Institut für Hydrologie der Albert-Ludwigs-Universität Freiburg i. Br.

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Transmission losses and soil moisture dynamics in the alluvial fill of the Kuiseb river, Namibia

Diplomarbeit unter der Leitung von Prof. Dr. Ch. Leibundgut
Freiburg i. Br., September 2004

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Summary

The aim of the present study was to experimentally examine soil moisture dynamics in the alluvial fill and the aquifer response to a flood in the *Kuiseb River* in Namibia. With a length of 560 km, the ephemeral *Kuiseb river* drains a catchment of approximately 14,700 km^2 in west–central Namibia. The rainfall in the catchment declines from a mean annual rainfall of ~350 mm in the headwaters at ~2000 m asl, to near zero at the coast (JACOBSON 1997).

This research study focuses on understanding the processes and rates of infiltration during flood events at a site specific scale. Therefore, a field campaign was carried out from December 2003 to April 2004 around *Gobabeb Desert Research Station,* which is situated in the lower *Kuiseb catchment*, in the *Namib Desert*.
Two floods were observed, with a peak discharge of approximately 90 m^3/s and a flood duration of two and four days.

Soil moisture dynamics in the active channel and in the overbank area were surveyed at four sites by Theta Probes. Due to the heterogeneous soil, a new method had to be developed to insert the probes with a minimum of soil disturbance. Therefore, a special drilling pipe was constructed.
The aquifer response to the floods was examined by measuring temperature, electrical conductivity and water level fluctuation in a monitoring borehole at *Gobabeb Research Station*. Further, floodwater and groundwater samples were collected and analysed for stable isotopes and major ions.

A distinct spatial variability of stratigraphy was examined and documented at several profiles with a maximal depth of 300 cm. Mainly sand is stratified with layers of different thickness consisting of clay and/or silt. The surface of the active channel is covered by a silt layer of varying thickness.
The aquifer responded with a rise of water table of 89 cm as a reaction to flood 1 and with 8 cm to flood 2. The rate of vertical advance of the wetting front was determined between 0.3 m/h and 0.15 m/h in two flood events. The calculated infiltration rates are between 0.26 mm/h and 0.89 mm/min. The rates of infiltration as well as the advance of the wetting front are lower than the results of other arid research areas published by other authors. It is assumed that the smaller rates at the *Kuiseb* are mainly caused by silt layers on the surface reducing the infiltration.
A lateral movement of the wetting front towards the dry overbank area could not be measured to a depth of 130 cm and up to a distance between 230 cm and 570 cm to the active channel.

The examination of soil moisture dynamics indicates transmission losses via infiltration between 2957 l/m^2 and 250 l/m^2 for the two observed floods.

Due to the heterogeneous character of the stratigraphy and the surface conditions of the riverbed, it is assumed that the infiltration at a single point in the active channel is not representative to the whole channel.
By hydro-chemical analysis of major ions and the analysis of stable isotopes, mixing of ground- and floodwater could not be evidenced. Though groundwater recharge could not be quantified on the basis of ion concentration, borehole observations gave a basis for recharge calculation. A recharge of up to 95,630.5 m^3/km river length was calculated. As the exact extent of the aquifer is not known, these calculations need to be considered as a rough estimate. A significant smaller amount of infiltration during the second flood was determined and can be explained as follows:

During flood 2, the surface of the active channel was mostly sealed by the wet silt cover deposited by the flood 1, which passed four days before.
A scour of this clogging layers didn‘t take place due to the less erosive character of flood two.

It is further assumed that the deeper alluvium was still at field capacity when flood two occurred and most of the infiltrated water could percolate to the aquifer. Taking into account, that despite of significant different amounts of run off, both floods were flowing approximately the same distance, it is indicated that during flood two significant less transmission loss took place.

Considering the results of this study, though measuring the water table reaction and soil moisture dynamics are the most appropriate of the applied methods for estimating transmission losses and groundwater recharge in short term studies in arid areas, the analysis of the processes of the alluvial fill of the *Kuiseb* need further investigations applying other methods i.e. a long term investigation about ion and isotope concentrations.
Overall, the main limiting factors for transmission losses seem to be the covering silt layers on the surface of the active channel together with the silt and clay layers within the stratigraphy.

Keywords: *Kuiseb River – Namib Desert* – transmission losses – ephemeral streams -soil moisture – arid

Zusammenfassung

Das Ziel der vorliegenden Diplomarbeit ist die experimentelle Untersuchung der Bodenfeuchtedynamik (Infiltration, Evaporation, Transpiration) im Alluvium sowie der Beobachtung der Aquiferreaktion auf Flutereignisse des *Kuiseb*-Flusses in Namibia. Der 560 km lange ephemerische Kuiseb entwässert ein Einzugsgebiet von 14,700 km² in west-zentral Namibia. Der mittlere jährliche Niederschlag beträgt ~350 mm im oberen Teil des Einzugsgebietes auf 2000 NN und nahezu 0 mm in Küstennähe (JACOBSON 1997).
Die Forschungsarbeit soll einem besseren Prozessverständnis und die Erfassung von Infiltrationsraten auf Feldskalenebene dienen. Dafür wurden von Dezember 2003 bis April 2004 Feldarbeiten in der Nähe der Wüstenforschungsstation *Gobabeb* durchgeführt, die im unteren Einzugsgebiet des *Kuiseb* Flusses (Namibia) liegt.
Im Untersuchungszeitraum konnten zwei Fluten mit einem maximalen Abfluss von etwa 90 m³/s beobachtet werden,

An vier Untersuchungsstellen wurde mittels Theta-Sonden die Bodenfeuchtedynamik im aktiven Flussbett und im Uferbereich untersucht. Zur Installation der Sonden in ein ungestörtes Bodenprofil der heterogenen Standorte wurde eine neue Methode entwickelt, wozu ein spezielles Bohrgerät konstruiert wurde.
Die Reaktion von Temperatur, Wasserstand und Leitfähigkeit des Grundwassers auf die Flutereignisse wurde mittels CTD – Divern in einem Beobachtungsbrunnen bei der Wüstenforschungsstation *Gobabeb* aufgenommen. Außerdem wurden Grund- und Flutwasserproben genommen und auf die wichtigen Ionen sowie auf Isotope (Deuterium und ^{18}O) analysiert.
Die ausgeprägte räumliche Variabilität der Stratigraphie wurde durch Profilansprachen von bis zu 3 m Tiefe hinsichtlich der Korngrößenverteilung mittels Fingerprobe untersucht und protokolliert. Größtenteils konnten Sande durchzogen von Schluff- und oder Tonlagen unterschiedlicher Mächtigkeit dokumentiert werden.
Die Oberfläche des aktiven Gerinnes ist mit unterschiedlich dicken Lagen von Feinmaterial aus Schluff oder Ton bedeckt.

Während der Flutereignisse stieg der Grundwasserstand bei der ersten Flut um 89 cm und um 8 cm bei der zweiten Flut. Das vertikale Fortschreiten der Feuchtefront betrug 0,3 m/h und 0,15 m/h in zwei Flutereignissen. Die berechneten Infiltrationsraten sind 0,26 mm/min und 0,89 mm/min. Die Infiltrationsraten sowie das Fortschreiten der Feuchtefront sind kleiner als die Ergebnisse, welche von anderen Autoren in anderen ariden Gebieten ermittelt wurden. Es wird angenommen, dass die geringeren Infiltrationsraten in *Kuiseb* hauptsächlich durch die Sperrschichten (Feinmateriallagen aus Ton und Schluff) verursacht werden, da diese die Infiltration verringern.
Ein laterales Fortschreiten der Feuchtefront in den Uferbereich konnte im Abstand von 230 cm bis 570 cm zum aktiven Gerinne und bis zu einer Tiefe von 130 cm nicht nachgewiesen werden. Die Untersuchung der Bodenfeuchtedynamik deutet nach

eigenen Berechnungen auf *Transmission losses* zwischen 250 l/m^2 bis 2957 l/m^2 für die zwei beobachteten Fluten durch Infiltration hin.
Aufgrund des heterogenen Charakters in der Stratigraphie und den variierenden Oberflächenbedingungen des Flussbettes können die Infiltrationswerte eines räumlich beschränkten Untersuchungsgebietes innerhalb des Flussbettes nicht als repräsentativ für das gesamte Gerinne betrachtet werden.
Durch die hydrochemische Untersuchung der Hauptionen und die Analyse der stabilen Isotope konnte 3 Monate nach den Flutereignissen eine Vermischung des Grundwassers und des Flutwassers nicht nachgewiesen werden. Obwohl die Grundwasserneubildung auf Grundlage der Ionenkonzentrationen nicht bestimmt werden konnte, stellen die Grundwassserstandsmessungen eine Basis für die Berechnung der Neubildung dar. Es wurde eine Grundwasserneubildung pro Kilometer Flusslänge von bis zu 95.630,5 m^3 berechnet. Diese Zahlen können nur als ungefähre Annahme dienen, da unter anderem die genaue Ausdehnung des Aquifers nicht bekannt ist. Für die signifikant geringere Infiltrationsmenge während der zweiten Flut könnte folgende Erklärungen gegeben werden:

- Die Flussoberfläche war während der zweiten Flut größtenteils bereits durch die feuchten Feinmaterialablagerungen der ersten Flut, welche vier Tage zuvor durchfloss, versiegelt.
- Ein “Aufreißen” dieser verklebten Schichten fand Aufgrund des wenig erosiven Charakters der zweiten Flut nicht statt.

Desweiteren wird angenommen, dass der Wassergehalt im tieferen Alluvium bei Ankunft der zweiten Flut bei Feldkapazität lag, so dass das der Hauptteil des infiltrierten Wassers zum Aquifer perkolieren konnte.
Trotz der deutlichen Unterschiede im Abflussvolumen der beiden Fluten kann unter Berücksichtigung der ähnlich langen zurückgelegten Flussstrecke beider Fluten angenommen werden, dass bei der zweiten Flut geringere *Transsmission losses* stattgefunden haben.

Obwohl das Monitoring des Grundwasserstandes und die Beobachtung der Bodenfeuchtedynamik von den angewandten Methoden für die Ermittlung von *Transmission losses* und der Grundwasserneubildung für Kurzzeitstudien in ariden Gebieten am geeignetsten zu sein scheint, benötigt man nach den Ergebnissen dieser Studie für die Prozessanalyse des Alluviums im *Kuiseb* weitere Untersuchungen, wie zum Beispiel Langzeitstudien zu Ionen- und Isotopenkonzentrationen für eine verlässliche Aussage.
Allgemein erscheinen lokale Schluff- und Tonablagerungen (ober- und unterirdisch) die entscheidenden Parameter für die Ausprägung der beobachteten Transmission losses zu sein.

Stichworte: Kuiseb – Wüste Namib – Transmission losses – ephemerische Flussläufe – Bodenfeuchte - arid

1 Introduction

The present study was carried out as subcontract given to the Institute of Hydrology, University of Freiburg by Dr. C. Külls, Hydroisotop GmbH (Nord), Gross Grönau.

Namibia is the driest country in southern Africa. The typical characteristics of arid regions, such as very few rainfall and high evaporation, result in the very rare occurrence of surface water in the research area. Further, surface water distribution varies heavily in space and time. Therefore, groundwater is an important source for water supply, if available. However, groundwater use is only sustainable, as long as the mean abstraction rates do not exceed the long term recharge values under present and future climatic conditions. Hence, reliable recharge estimates are the most important premise for sustainable groundwater management.
DE VRIES & SIMMERS (2002) give an overview of types, processes and estimation of recharge in dry climates. They conclude quantitative estimates from all principal recharge mechanisms, i.e. direct and indirect recharge. It is widely acknowledged that the importance of indirect recharge by infiltration through the beds of ephemeral water courses increases with aridity (e.g. LLOYD 1986, DE VRIES & SIMMERS 2002). Indirectly predicting recharge by transmission losses is a key factor for sustainable freshwater management in arid regions.

Although the significance of transmission losses has been known for many years (e.g. DUBIEF 1953, RENARD & KEPPEL 1966, SCHICK 1988), there is only few knowledge about the processes involved. Monitoring of surface water flow in arid environments is difficult due to low population density, remoteness of hydrological stations and short duration of floods. During a flood event several processes are active that change the hydrological conditions during the infiltration (e.g. air entrapment, scour and fill). For example, flood waters often carry silt and other fine material, which can effectively seal the alluvial surface and thus decrease the potential infiltration rate. This phenomenon was even observed during high velocity events (CRERAR *et al.* 1988). Furthermore the processes of scour and fill are complex and their interaction is not fully understood. Apart from infiltration, alluvial recharge is influenced by evapotranspiration processes.
Estimation of infiltration rates and loss volumes during real flood events remain uncertain, especially in large scale systems (WHEATER *et al.* 1997).

Recent studies at local scale in ephemeral streams have shown huge temporal and spatial variability of estimates for infiltration rates. HUGHES & SAMI (1992) conducted point measurements of soil moisture in the channel alluvium indicating large differences within small distances. Similar results were obtained by PARISSOPOULOS & WHEATER (1992), while conducting point measurements of infiltration rates. KUELLS *et al.* (1995) used artificial tracers (*Rhodamine*) to illustrate preferential flow paths. LANGE *et al.* (1998) applied artificial tracers along a 250 m steep channel reach during a flash flood in the southern *Negev Desert*, Israel. As flow declined, exfiltration from the channel alluvium was observed. In the northern *Negev Desert*, SCHWARTZ (2001) conducted measurements of moisture in channel alluvium at two specific cross sections during several flood events. The records of TDR and leafwetness moisture sensors documented more than two-fold differences in the rate of wetting-front advance (1.5 – 3.7 $m*hr^{-1}$). Moreover, transmission losses were significantly reduced when the time interval between two successive floods was less than one week. DUNKERLEY & BROWN (1999) observed a single flow event in a small desert stream in western New South Wales, Australia. The flow was entirely lost over a distance of 7.6 km transmission resulting in a loss rate of 13.2% per km. The factors influencing the flow losses included separation of flow to pools, scour holes and other narrow points along the channel, dead-end channels as well as mud drapes that sealed porous channel materials.

On a larger scale hydrometric data upstream and downstream of a channel reach can be used to compare inflow and outflow volumes and thus to quantify transmission losses. Studies have been carried out in the United States (LANE 1985), in Saudi Arabia (WALTERS 1990, SORMAN & ABDULRAZZAK 1993; 1997) and in Israel (SHENTSIS *et al.* 1999) to relate the volumes of transmission loss to flow and channel characteristic. GREENBAUM *et al.* (2002) used historical paleoflood records in addition to estimates of recent transmission losses to calculate long term estimates for indirect recharge. KNIGHTON & NANSON (1994) studied a long (400 km) and a short (32 km) reach of *Cooper Creek*, Australia. Applying input-output relationships for measured channel reaches combined with simple hydrological flow routing schemes showed that only in the shorter, more confined reach outflow hydrographs could be effectively estimated by the three parameter *Muskingum procedure*.
The above-mentioned studies can be summarised according to scale:

Small scale	Large scale
site-specific and direct observations, including • point measurements of infiltration or alluvial moisture, • measurements of moisture in channel alluvium at cross sections during real flood events • tracer applications along short channel reaches. They document considerable spatial and temporal variability inherent in the process of transmission losses. Meaningful upscaling of the results has not been achieved.	• Studies are mostly conducted in catchments or along channel reaches and involve water balance estimations. • The resulting regression equations or simple hydrological flow routing approaches remain site-specific and are often impacted by unknown lateral inflows. They require further verification and modification before being applied to other arid channels.

