Riparian vegetation in the Okahandja (left) and Swakop (right) River at the farm Graceland

4 Longitudinal sampling profile

In the previous chapter it is shown that the hydrological regime was altered by the construction of the two surface dams and that the alluvial aquifer is closely linked to streamflow. In order to characterise the groundwater system and to assess the impact of environmental changes on a large scale, a longitudinal sampling profile was taken along the Swakop River. The analysed parameters (stable isotopes of water, major ions, trace elements, chlorofluorocarbons and sulphur hexafluoride) give information not only on the water quality but are also indicators for groundwater recharge.

4.1 Methodology

4.1.1 Sampling locations

Between 14.08.2008 and 15.10.2008 a longitudinal profile of groundwater samples was taken in the Swakop River catchment. Figure 12 shows the location of the sampled boreholes along the alluvial aquifer and in the adjacent bedrock. The sampling points were chosen on the basis of the DWA database GROWAS while the final pattern was also partly determined by the accessibility to the boreholes. Bittner Water Consult (BIWAC) supported the sampling campaign with transport, expertise and pumping equipment. The groundwater samples were taken after the borehole was purged and the field parameters, electric conductivity and water temperature, stabilised. These parameters as well as pH and dissolved oxygen were measured. The key data on each borehole are summarised in table 2.

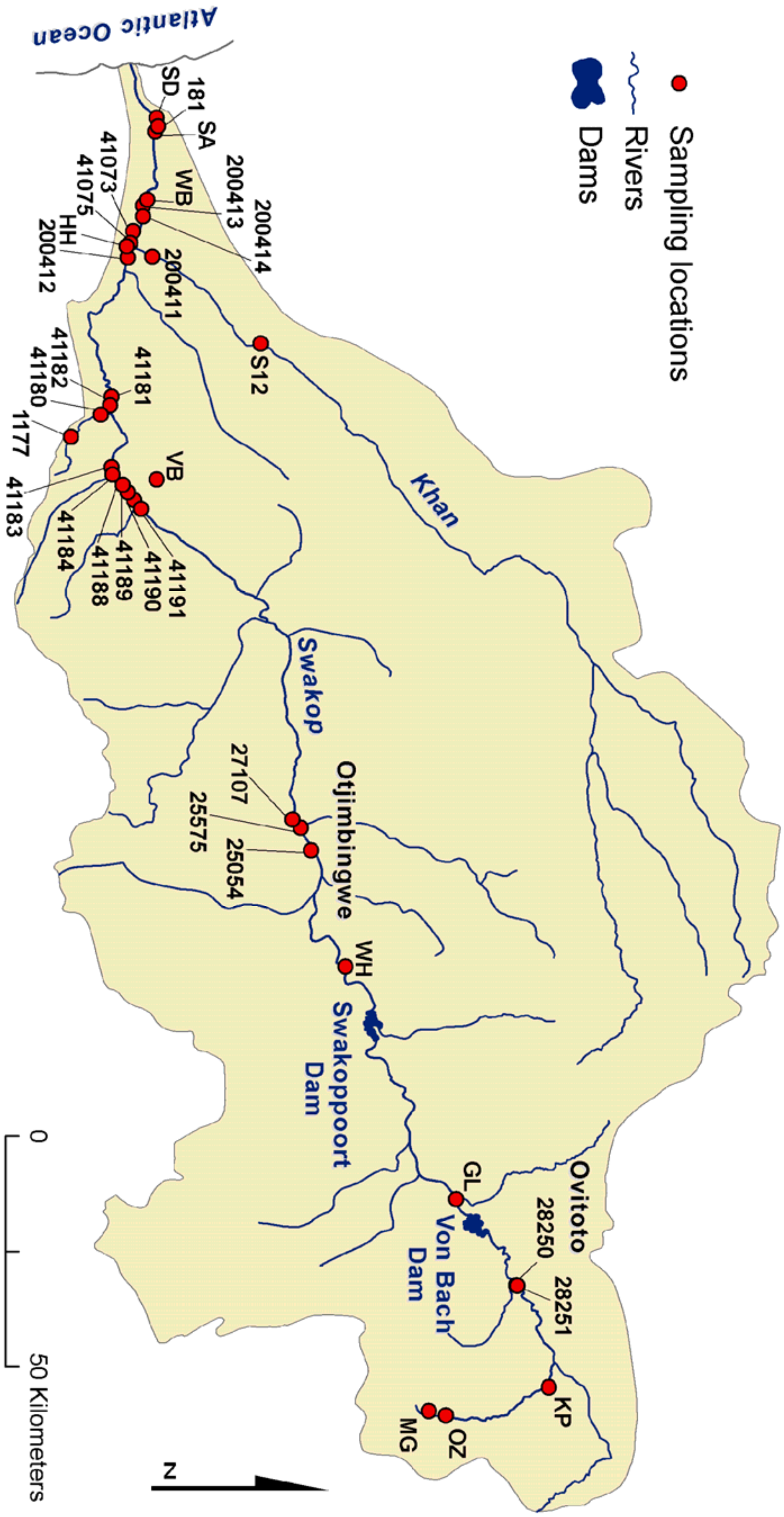


Figure 12: Sampling locations in the Swakop River catchment

Table 2: Key data on the sampling points

Labnumber	Wellnumber	Location	Latitude	Longitude	Altitude	River segment	Sampling date	BH depth	RWL	Water temperature	Electric conductivity
			dec. deg.	dec. deg.	m	km		m	m	°C	mS/cm
IHF_21866	MG	SR alluvium	-22.08751	17.36535	1496	404.6	11.10.2008			24.90	0.556
IHF_21843	OZ	SR alluvium	-22.05360	17.37451	1545	400.7	11.10.2008	45.0		22.40	0.115
IHF_21856	KP	SR alluvium	-21.85202	17.31221	1461	375.1	01.09.2008	100.0	35.00	23.90	0.554
IHF_21855	28251	schist/SR alluvium	-21.91717	17.10044	1425	347.7	01.09.2008	32.9	20.00	25.00	0.980
IHF_21854	28250	schist/SR alluvium	-21.91831	17.09873	1438	347.6	01.09.2008	33.0	18.00	24.70	1.106
IHF_21842	GL	SR alluvium	-22.03995	16.91975	1316	318.5	11.10.2008	80.0	13.00	23.70	0.488
IHF_21836	WH	SR alluvium	-22.26226	16.43104	1025	248.2	15.10.2008	8.0		26.60	0.998
IHF_21865	25054	SR alluvium	-22.33270	16.18630	895	213.8	09.10.2008	21.0	3.90	25.40	0.304
IHF_21847	25575	SR alluvium	-22.35306	16.13827	883	208.1	09.10.2008	8.4	2.95	26.10	0.954
IHF_21845	27107	SR alluvium	-22.36954	16.12118	870	205.7	09.10.2008	12.0		24.90	0.684
IHF_21835	41191	SR alluvium	-22.67072	15.46583	516	116.4	30.09.2008	29.0	11.79	27.90	2.610
IHF_21832	41190	SR alluvium	-22.68421	15.44658	501	113.8	30.09.2008	26.0	8.95	28.10	2.570
IHF_21837	41189	SR alluvium	-22.69666	15.42968	491	111.6	30.09.2008	22.0	5.73	28.00	2.410
IHF_21841	VB	granite	-22.64036	15.40287	728		01.10.2008	31.0	14.75	28.70	6.710
IHF_21840	41188	SR alluvium	-22.70691	15.41438	476	109.8	30.09.2008	21.0	3.72	27.50	2.220
IHF_21833	41184	SR alluvium	-22.72695	15.39308	460	106.4	01.10.2008	20.0	7.30	27.70	4.500
IHF_21834	41183	SR alluvium	-22.72939	15.37729	488	104.8	18.09.2008	19.0		28.20	4.170
IHF_21857	1177	tributary alluvium	-22.80931	15.31274	609		18.09.2008	41.2	7.53	30.00	12.480
IHF_21838	41180	tributary alluvium	-22.75087	15.26581	478		18.09.2008	41.6	10.54	29.10	9.600
IHF_21839	41182	SR alluvium	-22.73164	15.24620	357	88.5	18.09.2008	13.9	4.78	28.00	11.870
IHF_21846	41181	SR alluvium	-22.72947	15.22771	347	86.5	18.09.2008	12.4	5.12	28.60	10.110
IHF_21851	200412	SR alluvium	-22.69801	14.93269	209	48.1	14.08.2008	21.5	14.24	25.70	8.400
IHF_21860	HH	SR alluvium	-22.69926	14.90894	203	45.3	20.09.2008	14.0	8.00	28.30	6.990
IHF_21844	200411	tributary alluvium	-22.64910	14.93096	223		14.08.2008	22.7	18.54	27.80	5.790
IHF_21853	S 12	tributary alluvium	-22.43557	15.11418			15.08.2008	47.5	9.10	29.40	14.890
IHF_21852	41075	SR alluvium	-22.69253	14.90157	193	44.4	14.08.2008	17.9	7.18	28.10	6.860
IHF_21850	41073	SR alluvium	-22.68691	14.87644	180	41.6	14.08.2008	19.5	4.92	26.80	9.050
IHF_21849	200414	SR alluvium	-22.66777	14.84548	162	37.0	14.08.2008	30.9	10.11	26.60	10.050
IHF_21848	200413	SR alluvium	-22.66748	14.82314	151	34.4	14.08.2008	23.5	5.45	26.80	12.440
IHF_21859	WB	SR alluvium	-22.65929	14.81063	143	32.8	20.09.2008	15.0	8.00	26.40	14.160
IHF_21863	SA	SR alluvium	-22.64272	14.66568	41	16.4	02.10.2008	20.0	10.00	25.00	9.640
IHF_21864	181	schist and dolomite	-22.63758	14.65394	76	14.9	02.10.2008	14.0	4.00	26.20	11.700
IHF_21862	SD	schist and dolomite	-22.64014	14.63680	84	13.2	20.09.2008	14.0	6.30	24.60	15.680

Information on each sampling location, based on borehole completion reports, field observations and communication with farmers, is given below. The boreholes are sorted according to their location along the Swakop River, starting in the upper catchment.

Upstream of both dams

Midgard (MG), Otjiozonjati (OZ) and Katjapia (KP) are boreholes on farms in the most upper-most part of the Swakop River catchment. They are located approximately 100 to 200 m next to the riverbed. According to the farmers these boreholes are strong yielding, react on seasonal floods and never run dry. The boreholes supply water to a camping site (MG) and cattle post (OZ, KP).

28251 and 28250 are production boreholes for the water supply of Ovitoto and were sampled in cooperation with NamWater. They are drilled in the Otjisazu Igneous Complex that is an intrusive body into the local schist. Their location is just north of the confluence of the Otjisazu and Swakop Rivers. It is assumed that the major source of groundwater recharge occurs from floods in the Swakop River (NAMWATER, 1999).

Between the dams

The borehole on the farm Graceland (GL) was located 80 m away from the riverbed before the dams were constructed. Thereafter, the channel narrowed and today the borehole is about 200 m distant from the channel. In 2002 the water level was at 26 m below ground and fell until 57 m below ground. Intense rainfall resulting in Von Bach Dam spilling in 2006 recharged the borehole to a waterlevel of 9 m below ground.

Downstream of both dams

The borehole at the farm Westfalenhof (WH) lies in the alluvium about 14 km downstream of Swakoppoort Dam. According to the farmer, waterlevels never dropped below 4 m below ground. before the dam was constructed. In 2005 the borehole fell dry, but was recharged during the following rainy season.

25054 (Okaruse), 25575 (Town) and 27107 (Karikaub) are part of the water supply scheme for Otjimbingwe and its rural extensions. All three boreholes are situated in the alluvium of the Swakop River. Water is pumped on a daily basis or several times a week. Due to high water demand several boreholes of the water scheme have been over-utilised in the past.

LHU has several boreholes in the alluvium for monitoring and production. 41191, 41190, 41189, 41188 and 41184 are monitoring boreholes in the alluvium of the Swakop River. 41183 is a production borehole, also located in the alluvium, from where water is pumped to the mining area for dust prevention. Downstream of 41191 the saturated thickness of the alluvium decreases and downstream of 41183 the vegetation density increases which indicates the presence of a bedrock-high. The boreholes 41182 and 41181 are located downstream of the confluence with the Gawib River. 41180 is a borehole in the alluvium of the Gawib River about 2 km upstream of the confluence with the Swakop.

LH1177 belongs to the LHU mine and lies in the Gawib River close to the mining area and about 10 km upstream of the confluence with the Swakop River.

Vlakbank (VB) is a borehole in the adjacent bedrock (granite) near a Nature Conservation house located about 7 km north of the Swakop River. The borehole is very low yielding and hence sampling had to commence shortly after purging.

200412 is one of RUL's monitoring boreholes in the alluvium of the Swakop River. The borehole is low yielding and was pumped empty while purging the day before, but recovered sufficiently for sampling.

The farm Hildenhof (HH) is located in the Swakop alluvium just upstream of the confluence with the Khan River. The borehole, located next to the active channel, is strong yielding and pumped daily for farming purposes.

200411 and S12 are boreholes of RUL located in the alluvium of the Khan River approximately 6 km upstream of the confluence with the Swakop River and close to the mining area in a small Khan tributary, respectively.

41075, 41073, 200414 and 200413 are monitoring boreholes of RUL and were sampled together with the other RUL boreholes during a sampling campaign with BIWAC. The boreholes are located in the alluvium of the Swakop River downstream of the confluence with the Khan River.

The borehole on the farm Weizenberg (WB) is located in the alluvium of the Swakop River close to the active main channel supplying water for farming.

Swakopmund Asparagus SA is part of farming zone of the lower Swakop River. Groundwater is pumped from a well-field in the alluvium to a pond on the adjacent farm for irrigation of asparagus and olive trees. The farmer reports problems with mica which frequently causes blocked dripper lines. According to him, there are huge differences in groundwater quality between surrounding farming plots. In this area waterlines and driftwood of huge flood events in the 30's and 40's can be found.

The borehole at Sofia Dale (SD) is located around 900 m north of the Swakop River. According to the owner, the recharge area has been identified to be the Erongo Mountains or highlands around Arandis. Recharge by the Swakop River can be excluded due to a higher waterlevel in the borehole than in the riverbed. This seems to be the case at the borehole on farm 181 as well. At both plots the pumped groundwater is used for irrigation.

At each sampling point several bottles for parameter analyses were filled (figure 13):

Stable isotopes of water:	34	x	50 ml
Major ions:	29	x	100 ml
Trace elements:	24	x	250 ml
CFC/SF6:	14	x	1000 ml

Water samples for stable isotopes, major ions and trace elements were taken in PE bottles and the ones for trace elements were filtered (0.45 µm) in the field and acidified with HNO_3 (55 % Univar) for preservation. The sampling and storage of water for CFC and SF_6 analyses is explained below. All samples were sent to Germany by curier in October 2008 for analyses.

Figure 13: Sizes of sampling bottles for different parameters

4.1.2 Stable isotopes

The stable isotopes of water ^{18}O and ^{2}H are commonly used for hydrogeological investigations today as a complement for geochemistry and physical hydrogeology. As the isotopic composition of water is modified by meteoric processes, recharge waters of a certain environment carry a very specific signature (CLARK & FRITZ, 1997). Hence, stable isotopes provide an applicative tool for studying the origin and history of groundwater as well as recharge mechanisms (VOGEL & VAN URK, 1975).

Isotopes of an element have the same chemical characteristics but different nuclear masses. With modern measurement techniques, variations in isotope abundance can be detected with high precision. The isotope abundance ratios *R* for water are defined as:

$$R = \frac{^{18}O}{^{16}O} \text{ and } R = \frac{^{2}H}{^{1}H} \quad (1)$$

Isotopic concentrations δ are expressed in ‰ as the difference between the measured ratio and a standard, in most cases Vienna Standard Mean Ocean Water (VSMOW):

$$\delta = \frac{R_{sample} - R_{reference}}{R_{reference}} \cdot 1000 \quad (2)$$

The isotope abundance ratios are altered by fractionation processes due to higher binding energies of the heavier isotope compounds. At phase transitions more energy is needed to lift them to a higher energetic level. In turn, the lighter compounds change their state more easy. Isotope fractionation can be described by the fractionation factor α which is the ratio of the isotope ratios for the reactant and product:

$$\alpha = \frac{R_{reactant}}{R_{product}} \tag{3}$$

Lower temperatures result in greater differences in binding energies which enhances fractionation effects (CLARK & FRITZ, 1997). Different fractionation processes occur throughout the hydrological cycle resulting in a variety of fractionation effects (DANSGAARD, 1964): altitude effect, seasonal effect, amount effect, continental effect and latitude effect. The Global Meteoric Water Line (GMWL) defines the specific relationship for ^{18}O and ^{2}H in precipitation (CRAIG, 1961):

$$\delta^2 H = 8 \cdot \delta^{18} O + 10 \tag{4}$$

In many cases, the isotopic composition of groundwater equals the weighted mean annual composition of precipitation. However, in semi-arid and arid regions the isotopic composition of groundwater can differ notably from that of local precipitation. The isotopic signal in precipitation can be modified by several processes during recharge. Evaporation during runoff and infiltration is generally associated with indirect groundwater recharge while evaporation from the unsaturated zone is prevalent when groundwater is recharged directly (CLARK & FRITZ, 1997). Figure 14 shows that flood recharged groundwater can have an isotopic composition which is lighter compared to that of average rain (GAT, 1996). Its composition rather corresponds to that of exceptionally heavy downpours which indicates that groundwater recharge in these areas occurs sporadic and only after very high rainfall events (VOGEL & VAN URK, 1975). Further changes in the isotopic composition can result from mixing of groundwater types with different isotopic signatures (KÜLLS, 2000).