This research study focuses on understanding the processes and rates of infiltration during flood events at a site specific scale.
Field data was collected from December 2003 to April 2004 in the *Kuiseb* catchment, Namibia. The main focus of field work was around *Gobabeb Research Station*.
Soil moisture was measured and profiles were dug in order to analyze the grain size distribution. Temperature, specific conductivity and water level fluctuation of groundwater were measured. Flood water and groundwater samples were collected.
The hydro chemical analyses of water samples were carried out from July to August 2004 in Freiburg, Germany.
In order to increase the understanding of infiltration processes and to enable better quantification of infiltration rates during flood events, a field campaign was carried out from December 2003 to April 2004 in the *Kuiseb* catchment, Namibia. (see map in Figure 2 at page 8).
Two flood events were observed and sampled. The analyses of ground and stream water samples were taken, including major ions as well as stabile isotopes (Deuterium and ^{18}O). In addition to this, the aquifer has been observed concerning water temperature, specific electrical conductivity and water level fluctuations in monitoring wells at several distances to the channel and directly underneath the stream bed. These parameters as well as soil moisture data from various depth and different profiles were recorded during the field campain. Further profiles were dug to analyse grain size distribution at several locations.

2 Research Area

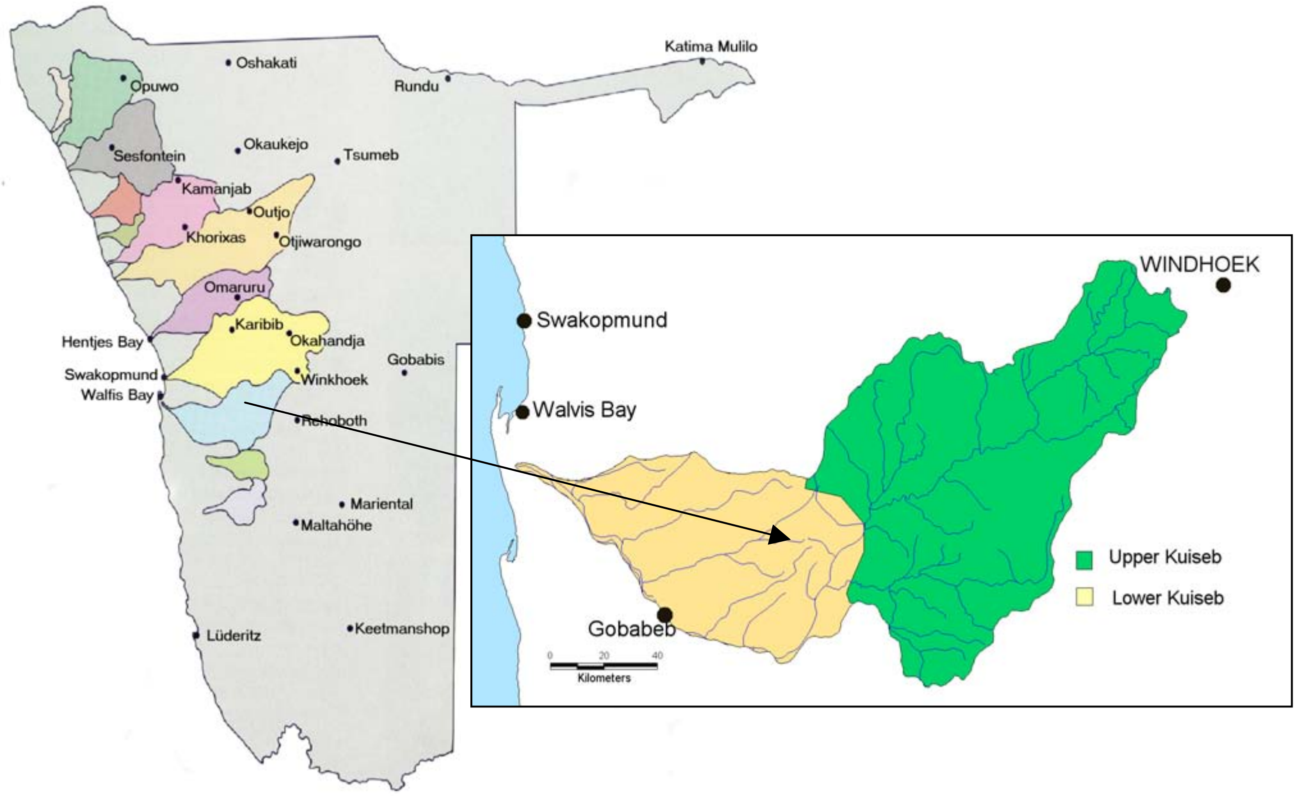


Figure 1: Research area
modified after JACOBSON et al.(1995)

The main study area was the lower *Kuiseb* around *Gobabeb*. The *Kuiseb*, an ephemeral river with a length of 560 km, drains a catchment of approximately 14,700 km^2 in west – central Namibia, although only 9,000 km^2 of this area is considered to be producing runoff, while the remaining part of the catchment area is largely desert plain yielding runoff only in exceptionally wet years (HATTLE 1985).
The rainfall in the catchment declines from a mean annual rainfall of ~350 mm in the headwaters to near zero at the coast (JACOBSON 1997).
The *Kuiseb* rises on the interior plateau of central Namibia, the *Khomashochland*, at an elevation of ~ 2,000 m. Westwards from the headwaters, the river has eroded a shallow, sinuous valley into Late Precambrium metasediments, largely composed of schists and quarzites which provide a large proportion of sandy bed loads transported within the river's lower reaches (WARD 1987). West of the escarpment separating the inland plateau from the coastal plains, the river has incised a deep canyon (>200 m) in similar rocks. The river is highly confined herein, often flowing over bedrock with no alluvium due to the comparatively steep gradient (0.003 – 0.004 m/m) and narrow channel (<100 m). The channel broadens 65 km from the coast (approximately 45 km above *Gobabeb*) (see Map in Figure 1), freeing the river channel to expand onto an increasingly wide floodplain. Some 42 km below *Gobabeb Station*, the floodplain width increases to over 1,000 m (JACOBSON 1997).

Within 20 km from the coast, low cresentic dunes cross the river, resulting in poorly defined channels terminating on coastal flats in the vicinity of the city of *Walvis Bay*. Gradients below the canon average 0.001 – 0.002 m/m, increasing again to > 0.004 m/m within 60 km from the coast, resulting in a slightly convex longitudinal profile in the lower river. When in flood, the river's lower reaches transport a sandy bed load and a suspended load high in silts. The sandy channel sediments within the lower 150 km are largely devoid of cobble or bedrock, excluding occasional bedrock dikes which cross the channel and form local knick points in the longitudinal profile. (WARD 1987)

2.1 Gobabeb

Gobabeb, where the *Gobabeb Desert Research Station* is located, is situated in the *Namib Desert*, 23°34' S, 15°03' E. The *Namib* is a hyper arid zone, a foggy coast desert consisting of dune fields in the south, and gravel plains in the north.
Gobabeb stands at about 408 m asl, approximately 60 km from the west coast. It is located along the *Kuiseb*.
The *Kuiseb* delineates the gravel plains in the north from the dune fields in the south.

2.1.1 **Climate**

The most important oceanographic feature in this region is the *Benguela current*. The current originates from *Antarctica* and influences the area between the *Southern Cape* and *Angola*. It is part of the *South Atlantic circulation system*, which is wind driven. The prevailing cold, onshore winds clearly contribute to the arid nature of the *Namib Desert*. The current transports enormous amounts of sand derived from the interior of the continent towards the north. Due to the influence of the cold *Benguela current*, the mean annual temperature is below 20°C at the coast, inducing a steep temperature gradient inland over a 50 km wide zone (AIN 1999).

Rainfall:
The long term mean rainfall for *Gobabeb* recorded from 1962 to 1996, is 20.8 mm per year, with annual total ranging from 2.0 to 115.1 mm. Most of the rain, about 77%, falls in summer, and only 23 % is winter rainfall (SHANYENGANA 1997).

Temperature:
The long term mean temperature for *Gobabeb* recorded from 1962 to 1996, is 20.1 °C. The range is between 1.0 and 42.8 °C (SHANYENGANA 1997).

Evapotranspiration:
The long-term mean Claas-A-pan evaporation measured at *Gobabeb* is 4631 mm (SHANYENGANA 1997). BATE & WALKER (1991) estimated the transpirational loss by all the vegetation with about 2.02 x 10^5 m^3 per km river length annually.

2.1.2 **Geology / Geohydrology / Vegetation**

The regional geology has been summarised by AIN (1999). The Namib Desert is underlain by Precambrian bedrock consisting of granites, gneisses and schists. These are separated from Tertiary and Quaternary deposits by the *Namib* Unconformity Surface, which was formed during the Late Cretaceous erosional phase. Outcrops of Precambrian rocks can be found all over the *Central Namib Region*. The oldest Tertiary deposits (50 - 20 Ma) pertain to the cross-bedded (aeolian) Tsondab Sandstone Formation, which underlies most of the *Central Namib Desert* south of the *Kuiseb River* and was laid down under arid conditions. The *Namib Desert* north of the *Kuiseb River* is overlain by alluvial sediments of the Namib Group (Early Miocene) indicating a wetter (i.e. less arid) climate with sporadic high energy events. Extensive calcrete formation occurred at the end of the Miocene. The Late Tertiary deposits of the *Sossus* Sand Formation indicate a return to arid conditions. The Pleistocene sediments show a mostly arid climate, which alternates sporadically with short slightly wetter periods. Evidence of lacustrine and moister conditions can be seen in the *Hudaob Tufa* deposits, the *Khommabes*.
Carbonates, the *Homeb* Silts and *Awa Gamteb* muds. Ephemeral rivers have deposited the most recent sediments in the form of lag deposits and silty river alluvium during floods. The modern coastline with its headlands, lagoons, bays and sabkhas is a result of the interaction (ECKARDT 1996).

Namib Sand Sea
The *Namib Sand Sea* is located south of the *Kuiseb*. It comprises a dunefield, that extends inland from the Atlantic coast for some 100 km between *Lüderitz* and *Sandwich Harbour*, just south of *Walvis Bay*. Southwest of *Gobabeb* the dunefield comprises linear dunes oriented northeast reflecting the prominence of the south-westerly winds. Vegetation is sparse within the dunefield but a few fog-dependent, endemic plant species, such as: *Stipagrostis sabulicola and Trianthema hereroensis* are found (SHANYENGANA 1997).

Namib Gravel Plains
Extending northwards from the *Kuiseb River*, there are the gravel plains of the *Namib*. These plains comprise a deflation surface covered by a thin layer of coarse sand and gravel, broken in places by granitic inselbergs and low kopjies. Calcrete, gypcrete and shallow suboutcrop of metamorphic and granitic basement lithologies underlie the gravel plains. In general these gravel plains are devoid of vegetation supporting lichen, a few dwarf shrubs and acacias. *Welwitschia mirabilis* are found in

a limited number of localities. Grasses, particularly *Stipagrostis* species are common, proliferating after rare rainfall events (SHANYENGANA 1997).

Kuiseb Alluvial Aquifer

The *Kuiseb* Alluvial Aquifer is not continuous. At several locations, basement rocks crop out on either side of the river channel restricting the lateral extent of the alluvium. Upstream of *Gobabeb* and approximately 5 km downstream, near *Soetrivier*, such outcrops exist. In the vicinity of the latter, geophysical surveying suggested that the depth to fresh bedrock is very limited. Such lateral and vertical restrictions to the alluvial channel constitute possible barriers to groundwater flow. Recharge to the alluvial aquifers occurs via vertical infiltration of runoff down the present day *Kuiseb River*, and from through-flow within the alluvial aquifers.

In AIN (1999), a porosity of 35% and average alluvium width with 150 m and a saturated thickness of 10 m is assumed, whereas BATE & WALKER (1991) estimated the average width of the alluvial aquifer with 307 m and the depth of 10 m.

There are two aquifers of differing water quality in the *Kuiseb* at *Gobabeb,* one on top of the other. A freshwater aquifer is underlain by a denser and more saline aquifer. In places the interface between the upper and lower groundwater is sharp but in other places a zone of mixing is present. It should be noted that the thickness of the layer of fresh water varies between 3 and 15 m and that the quality of water in this layer is also not constant (AIN 1999).

Riverine Vegetation

Riverine vegetation is mainly consisting of four species: Anatrees (*Faidherbia albida*), Camel Thorn (*Acacia erioloba*), False Ebony (*Euclea pseudobenus*) and Tamarix (*Tamarix usneoides*) (BATE & WALKER 1991).

2.1.3 Flood occurrence and runoff at Gobabeb

Flow in the *Kuiseb* is short – lived and highly variable. Records at *Gobabeb* indicate the river flows between 0 – 105 days per year. For instance, in the early 80's the river did not flow for more than four years, consecutively (SHANYENGANA 1997).

Flows in the *Kuiseb* seldom reach the Atlantic. The WNNR report (1984) states that in the time span between 1937 – 1984 flow only reached the sea 15 times. JACOBSON (1997) calculated a mean annual runoff from 1979 – 1993 of 4.65 x 10^6 m^3. The annual range however is between 0 – 220 x 10^6 m^3 (AIN 1999).

Hydraulically, the *Kuiseb* is the most thoroughly monitored river of western *Namibia*, with 8 rainfall and 14 flow gauging stations distributed within the catchment. Unfortunately no data from 2004 floods were available for the present study.