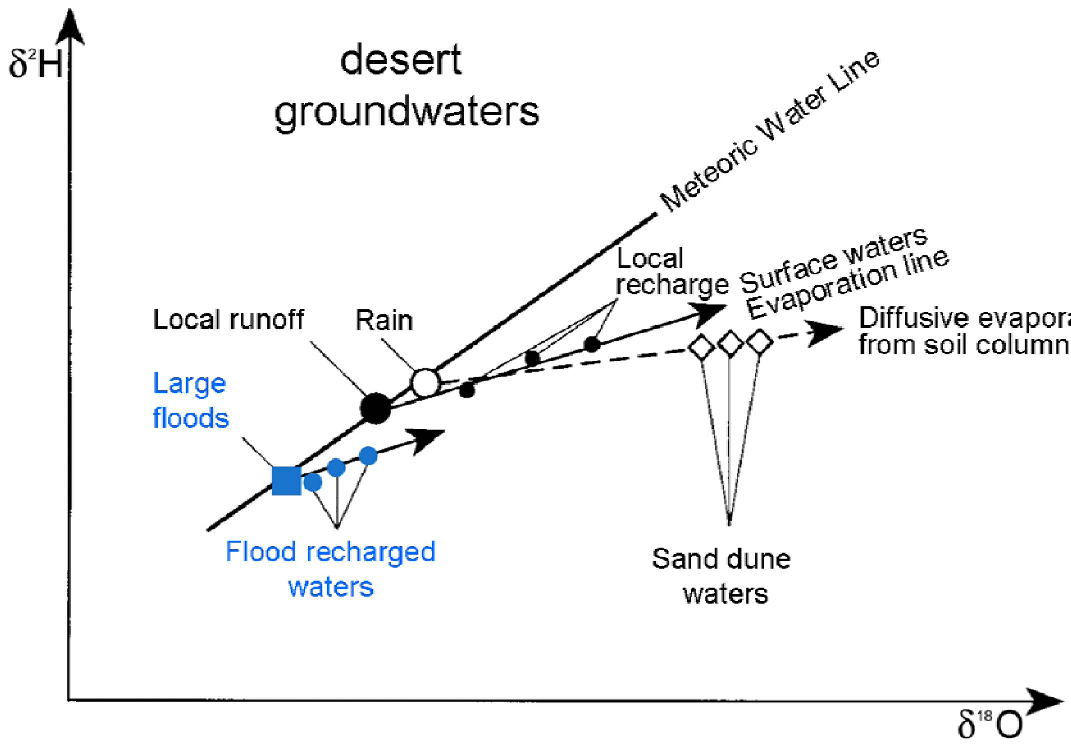


Figure 14: Groundwater formation in deserts and the isotopic composition (modified from GAT, 1996)

The isotopic composition of a groundwater sample, before evaporative enrichment occurred, can be obtained using the following equation (KÜLLS, 2000):

$$\delta^{18}O_{corrected} = \frac{\delta^{2}H_{measured} - e \cdot \delta^{18}O_{measured} - d}{8 - e} \qquad (5)$$

where e is the slope of the evaporation line and d is the deuterium excess of global precipitation. The corrected values help to better characterise the source area

In this study, ^{18}O and ^{2}H both were analysed in the laboratory of the Instiute of Hydrology in Freiburg. Analysis of ^{18}O was conducted with the Isotope Ratio Mass Spectrometer (IRMS) Type Delta S, produced by Finnigan Mat, with a measuring error of 0.2 ‰. ^{2}H was analysed by a Liquid Water Isotope Analyzer with the Tunable Diode Laser Absorption Spectrometry (TDLAS), Los Gatos Research. The measuring error for the TDLAS is 0.6 ‰ (LOS GATOS RESEARCH, 2008).

4.1.3 Major ions

Analysing the composition of major ions in groundwater contributes to a better understanding of the hydrogeochemistry of a system and thus can provide more information on the origin and quality of groundwater. The Swakop River catchment consists of several different geological units and the major ion chemistry of the groundwater samples is expected to help in identifying sources and areas which contribute to the different aquifer segments.

The analysis of anions and cations was conducted in the laboratory of the Institute of Hydrology in Freiburg with an ion chromatograph (IC) DX 500 from Dionex. The samples were analysed for chloride (Cl), nitrate (NO_3) and sulphate (SO_4) as well as for sodium (Na), potassium (K), magnesium (Mg) and calcium (Ca). All samples were filtered with a 0.45 µm membrane and some of them were diluted. The different calibration standards which were used in the measuring series range from 0.5 – 100 mg/l. The volume for analysis was 5 ml for anions and 5 ml for cations. For anions the measurement error is around 4 % and for cations around 5 %. Bicarbonate (HCO_3) and Total Dissolved Solids (TDS) were later on calculated with the software AQUACHEM. A useful graphical format to present major ions data are Piper and Schoeller diagrams which were produced with the software AQUACHEM.

4.1.4 Trace elements

Trace elements are commonly analysed within baseline studies. Data sets of trace elements may provide valuable information for evaluating groundwater flow histories. In the Swakop River catchment uranium concentrations in groundwater are of special interest and need to be carefully monitored due to the mining activities.

Trace elements were analysed by the Regierungspräsidium Freiburg, Landesamt für Geologie, Rohstoffe und Bergbau with Inductively Coupled Plasma Mass Spectrometry (ICP-MS).

4.1.5 Fluoride and Silicate

Fluoride (F) was analysed in order to get additional information on the natural background of SF_6. The concentrations of silicate (SiO_3) in groundwater are determined by pH, T , rock type and residence time (UHLENBROOK, 1999). Groundwater in the bedrock is expected to have long residence times resulting in higher SiO_3 concentrations. Therefore, it can be used to detect lateral inflow from the basement into the alluvium.

F was analysed SiO_3 by photometry and F with an ion selective electrode in the laboratory of the Institute of Hydrology, Freiburg.

4.1.6 CFCs and SF_6

For a better understanding of the hydrological system, knowledge about the age of groundwater and residence times is important and provides integrated information on groundwater dynamics, groundwater recharge and helps to define sustainable yields. The age of groundwater can be determined knowing the concentrations of anthropogenic trace gases like chlorofluorocarbons (CFCs) and sulphur hexafluoride (SF_6) in groundwater. These concentrations can be, compared to some other dating techniques, rapidly determined and the sampling procedure and the analysis are relatively simple (GOODDY et al., 2006). The CFC method was developed during the last 20 years and has been used as an age dating tool in numerous studies in the USA (BUSENBERG & PLUMMER, 1992; COOK et al., 1995) and in Europe (GOODDY et al., 2006;OSTER et al., 1996). SF_6 was often applied solely or in multi-tracer studies (BAUER et al., 2001; BUSENBERG & PLUMMER, 2000). More recently the methods have been applied in arid regions of Africa (EL-GAMAL, 2005; WACHTLER, 2006).

Groundwater age, using the CFC and SF_6 method, refers to the date when the water was isolated from the soil atmosphere and recharged to the groundwater system. It is based on certain simplifying assumptions and hence is an apparent or model age. The isolation of water from the unsaturated zone is dependent on the recharge rate, porosity of the unsaturated zone soil, aqueous und gaseous diffusion coefficient and magnitude of water table fluctuations (PLUMMER & BUSENBERG, 2000).

CFCs

The CFC method forms an alternative to well established methods like age dating with tritium which has become constantly unreliable as atmospheric concentrations are declining, especially in the southern hemisphere. CFCs are volatile, synthetic compounds of carbon, chlorine and fluorine whose commercial production started at the beginning of the 1930s. CFCs are non flammable, very low in toxicity, and used for various industrial and refrigerant applications. Production of CFC-12 (dichlorodifluoromethane) was followed by CFC-11 (trichlorofluoromethane) and then most notably by CFC-113 (trichlorotrifluoroethane). After release to the atmosphere, CFCs entered into the hydrological cycle. During the 70s and 80s the mixing ratios in air showed a monotone increase (figure 15). CFCs are a major contributor to the depletion of the ozone layer and hence, several nations agreed to limit production in 1987 and to cut off in 1996. Therefore, concentrations are decreasing since the late 80s (IAEA, 2006). Table 3 summarises some important characteristics of the three different CFC compounds.

Table 3: Characteristics of CFC-11, CFC-12 and CFC-113 (IAEA, 2006;VOLK et al., 1997)

	CFC-11	**CFC-12**	**CFC-113**
chemical formula	$CFCl_3$	CF_2Cl_2	$C_2F_3Cl_3$
production start	1936	1930	1944
cumulative production in the 80s (Mio. t)	7.7	10.2	2.4
atmospheric peak (northern hemisphere)	1994	2001	1996
lifetime (years)	45 ± 7	87 ± 17	100 ± 32
recharge estimation	post-1950	post-1945	post-1957

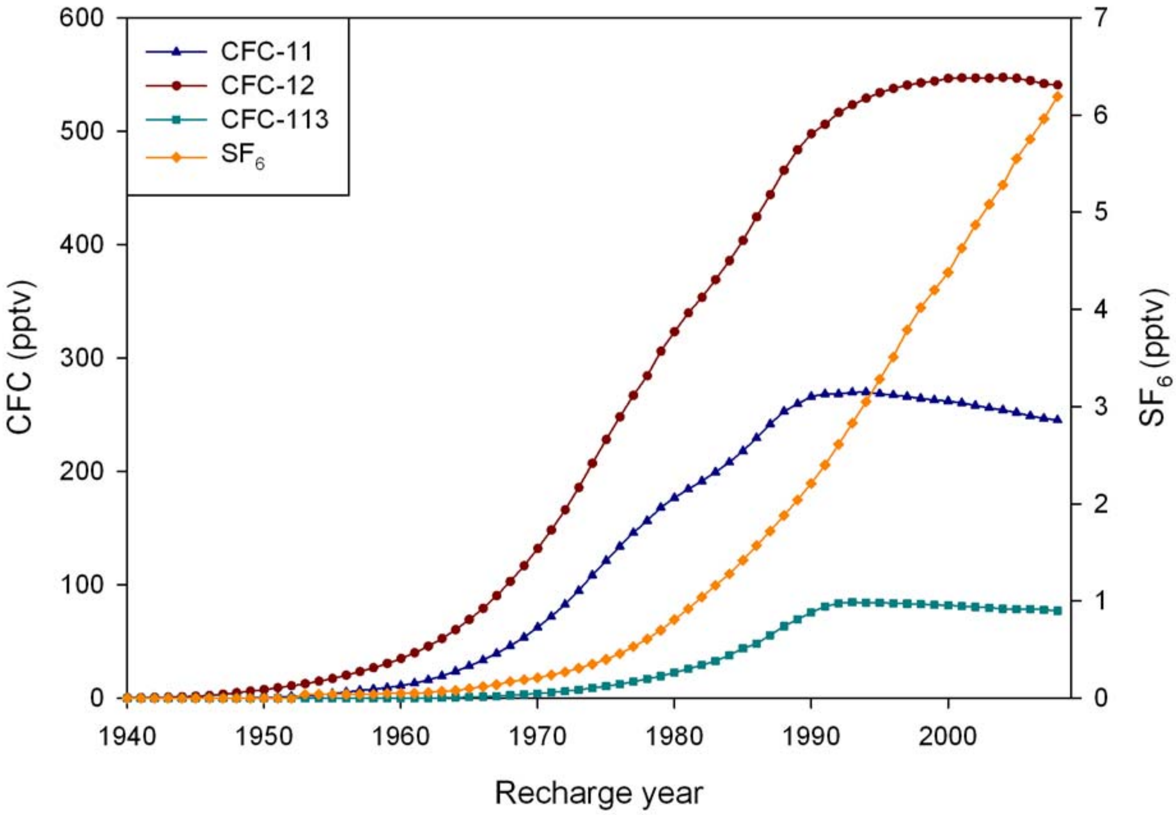


Figure 15: Atmospheric input functions for CFC and SF_6 on the southern hemisphere (data source: CDIAC, 2008)

Age dating with CFCs is based on the following principles (IAEA, 2006):

- the history of atmospheric CFC concentrations, the input function, is known or has been reconstructed
- Henry's law solubilities are known as a function of temperature, pressure and salinity
- concentrations in air and young groundwater can be measured sufficiently precise

With the CFC method, the historical date at which a parcel of water was recharged to a groundwater system can be estimated. An important assumption is that at this point the water sample was in solubility equilibrium with the unsaturated zone. Therefore temperature and pressure during recharge have to be estimated. To determine the recharge date, groundwater concentrations of dissolved trace gases are converted to original atmospheric concentrations and then compared to the input function. This conversion allows comparing multiple samples which were recharged under different conditions. The required calculation procedure is shown below according to IAEA (2006). In order to estimate the total atmospheric pressure p during recharge, the recharge altitude h (m a.s.l.) is needed:

$$\ln p = \frac{-h}{8300} \tag{6}$$

The CFC method is based on Henry's law saying that the dissolved concentration c_i (mol/l) is a function of partial pressure p_i (Pa) and of the Henry constant k_{Hi} (mol/l Pa):

$$c_i = k_{Hi} \cdot p_i \tag{7}$$

While p_i is defined as:

$$p_i = x_i \left(p - p_{H_2O}\right) \tag{8}$$

where x_i is the volumetric ratio of gas in air in parts per trillion by volume (pptv) and p_{H_2O} is the water vapour pressure (Pa). k_{Hi} is calculated, taking the temperature and salinity dependence into account:

$$\ln k_{Hi} = a_1 + a_2\left(\frac{100}{T}\right) + a_3 \ln\left(\frac{T}{100}\right) + S\left[b_1 + b_2\left(\frac{T}{100}\right) + \left(\frac{T}{100}\right)^2\right] \tag{9}$$

where T is the temperature (K) and S the salinity (‰). The coefficients for calculating k_{Hi} are given in the appendix (B.1) (IAEA, 2006). The measured concentrations c_i are used to calculate the initial gas concentration which then is compared to the input function in order to determine the age of the groundwater sample:

$$x_i = \frac{c_i}{k_{Hi}(p - p_{H_2O})} \qquad (10)$$

Various models can be applied to determine the groundwater age, e.g. the piston flow and the exponential model (figure 16).

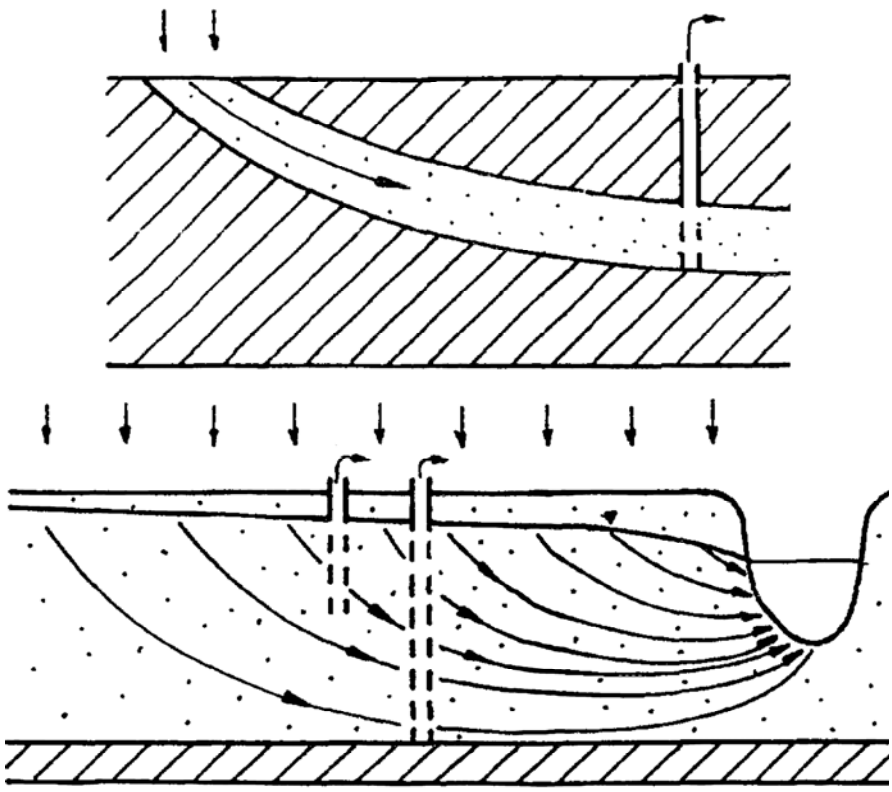


Figure 16: Schematic situations showing the possible application for the PM (above) and the EM (below) (modified from MALOSZEWSKI & ZUBER, 1996)

The piston flow model (PM) is based on the assumption that the travel time through the unsaturated zone is minimal and that groundwater molecules move by advection only. Other transport processes between the point of recharge and sampling must be insignificant or absent. Recharge occurs concentrated on a zone which is negligible small in the direction of flow. Although the PM is based on certain simplifying assumptions, its application may be convenient for fast and easy estimations. Applying the exponential model (EM), it is assumed that the residence times are distributed exponentially. It can be applied to unconfined aquifers with constant thickness and uniform recharge. Latter is the reason that residence times adding up to the sample are very variable (MAŁOSZEWSKI & ZUBER, 1996). In alluvial aquifers groundwater recharge according to the PM can occur in zones of local preferential recharge. The EM can be applied for alluvial aquifers based on the conception of so-called recharge patches at each borehole. These patches represent zones upstream of the borehole where the alluvium is recharged uniformly by floods. Furthermore, a mixing model can be used to estimate the recharge year. Thereby it is assumed that an old, CFC-free component mixes with a recent component (IAEA, 2006). Since CFC concentrations in the atmosphere are not a linear function of time, mixing calculations should be conducted only with dissolved concentrations in pmol/l. For that reason, the calculated atmospheric concentrations are converted into dissolved concentrations again where standard conditions of T, h and S are used to calculate k_H.