3 Methods

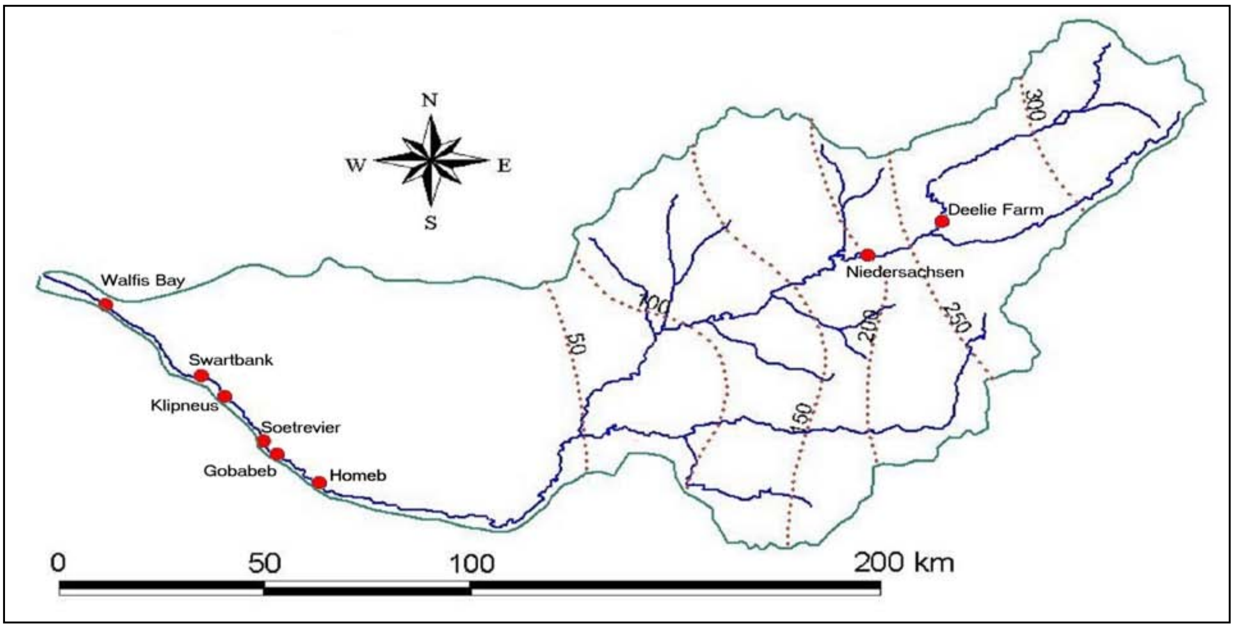


Figure 2: Research sites in the Kuiseb catchment

In order to examine experimental soil moisture dynamics and an aquifer response to a flood event, field data were collected in period of 4 ½ month from December 2003 to April 2004 in the *Kuiseb* catchment, Namibia. The main focus of fieldwork was around *Gobabeb Research Station* (Figure 2). For a general overview on what kind of examination was conducted at which site see Table 1.

3.1 Fieldmethods

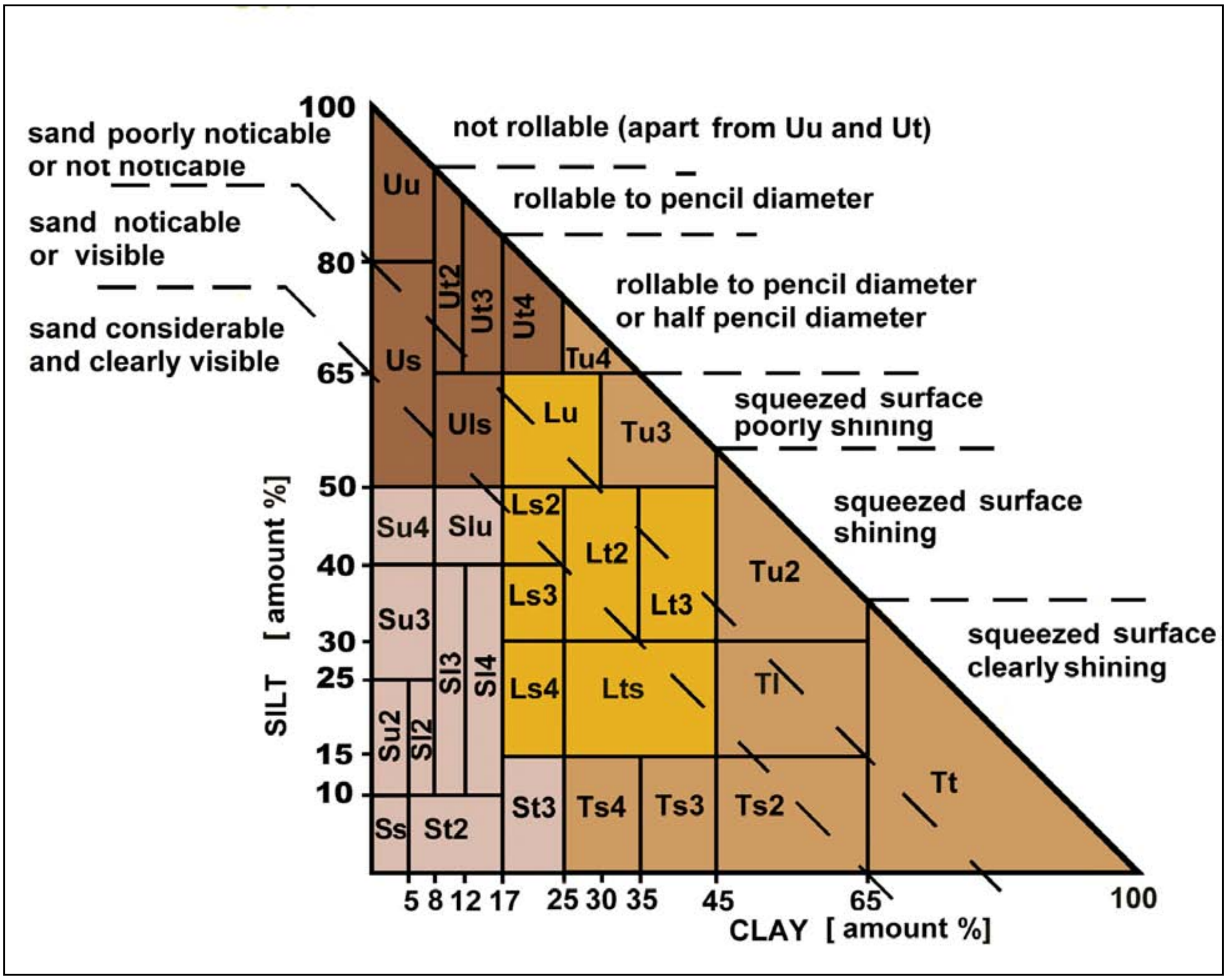
Table 1: Research site and kind of field work

Location	grain size distribution	soil moisture dynamics	groundwater sampling	flood water sampling	aquifer obser-vation: SC, temp., water level	water level floods
Us Pass Deeliefarm			X	X [1]		
Niedersachsen	X [1]	X		X [1]		
Homeb			X			
Gobabeb	X	X[2]	X	X	X	X
Soetrevier			X			
Klipneus			X			
Swartbank			X			
Saltsprings Soetrevier			X [1]			
15 Namwater boreholes			X [1]			

[1]: one - time sampling/not regularly [2] : at four research sites

3.1.1 Grain size distribution / stratigraphy

40 profiles to a maximum depth of 310 cm were dug in the alluvial fill of the *Kuiseb*. The profiles were analyzed for grain size distribution according to a finger test proposed by AG Boden (2002) (see Figure 3). In addition, several soil samples were sieved to a size of 63 µm. These profiles include the characterization of the soils where the Theta Probes have been inserted. Most profiles were dug at *Gobabeb* (active channel and overbank area). Only one profile was dug at the farm *Niedersachsen* in the active channel.



T = clay, t = clayey; L = loam, l = loamy; U = Silt , u =silty; S = sand, s = sandy
Figure 3: Grain size triangle

3.1.2 Water level measurement during flood

Water level readings were regularly taken while the *Kuiseb* was flowing at *Gobabeb Station* and additionally there are some data available for the *Gobabeb* weir.
Readings were taken from gauge plates (see Figure 4), 31 readings for the first flood (18.01.-21.01.2004) and 12 readings from the second flood (26.01.04 – 27.01.2004).
Readings were initiated according to a flood warning system, which was set up by contacting farmers of upstream locations.

Figure 4: Gauge plates at Gobabeb Station

3.1.3 Examination of soil moisture dynamics

The soil moisture was surveyed by Theta Probes Type ML2x from *Delta – T devices Ltd.*. The Theta Probe indirectly measures volumetric soil water content.
Volumetric soil water content is the ratio between volume of water and total sample volume. This is a dimensionless parameter, expressed either as percentage [V%], or a ratio [m^3/m^3]. The accuracy is ± 0.05 [m^3/m^3]
The measurements were recorded by a data logger (*Micromec multisens*, produced by *Technetics*). The logger was recording in intervals of 5 minutes with a stabilization time of 5 seconds.
At *Gobabeb*, the probes of two from four sites were permanently observed by a logger. Power was supplied by a rechargeable battery. Both, the logger and the battery, were inserted in a specially developed instrument suitcase (by Institute of Hydrology, *Freiburg*).
Two times a day a logger was connected to the probes at the two other sites to also measure soil moisture there. Once a week, when the battery had to be changed, the data were downloaded.

Installation of Theta Probes:

Due to the heterogeneous soil, a method to insert the probes with a minimum disturbance of soil had to be developed.

First a drill pipe was developed and built by the author and a field assistant.
The Drill pipe consists of two iron pipes, one pipe (A) with a diameter of 5 cm and an other pipe (B) with a diameter of 3.5 cm.
Onto the inner pipe B a drill bit (C) was welded with its outer diameter fitting exactly into the outer pipe A.
The smaller pipe B was put in pipe A in a way that the drill bit was standing over; both pipes were connected with an iron stick (D) at the upper end (see Figure 5).

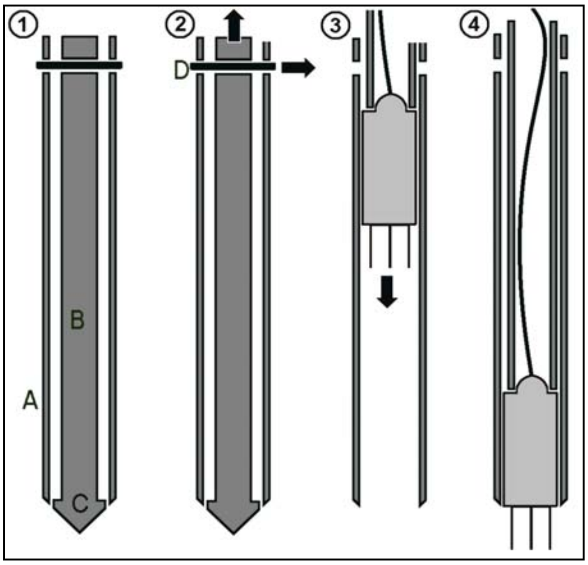


Figure 5: Construction scheme

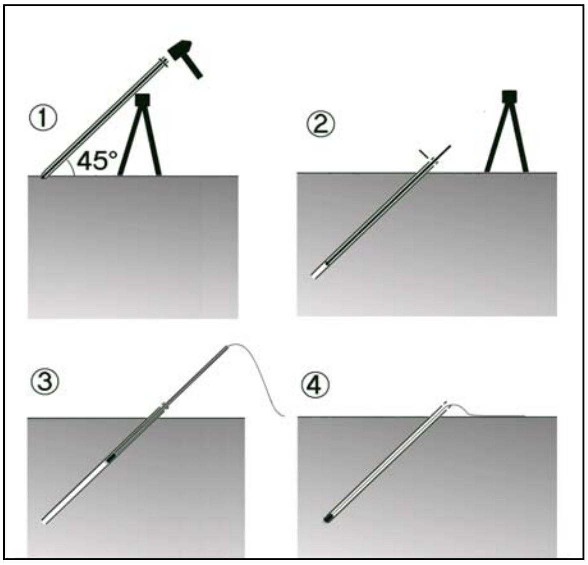


Figure 6: Insertion scheme

When both pipes were well connected to each other by the iron stick, they were hammered into the soil in an angle of 45°. This angle was ensured by using a wooden trestle of a height of 75 cm, which was placed in 75 cm distance to the puncture (see Figure 6).
Using an angel of 45° also has the advantage to easily calculate the final depth. The pipes had a length of 150 cm, resulting in a (vertical) depth of ~ 106 cm. For deeper probes, an extension had to be connected by welding them together at the research site. In order to do this, a mobile welding machine powered by a Diesel-generator had to be brought into the riverbed (Figure 7).

Figure 7: Welding of drill pipes

After reaching the final depth, the inner pipe was pulled out. Then the depth was checked with a smaller iron pipe in order to avoid that the Theta Probe sensors are situated inside the pipe. Afterwards the probe was inserted with a guide pillar (see 3 in Figure 5 and Figure 6). Finally, the sensors of the probe were placed outside the pipe (see 4 in Figure 5, Figure 6 and Figure 8).

Figure 8: Drilling Pipes for the insertion of the Theta-Probes

To inhibit preferential flow the pipes were carefully filled up with sand and silt. On top of the filling plastic foil was fixed with duck tape.
In order to avoid cable damages, the Theta Probes´ connecting cables were buried to a depth of ~ 30 cm. After the first flood these cables were additionally fixed on an iron chain, which was connected to the pipe on one side and on a tree at the other side.
The data logger and rechargeable battery (at the permanent sites) were either fixed in a tree or in a rock fracture in a save height of more than 2 m above ground, so that no floodwater could reach the instrument.

Research sites:

Preliminary Investigation Site, *Niedersachsen*

Some preliminary investigation was done in the upper catchment, on the farm *Niedersachsen* (see Figure 2). The main purpose was to test the developed method for inserting the Theta Probes. Originally, it was planed to bury the probes, but due to the heterogeneous soils at *Gobabeb* region and the existing silt layers, the “drilling method” as described above was developed to obtain data from undisturbed soil profiles .

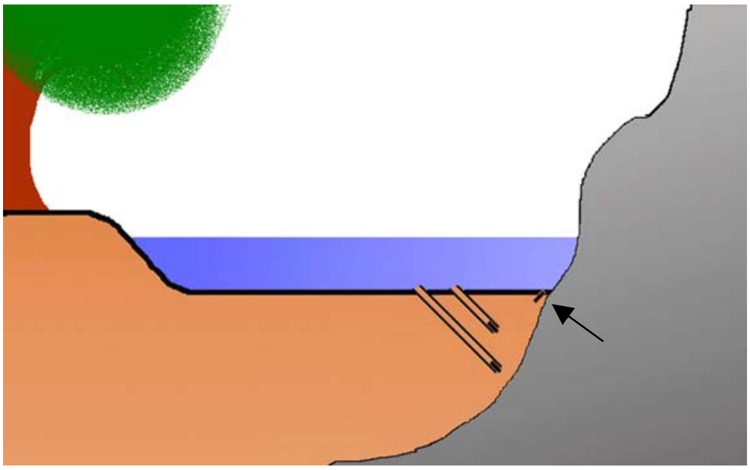


Figure 9: Location of Theta Probes at Niedersachsen
(not in scale)

This new method couldn't be checked at *Gobabeb*, because at this time the research permit to work in the riverbed of the *Namib Naukluft Park*, where the *Kuiseb* at *Gobabeb* is located, was not given yet. *Niedersachsen* was chosen because it is located outside of the park, in the *Khomashochland*, the upper catchment, where the probability to observe a flood event is much higher than in the lower catchment. As a main research site, this area was not suitable, mainly because of its inaccessibility.
Three probes were installed in the active channel at depths of 5 cm, 35 cm and 70 cm in order to measure soil moisture dynamics caused by infiltration. The probe in 5 cm depth should give an indication about the flood's arriving time. .

Four sites next to *Gobabeb* station were chosen:

<u>Site One, "Anatree site"</u>

Figure 10: Location of Theta Probes at "Anatree Site"

At this site five probes were established. Probe A was in the active channel at 100 cm depth. The other four were inserted in the overbank area. Probe B was installed at a depth of 130 cm and in 2.3 m distance to the active channel. Probe C, D and E were installed at a depth of 50 cm, 80 cm and 130 cm, respectively, next to a big Anatree (*Faidherbia albida*) and in a distance of 5.30 – 5.7 m to the active channel. The purpose of the "Overbank Probes" was to observe a lateral movement of the wetting front. In case of flooded overbank these probes should also measure soil moisture dynamics caused by infiltration, evaporation and evapotranspiration. These probes were permanently connected to a data logger. The logger was fixed 2 m above ground in an Anatree.

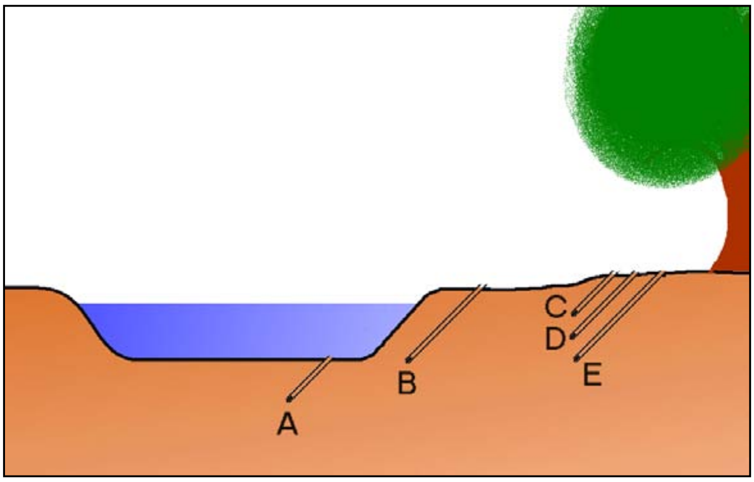


Figure 11: Schematic distribution of Theta Probes at Anatree site (not in scale)

Site two, "Rock site"

At this site four probes were established in the active channel. A shallow "starter probe", (Probe F in Figure 13), was installed, well protected in a rock fracture, at a depth of 5 cm, its purpose was to give exact time of the flood arriving. The other three probes were placed at a depth of 80 cm (Probe G in Figure 13), 100 cm (Probe H in Figure 13) and 300 cm (Probe I), respectively. The three deep probes should log soil moisture dynamics caused by infiltration and evaporation without any influence by vegetation. There was no vegetation in the direct surrounding of the probes.

Figure 12: Bringing in probes at rock site

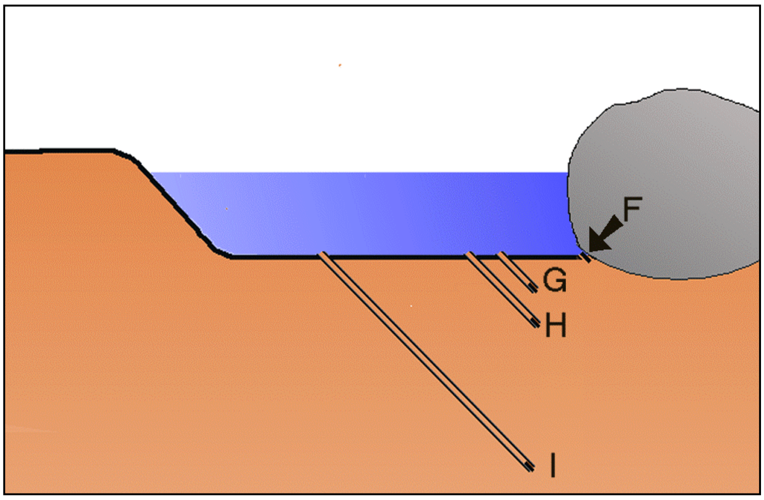


Figure 13: Schematic distribution of Theta Probes at rock site (not in scale)

Site three, “Pure Evaporation Site”

This site was set up to measure the soil moisture dynamics caused by evaporation and evapotranspiration. The set up was installed on the last day of the second flood, on the 27.01.2004. Two probes were inserted in the active channel very close to the riverine vegetation, here a young Anatree. These probes were inserted at a depth of 50 cm (Probe J in Figure 14) and 100 cm (Probe K in Figure 14). The other two Probes were inserted in 10 m distance, where they were assumed to not be influenced by vegetation, in the active channel at a depth of 50 cm (Probe L in Figure 14) and 100 cm (Probe M in Figure 14).These probes were permanently connected to a data logger apart from times of floodwarning.

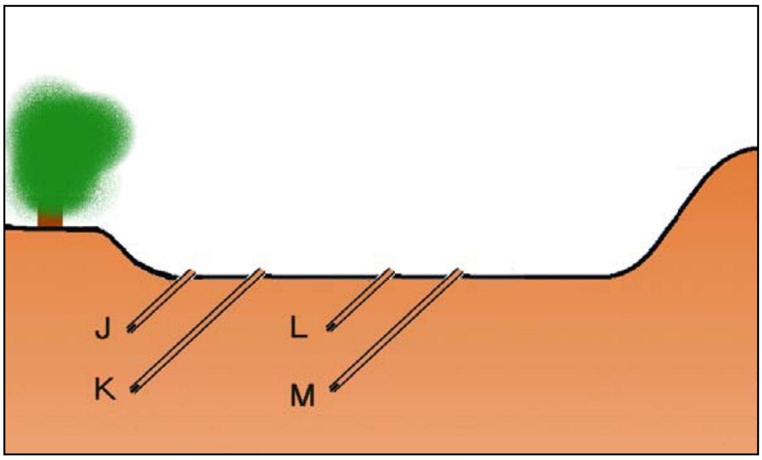


Figure 14: Schematic distribution of Theta Probes at evaporation site (not in scale)

Site four, “Spare Site”

This site was built up five days after the second flood, on the 01.02.2004. The reason for this late set up was, the cables and instruments were destroyed by the first flood at research site 2 and had to be fixed and made waterproof again. Its purpose was to measure soil moisture dynamics caused by infiltration and evaporation in case of a third flood. Two probes were inserted in the active channel without influence of vegetation. Probe N (Figure 15) was at a depth of 100 cm and Probe O (Figure 15) was at a depth of 200 cm.

In times of floodwarning at this site, the second logger was installed permanently.

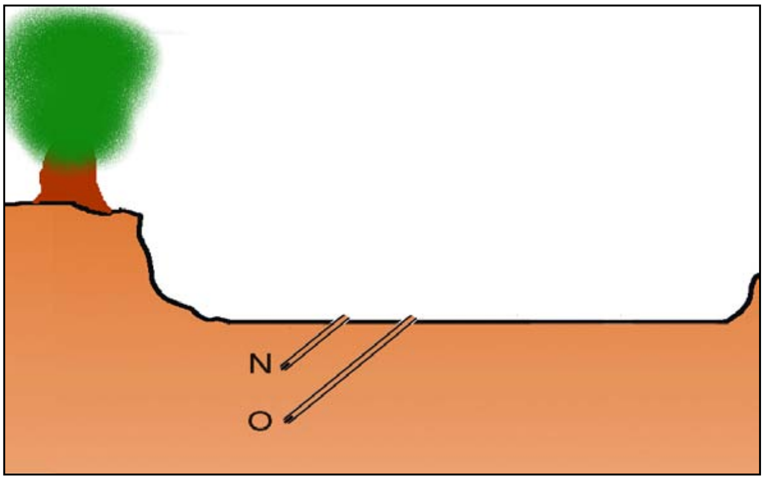


Figure 15: Schematic distribution of Theta Probes at spare site (not in scale)

3.1.4 Examination of aquifer response

3.1.4.1 Temperature, water table fluctuation, electrical conductivity

A change of electrical conductivity (EC), temperature and water level can be a sign of changing groundwater flow and it can be an aquifer response to a flood event.

These measurements were done by a CTD – Diver DI243 produced by *Van Essen Instruments*.
To examine the aquifer response to a flood event, a CTD – Diver, was installed in a monitoring borehole (BG 29547), which is 31 m away from the active channel and 20 m away from the production borehole of *Gobabeb*. These boreholes are all situated in the alluvial aquifer. The CTD – Diver was installed with a stainless steel cable at a depth of 10.5 m (below ground). A CTD – measures electrical conductivity (EC), temperature, and depth.

The electrical conductivity (accuracy 1% of range) was converted to conductivity at 25° C; which is the specific conductivity (SC). The EC probe was calibrated once a month.
The accuracy of temperature measurement is ± 0.1 C°.

The diver measures the height of a water column by measuring water pressure (long term stability ± 3 cm). This pressure is absolute; it is the pressure of the water column together with barometric pressure. To get a real water pressure, the barometric pressure (long term stability ± 1 cm) has to be subtracted. The barometric pressure was measured with a Baro Diver DI250 produced by *Van Essen Instruments*. The Baro Diver was installed ~ 300 m away from the monitoring borehole in a room of *Gobabeb Research Station*. Both divers were measuring in 1 minute interval. The data download from the CTD – Diver was latest done 10 days after starting a new series of measurements.

3.1.4.2 Water sampling

A change in the hydrochemistry and isotope signature can be a sign of changing groundwater flow and it can be an aquifer response to a flood event.
Groundwater and floodwater samples were collected in order to analyse them for stable isotopes (^{18}O, ^{2}H) and for major ions (anions: chloride (Cl^-), nitrate (NO_3^-), sulfate (SO_4^{2-}); cations: sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}).
Except from the samples from *Deelie Farm*, the water samples were stored in a fridge directly after being collected.

<u>Sample sites and sampling times</u>

<u>Gobabeb Station</u>

The groundwater samples were collected from the production borehole (BG 35016), which is situated on the overbank area at 34 m distance to the active channel. One release is situated directly at the water tower at *Gobabeb Research Station*. Normally the pump is operating once a day, in the morning. The samples were taken after at least 15 minutes of pumping. Groundwater samples were collected on a weekly basis; while the *Kuiseb* was flowing, groundwater samples were taken once a day.
In addition to the groundwater samples, 20 floodwater samples of the first flood event and 10 samples of the second flood event have been collected at *Gobabeb Research Station.*
Unfortunately, before the flood events there was no possibility to collect groundwater samples on the sites of *Homeb, Soetrevier, Klipneuss, Swartbank* and *Deeliefarm.*

<u>Homeb</u>

Groundwater samples were collected on a weekly basis. The borehole is situated in the active channel. Unfortunately there was no release at the pump. The water is pumped into tanks with a volume of 5 – 10 m^3. At these tanks, taps were installed. “Mixed water samples” from these tanks were collected. The hypothesis was, that the water consumption may be high enough to renew the water bulk in a week’s time.

Soetrevier

Groundwater samples were collected on a weekly basis. The borehole is also situated in the active channel. Unfortunately there was also no release at the pump and water samples could only be taken from the tanks.

Klipneus

Groundwater samples were taken on a weekly basis. At this place it was the same situation as at *Homeb* and *Soetrevier* and only “mixed water samples” could be collected. Furthermore at the end of the sampling period the pump was broken.

Swartbank

Swarbank is approximately 25 km downstream of *Gobabeb*. Groundwater samples were taken on a weekly basis. At *Swartbank* two boreholes are situated in the active channel. An old borehole with a hand pump and next to it the new borehole (Figure 16). Two samples on a weekly basis were collected at this site, one sample from the hand pump after ten minutes of pumping and the second sample, also a “mixed water sample” was taken from the tank, because at the beginning of the sample period the pump of the new borehole was broken.

Figure 16: *Swartbank*, old well point with hand pump and the new borehole

Deelie Farm

In the upper catchment ~ 230 km from *Gobabeb*, a borehole is constructed in the active channel. There is a release at the pump. Samples were collected by a farm worker twice a week after five minutes of pumping. These samples couldn’t be stored in a fridge directly after collection, unless they were directly collected by the author.
These samples were fetched twice a month .

<u>One – time sampling points</u>

15 groundwater samples were collected from different *Namwater* boreholes. These boreholes are all production boreholes where the pumps are operating 24 hours a day. Furthermore two samples of an abandoned borehole at *Gobabeb Station* were collected after 5 minutes of pumping time. The abandoned borehole is at 20 m distance to the *Gobabeb* production borehole (next to the monitoring bore hole).
Five floodwater samples from different places in the upper catchment were taken from different floods. Additionally, two salt spring samples were taken.

3.2 Laboratory analysis

In order to observe an aquifer response to a flood event groundwater and floodwater samples were analyzed for major ions and stable isotopes. The analyses of stable isotopes by mass spectrometry were carried out in the laboratory of the Institute of Hydrology University Freiburg, Germany by institute staff.
Sample preparation and analyses of the major ions were done by the author.

3.2.1 **Major ions**

The determination of major ions was done with an ion chromatograph DX 500 from *Dionex.*
The calibration was made with 17 calibration standards from 0.5 mg/l – 100 mg/l.
118 samples were analyzed for anions and cations. For control purposes in each measurement series, at least 30 calibration standards were measured. The measurement error for the determination of cations is around 4% and for anions around 5%.
For this kind of analysis, most of the samples had to be diluted (sample series see Table 2, all samples see annex II). Depending on the sample site and the kind of ion to be measured, different attenuation ratios hat to be choosen. in order to determine, in which concentration the samples had to be attenuated, a preliminary investigation had to be done.
Dilution ratio 1:100 for example means that 1 ml sample water was filled up with distilled water up to 100 ml. After dilution the samples were filtered by a 45 µm membrane.

Table 2: Dilution Ratio

Sample site	Dilution Anions	Dilution Cations
Flood water	no dilution	no dilution
Deelie farm	10:100	10:100
Homeb	5:100	5: 10
Gobabeb production borehole	5:100	5: 50
Soetrevier	10:100	5: 10
Klipneus	5:100	5: 10
Swartbank hand pump	5:100	5: 20
Swartbank new borehole	5:100	5: 20

3.2.2 **Stabile Isotopes Deuterium and Oxygen 18**

δ – Notation: The concentrations of ^{18}O and ^{2}H in water are expressed in terms of the deviation of the concentration ratios from Vienna standard mean ocean water (V – SMOW) after MOSER & RAUERT (1980).

$$\delta\, sample \stackrel{!}{=} \frac{R_{SAMPLE} - R_{STANDARD}}{R_{STANDARD}} \cdot 1000\,‰$$

with: R_{SAMPLE} = Ratio of isotopes in the sample
$R_{STANDARD}$ = Ratio of isotopes in the standard

The analysis of the stable Isotopes were done with Isotope Ratio Mass Spectrometer (IRMS) Type Delta S, produced by *Finnigan/ Mat*.
All 118 samples were analyzed for ^{18}O and ^{2}H. The measurement error for Deuterium is ± 2 ‰ up to 26.2.04. Due to an instrument failure, later measurements are not reliable.
For ^{18}O-measurements, the standard deviation is 0.2 ‰.