With each CFC compound a recharge year is determined resulting in three recharge years for each sampling location. According to the guidelines of the USGS CFC LAB (2008) groundwater age can be assigned as follows:

- If all three recharge years agree, the results are most reliable.
- If the recharge years determined with CFC-11 and CFC-12 agree and the recharge year determined with CFC-113 indicates a younger age, mixing may have occurred. This results from atmospheric concentrations of CFC-113 having a modest increase relative to CFC-11 and CFC-12.
- If the CFC-12 and CFC-113 recharge years agree and the recharge year determined with CFC-11 indicates an older age, CFC-11 has likely been degraded.

While applying the CFC method it has to be considered that several effects and processes can modify the groundwater age (IAEA, 2006): ccontamination, unsaturated zone transport, recharge temperature, sorption, microbial degradation, matrix diffusion, hydrodynamic dispersion and excess air. Latter causes higher dissolved CFC concentrations in groundwater than can be explained by equilibrium solubility with the atmosphere. A study from South Africa showed that excess air in groundwater is the rule rather than the exception (HEATON & VOGEL, 1981). It is not always known which processes in the environment under study actually modify the apparent age to which extend Therefore, it is useful to consider additional geochemical and hydrological information for the final age interpretation.

SF_6

The slowing and turnover of CFC atmospheric mixing ratios can lead to ambiguous results using CFCs for age dating of groundwater recharged post 1990. A promising alternative provides a method using sulphur hexafluoride (SF_6) as its concentrations are still increasing. SF_6 is a colourless, odourless, non-flammable, non-toxic and stable gas which is primarily of anthropogenic origin and used as an electrical insulator in high voltage switches and transformers. Industrial production started in 1953 and reached 85 700 t in 1997. SF_6 is currently of a certain interest as it has an extremely high greenhouse warming potential (IAEA, 2006). During the last 40 years the tropospheric mixing ratio of SF_6 has increased from a steady-state value of 0.054 ± 0.009 to more than 4 pptv (BUSENBERG & PLUMMER, 2000). The historical concentrations of SF_6 in the atmosphere are well known and current concentrations are still increasing which makes it a promising dating tool for very young groundwater (post-1990). The analyses precision is very high (< 0.01 fmol/l) so that dating is possible from about 1970 up to now although atmospheric mixing ratios are very small. The solubility of SF_6 in water is very low and hence excess air might occur in large amounts. The calculation procedure is according to the one for CFCs (IAEA, 2006). SF_6 is apparently stable in soils, appears to be resistant to biodegradation and does not show significant sorption or degradation under reducing environments which is the case with CFCs. Usually anthropogenic contamination is very local as it is not present in any commonly used household product (BUSENBERG & PLUMMER, 2000). However, dating with SF_6 can be complicated by the presence of a high natural background. SF_6 was detected in fluorites and in two of eight analysed granites (HARNISCH & EISENHAUER, 1998). Furthermore, BUSENBERG & PLUMMER (2000) measured small but significant concentrations of SF_6 in 16 minerals and rocks of igneous metamorphic, hydrothermal and sedimentary origin. The detection limit was many times lower than in the study by HARNISH & EISENHAUER (1998). Both studies indicate that SF_6 concentrations are generally lower in mafic and higher in silic igneous rocks.

Sampling procedure

It is of major importance that there is no contamination with atmospheric air when taking groundwater samples for the analysis of CFC and SF_6. Usually groundwater samples have lower concentrations than waters which have been exposed to modern air (IAEA, 2006).

Figure 17 shows the different steps of the sampling procedure. In advance, the borehole needs to be purged and the pumping rate to be adjusted in order to prevent the occurrence of air bubbles in the sampling tube. 1) The 1 l glass bottle which is stored in a brazen can which in turn is put into a 20 l bucket is filled while the sampling tube is placed on the ground of the bottle. All parts of the closure are also placed inside the bucket after being flushed with sampling water. The water overflows into the can and 2) also into the bucket. 3) Finally, when also the bucket overflows, the tube is removed, and the bottle is carefully closed under water, likewise the can. Only then the can is taken out the bucket and checked if completely leak-proof.

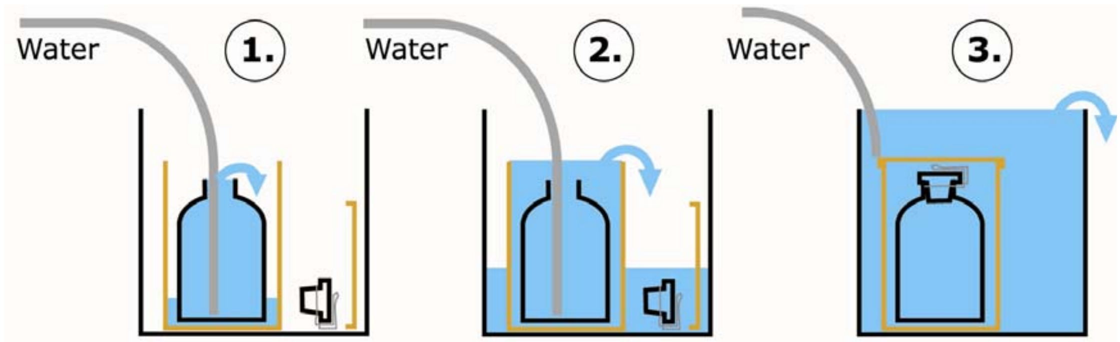


Figure 17: Sampling procedure for CFC and SF_6 (HAERING, 2006)

The analysis of CFC and SF_6 has been conducted using an electron capture detector and gas chromatography (GC-ECD) in the trace substance laboratory of Dr. Harald Oster, Wachenheim.

4.2 Results

4.2.1 Stable isotopes

The results of the isotope analysis and the correction for evaporative enrichment are given in table 4. The measurement error for $\delta^{18}O$ is 0.2 ‰ and 0.6 ‰ for δ^2H.

Table 4: Measured and corrected values for $\delta^{18}O$ and $\delta^{2}H$

Location	$\delta^{18}0$	$\delta^{2}H$	$\delta^{18}0$ corrected	δ^{2H} corrected
	‰ VSMOW	‰ VSMOW	‰ VSMOW	‰ VSMOW
ALLUVIUM				
SA	-5.99	-41.84	-7.29	-48.34
WB	-5.31	-40.13	-7.86	-52.89
200413	-5.43	-40.85	-7.90	-53.19
200414	-6.29	-46.09	-8.22	-55.73
41073	-6.80	-47.52	-7.85	-52.77
41075	-6.94	-47.86	-7.73	-51.81
HH	-5.80	-40.30	-7.09	-46.74
200412	-5.59	-41.34	-7.81	-52.44
41181	-5.83	-40.00	-6.94	-45.56
41182	-5.83	-40.58	-7.14	-47.09
41183	-6.50	-42.92	-6.81	-44.49
41184	-7.03	-44.73	-7.03	-44.73
41188	-7.57	-51.03	-7.57	-51.03
41189	-6.93	-46.34	-7.23	-47.87
41190	-6.74	-41.94	-6.74	-41.94
41191	-6.94	-44.94	-6.94	-44.94
27107	-4.07	-27.82	-5.82	-36.52
25575	-7.75	-52.44	-7.89	-53.13
25054	-7.81	-52.83	-7.81	-52.83
WH	-4.63	-35.14	-7.33	-48.61
GL	-7.38	-49.31	-7.38	-49.31
28250	-6.68	-47.74	-8.11	-54.88
28251	-6.57	-45.81	-7.65	-51.21
KP	-7.05	-44.66	-7.05	-44.66
OZ	-6.57	-40.08	-6.57	-40.08
MG	-7.31	-45.32	-7.31	-45.32
ALLUVIUM TRIBUTARIES				
41180	-5.13	-34.24	-6.20	-39.57
200411	-6.88	-47.79	-7.79	-52.35
S 12	-2.11	-19.43	-6.29	-40.30
1177	-5.24	-35.70	-6.50	-41.99
1004	-5.17	-37.82	-7.32	-48.53
OTHERS				
VB	-4.65	-35.37	-7.37	-48.95
SD	-5.26	-37.46	-7.05	-46.38
181	-5.75	-38.94	-6.73	-43.83

The measured values of the samples, taken in the alluvium of the Swakop River, range from -7.81 (25054) to -4.07 ‰ δ^{18}O (27107). Both sampling points are located at Otjimbingwe which shows that the isotopic composition can be highly variable within a small distance. The heaviest composition of all samples can be found in the alluvium of a Khan tributary with a value of -2.11 ‰ δ^{18}O (S12).

Data on $\delta^{18}O$ and $\delta^{2}H$ in rainfall at Windhoek is shown in figure 18 together with the Global Meteoric Water Line (GMWL) and the groundwater samples taken in the Swakop River catchment. The rainfall data is published by the IAEA (International Atomic Energy Agency) within the framework of GNIP (Global Network of Isotopes in Precipitation). The local precipitation values at Windhoek plot along the GMWL with a weighted average of -4.3 ‰ $\delta^{18}O$. Thus, a local meteoric water line is not defined for the purpose of this study.

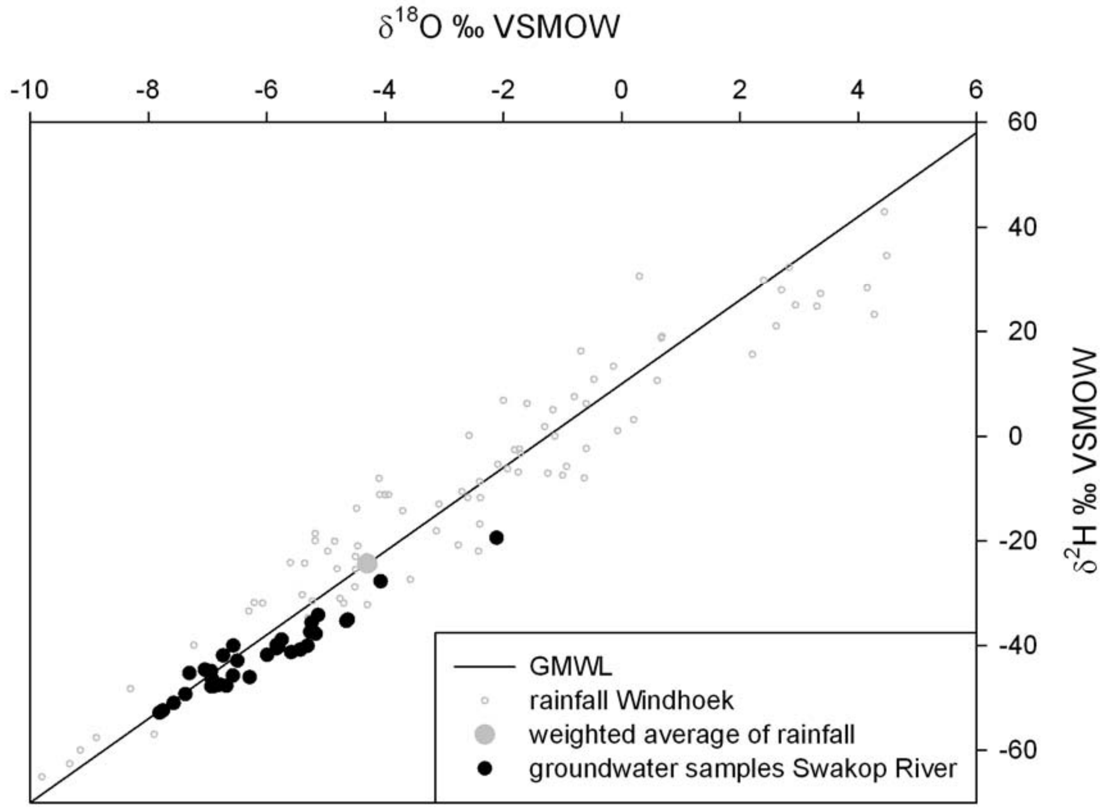


Figure 18: $\delta^{18}O$ – $\delta^{2}H$ diagram of the GNIP rainfall data at Windhoek and all groundwater samples as well as the GMWL

Figure 19 gives a more detailed view of the groundwater samples. Compared to the weighted average of rainfall, the groundwater samples have a lighter isotopic composition. Some of the samples plot close to the GMWL while others, lying below the GMWL, show an evaporative enrichment. The latter samples plot closer to an evaporation line which was defined on the basis of the samples taken in the alluvium of the Swakop River. The evaporation line has a slope of 5 which is typical for arid regions (CLARK & FRITZ, 1997) and intersects the GMWL at -7.3 ‰ $\delta^{18}O$. The samples taken in the alluvium of tributaries (Khan and Gawib) as well as in the adjacent bedrock and floodplain also plot close to the defined evaporation line.

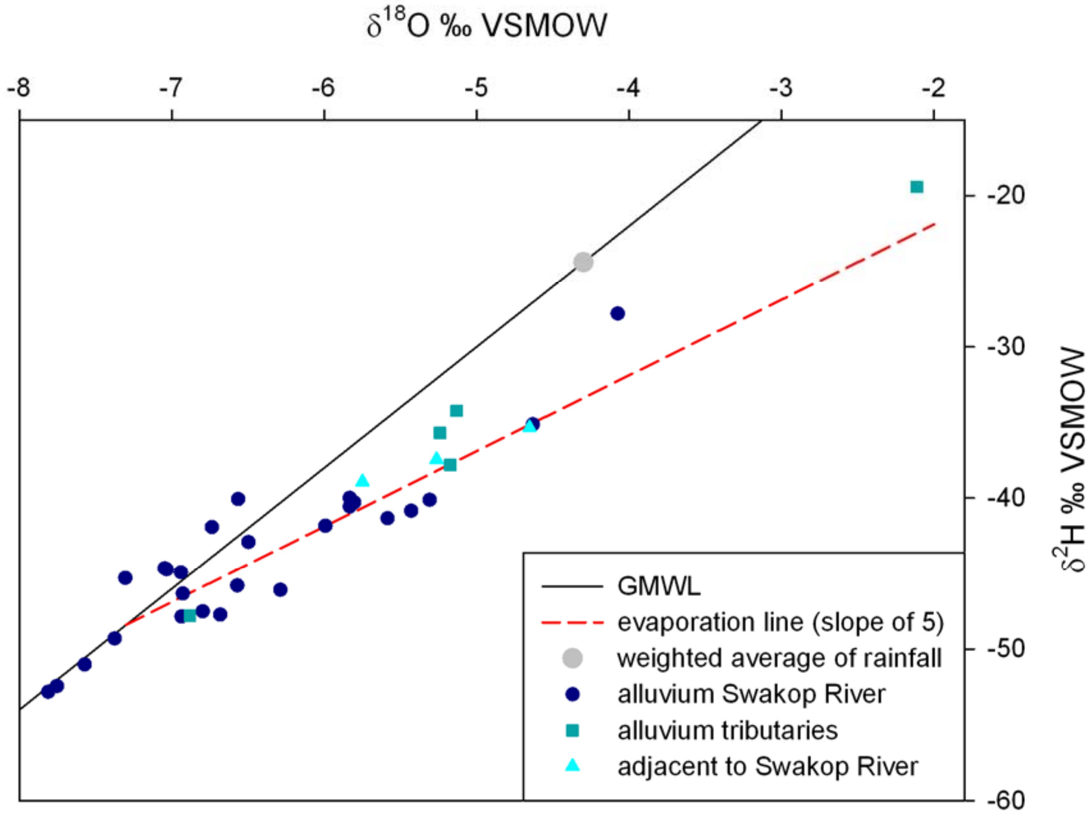


Figure 19: Detailed $\delta^{18}O$ – $\delta^{2}H$ diagram of the groundwater samples including the GMWL, evaporation line and the weighted average of rainfall at Windhoek

In figure 20 the longitudinal profile of $\delta^{18}O$ values and the respective correction is shown for the samples taken in the alluvium of the Swakop River. The black line which connects the measured $\delta^{18}O$ value and the respective corrected value indicates the extent of evaporative enrichment. Assuming an altitude effect (dashed line) of -0.2 ‰/100 m for $\delta^{18}O$, depleted values of up to -3.5 ‰ could be expected in the lower catchment. However, it is obvious that the isotopic longitudinal profile does not follow the line of the altitude effect. The samples plot rather variable within a range of -8.22 ‰ to -5.82 ‰. When there is an alignment between the $\delta^{18}O$ value and the respective correction, there has been no evaporative enrichment which is the case for the majority of the samples in group 1 (upper catchment) except for two samples (28250 and 28251). These boreholes are drilled in the fractured aquifer adjacent to the alluvium. One sample in this group, GL, is located downstream of Von Bach Dam and shows a similar isotopic composition as the samples further upstream and no evaporative enrichment.

Group 2 is highly inhomogeneous. WH is located immediately downstream of Swakoppoort Dam. The corrected $\delta^{18}O$ value is accordant to GL, but the evaporative enrichment is the highest amongst all alluvial samples. The remaining samples in group 2 belong to the Otjimbingwe water scheme. It is noticeable that 27107 is heavier and shows evaporative enrichment compared to 25054 and 25575. The samples of group 3 belong to the Swakop River section close to the LHU mine. Two groups can be distinguished: 41191 to 41183 which show almost no evaporative enrichment in contrast to 41182 and 41181. Group 4 is the last group before the Swakop River ends into the Atlantic Ocean. Apparently all samples in this group show high evaporative enrichment and the majority of corrected $\delta^{18}O$ values is relatively light. The value of the sampling location in the Khan River (200411), which is not displayed in figure 20, but given in table 4, is of a similar composition.

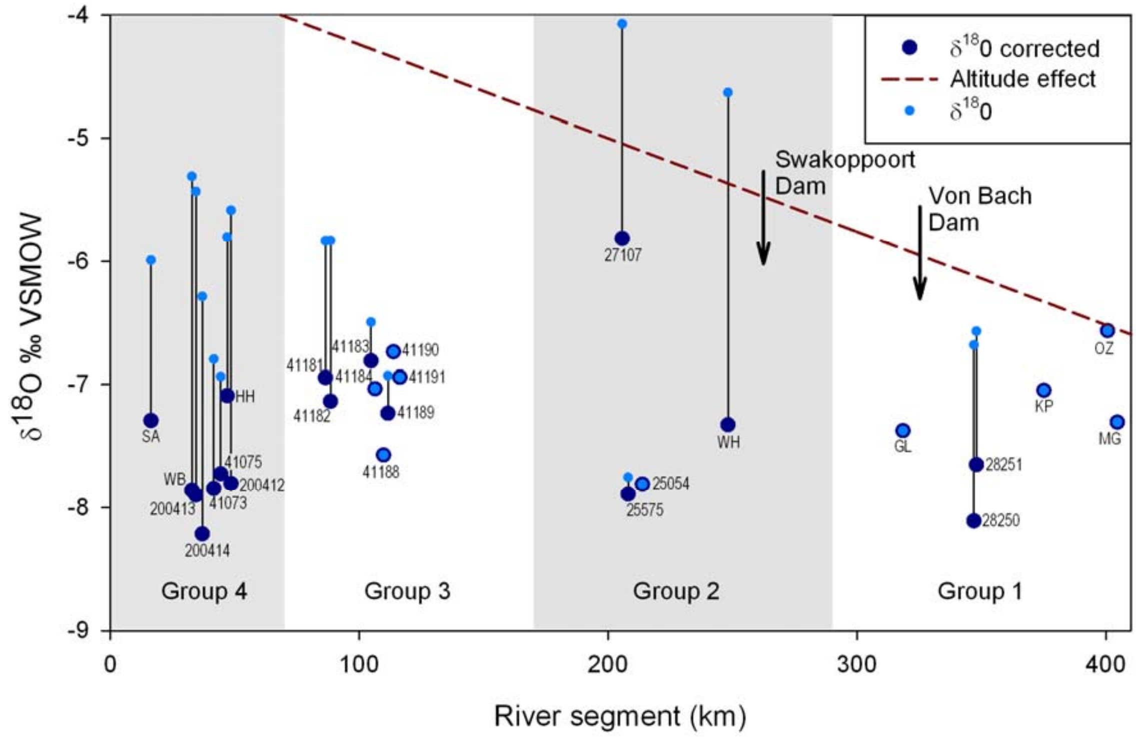


Figure 20: Longitudinal $\delta^{18}O$ profile of groundwater samples taken in the alluvium of the Swakop River

4.2.2 Major ions

The results of the laboratory analysis are given in the appendix (A.1). From the Piper and Schoeller diagram (figure 21) two types of samples can be distinguished: a type of fresh groundwater and a type of mineralised groundwater. The fresh water type splits into group A (black) and group B (blue) while the mineralised water type can be further divided into group C (green) and group D (red). One sample (MG) was excluded as it did not match with any of the groups.

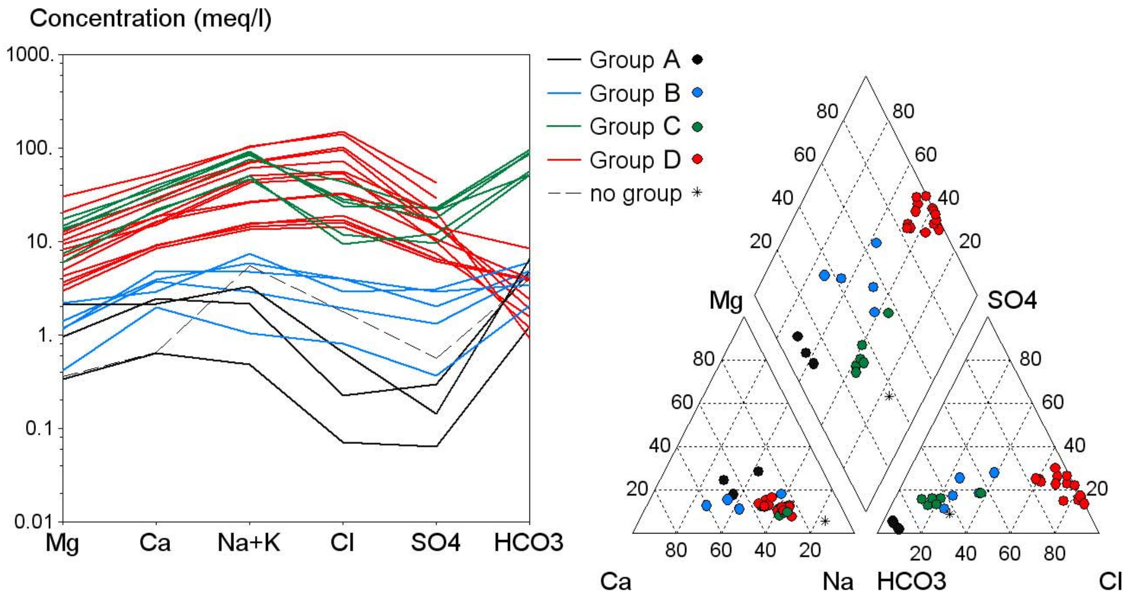


Figure 21: Schoeller (left) and Piper (right) diagram for the groundwater samples

Group A is the less mineralised group having the lowest Cl and SO_4 concentrations of all groups (figure 21, Schoeller), but it shows the highest percentages of HCO_3 (figure 21, Piper). The curve of group B in the Schoeller diagram is similar to that of group A, but more balanced with higher values of Cl und SO_4 and a slight difference in Ca and Na+K concentrations. Group C looks like a parallel shift of group A towards higher concentrations in the Schoeller diagram. Group D is highly mineralised showing the highest percentages of Cl and SO_4. Group C and group D differ in the composition of anions, but have similar concentrations of cations. Figure 22 shows the groups and their location as well as the rock types in the catchment. Group A, B and D can not be clearly associated with a specific geological unit while group C is located solely in the lower catchment where certain rock types occur.

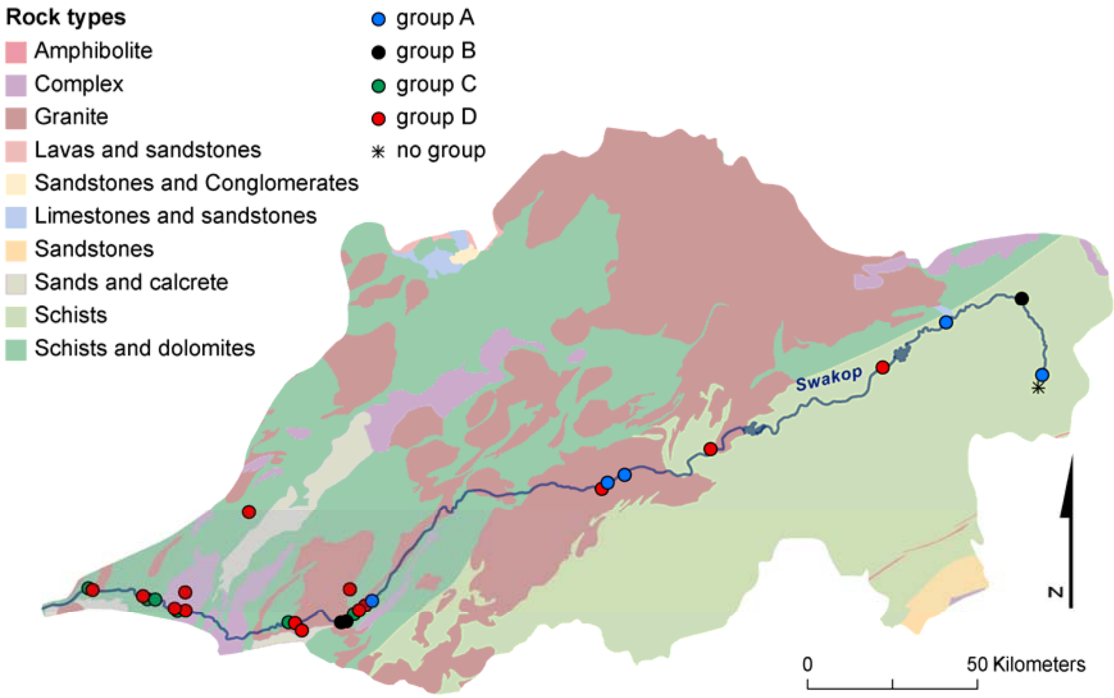


Figure 22: Samples grouped according to the major ion chemistry and the rock types in the Swakop River catchment

In figure 23 Cl is plotted with Na, Mg, Ca and SO_4 and compared to the marine relative ion abundance (black line). The ion concentrations in groundwater are usually lower than in seawater while the relative abundance of some of the dissolved ions can be similar to the marine abundance. Variations from the black line indicate that seaspray is not the only origin of ions in the groundwater. Group D maintains the marine relative abundance of Na and Cl, except for high concentrations where a slight excess of Cl can be observed. Group C shows an excess of Na. The pattern for the abundance of Mg is similar. All groups have an excess of Ca and SO_4 compared to seawater. In group D Cl has a clear positive linear correlation with all other ions (Na, Mg, Ca, SO_4) while the samples in the other groups plot rather fuzzy.

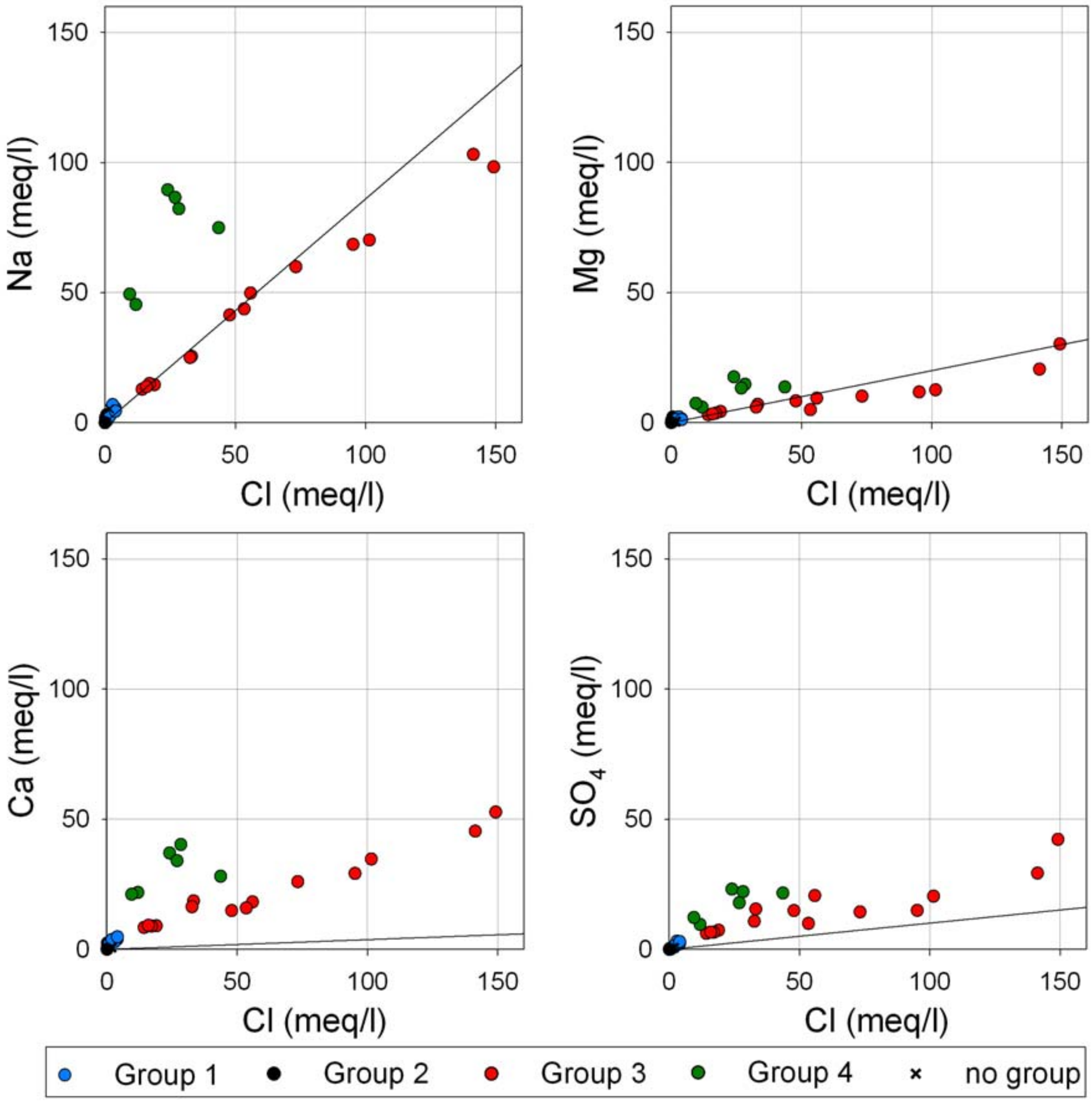


Figure 23: Relation between Cl and other ions compared to the marine relative abundance (black line)

4.2.3 Trace elements

The results of the laboratory analysis are given in the appendix (A.3). Figure 24 shows a fingerprint graph of selected trace elements. OZ was chosen as a reference sample as it is assumed to be the less influenced. The other samples were sorted according to a decreasing order of trace element concentrations at OZ. Two peaks are significant in figure 24: Li and U. Concentrations in the lower catchment (reddish colours) tend to be higher than in the upper catchment (bluish colours). The measured uranium concentrations range from 0.064 µg/l (OZ) to 357 µg/l (S12).

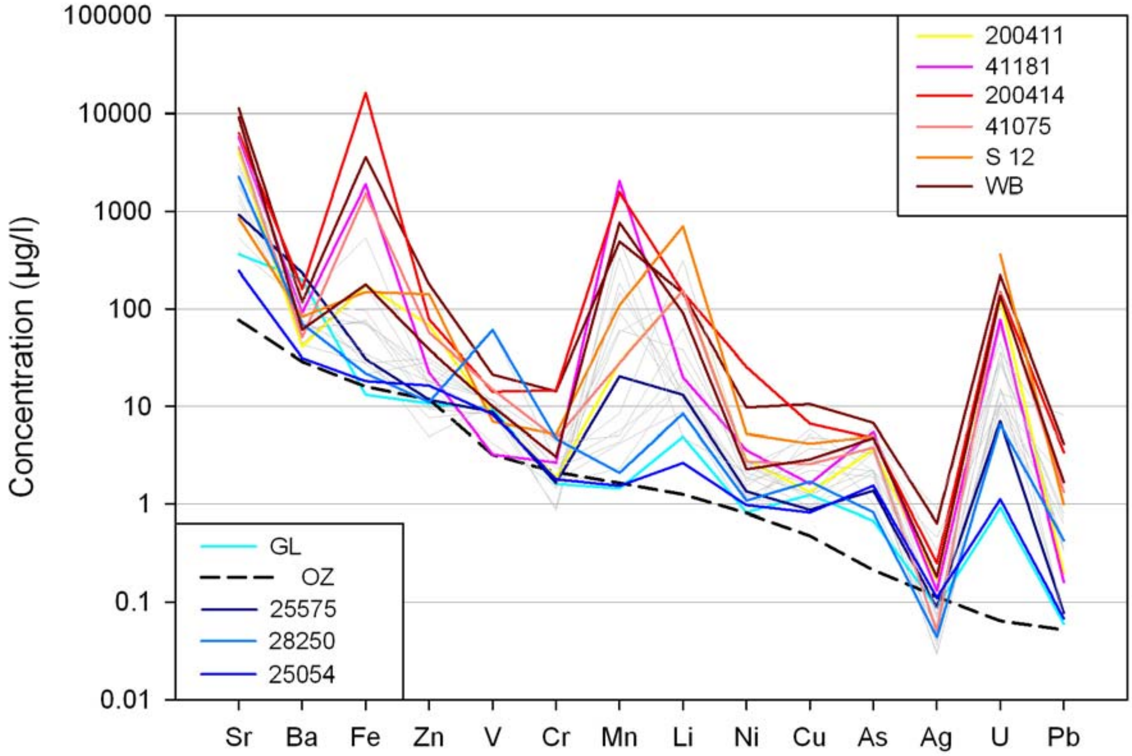


Figure 24: Trace elements in the Swakop River catchment (reddish colours: upper catchment, bluish colours: lower catchment)

4.2.4 CFCs

The measured concentrations of dissolved gas in picomol per litre (pmol/l) and the corresponding error for the 14 sampling locations are given in table 5. The measured values range from < 0.01 pmol/l to 2.5 pmol/l for CFC-11, from 0.01 pmol/l to 1.4 pmol/l for CFC-12 and from < 0.01 pmol/l to 0.28 pmol/l for CFC-113.