<u>Methods in brief</u>

In order to examine experimental soil moisture dynamics and an aquifer response to a flood event, field data were collected in a period of 4 ½ month in the *Kuiseb catchment, Namibia*.
The main focus of field work was around *Gobabeb Research Station*.
Soil moisture dynamics in the active channel and the overbank area were surveyed by Theta Probes. 40 profiles were examined to grain size.
Due to the heterogeneous soil, a method to insert the probes with as little disturbance of soil as possible was developed. A drilling pipe was constructed and tested at a preliminary research site in the upper *Kuiseb catchment*. Afterwards four research sites were established around *Gobabeb*.

The examination of the aquifer response to a flood was done by measuring temperature, electrical conductivity and water level fluctuation with a CTD – Diver which was installed in a monitoring borehole at *Gobabeb station*.
To examine the aquifer response to a flood, floodwater and groundwater samples were collected in order to analyze them for stable isotopes and major ions. The hydro chemical analyses of the samples were done in *Freiburg, Germany*.

4 Results and discussion

4.1 Profiles / stratigraphy/ grain size distribution

The grain size distribution / stratigraphy near *Gobabeb* site (*Kuiseb* active channel and floodplain) is heterogeneous.

The surface in the active channel is covered by a silt layer, which varies from one mm to a couple of centimeters thickness. Grain size distribution in the fine material is also varying (see Figure 17).

Figure 17: Different structures of silt cover near Gobabeb (matchbox as a relation to the size)

The profiles of the active channel show a distinct spatial variability: There are several profiles where only sand was found (Figure 18) down to a depth of 175 cm, other profiles show only a thin layer of fine material, whereas others show several layers of fine material of different thickness in between of layers of sand (Figure 19). Profiles with layers of coarse material were also observed (Figure 20 and Table 5).

Figure 18: Profil 2 (sand)

Figure 19: Profil 4a (sand, clay, silt)

Profile No: **2**		
Location	south site active channel	
Depth [cm]	**Description**	**Specification**
Cover	0,5 - 1 cm clayey silt	Ut3 lu u
0 -140	medium sand stratified with fine sand	mS ss s

Table 3: Description of profile 2

Profile No: **4A**		
Location	Gobabeb pipeline active channel (Erosion line)	
Depth [cm]	**Description/ Remarks**	**Specification**
Cover	thin clayey silt cover	Ut2 lu u
0 -13	silty sand	Su 4 us s
13 - 17	sandy silt containining organic material (roots, plant remains)	Us su u
17 - 24	sandy silt	Us su u
24 - 37	medium sand	mS ss s
37 - 48	clayey silt with very thin sandlayer in between	Ut3 lu u
48 - 52	fine sand	fS ss s
52 - 54	clayey silt	Ut3 lu u
54 - 67	fine sand	fS ss s
67 -75	sandy loam at the lateral extension sandy clay	Ls 2 ll l-Ts lt t
75 -175	medium sand	mS ss s

Table 4: Description of profile 4A

The floodplain soil profiles expose the same distinct spatial variability. In this small amount of samples, it seems that close to trees more fine material is accumulated, while in several open areas, there was no fine material found down to a depth of 150 cm. In Annex I, 35 profiles are described in detail.

Figure 20: Lateral extension of Profile 16D.

Profile Number: 16 D		
Location	north site , active channel	
Depth [cm]	**Description**	**Specification**
Cover	0.5 cm clayey silt cover	Ut 3 lu u
0 - 10	fine sand	fS ss s
10 - 20	medium sand containing organic material (plant remains)	
20 - 50	medium sand	mS ss s
50 - 70	medium sand nerved with coarse gravel, containing small pebbles	
70 - 80	coarse gravel containing pebbles up to 10 x 7 x 4 cm	
80 - 92	silty sand heavily penetrated by roots	Su2 sl s
92 - 96	coarse sand containing fine gravel	gS ss s
96 - 120	medium sand	mS ss s
120	boulder/ rockbasement	

Table 5: Lateral extension of Profile 16 D

Layers of coarse material containing pebbles up to 10x7x4 cm

4.2 Flood events at Gobabeb Station

From December 2003 to April 2004 two floods passed *Gobabeb Station*, whereas two other floods stopped flowing approximately 30 km upstream.

4.2.1 Flood event one

After heavy rainfalls in the upper catchment the flood arrived on the 18^{th} of January at 6:31 at *Gobabeb station*. It was a medium flood with a maximum height of 180 cm at *Gobabeb Station*. The water level was rising very fast. In ten minutes time a level of 160 cm was reached. The peak was reached after 2.5 hours. The travel time of runoff was approximately 1.7 m/s. The travel time was estimated by arriving time at the settlement *Homeb* observed by settlers.
Little trunks and brunches were transported with the flood front.
The peak discharge was approximately 90 m^3/s (estimated by flooded river width, velocity and water level of the flood at *Gobabeb Station*).
The *Kuiseb* was flowing for four days and stopped flowing during the night from the 21^{th} to 22^{th} of January. The water stopped flowing 5 km after *Roibank station* (MAREIS 2004).
The alluvium at research site two was shifting down to ~ 90 cm by flood one. At this site the cables of the Theta Probes were disrupted and the Theta Probe at 80 cm was lost, while the probe at 100 cm depth was still in place.

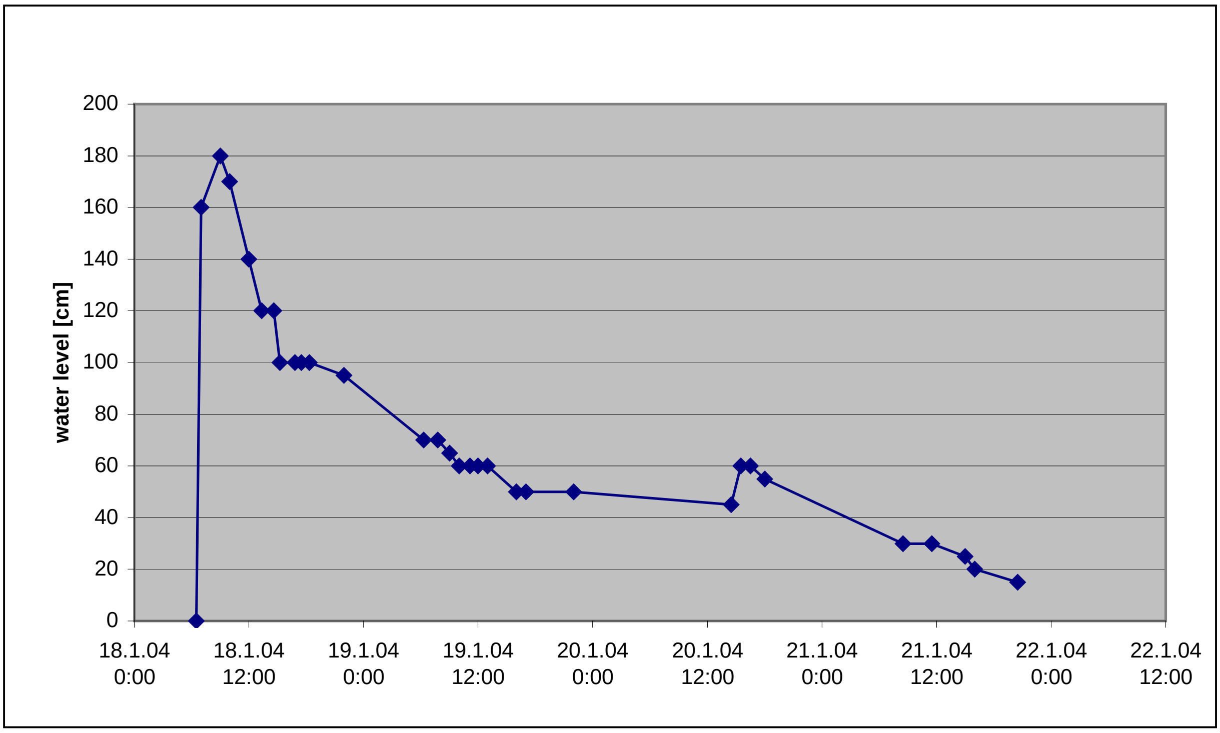


Figure 21: Flood event one, water level at Gobabeb Station


Figure 22: Flood event one

4.2.2 Flood event two

After relative poor rainfalls in the upper catchment the flood arrived four days after the first flood, on the 26th of January between 7:45 and 8:25 *Gobabeb station*. It was a small flood with a maximum height of 55 cm at *Gobabeb Station*. The travel time of the flood was approximately 0.5 m/s. The travel time was estimated by arriving time of the flood ~15 km downstream. The peak discharge was approximately 8 m^3/s (estimated by flooded river width, velocity and water level of the flood at *Gobabeb Station*). The *Kuiseb* was flowing for two days and stopped flowing during the night from the 26th to 27th of January 2004. Nevertheless the *Kuiseb* was flowing till *Roibank station* (MAREIS 2004).

This flood had a less erosive character than flood one.

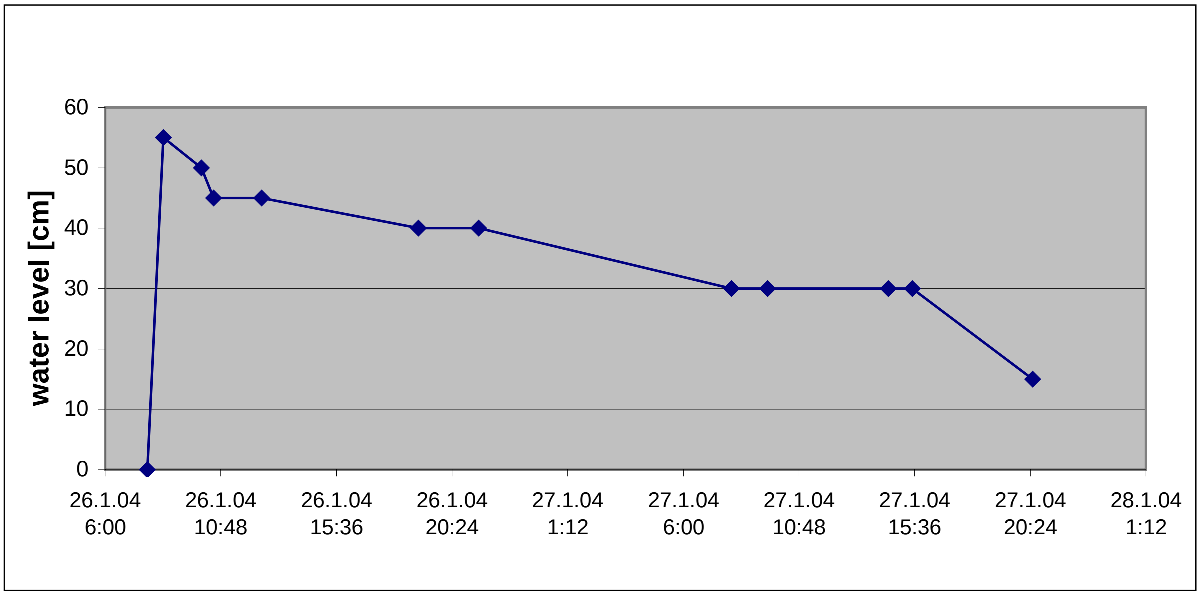


Figure 23: Flood event two

Figure 24: Flood front of flood two, the floodplain can be seen on the right.

Discussion

The loss of the Theta Probe in 80 cm depth was possibly caused by erosion or by shifting sand. “Shifting dunes” in rivers were observed by Israeli researchers in Botswana (GRODEK 2004).
Despite of significant different amounts of runoff, both floods were flowing approximately the same distances. It is assumed that the surface of the active channel during flood two was mostly sealed by the wet silt cover deposited by the flood one four days before.

4.3 *Soil moisture*

4.3.1 **Preliminary Investigation Site "Farm Niedersachsen"**

Measurement period: 31.12.2003 – 13.01.2004.
The measurements were stopped at the 13th at this research site in order to install the instruments at the final research sites at *Gobabeb Station*.

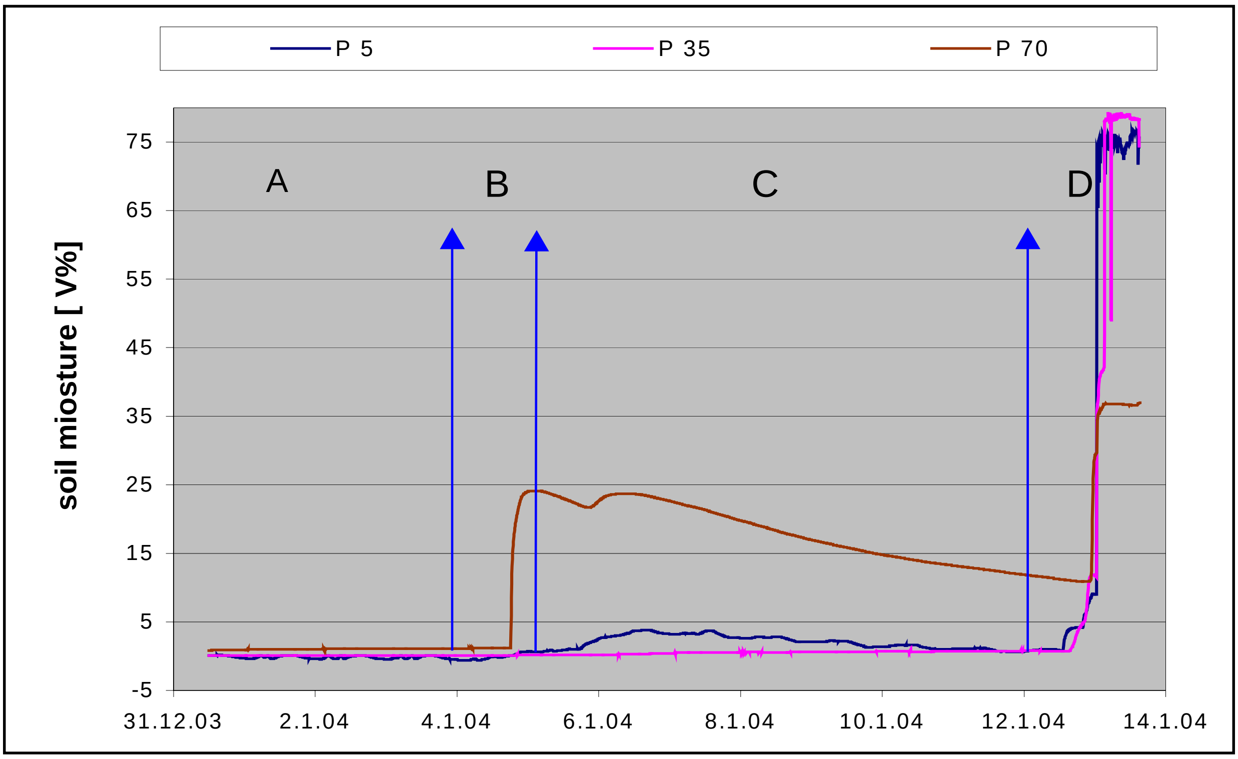


Figure 25: Soil moisture dynamics Niedersachsen

Results see Table 6.