First, the initial atmospheric volume ratio was calculated from the dissolved concentrations in water according to the calculation procedure explained in section 4.1.6.. In a next step the initial atmospheric values as well as the input functions were converted into dissolved concentrations for standard conditions in the study area: a recharge elevation of 600 m, a recharge temperature of 20 °C and a salinity of 2 ‰. The results thereof are given in the appendix (B.2 and B.3).

The PM, EM and mixing model were applied to identify dominant recharge processes. In figure 25 the mixing ratios of CFC-12 and CFC-113 are plotted for the model input function as well as for the samples. The mixing line for 1990 is also shown. As errors are fairly high, it is not possible to clearly assign most of the samples to either one of the models. However, only two samples (GL, 41181) cannot be interpreted with this approach.

Table 5: Measured CFC concentrations as well as field parameters

Location	Recharge altitude	Recharge temperature	Salinity	measured dissolved concentrations					
				CFC-11	error	CFC-12	error	CFC-113	error
	m.a.s.l.	°C	‰	pmol/l		pmol/l		pmol/l	
OZ	1545	20	0.40	2.2	0.3	1.4	0.1	0.23	0.05
28250	1438	20	0.59	1.2	0.2	0.84	0.05	0.13	0.05
GL	1316	20	0.59	2.5	0.3	1.2	0.1	0.28	0.05
WH	1025	20	1.70	1.2	0.2	1.3	0.1	0.12	0.05
25575	883	21	0.61	0.6	0.1	1	0.1	0.06	0.05
VB	728	23	3.15	1.3	0.2	0.87	0.05	0.1	0.05
41191	516	23	0.60	0.27	0.05	0.43	0.05	0.03	0.05
41183	488	23	0.07	0.31	0.05	0.13	0.05	0.03	0.05
41180	478	23	1.77	0.04	0.05	0.01	0.05	< 0.01	-
41181	347	23	3.20	0.04	0.05	0.21	0.05	< 0.1	-
200411	223	20	7.11	2	0.2	1.2	0.1	0.19	0.05
HH	203	20	3.13	1.2	0.2	0.85	0.05	0.1	0.05
WB	143	19	10.03	< 0.01	-	0.11	0.05	< 0.01	-
181	76	18	5.65	2.2	0.3	0.51	0.05	0.05	0.05

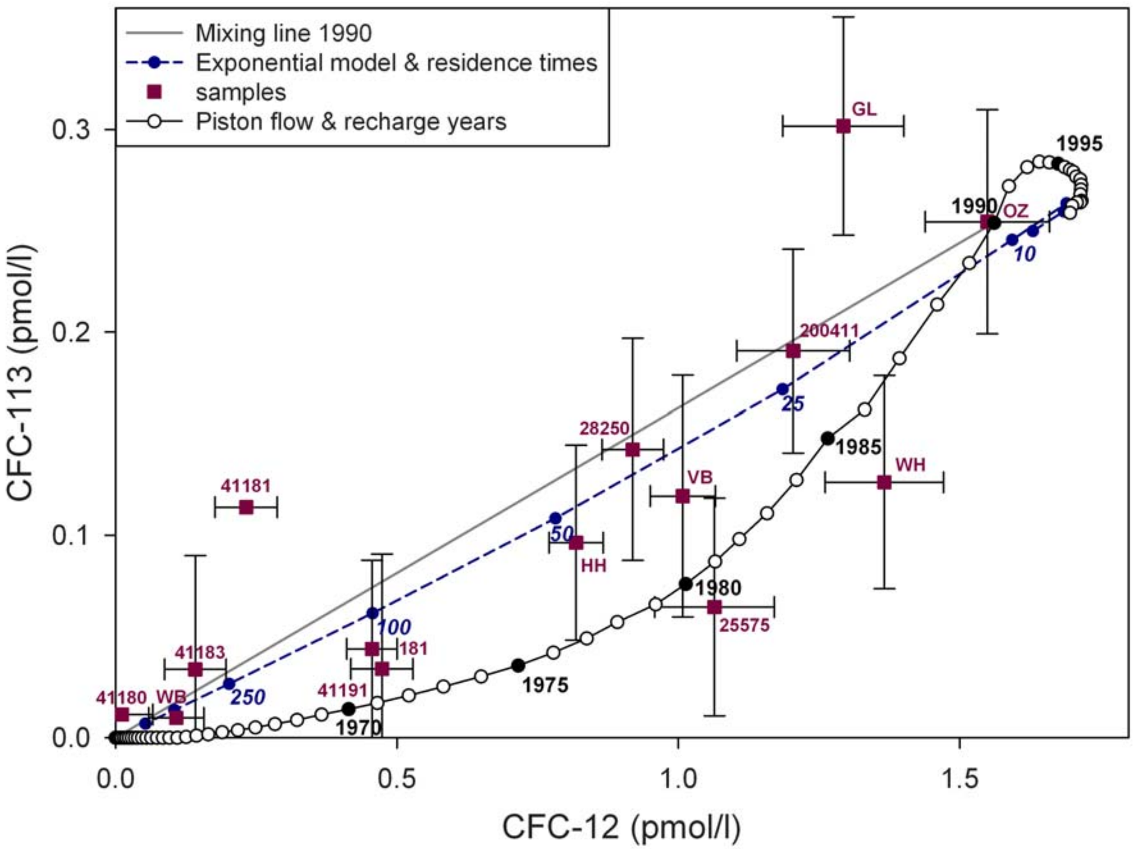


Figure 25: Bi-plot of CFC-12 and CFC-113: application of PM, EM and mixing model

For a simplified estimation, the PM has been used to determine the recharge year of the samples. Figure 26 shows the calculated initial atmospheric volume ratios for CFC-12 (left) and the input function (right). In order to obtain the recharge year of a certain groundwater sample, the concentration is compared to the input function that is shown here as an example for sample 25575. The resulting recharge year is 1984 ± 2 years.

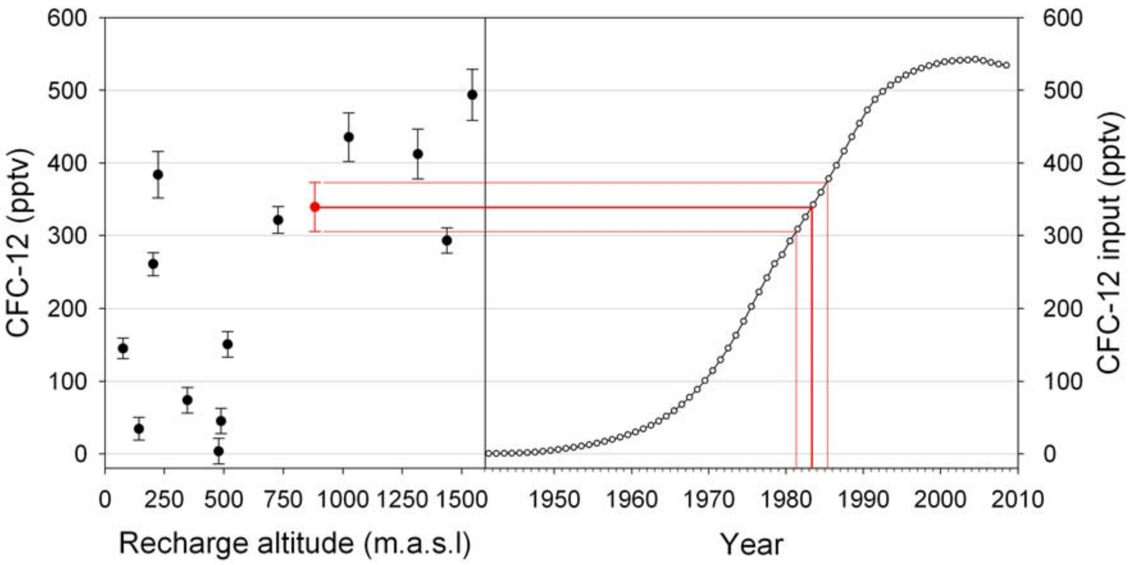


Figure 26: Input function and initial atmospheric values of CFC-12 in pptv

This method was applied to all samples and also with CFC-11 and CFC-113. The results are given in table 6: three recharge years, one for each CFC compound, at each sampling location as well as, accounting for the errors, a range of recharge years. For a certain sample, the deviation from the measured value indicating either an older or younger recharge year is not always equal because of the non-linear increase of the input function, e.g. for WB the CFC-12 recharge year is 1962 and the dating range is 1957-1965. In some cases, e.g. CFC-11 for 41180, the lower limit could not be determined as the concentration falls out of the datable range. If no error, but only a maximum concentration was specified in the laboratory report, the determined recharge year indicates the upper limit of the dating range. At GL no recharge year could be determined with CFC-113 as the sample was contaminated which means that the measured concentration was higher than the atmospheric input concentration ever was. According to the construction years of Von Bach and Swakoppoort Dam (1970 and 1978), the samples can be classified into three groups: groundwater recharge took place after (yellow), in between (orange) or before (red) the construction of the dams (table

6). In the following, the yellow recharge years are referred to as young and the red ones as old. Figure 27 displays the longitudinal profile of recharge years.

Table 6: Recharge years determined with three CFC compounds and range of recharge years

Location	CFC-11		CFC-12		CFC-113	
	recharge year	range	recharge year	range	recharge year	range
OZ	1987	1984-1990	1992	1990-1997	1993	1990-*
28250	1977	1975-1978	1981	1980-1982	1987	1983-1990
GL	1989	1986-1995	1988	1986-1989	cont.	-
WH	1976	1975-1978	1989	1987-1991	1986	1982-1989
25575	1971	1970-1972	1984	1982-1986	1981	1971-1986
VB	1978	1976-1980	1983	1982-1984	1986	1981-1989
41191	1967	1966-1968	1973	1972-1974	1977	*-1983
41183	1967	1966-1968	1964	1960-1966	1977	*-1983
41180	1956	*-1957	1949	*-1959	<1971	-
41181	1956	*-1957	1968	1966-1969	< 1985	-
200411	1983	1981-1985	1986	1984-1988	1989	1987-1992
HH	1976	1974-1977	1979	1978-1980	1984	1979-1987
WB	< 1953	-	1962	1957-1965	<1970	-
181	1982	1980-1985	1973	1972-1974	1978	1963-1983

* out of datable range

recharge after dam construction
recharge between dam construction
recharge before dam construction

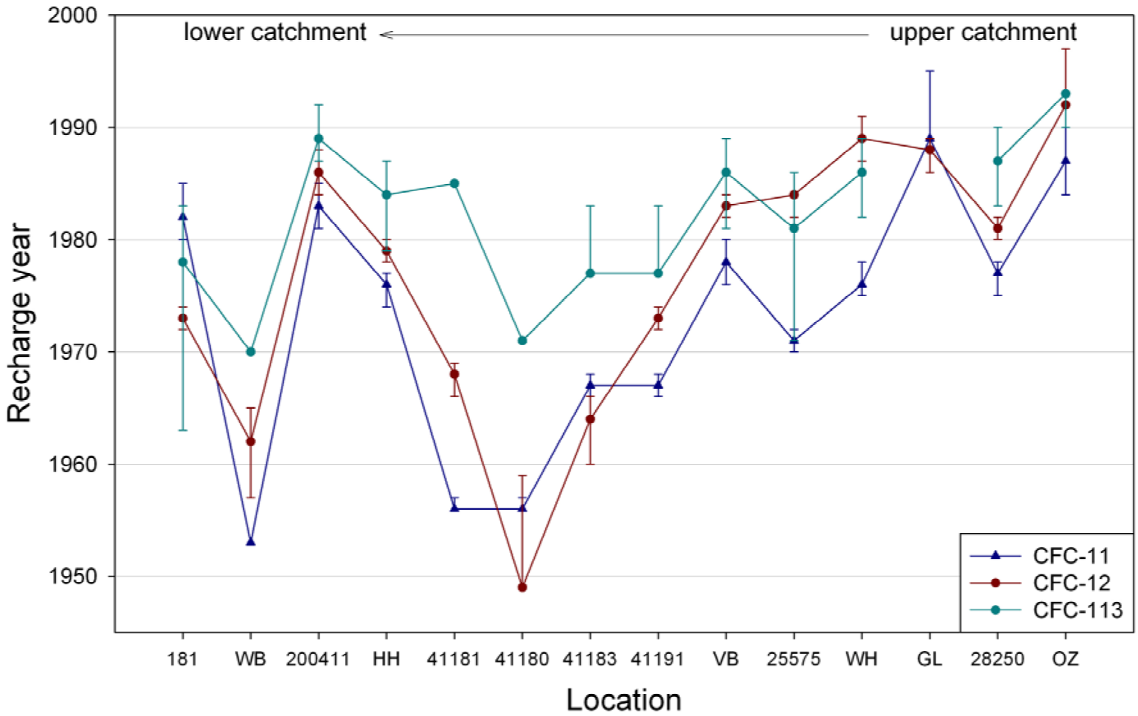


Figure 27: Longitudinal profile of recharge years for CFC-11, CFC-12 and CFC-113 in the Swakop River catchment

From the upper catchment towards 41180 in the lower catchment, recharge years indicate increasing groundwater ages. Further downstream, the recharge years are rather variable. Especially the sampling location at 200411 in the Khan River shows recharge years indicating a distinctively younger groundwater age.

In figure 28 the correlation between the three CFC compounds is displayed. The recharge years determined with CFC-11 indicate older groundwater ages than the ones determined with CFC-12 and CFC-113, except for GL 181, 41183 and 41180. CFC-113 recharge years indicate younger groundwater ages than CFC-11 and CFC-12, except for WH, 25575 and 181.

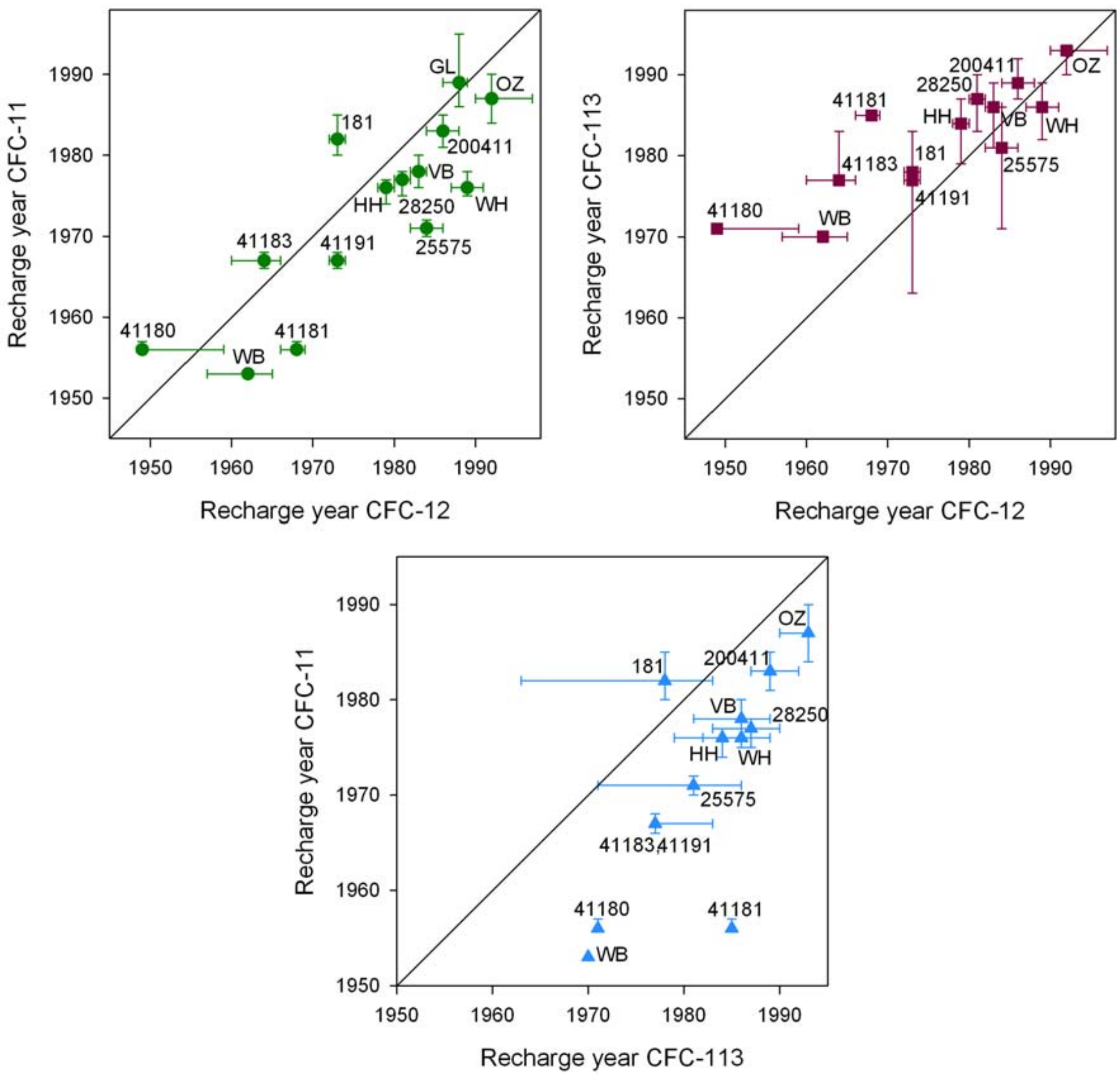


Figure 28: Correlations between the three CFC compounds

4.2.5 SF_6

Table 7 gives the results of the SF_6 laboratory analysis. The concentrations range from 1 fmol/l to 330 fmol/l. Most of the values are excessive, but two (VB and WB) are extremely high and no error could be determined. The measured dissolved concentrations were converted into atmospheric concentrations according to the procedure applied for CFCs. The results were compared to the SF_6 input curve (figure 29). For the southern hemisphere the maximum concentration in the atmosphere is 6.19 pptv in 2008. For the most part, measured concentrations were significantly higher than the input function. Thus, a recharge year could be determined only the five samples OZ, 28250, WH, 25575 and 41180. The recharge years and, accounting for the errors, the range of recharge years are also given in table 7.

Table 7: Measured and dissolved concentrations of SF_6 and resulting recharge years

Location	measured dissolved concentrations		calculated atmospheric concentrations		recharge year	range
	fmol/l		pptv			
OZ	1	0.1	4.54	0.45	2001	1998-2002
28250	1	0.2	4.49	0.90	2000	1996-2004
GL	1.6	0.2	7.08	0.88		
WH	1.5	0.2	6.48	0.86	> 2005	
25575	1.6	0.2	6.95	0.87	> 2007	
VB	330		1543.63			
41191	17	3	75.50	13.32		
41183	6	0.6	26.41	2.64		
41180	1.2	0.2	5.37	0.89	2004	2001-2008
41181	12	3	53.56	13.39		
200411	45	9	185.98	37.20		
HH	23	5	91.03	19.79		
WB	112		456.26			
181	11	3	41.00	11.18		

For WH and 25575 not more than a minimum recharge year could be determined as only the lower boundary of the error bar had a match with the input curve. All the recharge years determined with SF_6 indicate distinctively younger groundwater ages compared to the ages determined with the CFC method.

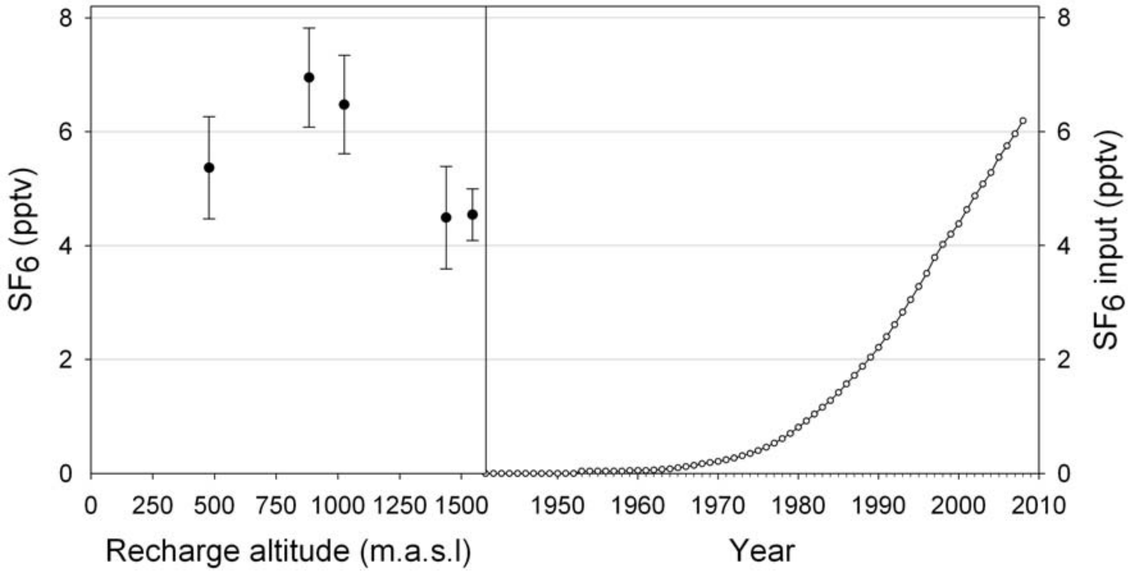


Figure 29: Input function and initial atmospheric values of SF_6 in pptv

Figure 30 shows that samples in the lower catchment tend to be more excessive in SF_6 concentrations than in the middle and upper parts.

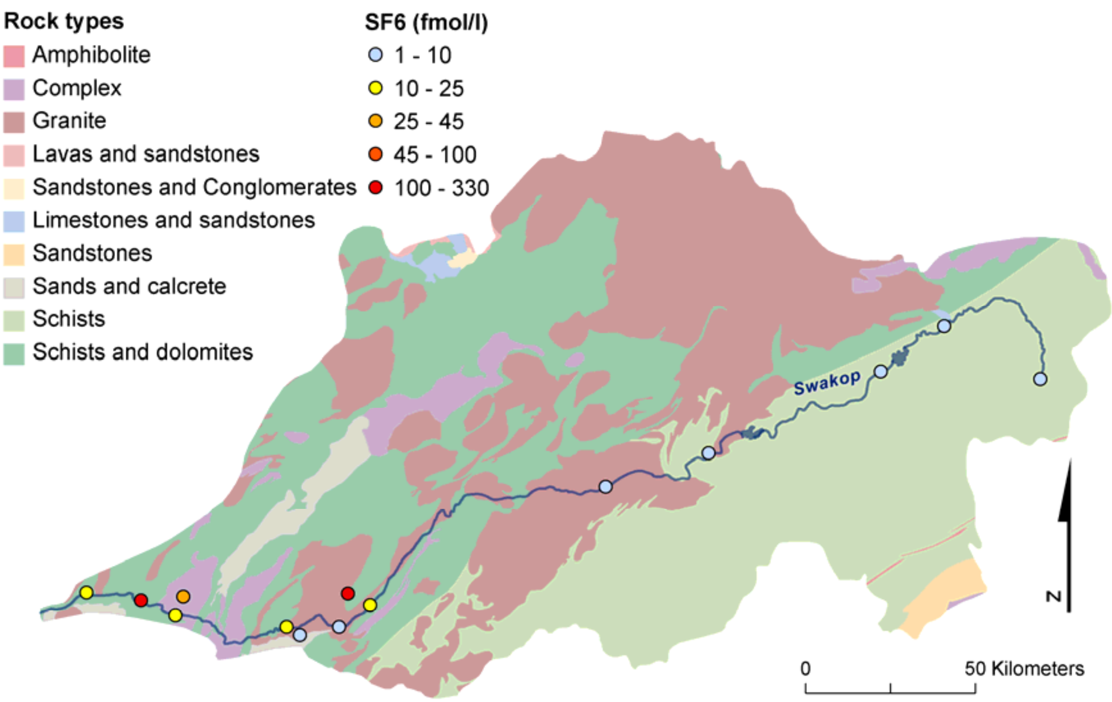


Figure 30: Measured SF_6 concentrations and rock types in the Swakop River catchment

4.2.6 Summary

In figure 31 the most concise results of the longitudinal sampling profile are summarised.

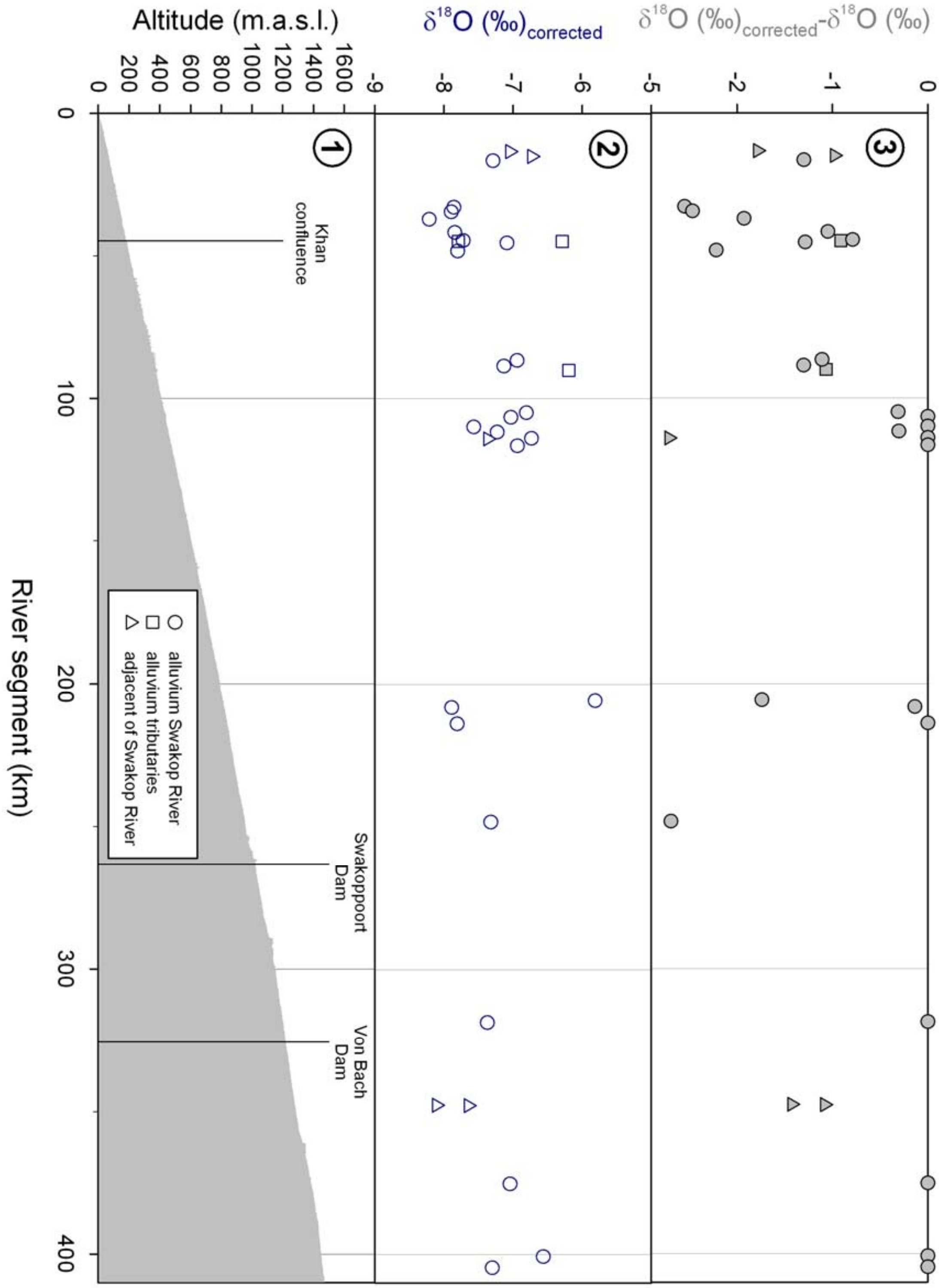
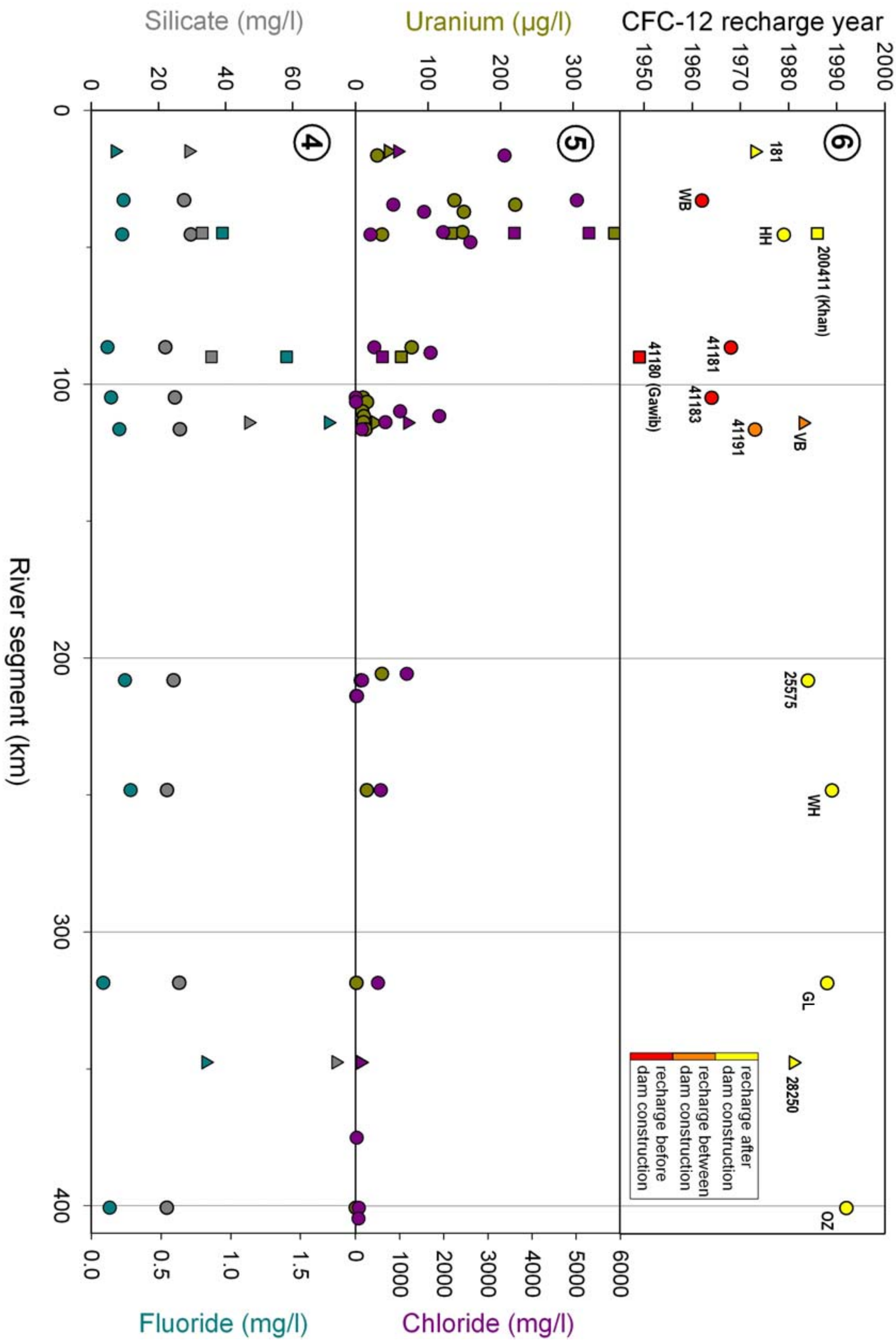


Figure 31: Summary of the longitudinal sampling profile


CFC-12 recharge year
Uranium (µg/l)
Silicate (mg/l)
Chloride (mg/l)
Fluoride (mg/l)
River segment (km)
6
5
4
181
WB
HH
200411 (Khan)
41181
41180 (Gawib)
41183
41191
VB
25575
WH
GL
28250
OZ
recharge after dam construction
recharge between dam construction
recharge before dam construction

(1) The longitudinal altitude profile along the Swakop River was calculated from the digital elevation model (DEM).

(2) The corrected $\delta^{18}O$ values do not follow the altitude effect, but plot in a belt without a distinct longitudinal trend.

(3) The difference between the corrected and measured $\delta^{18}O$ values indicate the evaporation extent which appears to be the most pronounced in the lower catchment.

(4) The Cl concentrations increase towards the coast, however, low concentrations can be found along the entire profile.

(5) F and likewise SiO_3 concentrations in the groundwater samples do not show a clear longitudinal pattern. Values are higher in samples from tributaries and from the adjacent basement.

(6) Uranium concentrations increase from the headwaters towards the coast. However, low concentrations are found along the entire profile similar to the measured Cl concentrations.

(7) Groundwater ages increase generally towards the coast, except for samples in the Khan River, the adjacent basement and HH.

4.3 Discussion

4.3.1 Stable isotopes

The analysis of stable isotopes (^{18}O and ^{2}H) shows that the groundwater samples taken in the Swakop River catchment are mainly of a lighter isotopic composition than the weighted average mean of precipitation at Windhoek. This bias results from the effect previously described by VOGEL & VAN URK (1975) which is saying that only intense and thus light rainfall events contribute to groundwater recharge in arid regions. The altitude of the rainfall station at Windhoek is 1728 m a.s.l. which can be assumed to correspond to the recharge altitude of the uppermost sampling points. Thus, the IAEA rainfall data is considered to be suitable as an input function. There is no altitude effect detectable in the groundwater samples and the isotopic composition is consistently light along the alluvial aquifer. This indicates a high longitudinal connectivity of floods between the upper and the lower catchment. Hence, it can be assumed that the isotopic composition in the groundwater of group 4 is determined by recharge from large floods which were generated at the highest altitudes in the catchment.

Group 1

The samples taken at farm boreholes (MG, OZ, KP, GL) show no evaporative enrichment which confirms that flood events and thus groundwater recharge occurs frequently and no evaporation from open water surfaces takes place. The boreholes at Ovitoto (28250 and 28251) are assumed to be recharged mainly by floods in the Swakop riverbed, but they also receive a certain amount of direct recharge which might account for the evaporative enrichment.