Table 6: Volumetric soil moisture data measured at Farm Niedersachsen from 31.12.2003 – 13.01.2004

Starter probe, 5 cm depth (P5): **The starter probe was situated in medium sand.**	**Probe in 35 cm depth (P35):** **The probe was imbedded in medium sand.**	**Probe in 70 cm depth (P70):** **This probe was situated in coarse sand and fine gravel layer.**
31.12.2003 - 04.01.2004 (Phase A)		
The readings showed values between 0,2 and (–) 0, 5 %	The sand had a constant value of 0.1 %	The sand had a constant soil moisture of about 1 %
04.01.2004 – 05.01.2004 (Phase B)		
A very poor rise to about 1% was observed	The value was still 0.1 %	04.01.2004 (18^{05}) the soil moisture was rising steeply from 1 % to a maximum of 24.1 % in 6 hours. For about 5 hours the water content was at the same level, while afterwards the soil moisture was decreasing.
05.01.2004 – 12.01.2004 (Phase C)		
5.1.2004 at 18:00, the soil moisture started to rise slowly to a maximum of about 4 % on 6.1.2004, fluctuate one day around this value and decreased to 0.9 % at the 12.01.2004	The value increased slightly in this period from 0.1 to 0.8 %.	5.1.2004 at 21:20 the soil moisture started to rise from 21.8 % to a maximum of 23.7 % on the 6^{th} and was for about 7 hours at this level. Afterwards the moisture decreased slowly again.
12.01.2004 – 13.01.2004 (Phase D)		
On the 12.1.2004 (13^{20}) the soil moisture started rising again from 0.9 % to 9 % in 11 hours. On 13.1. at 00:35 the values showed an abrupt rise from 9 to about 74 % in 5 minutes	On the 12.1.2004 (15^{30}) the soil moisture content was increasing from 0,9 % to 11.5 % in 9 hours. On 13.1. at 00:35 the values show an abrupt rise from 11.5 to about 35.8 % in 5 minutes. Afterwards, the content was increasing to 42.1 % at 03:10. At 3:10 the values showed another abrupt increase in 5 minutes time to 78 %.	On the 12.1.2004 (22^{15}) the soil moisture was rising again from 10,9 % to 29.7 % at 00:40 the values showed an abrupt rise of about 5%. Afterwards the soil moisture increased in two hours time to a constant value of about 37 %.

Note: Farm Niedersachsen
This research site is in the upper catchment of the *Kuiseb*, where the *Kuiseb* floods are normally generated. There were no data available about the precipitation at this research site. In the surrounding typical for this area, the rainfall showed a high spatial and temporal variability. One farm didn't have any precipitation while at the other farm 33 mm were measured in two days and a third farm in this area had 5 mm of precipitation in a weeks time.
When the author arrived at the *Kuiseb* on the 13. 01., the river was flowing. Nobody in the area did observe the starting time of the flood due to the fact that the next farmhouse is one and half hour's drive away from this site. The flood was observed (by the author) on the 13.01. 2004 with a water level from approximately 80 cm.

Discussion:

In Phase A there is no change in the water content observed at all three depths.
It is assumed that in this time no rainfalls occurred.

Phase B:
Two (P5, P70) of the three probes were showing an increase of soil moisture.
The slight increase of water content in 5 cm depth probably was caused by very slight rainfalls. While the probe in 35 cm showed no reaction, the probe in 70 cm depth showed a significant rise in water content. This was possibly caused by a flood which stopped flowing on the surface before it reached the research site, while underneath the surface, it was still flowing in the coarse underground. Another possibility would be a preferential flow. This research site was situated in the *Kuiseb* canyon where the alluvium is confined by rocks under these circumstances, there is also a possibility that rainfall was flowing down the rocky slope, resulting in a preferential flow that led to an increase of soil moisture in 70 mm depth without affecting the upper soil layers.

Phase C:
The increase of soil moisture at the surface (P5) was higher than in phase B and was possibly also caused by light rainfalls. P 35 shows only a very poor increase of water content, which might be caused by capillary rise (fringe). The reasons for the rise of the water content in the depth were possibly the same as in Phase B.

Phase D:
It is not known whether the increase of soil moisture on the 12.01. at the depth of 5 and 35 cm was caused by heavy rainfall or if the river was partly flooded.
It is assumed that on the 13th January at 0:35, the first few centimeters of the alluvial soil were eroded by the flood. That would explain the abrupt rise from 74 V% in 5 minutes time in a depth of 5 cm, whereas later on the probe was no longer imbedded in soil. The simultaneous abrupt rise to 35.8 V% soil moisture in a depth of 35 cm

verifies these findings. The abrupt rise of soil moisture content in 70 cm depth can also be explained by this event. The soil didn't erode down to 35 cm at this time.
The abrupt rise of water content in 35 cm depth to (unrealistic) 78 V% is very likely caused by another erosion event to a depth of at least 40 cm from the original surface. The erosion-theory was proved by the fact, that, when the probes were collected on 13th January, P5 and P35 were swimming in the flood.
The soil in 70 cm depth was fully saturated with approx. 37 V%.

As the main purpose of this exercise however was to test the method of data collection and the instruments used, the test of the insertion method was successful, despite the fact that the probes in the depth of 5 cm and 35 cm did not last in their original position. Both probes were swimming in the flood when the author was arriving on the 13th. Only the probe in 70 cm depth remained in its original position and was still imbedded in soil. The method of insertion proved to be suitable. In order to prevent an erosion of the probes, lateron they were inserted to a minimum depth of 80 cm at *Gobabeb station*.

4.3.2 Gobabeb

4.3.2.1 Site one “Anatree Site”

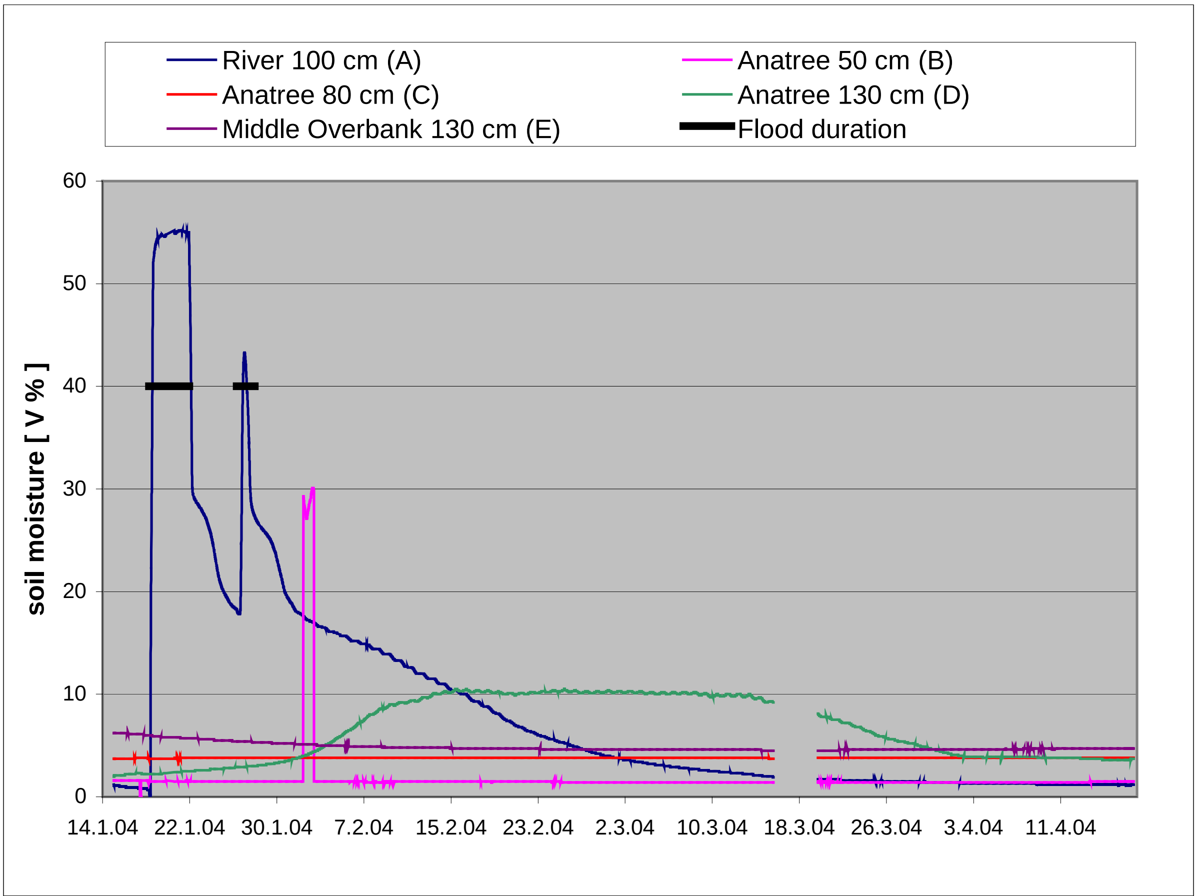


Figure 26: Soil moisture dynamics at “Anatree Site”

Measurement period: 15.01. – 17.04.2004
The results of the whole measurement period is shown in figure Figure 26

<u>Results from the probe lectures:</u>
Probe Anatree; 50 cm depth (Probe C):

The probe was imbedded in silt (Uu)
This Probe reported constant values between 1.4 and 1.6 V% over the whole measurement period except for 01.02.2004
There was an abrupt rise from 1.5 to 29.4 V%. For one day, on the 01.02,. the value ranged between 27.1 and 30.1 V% and was decreasing in the same way from 29.7 to 1.5 V% in 5 minutes.

Probe Anatree; 80 cm depth (Probe D):

The probe was imbedded in clayey silt (Ut4)
The water content in 80 cm depth was constant 3.8 and 3.7 V% over the whole measurement period.

Probe Anatree; 130 cm depth (Probe E):

The probe was inserted in silty sand (Su3), close to a huge Anatree root which was damaged by the insertion of the probe.
The initial value of water content was 2 V%.
The values were increasing right from the beginning to a level of around 10 V% in a months time.
Afterwards, the value was constantly fluctuating in a daily rhythm around 10 V%.
The minimum of fluctuation was at night; the maximum at day time. The difference between minimum and maximum was 0.3 V%.
After one month the soil moisture started to decrease constantly from 10 to 3.9V% in 19 days. Afterwards the soil moisture further decreased very slowly from 3,9V% to 3.6V% during 15 days until the end of the measurement period.

Probe Middle Overbank 130 cm depth (Probe B):

The probe was inserted in silty sand (Su2).
The water content was slightly decreasing from 6.2V% at the beginning of the measurement period to 4.7V % at the end.

Probe River 100 cm depth (Probe A):

The probe was imbedded in silty sand (Su3), which was penetrated by abundant roots. Directly underneath the probe a layer of silty clay (Tu4) was located.
The initial water content was 1.1V%.

<u>Results from the probe lectures “River”</u>

Flood event one reached this site on the 18.01.04 at 06:31.

18.01. 07:20:	the soil moisture started to decrease to finally (-) 2.4V%.
18.01. 09:50:	the water content started to increase sharply (200 min after floods arriving time).
18.01. 16:00:	a water content of 52.2 V% was reached. In the following three days (79 hours) the water content was in this range. The maximum of water content was 55.2 V%.
21.01. 22:40:	start of declining water content in four steps. The water content decreased very sharp by 25.3 V% in about 8 hours time to 29.6.V%.
22.01. 6:50:	a slower decrease of 2.6 V% was observed for 29 hours to 27 V%.

23.01. 12:50: again a steeper gradient of decrease was observed; - 6 V% in 29 hours until the 24th at 17:50 to 21 V%. From then on, it decreased further to 18 V% until the 26.01.2004.

Flood event two reached this site on the 26.01.04 at 08:15. The water content was 18 V% when this flood arrived.

26.01. 15:10: water content started to increase.
27.01. 00:00 a maximum of 43V% was reached. For two hours time, the water content was at the same level.
27.01. 02:00 start of declining water content in four steps. The water content decreased in 12 ½ hours by 14 V% from 43 V% to 29 V%.
27.01. 14:35: a slower decrease from 29 to 25 V% (-4 V%) during 46 hours was observed.

From the 29.01.2004 to the 30.01.2004 at 17:20 a steeper gradient was observed. The soil moisture decreased by 5V% to 20 V% during 29 hours.
From the 30.01.2004 to the 31.01.2004 the water content decreased during 24 hours by 2 V% to 18 V%.
Moreover, the soil moisture graph shows a "daily pattern". At night there is no or very little decrease of the water content, while at day time a decline of 0,4 – 0,6 V% is noticeable. This pattern was observed for three weeks until the 20.02.2004, down to a water content of 7.4V%.
At the end of the measurement period the water content of 1.2 V% was nearly the same as at the beginning of the measuring period.

4.3.2.1.1 Vertical wetting front

The advance of the vertical wetting front can be calculated for the two flood events as follows:
Flood one: 1m in 200 minutes = 0.3 m / h
Flood two: 1m in 405 minutes = 0.15 m / h

4.3.2.1.2 Infiltration rate

Flood event one:

It is assumed, that the soil was fully saturated in a range between 52 and 55 V% for 79 hours and that in this time infiltration to the deeper alluvium took place. From this, the infiltration rate until full saturation can be estimated as follows:

Soil moisture was calibrated to $1m^3$ (1V% = 10 l)
with: increase of soil moisture by time = infiltrated amount by time
l/m^2 = mm
51V% increase in 9 ½ hours. = 510 l/m^3 in 570 minutes = 0.89 mm/min

Flood event two:

A rough estimation of the infiltration rate until the maximum of soil moisture was reached can calculated as follows:

Increase of 25 V% in 15 ¾ hours = 250 l/m^2 in 945 minutes = 0.26 mm/min

4.3.2.1.3 Calculation of hydraulic conductivity and infiltration to the deeper alluvium:

A decrease of 25.3 V% in 8 hours and 10 minutes was observed on the 21.01.2004, after the first flood.
It is assumed that the sharp decrease of water content was mainly caused by infiltration to the deeper alluvium. The possible effect of evapotranspiration can be neglected due to the time (at night) and duration of the process. Assuming that the underlying soil was still saturated, hydraulic conductivity can be calculated as follows.

Soil moisture was calibrated to $1m^3$ (1V% = 10 l)
with: decrease of soil moisture by time = infiltrated amount by time
l/m^2 = mm
253 l/m^2 were infiltrating to the deeper alluvium in 490 minutes = 0.52 mm/min = 744 mm/day.