Group 2

GL lies downstream of Von Bach Dam and WH, which belongs to group 2, is located immediately downstream of Swakoppoort Dam. The samples have a similar isotopic composition, but differ in the extent of evaporative enrichment which is low at GL and high at WH. This can be explained by differences in the walls of the two dams. The dam wall of Von Bach Dam is made of rock fill and thus leaking while the wall of Swakoppoort Dam is out of concrete and cuts off surface and groundwater flow. Hence, WH only receives any recharge when Swakoppoort Dam spills. Further downstream, the high variability of isotopic composition and evaporative enrichment at Otjimbingwe can be explained by different sources or times of groundwater recharge.

Group 3

The persistent light isotopic composition indicates that groundwater recharge is dominantly from large and thus light flood events generated in the uppermost parts of the catchment. This leads to an inverse pattern than expected from the altitude effect.

Group 4

The majority of samples in this group located around the confluence with the Khan River have even a lighter composition than group 3. This result furthermore supports the idea of the high connectivity in terms of groundwater recharge. Sampling locations downstream of the confluence (41075, 41073, 200413, 200414 and WB) are additionally influenced by recharge from floods which were generated in the uppermost catchment (1500 m a.s.l.) of the Khan River. HH and likewise SA reveal a heavier composition which indicates that these boreholes receive a certain fraction of groundwater recharged at lower altitudes.

The longitudinal isotopic composition of the groundwater samples implies that there is or has been a high connectivity between the upper and the lower catchment in terms of flood recharge.

4.3.2 Major ions

The major ion samples were grouped in order to find indicators for areas of pronounced groundwater recharge and of increased lateral inflow from the bedrock. Variations in the major ion chemistry from the marine relative ion abundance imply that there are other processes involved which influence the geochemistry of the groundwater (MAZOR, 2004). The excess of Na (group C) can be an indicator for feldspar dissolution or cation exchange in clays (exchange of Ca and Mg with Na) (MAHLKNECHT et al., 2004). The groups describe the geochemical evolution of recent recharge to a highly mineralised groundwater in the desert:

Group A

This group is the less mineralised and is thus assumed to be composed of fresh groundwater containing the largest proportion of floodwater. Therefore, it can be used as an end-member for mixing analysis.

Group B

The groundwater in this group shows increased mineralisation. It is assumed that the groundwater has longer residence times and is therefore a mix of group A with a small fraction of group D.

Group C

This group shows the most significant deviations from the marine relative ion abundance. Two major processes were identified which contribute to the hydrochemical evolution of this group: water rock-interaction and cation exchange in clays.

Group D

These samples show the highest mineralisation and therefore represent potential end-members. The relative abundance of some ions (Cl, Na, and Mg) corresponds to seawater. Thus, these ions originate mainly from seaspray. The wide range of concentrations results from different extents of evaporation. Furthermore, water-rock interaction is involved in the hydrogeochemical evolution, but as Mg preserved the marine relative abundance, no dolomite was involved (MAZOR, 2004). There is no Na excess observed in this group which might be an indicator that this groundwater type originates to large parts from the bedrock where cation exchange is not significant. This supports the idea that fractions of this water type originate from basement groundwater which was recharged directly explaining the source of evaporative enrichment.

Areas with favourable characteristics for groundwater recharge have an ionic composition similar to group A and B. In other areas, where groundwater recharge is less frequent and the conditions are conductive for lateral inflow from the bedrock, the groundwater composition is according to group C and D.

4.3.3 Trace elements

The fingerprint graph showed high levels of U in the lower parts of the catchment. At the same time, Li concentrations are increased whereof weathering of pegmatite could be the origin (HEM, 1992). Concentrations are especially high in the Gawib and Khan Rivers. Therefore, U and Li concentrations are also increased in the alluvium of the Swakop River downstream of the respective confluence. The Central Namib is known to have increased concentrations of U in the surface layers of the peneplain. Therefore, the high concentrations in groundwater are not necessarily from anthropogenic origin, but may be derived from weathering of uranium bearing rocks in the area (CSIR, 1997).

4.3.4 CFCs

The application of the PM, EM and mixing model showed that almost none of the samples clearly matched with either one of the models. This is partly due to the high error, but also because these models are a strong simplification of the natural processes. It is important to note that CFC-free components in a sample always contribute to the groundwater age with an age of 0, even if it is much older. Applying other age dating methods, for instance radiocarbon dating, much older groundwater ages are possible to be determined. Thus, the obtained ages need to be regarded as mean residence times.

The longitudinal profile and the correlation of recharge years (figure 27 and figure 28) show that the recharge years from the three CFC compounds rarely agree. This can partly be ascribed to degradation processes under anaerobic conditions. In general, conditions in alluvial aquifers are oxidising. However, reducing environments can occur due to higher temperatures and organic matter. Various studies have found CFC-11 to be the most rapidly degraded of all three compounds (IAEA, 2006) which can be observed for almost all samples. CFC-12 is the most stable and was therefore used as the age determining compound (figure 26). Mixing of young and old groundwater can be assumed where the youngest recharge year is determined with CFC-113.

Several factors can modify the recharge year resulting in the ambiguous distribution shown in figure 25. Under- or overestimation of the recharge temperature of ± 2 °C leads to errors of 1-3 years for groundwater recharged prior to 1990. The recharge temperature in the Swakop River catchment was assumed to correspond to the mean annual temperature (data source: ATLAS OF NAMIBIA). If monthly temperature is available, the recharge temperature can be estimated more precisely by taking into account that most recharge occurs during the rainy season in summer. The recharge altitude was estimated to be the altitude of the sampling location for simplifying reasons. Especially for post-1990 recharge an exact estimation of the recharge altitude is highly significant. However, most of the samples were determined to be recharged before 1990. The samples have not been corrected for excess air as the required noble gases were not included in the analysis. None of the samples, except for CFC-113 at GL, exceeds the concentrations of the input function. However, the effect of excess air might account for a significant error in the determined recharge years. As recharge temperatures are relatively high in Namibia and it is about an ephemeral stream in an arid region, the effects are expected to be large. CFC-12 is more affected than CFC-11 and CFC-113 and younger waters rather than older waters (BUSENBERG & PLUMMER, 1992). Quantities of excess air in groundwater are reported to range between 0 and 50 cm^3/kg. However, usually values are less than 10 cm^3/kg (WILSON & MCNEILL, 1997). Calculations in IAEA (2006) show that the presence of 30 cm^3/kg of excess air in a water sample formed at 30 °C can lead to a maximum error of 11 years or contamination effects compared to actual groundwater age. The effect of excess air can not be quantified in this study, but has to be kept in mind during data interpretation. For the discussion of the longitudinal age distribution, the samples were sorted in the same groups as in the stable isotope section (4.2.1).

Group 1

In the upper catchment (OZ, 28250, GL) groundwater ages are young pointing to recharge before the dams were built. OZ and 28250 receive frequent groundwater recharge from floods undisturbed by the dams. GL, which is located between dams, is replenished by dam spills and dam leakage.

Group 2

WH and 25575 lie downstream of the dams. WH is solely recharged when Swakoppoort Dam spills. This was the case in 2006 and 2008 which results in the young groundwater age. In this segment of the alluvial aquifer, flood contributions are significant which explains the young groundwater age at 25575.

Group 3

Further downstream, the LHU group (41191, 41183, 41181 and 41180) is significantly older. Here, groundwater recharge predominantly occurred before the dams were built. Back then, large floods reached further and contributed to groundwater recharge in this segment. Today these large floods are captured by the dams and only partially released through the spillways. Subsequent, these small or medium floods lead to groundwater recharge immediately downstream of the dams, but not further.

The groundwater age at VB, a sampling location in the granite, is clearly younger than the age of the alluvial LHU samples. The borehole is close to a small stream, but it can be assumed that it receives a certain amount of indirect recharge from the basement aquifer.

Group 4

HH is located upstream of the confluence with the Khan River and shows a young groundwater age. As this age is distinctively younger than the ones at

LHU, there must be young component other than flood recharge contributing to the age distribution of HH. It could be possible that young groundwater from the Khan River enters the alluvial aquifer in this segment through faults or fissures. Groundwater at the sampling location in the Khan River, 200411, is young which points to frequent groundwater recharge: large floods are produced at high altitudes of the sub-catchment (1500 m a.s.l.) Since there are no large dams along the Khan River, floods can travel downstream without interruption and contribute to groundwater recharge in the lower alluvium. The groundwater age determined at WB, located downstream of the confluence, is old. Possibly, WB is located in a zone where groundwater with very long residence times discharges into the alluvium from the aquifer beneath. The sampling point 181 shows a young groundwater age. It can be assumed that this borehole receives recharge from the Erongo Mountains or the area around Arandis, similar like SD.

Although there are many uncertainty factors associated with the CFC method, an important conclusion can be drawn from the longitudinal profile of recharge years: groundwater ages in general increase from the upper catchment towards the sea and the majority of groundwater in the alluvium of the lower catchment was recharged before the dams were built.

4.3.5 SF_6

Most of the measured SF_6 concentrations significantly exceed the input function for the southern hemisphere. As for CFCs, no excess air correction has been conducted for SF_6. Excess air has most effect on sparingly soluble gases and thus, the effect on SF_6 is larger than on CFCs (GOODDY et al., 2006). In a study of BAUER et al. (2001) it was shown that up to 30 % of the measured SF_6 values in groundwaters in Germany may originate from excess air. As mentioned above, excess air in semi-arid regions is expected to be even higher. However, excess air alone cannot explain the high concentrations measured in the samples of the Swakop River catchment. Contamination of groundwater with SF_6 is very unlikely in the catchment as there is no such industry. Hence, it is assumed that the measured concentrations result from naturally occurring SF_6. The highest values are observed in the lower catchment at sampling points in the bedrock or where the contribution from the surrounding bedrock is assumed to be high. Granites, where fluorite is an accessory mineral, can contain very high concentrations of

SF_6 and also in sedimentary dolomites, significant concentrations can be detected (BUSENBERG & PLUMMER, 1992; HARNISCH & EISENHAUER, 1998). Both rock types are present in large parts of the study area which further supports the idea of geogenic sources of SF_6 in the Swakop River catchment. Therefore, SF_6 is not suitable as an age dating tool in the Swakop River catchment, but can be used as a tracer for inflow from the basement due to its geogenic origin. It was found to be more excessive in the lower parts of the catchment. The occurrence of SF_6 excess could not be clearly associated to increased F concentrations. However, geogenic SF_6 not only originates from weathering fluorite bearing rocks, but also from other sources like diagenetic fluids (IAEA, 2006).

5 Perceptual groundwater model

In order to quantitatively assess the impacts of the water resource developments in the Swakop River catchment on the alluvial aquifer, the application of a groundwater model can provide essential information. This requires a profound understanding of the major relevant processes associated with the groundwater system. Therefore, a perceptual model of the alluvial aquifer was developed based on the results of the longitudinal sampling profile, field observations as well as on the literature review on arid zone hydrology and the Swakop River catchment. The dominant processes identified during the data evaluation, are described in the following:

Indirect recharge

The groundwater in the lower catchment is clearly marked by a light isotopic composition resulting from large flood events which were generated in the upper catchment. Thus, the longitudinal distribution of stable isotopes indicates a high connectivity of flood events in the Swakop River catchment (section 4.3.1). However, the age distribution implies that groundwater recharge in the lower river segments occurred predominantly before the dams were constructed (section 4.3.4). Since the dams interrupted the high lateral connectivity, flood contributions from tributaries gained on importance for groundwater recharge along the alluvium of the Swakop River. The isotopic composition of these lateral flood contributions is heavier than of former floods generated at the highest altitudes of the catchment. Thus, it can be expected, that the isotopic composition of groundwater in the lower segments will adapt to the composition of lateral flood inflows over time. For the quantification of indirect recharge, streamflow data at a high resolution is essential in order to account for the highly relevant flood duration. It has been mentioned in section 3.1 that it is difficult to obtain streamflow records of sufficient quality and length to model transmission losses adequately. Using the unit runoff map (DWA, 1992) to gain streamflow data, it has to be considered that this method only returns the mean annual runoff volumes and the variability from year to year is not taken into account. Besides, the yearly temporal resolution renders the method unsuitable to determine the input of a detailed groundwater model.

Direct recharge

Groundwater recharge to the surrounding bedrock occurs from rainwater infiltration (direct recharge) outside the riverbed. Whether the surrounding bedrock needs to be included into the model or not, depends on spatial scale requested for modeling.

Evapotranspiration

Evaporation from open water occurs from ponds which form during flood events or from the groundwater table where bedrock-highs force the groundwater table to the surface. Besides, during the process of direct recharge outside the riverbed water is evaporated from the unsaturated zone. All three processes lead to an isotopic enrichment and an increased Cl content in the groundwater. It is rather difficult to clearly distinguish the three processes leading to evaporative enrichment in the groundwater only from isotopic and Cl data. Anyway, it has been shown that groundwater in the lower catchment is more significantly affected by evaporation than in the upper catchment (section 4.3.1 and 4.3.2). Furthermore, water is lost by transpiration of the riparian vegetation. In areas where the groundwater table approaches the surface, dense forests of phreatophytes form and water losses are especially high. Evapotranspiration along the alluvial aquifer can be calculated with the method according to HELLWIG (1971). Therefore, vegetated and permanent wet areas need to be quantified renewed, for instance from aerial photos or investigations in the field.

Lateral flow

Groundwater exchanges between the alluvial aquifer and the surrounding bedrock, if the latter is not impermeable. Thereby, the topography of the surrounding area plays an important role as it causes differences in the hydrostatic pressure. The porosity of the surrounding aquifer furthermore affects the groundwater level. In the surrounding bedrock, porosities are significantly lower and therefore water tables react stronger on the same amount of recharge. Besides, geological special features like faults promote the groundwater inflow from the bedrock into the alluvial aquifer.

In the upper catchment lateral flow appears to be directed from the alluvium to the bedrock, at least during and immediately after flood events. According to the major ion composition of the boreholes at Ovitoto and KP, which are drilled into the basement adjacent to the Swakop River, they belong to the fresh water type (section 4.3.2). Besides, farmers and NamWater report the major source of recharge to be the Swakop River. In the lower catchment the Swakop River is deeply incised into the basement, which is not the case in the upper catchment where relief is much more flat. Thus, the groundwater levels at VB, SD and 181 indicate a hydraulic gradient from the bedrock to the alluvium (section 4.1.1). This finding is also supported by the major ion composition of alluvial samples in the lower segment which is basically according to the mineralised type. Increased SiO_3 concentrations at boreholes in the tributaries and in the adjacent basement are indicators for inflow from the crystalline basement (section 4.2.6).

Pumping

Groundwater is removed from the alluvial aquifer by pumping, for instance at the WSS Otjimbingwe and Ovitoto as well as at the LHU mine. For these locations pumping records are available which must be included in the model. The abstractions in the farming zone in the lower catchment are not reproducible in detail, but there are estimations.

Groundwater inflow/outflow

Groundwater moves downstream within the alluvial aquifer with a calculated true velocity of 5.5 m/d (CSIR, 1997). In places where the alluvial aquifer is compartmentalised, groundwater levels are regulated by flood recharge, abstractions and evapotranspiration rather than by groundwater inflow from the alluvium upstream (BIWAC, 2006; NAMWATER, 2005) These areas can be identified from high Cl contents, isotopic enrichment and waterlevel data, for instance at the LHU segment (41191 to 41181) (sections 4.3.2, 4.3.1 and 4.1.1.). Further information on the location of compartment barriers may be obtained from geophysical investigations and from vegetation mapping.

Combining these major relevant processes yields a perceptual model of the Swakop River groundwater system which is shown in figure 32.