4.3.2.1.4 Overall infiltration:

Overall infiltration = infiltration from surface + infiltration to the deeper alluvium.

Flood one:

The primary infiltration from surface was calculated with 510 l/m^2.

Assuming that, while the sensor was measuring full saturation, permanent infiltration to the deeper alluvium with an infiltration rate of 0.52 mm/min was continuing for 79 hours, infiltration of 2447 l/m^2 was calculated.

Together with the primary infiltration of 510 l/ m^2, an overall infiltration of 2957 l/m^2 was calculated.

Flood two:

It is assumed that only at the beginning of the flood infiltration took place.

Due to this the infiltrated amount was calculated with 250 l/m^2 (see infiltration rate calculation above).

4.3.2.2 Site two "Rock Site"

This site is approximately 700 m downstream of "Anatree Site".

The measurement period at this site was from 14.01.2004 to 29.03.2004.

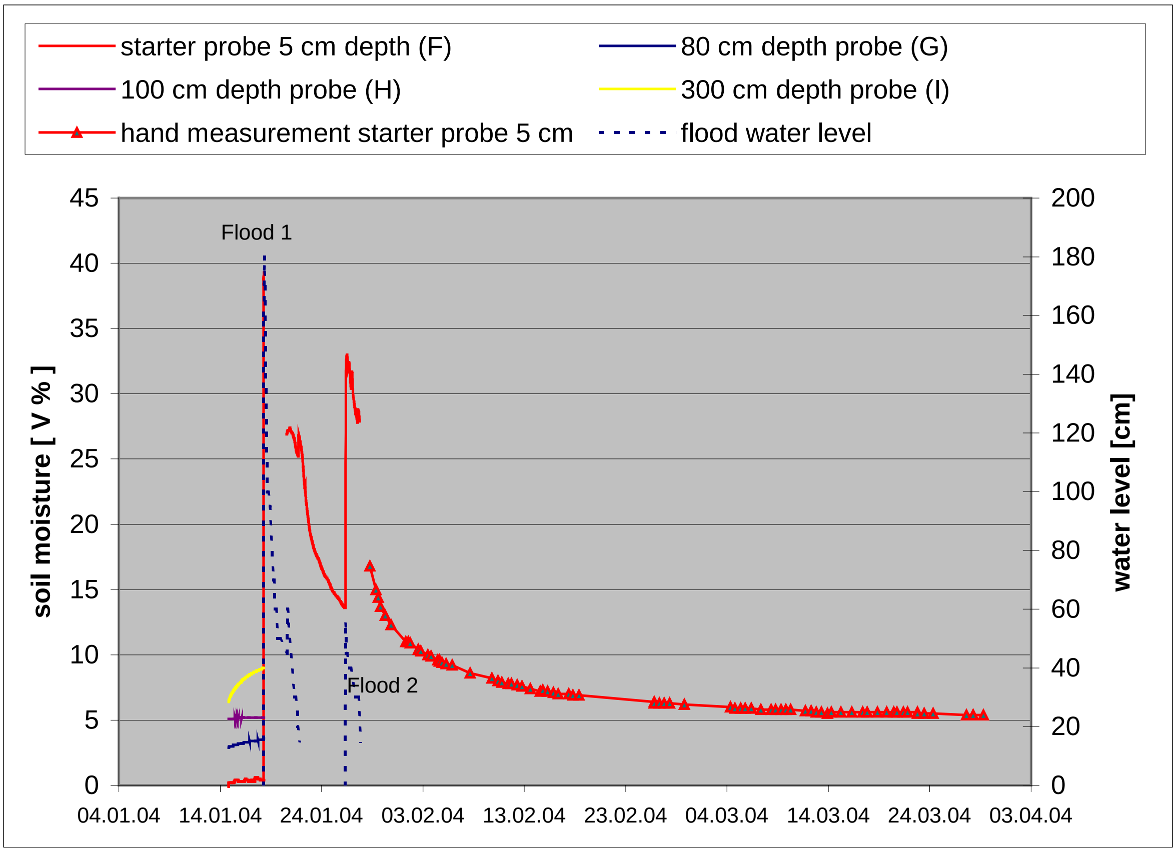


Figure 27: Soil moisture dynamics at "rock site"

Probe 80 cm depth (Probe G):

The initial water content was 2.9V%. It was increasing to 3.6 V% at the last measurement before the cable were disrupted at 7:20 on the 18.01.2004.

Probe 100 cm depth (Probe H):

The probe was inserted in medium grained sand (mS).

The initial water content was 5.1 / 5.2 V% until the measurements were disrupted on the 18.01.2004.

Probe 300 cm depth (Probe I):

The probe was situated in medium grained sand (mS).

The initial water content from 6.4 V% was increasing to 9 V% when the measurements were disrupted at the 18.01.2004.

Starter Probe 5 cm depth (Probe F):

The probe was inserted in medium grained sand (mS).

After the flood events the probe was imbedded in a layer of a clogging mixture from clay, silt, sand, little sticks and rotten plants. And the sensors of the probe were close to the surface.

At the beginning of the measurements the value of the soil moisture content was fluctuating between 0.2 and 0.6 V%.

18.01. 06:35	The value was abruptly rising from 0.4 to 38.4 V% in 5 minutes. In the following 40 minutes the water content was increasing to 39.3V%. Then the measurements were disrupted.
20.01. 13:25	The measurement started again with a value of round 27 V%. After a period of decreasing water content the values were increasing for a short time to again 27 V% then the water content was decreasing constantly until the 26.01.2004 to 13.6V%.
26.01. 08:40	Flood two arrived. The water content started increasing to 32V% after one hours time, reached the maximum of 33V% and then steadily decreased while fluctuating to 28 V% on the 27th. At this stage the permanent measurement was stopped and the soil moisture was measured then at least once a day.
29.03.	The moisture was 5.4 V% at the end of the measurement period.

This site was declared abandoned due to the fact that after the first flood only the starter probe was still working. The cables of the other three probes were disrupted by the flood and the probes had to be dug out.
The probe in 80 cm depth was lost while the probe in 100 cm depth was still in place. The probe in 300 cm depth was also at the point were it was inserted.

4.3.2.3 Site three “Pure Evaporation Site”

Measurement period: 27.01. -31.03.2004. For exact positions of probes J-M.

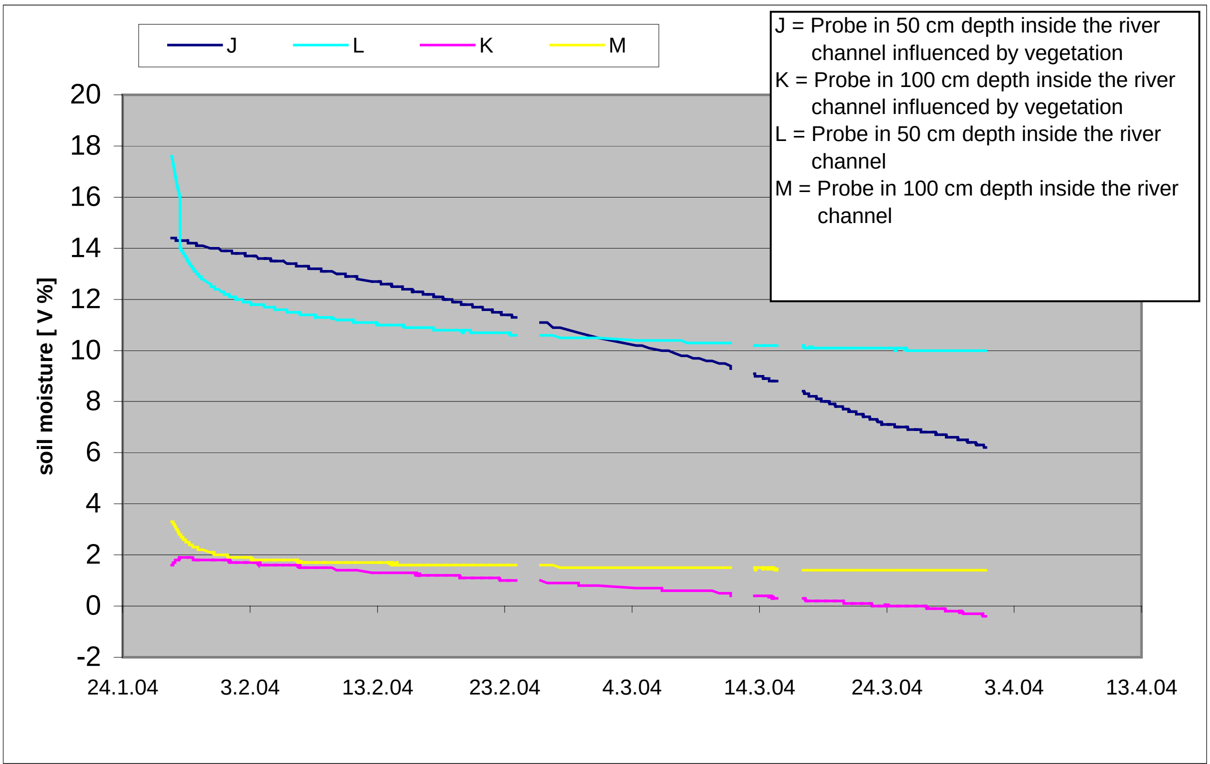


Figure 28: Soil moisture dynamics at “evaporation site”

Probe 50 cm depth next to vegetation (Probe J):

The probe was imbedded in silty sand layer (Su4) which was relatively heavily penetrated by small roots.

The initial water content from 14.4 V% was constantly decreasing to 6.2V% after two month.

Probe 100 cm depth next to vegetation (Probe K):

The probe was situated between pebbles and coarse sand.

The initial water content was 1.6 V% and at the end of the measuring period - 0.4 V%.

Probe 50 cm depth (Probe L):

The probe was imbedded in medium sand (mS).

The initial water content was 17.6V%. The soil moisture decreased in three steps: First the decline was steep, 3.6 V% loss in 16 hours,
then it decreased 2V% (to 12V%) in five days,
from there on the water content decreased in two month time 2 V% to finally 10 V%.

Probe 100 cm depth (Probe M):

The probe was situated between pebbles.
The initial water content was 3.3 V% the final water content 1.4 V%.

4.3.2.4 Site four "Spare Site"

Measurement period: 01.02. -17.04.2004

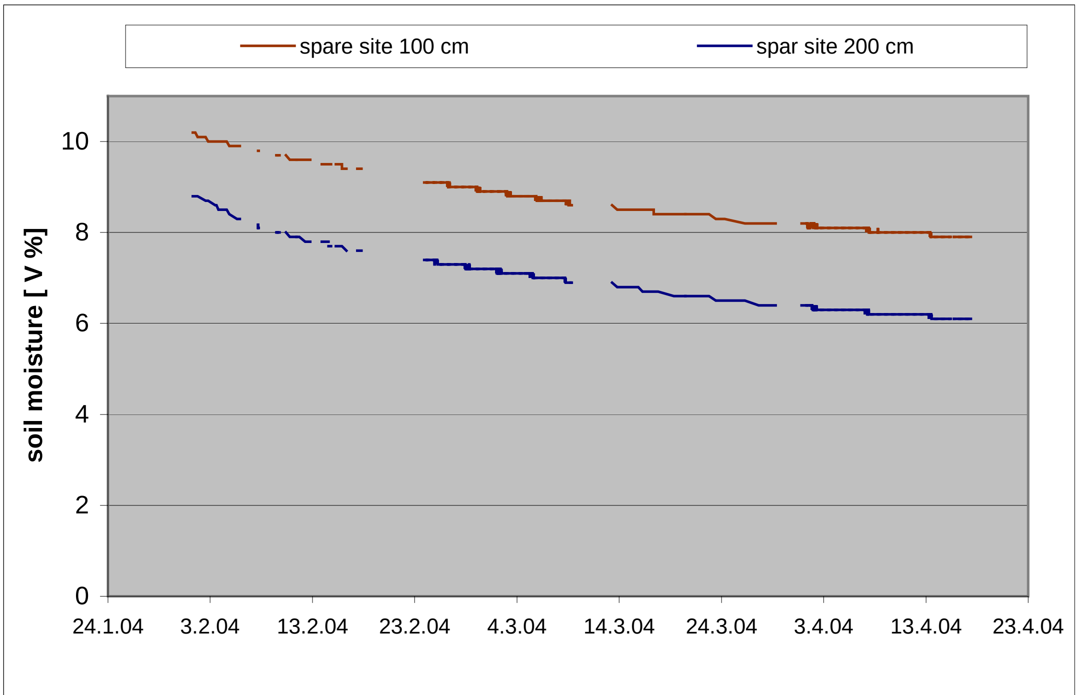


Figure 29: Soil moisture dynamics at "spare site"

Probe in 100 cm depth: The probe was imbedded in fine sand (fS).

The initial water content was 10.2 V% the final soil moisture 7.9 V%.

Probe in 200 cm depth:

The probe was imbedded in a layer of silty Sand (Su4) surrounded by a few fine roots from the camel thorn tree.
The initial water content was 8.9 V%, the final water content was 6.1 V%.

Discussion of soil moisture results at main research site "Anatree"

Field capacity and permanent wilting point

The pattern of the soil moisture graph while decreasing after floods indicates a field capacity of around 29 V% .It is assumed, that the convex curve of decreasing soil moisture afterwards, is caused by capillary fringe from the soil underneath.
The permanent wilting point is assumed to be at 7.4 V% because of the daily pattern of decrease of the soil moisture from the 31.1.2004 to 20.2.2004. The higher rate of decrease at daytime was mainly caused by losses due to transpiration of vegetation and due to evaporation. With the end of this daily pattern at 20.2.2004, it is assumed that the permanent wilting point was reached. At this time, a water content of 7.4 V% was measured.

Evaporation/Evapotranspiration

It was assumed that after reaching the field capacity water losses were only caused by evapotranspiration.

Evapotranspiration after flood event one
After reaching the assumed field capacity a water loss of 11.5 V% in 4 days (2.9 V%/d) was observed.

Evapotranspiration after flood event two
After reaching the assumed field capacity a water loss of 11 V% in 4 days (2.8V%/d) was observed.
Afterwards the water content decreased to the assumed permanent wilting point of 7.4 V%, which is equivalent to a decrease of 10.6 V% in 20 days (0.53 V% / day). The decrease is mainly caused by evapotranspiration.
Afterwards the losses decreased by 0.1 V %/day (6.2 V% in 57 days).
At an average, evapotranspiration after the second flood was calculated to be 0.34 V% per day (in an 81 days period) .
It is assumed that the water content will not decrease further; the initial value of water content was reached at the end of the measuring period.