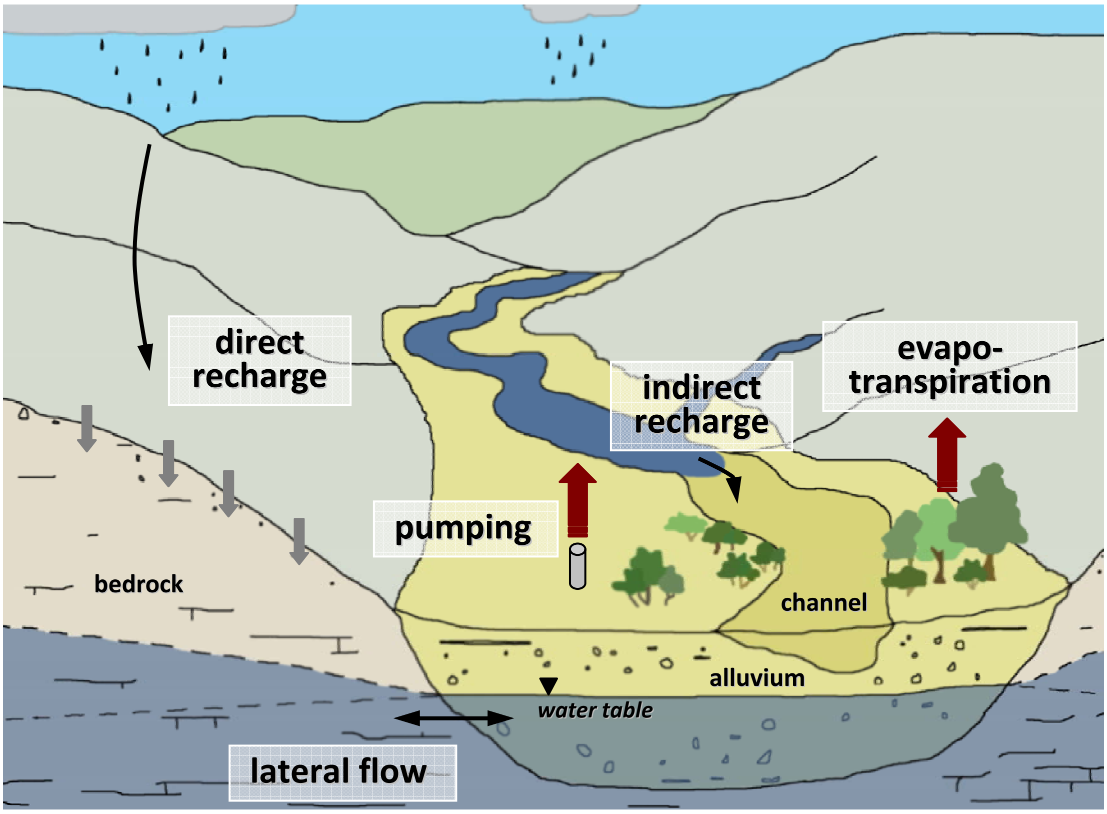


Figure 32: Perceptual model of the major hydrological processes along the alluvial aquifer of the Swakop River

It has been shown in chapter 3 that streamflow and groundwater of ephemeral systems are closely linked. Flow regime modifications therefore interfere with the natural state of the alluvial aquifer. A reduction in floods leads to reduced groundwater recharge and, together with pumping, to dropping water tables. This reduces water losses from evaporation and transpiration which cease at a certain low level. At the same time, low water tables can increase groundwater recharge from floods as there is more void storage volume available. Hence, more streamflow is absorbed by storage which furthermore leads to a decrease in downstream flood survival. Low water tables in the alluvium increase the gradient to the bedrock and thus lateral inflow. This flow can be reversed when water tables rise very high in the alluvium after large flood events. Thus, it becomes apparent that the processes associated with alluvial aquifers are highly complex and dynamic

It has to be considered that in general modelling of ephemeral systems is more difficult than perennial systems as transmission losses are one of the most difficult hydrological processes to quantify. Difficulties arise from the lack of sufficient observed streamflow and groundwater level data to calibrate the model or to validate regional model parameter. Modelling ephemeral systems requires at the best a daily time-step as some of the processes are short duration events (HUGHES, 2005). The perceptual model developed within this work provides a proper base to apply a detailed groundwater model in the Swakop River catchment. For calibration and validation, further field investigations and data processing are required.

6 Conclusion

The aim of this study was to identify effects resulting from environmental impacts on the alluvial aquifer of the Swakop River. Furthermore, it was projected to estimate the indirect groundwater recharge for a defined segment of the alluvial aquifer under different scenarios.

Locals reported alterations of the streamflow and groundwater characteristics since the dams were constructed. These observations were confirmed in this study: on the basis of previous reports and streamflow data it was shown that the hydrological regime of the Swakop River was significantly impacted by the construction of the Von Bach and Swakoppoort Dam.

The groundwater system of the alluvial aquifer was characterised on the basis of a longitudinal sampling profile. The parameters gave information on the water quality, but served also as indicators for the spatial and temporal distribution of groundwater recharge. Stable isotopes showed that the longitudinal distribution of groundwater recharge is not marked by the altitude effect indicating a high dependency of the lower alluvial aquifer on floods generated in the headwaters of the catchment. The ion composition of the groundwater samples provided insight into the high longitudinal variability of the groundwater quality. High concentrations of U were detected in the groundwater of the lower catchment. It was not investigated if these high levels result from the modern mining activities or from weathering of U bearing rocks. The results may serve as a contribution further monitoring and baseline studies. With the application of the CFC age dating method changes in the distribution of groundwater recharge along the alluvium resulting from the dam construction were detected. The analysis of SF_6 revealed a high natural geogenic background in the catchment which makes it unsuitable as an age dating tool. An integrated examination of these findings indicates that the alluvium of the middle and upper Swakop River is replenished frequently from floods in the main channel, tributary inflow, dam spillage and leakage respectively. The water quality in the middle and lower parts appears to be highly variable. The reasons therefore were identified to be lateral inflow from the basement, increased evaporation and zones in the alluvium which are more favourable for indirect recharge than others.

The objective to estimate indirect groundwater recharge of a defined segment for different scenarios could not be achieved. It turned out to be difficult to model the aquifer dynamics in detail due to the shortage of data for calibration and validation. However, the results of the longitudinal profile were used to develop a perceptual model of the alluvial aquifer of the Swakop River. Thereby, major relevant processes associated with the groundwater system were identified and described. The partition of the alluvium into compartments due to bedrock-highs was found to be characteristic for the Swakop River. The conceptual model applied by CSIR (1997) was calibrated inadequately and could not account for the complex aquifer dynamics due to the coarse time-step and various simplifying assumptions. Thus, a future model application requires extensive data processing for sound calibration and possibly further field investigations to validate regional model parameter. It should moreover be based on a monthly or even daily time-step to account for the characteristics of ephemeral systems (HUGHES, 2005). The perceptual model developed in this study serves as a basis for a detailed future modeling of the alluvial groundwater resources and thus for the determination of the water requirements for both people and the environment.

The importance of Namibia's ephemeral systems is widely recognised. Policies aim at determining the environmental flow requirements for each basin. However, this remains to be achieved for most of them and also for the Swakop River catchment. Various methods are available elsewhere in southern Africa, but have to be tested and adapted to the Namibian conditions, including the harsh climate and the increasing human water needs (BETHUNE et al., 2005). The Swakop River catchment, a heavily used and sensitive environment, requires basin-wide river management, likewise to the neighbouring Kuiseb catchment (MANNING & SEELY, 2005), in order to assure a sustainable use of the catchments resources in future.

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Appendix

A Data

A.1 Major ions

Location	Cl	NO_3	SO_4	Na	K	Mg	Ca
	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
41191	673	19.3	354	335	27.2	52.0	181
GL	8.01	93.8	14.3	44.7	8.92	11.8	48.9
OZ	2.53	7.65	3.08	9.09	3.67	4.10	12.9
WH	141	31.8	97.1	129	11.1	17.0	78.2
41189	566	18.3	316	318	23.5	40.9	185
41180	1894	48.2	478	1006	50.4	60.3	318
41190	607	17.5	314	346	24.6	44.3	179
200411	1696	55.4	715	952	43.6	101	299
41182	1005	4.90	1063	1891	64.7	179	807
41184	1178	2.40	743	586	37.7	85.0	373
41188	505	17.7	293	295	22.8	36.2	168
27107	68.1	0.75	63.7	61.1	8.63	14.4	75.1
41181	3597	4.90	980	1614	62.7	153	695
41183	1157	6.25	517	576	35.1	72.3	328
VB	421	169	459	1044	47.2	72.4	438
25575	143	12.4	140	102	10.9	14.1	96.5
200413	853	30.4	1112	2057	68.3	214	742
200414	1546	27.8	1039	1722	65.6	166	562
200412	2597	18.0	691	1378	59.3	123	521
41075	1982	58.0	990	1146	48.0	114	365
S 12	5289	11.3	2028	2260	116	368	1057
28250	104	17.9	148	160	15.3	26.6	58.0
KP	23.2	1.70	6.89	72.0	5.73	25.6	43.1
WB	5010	4.30	1407	2371	75.6	250	911
HH	336	17.1	587	1137	45.8	90.2	424
SA	3374	37.1	717	1576	54.8	143	585
181	953	64.4	859	1990	61.4	161	683
25054	28.4	17.0	17.7	20.0	6.57	5.07	39.4
MG	63.7	0.61	27.0	122	6.08	4.34	13.2

A.2 Fluoride and Silicate

Location	F^-	SiO_2
	mg/l	mg/l
181	0.17	29.0
WB	0.23	27.6
HH	0.22	29.6
200411	0.94	33.1
41181	0.115	22.0
41180	1.40	35.8
41183	0.14	24.9
41191	0.20	26.4
VB	1.70	46.9
25575	0.24	24.5
WH	0.28	22.5
GL	0.084	26.2
28250	0.82	73.0
OZ	0.13	22.5

A.3 Trace elements

Location	Ag	As	Ba	Bi	Cd	Co	Cr	Cu	Li	Ni
	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l
41191	0.040	2.179	69.58	<0,001	0.610	<0,002	1.583	2.623	18.36	1.168
GL	0.088	0.681	200	0.001	0.019	0.019	1.614	1.243	4.914	0.825
OZ	0.113	0.211	28.79	0.012	<0,009	0.013	2.132	0.474	1.26	0.808
WH	0.053	1.007	113	0.001	0.028	0.006	1.736	5.237	8.914	0.761
41189	0.029	2.092	77.22	0.003	0.024	<0,002	1.905	0.937	12.32	1.146
41180	0.075	6.234	43.82	<0,003	0.057	<0,006	2.760	1.218	312	2.616
41190	0.458	2.192	148	<0,001	0.265	<0,002	2.519	5.859	16.10	1.788
200411	0.168	3.630	41.05	0.002	0.134	0.394	1.872	1.332	156	2.848
41184	0.036	3.406	125	0.002	0.038	0.372	0.910	0.944	12.04	1.898
41188	0.030	1.903	59.25	0.002	0.028	0.030	0.860	2.234	11.06	1.225
27107	0.106	2.254	118	0.002	0.032	0.698	1.541	1.265	4.812	2.114
41181	0.13	5.45	91	0.06	<0,09	0.14	2.67	1.62	20	3.57
41183	0.086	3.328	143	0.020	0.038	<0,004	1.450	3.746	14.54	1.548
VB	0.069	4.170	42.76	<0,003	0.075	0.105	1.890	1.131	137	2.523
25575	0.089	1.379	232	0.001	0.018	<0,002	1.651	0.873	13.18	1.350
200413	0.64	6.80	118	0.09	0.13	2.54	14	11	145	9.77
200414	0.25	4.75	161	0.22	0.11	7.86	15	6.67	148	26
41075	0.051	3.819	51.16	<0,003	0.051	0.549	4.707	2.577	155	2.739
S 12	<0,09	4.94	83	<0,01	0.25	0.41	5.14	4.18	699	5.24
28250	0.044	0.824	70.06	<0,001	0.050	<0,002	4.702	1.706	8.435	1.088
WB	0.18	4.76	61	<0,01	0.19	1.53	3.07	2.87	91	2.28
HH	0.045	4.341	62.68	<0,003	0.468	<0,006	2.346	4.839	27.95	2.457
SA	0.339	5.184	74.42	<0,003	0.066	0.261	3.042	1.557	38.18	2.706
181	0.89	4.78	90.11	0.03	<0,09	<0,02	4.33	2.65	63	1.72
25054	0.110	1.546	31.39	0.01	0.016	0.015	1.804	0.818	2.655	0.977

Location	Pb	Sb	Sr	Th	Tl	U	V	Zn	Fe	Mn
	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l
41191	8.176	0.021	1896	0.006	<0,009	13.73	10.03	28.59	21.61	2.344
GL	0.060	0.017	361	<0,002	<0,009	0.927	9.369	10.74	13.21	1.445
OZ	0.052	0.017	76.28	0.003	<0,009	0.064	3.212	11.80	15.96	1.641
WH	0.081	0.022	532	0.015	<0,009	15.32	9.815	10.52	95.75	4.238
41189	0.641	0.028	1467	0.005	<0,009	11.21	8.957	7.699	31.55	91.350
41180	0.357	<0,045	4175	<0,006	<0,027	63.22	60.41	15.95	173	8.484
41190	1.876	0.032	1768	0.008	0.010	10.59	10.47	25.20	69.89	5.683
200411	0.196	0.698	4036	0.010	<0,018	132	8.288	68.02	175	28.530
41184	0.442	0.050	2996	<0,004	<0,018	15.49	8.262	9.416	27.17	508
41188	0.365	0.018	1294	0.008	<0,009	8.869	9.949	9.844	76.50	184
27107	0.068	0.051	388	0.004	<0,009	35.96	4.188	16.31	532	333
41181	0.16	<0,15	5759	<0,02	<0,09	77	3.24	22	1861	2024
41183	0.442	0.042	2666	0.006	<0,018	9.990	8.408	18.09	34.44	146
VB	0.804	0.033	3982	<0,006	<0,027	27.32	11.48	31.23	28.02	57.73
25575	0.078	0.029	922	0.003	<0,009	7.082	8.800	11.72	30.79	20.45
200413	4.13	<0,15	11230	1.00	<0,09	220	21	179	3561	487
200414	3.42	<0,15	6317	1.80	<0,09	149	14	78	16120	1552
41075	1.332	0.039	4522	0.231	<0,018	147	15.03	57.23	1504	28.01
S 12	0.99	<0,15	843	0.21	<0,09	357	7.01	141	149	109
28250	0.430	<0,015	2239	0.003	0.007	6.538	60.71	11.10	21.83	2.098
WB	1.68	<0,15	9151	0.02	<0,09	136	10	38	178	760
HH	4.011	0.042	4224	<0,006	<0,027	36.20	11.51	21.00	73.32	4.374
SA	0.708	0.066	6127	<0,006	<0,027	29.80	10.510	4.911	33.79	60.42
181	0.33	<0,15	7666	<0,02	<0,09	45	12	18	69	5.03
25054	0.068	0.034	244	0.003	<0,009	1.120	8.287	16.45	18.24	1.539

B CFC calculations

B.1 Coefficients for the determination of k_{Hi} (IAEA, 2006)

CFC	a_1	a_2	a_3	b_1	b_2	b_3
K_H in mol·kg^{-1}·(1013.25 hPa)$^{-1}$						
CFC-11	–136.2685	206.1150	57.2805	–0.148598	0.095114	–0.0163396
CFC-12	–124.4395	185.4299	51.6383	–0.149779	0.094668	–0.0160043
CFC-113	–136.129	206.475	55.8957	–0.02754	0.006033	—
K_H in mol·L^{-1}·(1013.25 hPa)$^{-1}$						
CFC-11	–134.1536	203.2156	56.2320	–0.144449	0.092952	–0.0159977
CFC-12	–122.3246	182.5306	50.5898	–0.145633	0.092509	–0.0156627
CFC-113	–134.243	203.898	54.9583	–0.02632	0.005874	—

B.2 Calculated atmospheric concentrations

Location	Recharge altitude	Recharge temperature	Salinity	calculated atmospheric concentrations					
				CFC-11	error	CFC-12	error	CFC-113	error
	m.a.s.l.	°C	‰	pptv		pptv		pptv	
OZ	1545	20	0.40	212.50	28.98	493.83	35.27	75.77	16.47
28250	1438	20	0.59	114.60	19.10	292.94	17.44	42.34	16.29
GL	1316	20	0.59	235.17	28.22	412.21	34.35	89.83	16.04
WH	1025	20	1.70	110.13	18.36	435.48	33.50	37.55	15.64
25575	883	21	0.61	56.01	9.33	339.24	33.92	19.20	16.00
VB	728	23	3.15	133.49	20.54	321.32	18.47	35.51	17.75
41191	516	23	0.60	26.31	4.87	150.89	17.54	10.12	16.87
41183	488	23	0.07	29.94	4.83	45.22	17.39	10.04	16.73
41180	478	23	1.77	3.93	4.91	3.53	17.66	3.40	-
41181	347	23	3.20	3.92	4.90	74.01	17.62	33.88	-
200411	223	20	7.11	175.63	17.56	383.82	31.99	56.78	14.94
HH	203	20	3.13	100.95	16.82	260.85	15.34	28.67	14.33
WB	143	19	10.03	0.86	-	34.39	15.63	2.89	-
181	76	18	5.65	170.22	23.21	145.26	14.24	13.05	13.05

B.3 Calculated dissolved concentrations

Location	Recharge altitude	Recharge temperature	Salinity	calculated dissolved concentrations (standard conditions)					
				CFC-11	error	CFC-12	error	CFC-113	error
	m.a.s.l.	°C	‰	pmol/l		pmol/l		pmol/l	
OZ	1545	20	0.40	2.43	0.33	1.55	0.11	0.25	0.06
28250	1438	20	0.59	1.31	0.22	0.92	0.05	0.14	0.05
GL	1316	20	0.59	2.69	0.32	1.29	0.11	0.30	0.05
WH	1025	20	1.70	1.26	0.21	1.37	0.11	0.13	0.05
25575	883	21	0.61	0.64	0.11	1.06	0.11	0.06	0.05
VB	728	23	3.15	1.53	0.24	1.01	0.06	0.12	0.06
41191	516	23	0.60	0.30	0.06	0.47	0.06	0.03	0.06
41183	488	23	0.07	0.34	0.06	0.14	0.05	0.03	0.06
41180	478	23	1.77	0.04	0.06	0.01	0.06	0.01	-
41181	347	23	3.20	0.04	0.06	0.23	0.06	0.11	-
200411	223	20	7.11	2.01	0.20	1.20	0.10	0.19	0.05
HH	203	20	3.13	1.16	0.19	0.82	0.05	0.10	0.05
WB	143	19	10.03	0.01	-	0.11	0.05	0.01	-
181	76	18	5.65	1.95	0.27	0.46	0.04	0.04	0.04

C Impressions from the Swakop River catchment

Photo 1: Sampling at Weizenberg

Photo 2: Lower Swakop River

Photo 3: Swakop River during the rainy season (BASSINGTHWAIGHTE, 2008)

Photo 4: Khan River

Ehrenwörtliche Erklärung

Hiermit erkläre ich, dass die Arbeit selbstständig und nur unter der Verwendung der angegebenen Hilfsmittel angefertigt wurde.

Freiburg im Breisgau, den

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(Vera Marx)