Lateral movement of the wetting front

An increase of water content after the floods in the overbank area, at Anatree 80 cm and middle Overbank in 130 cm depth could not be observed.
The observed abrupt decrease and increase of soil moisture on the 01.02.2004 at the Anatree in 50 cm depth was possibly caused by an instrument failure of this Theta Probes. But the other values seem to be correct, because when the probe was dug

out the final value was proofed by another probe and showed a value in the same range.

Probe Anatree 130 cm depth: due to the fact that the other probes in the overbank area did not show any significant changes in the soil moisture, it is very likely that the increase of soil moisture at this place was not caused by lateral movement of the wetting front caused by flood. Hence it is assumed that the increase of soil moisture was caused by an Anatree root, because while inserting the probe, the root of the Anatree was damaged. However, the sensors of the probe didn’t have any contact to the root.

It is possible that due to the lesion of the root water was excreted, while water was transported up to the canopy (personal communication, Dr. Arthur Geßler, Department of Tree Physiology, July 2004).
This would explain the daily fluctuation of soil moisture with a maximum at daytime and a minimum at night.
Possible reasons for the decay of soil moisture after a month are:

- The water supply to the root was interrupted because of a decline of the groundwater level to a lower level , or
- a callus was built at the damaged root and no more root water could escape or the root was dead.

No lateral movement of the wetting front up to a depth of 130 cm and in a distance between 230 and 570 cm to the active channel could be measured with the Theta probes at the overbank area.

Discussion of soil moisture results at site 2 “Rock site”

Soil dynamics

It is assumed that the probe at 80 cm depth was moved by shifting sand or by erosion. Shifting sand like “Shifting dunes” in rivers were observed by Israeli researchers in Botswana (GRODEK 2004).

Evaporation

Due to the fact that field capacity of the soil mixture surrounding the starter probe could only be estimated very roughly, a value was assumed, where it was assured that only evaporation as a source of water losses, took place.

From there on (30.01.2004), at a soil moisture content of 13 V%, evaporation was roughly estimated. It was assumed that no vegetation influenced the water loss at this place.
In 2 months (60 days) a loss of 7.6 V% soil moisture in 5 cm depth was measured.
At an average 0.13 V% per day (in a two month period) were evaporated.

Discussion of soil moisture results at site 3 "Evaporation site"

Probe 50 cm depth next to vegetation (Probe J) :

It is assumed that the decrease 8.2 V% in 64 days was mainly caused by evapotranspiration.

At an average 0,13 V% per day (in a two month period) were evapotranspirated.

Probe 100 cm depth next to vegetation (Probe K):

It is assumed that the decrease of 2V% in 64 days was mainly caused by evapotranspiration The negative value is in the accuracy range. It is assumed that the relative values are correct.

At an average 0.03 V% per day (in a two month period) were evapotranspirated.

Probe 50 cm depth (Probe L):

It is assumed that with 14 V% the field capacity was reached and from there on it is possible that the evaporation was the only process causing water losses in the soil. Thus it appeared that 4V% evaporated in 63 days.

At an average 0.06 V% per day (in a two month period) evaporation took place.

Probe 100 cm depth (Probe M):

It is assumed that the loss of 1.9 V% soil moisture content in 64 days was mainly caused by evaporation.

In average 0.03 V% water loss per day (in a two month period) caused by evaporation took place.

Discussion of soil moisture results at site 4 "spare site"

Probe in 100 cm depth (Probe N):

The loss of 2.3 V% in 77 days is possibly caused by evaporation only.

At an average 0,03 V% water loss per day (in a 77 days period) caused by evaporation took place.

Probe in 200 cm depth (Probe O):

It is assumed that the loss of 2.8 V% soil moisture in 77 days in a depth of 2 m is mainly caused by vegetation. SORMAN & ABDULRAZZAK (1995) determined that the maximum depth of direct evaporation influence is limited to the first 150 cm under surface. At an average 0,04 V% water loss per day (in a 77 days period), assumingly caused by vegetation, took place.

Table 7: Summarized water losses caused by vegetation and evaporation from all research sites at Gobabeb.

Location	Loss per day V%	Calculation period	Soil description	Depth [cm]	Vegetation influenced	evaporation
Anatreesite Probe A	0,34	81	Su 3	100	X	X
Site Three, “Pure Evaporation Site” Probe J	0,13	64	Su4	50	X	X
Site Three, “Pure Evaporation Site” Probe K	0,03	64	Pebbles and coarse sand	100	X	X
Site Three, “Pure Evaporation Site” Probe L	0,06	63	mS	50	-	X
Site Three, “Pure Evaporation Site” Probe M	0,03	64	Pebbles and sand	100	-	X
Rock site Probe F	0,13	60	mixed layer	5	-	X
Spare site Probe N	0,03	77	fS	100	-	X
Spare site Probe O	0,04	77	Su 4	200	X	-

General Discussion

The infiltration rates from surface to 100 cm depth in the unsaturated zone at Anatree site with 0.89 mm/min and 0.26 mm/min seem small. KÜLLS (1994) determined a mean infiltration of 100 mm/h (1.66 mm/min) for the unsaturated zone from a field experiment in an ephemeral channel alluvium in Israel.

However, the infiltration rate at Anatree has to be considered as a minimum infiltration rate, because this rate could only be calculated based on the increase of soil moisture in 100 cm depth. Unfortunately there was no probe below this probe, so the infiltration to deeper parts of the alluvium at this time could not be observed and considered. However, there is a high possibility, that water infiltrated to the deeper alluvium before the maximum of soil moisture was reached.
The rate of wetting front advance (0.3 m/h and 0.15 m/h) seems to be very small, if compared with values from SCHWARTZ (2001). He conducted measurements of moisture in channel alluvium at two specific cross sections during several real flood

events and documented a rate of wetting front advance between 1.5 – 3.7 m /h. It is assumed, that due to the heterogeneous stratigraphy and processes like scour and fill, at other places in the alluvial fill of the *Kuiseb,* the measured rate of wetting front advance could have been higher. The response of the water table to, for example flood one, in the monitoring hole (see chapter 4.4) after seven hours suggests, that at other places the rate of wetting front advance was higher. It also has to be considered, that the silt layer very likely was reducing the rate of infiltration and the rate of wetting front advance.

The second flood was less erosive then flood event one and the surface was sealed by the wet silt cover caused by the first flood four days before. Due to these circumstances less infiltration/transmission losses could take place.

Field capacity and permanent wilting point:

The values for field capacity and permanent wilting point seem to be reasonable after comparing them with literature values (AG BODEN 1996).

The water losses in the first four days after reaching field capacity at Anatree site - assumingly caused by evapotranspiration - are very high.

The water losses after reaching field capacity after the floods of 2.9 and 2.8 V% /d are very likely not only caused by evapotranspiration. The values are equivalent to 28 and 29 mm water loss per day (calibrated to one meter depth assuming that the same water losses occurred over one meter). Assuming a maximum loss by evaporation of 9.4.mm after SORMAN & ABDULRAZZAK (1995), the surrounding plants would consume 19.6 mm water per day and m^2. This seems to be very high.

BATE & WALKER (1991) estimated the transpirational loss by all the vegetation with about 2.02 x 10^{5} m^3 per km river length, annually. They were assuming an aquifer width of 307m. To get an rough idea of the amount plants can consume in an average per m^2/d , the value BATE & WALKER (1991) estimated was calibrated to 1 m^2/d and is about 1.8 mm/d .

One possibility to explain the high water losses is an additional lateral movement of soil moisture, e.g. a lateral flux to dry overbank areas.

In general, water losses caused by evaporation/ evapotranspiration in the upper alluvium seem to be small. High amounts of water loss likewise were only observed in the first days after the flood. This was due to the fact that only at this time the upper alluvium has high water content.

SORMANN & ABDULRAZZAK (1995) determined the effective depth of evaporation to 150 cm below surface. This allows to determine an upper boundary for water losses by evaporation.

Conclusion

Two floods during the measurement period were observed at Gobabeb and could be considered for the examination of soil moisture dynamics.
The rate of advance of the wetting front was 0.3 m/h for flood one and 0.15 m/h for flood two. The infiltration rates were 0.89 mm/min and 0.26 mm/h, respectively.
The rates of infiltration as well as the rates of advance of the wetting front are small compared to the values published by other authors. It is assumed that the smaller rates are mainly caused by a thick silt layer on the surface, which reduced the infiltration.
A lateral movement of the wetting front towards the dry overbank area could not be measured up to a depth of 130 cm and in a distance between 230 cm and 570 cm to the active channel.
The examination of soil moisture dynamics indicates transmission losses via infiltration of 2957 l/m^2 for flood 1 and 250 l/m^2 for flood two. However, these infiltration rates were only measured at a single point in the active channel and are not representative to the whole channel. It is assumed that due to the heterogeneous character of the stratigraphy the infiltration is possibly higher at places with less silt or clay layers. At places with more or thicker silt or clay layers less infiltration could be possible.
In general water losses caused by evaporation / evapotranspiration in the upper alluvium seem to be small. High amounts of water loss were only observed in the first days after the flood due to the fact that only at this time the upper alluvium has high water content.

4.4 Groundwater observation

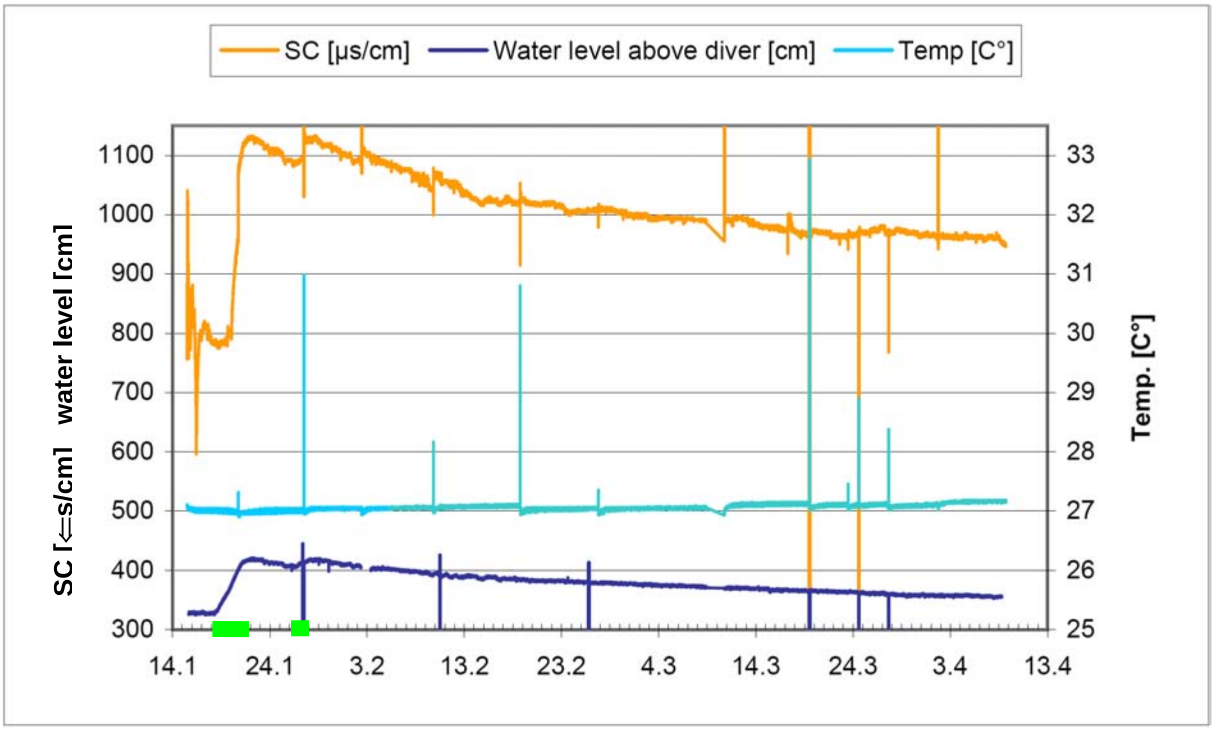


Figure 30: Temperature, water table fluctuation and electrical conductivity (SC)
Green: Flood duration

4.4.1 **Temperature**

The groundwater temperature for the whole measurement period was between 27 and 27.2°C.

4.4.2 **Water table fluctuation**

At the beginning of the measurement (15.01.2004) the water level was 7.33 m under surface and fluctuated between 7.32 m and 7.38 m for the next days.
Seven hours after the first flood (18.01.2004) arrived, the water table started to rise significantly with a sharp increase of 84 cm in 72 hours to 6.44 m (*21.01.2004, 06:00*) under surface.
From there on the water level was fluctuating for three days (50 hours) in this magnitude, between 6.39 m and 6.44 m below ground. The maximum level was 6.39 m below surface.
On the 23.01.2004, one day after the river stopped flowing, the water level starts decreasing to reach 6.52 m below surface on the 26.1.2004.

11 hours after arriving time of flood event two, the water table started to rise 13 cm in 23 hours to 6.39 m at 27.01.2004 18:00.
From then on, the water level was fluctuating in a range between 6.39 m and 6.44 m below ground for 1 ½ day (36 hours).
Aftre that, it was constantly decreasing until the end of the measuring period.
Draw downs and recoveries caused by pumping from the production borehole causing fluctuations of roughly 5 cm max around 6 cm are visible.
Maximum of water level rise after flood one: 89 cm
Maximum of water level rise after flood two: 13 cm

According to AIN (1999) and SMIT (1978) the mean porosity in the *Kuiseb* is 35%.
The average width of the alluvial aquifer at *Gobabeb* was estimated by BATE & WALKER (1991) with 307 m, using these values and the water table rise, a rough recharge calculation for 1 km river length was done with:

Recharge = porosity x water table rise x aquifer width x transect length
Recharge Flood one = 0.35 x 0.89m x 307m x 1000 m = 95,630.5 m^3/km river length
Recharge Flood two = 0.35 x 0.08m x 307m x 1000 m = 8,596.0 m^3/km river length

4.4.3 Specific electrical conductivity

The initial value of specific electrical conductivity (SC) was 764 µs/cm. During the first day after the insertion the conductivity graph shows a very flashy distribution in a range from 596 to a maximum of 1041 µs/cm

Afterwards the SC was relative stable between 775 µs/cm and 790 µs/cm. 33 hours after the first flood arriving, a first increase of the SC was observed. A very steep increase of the SC was observed 43 hours after the beginning of the first flood on the (20.01.2004 00:37). It was increasing to a maximum of 1132 µs/cm. The SC decreased for about 50 µs/cm after the flood one, before it started increasing again 16.5 hours after beginning of flood event two.

55 hours after the second flood event a second maximum of 1134 µs/cm was reached on the 28.1.2004 (15:25). From there on the SC was decreasing to 946 µs/cm at the end of the measuring period.

<u>Discussion:</u>

Compared with the measured rate of advance of the wetting front, the water table showed a relative fast reaction, rising seven hours after flood one arrived. Especially considering the fact, that the borehole is in 31 m distance to the active channel. It is assumed that due to the heterogeneous stratigraphy the rate of advance of the wetting front at other places of the channel was much higher and it should also be

considered that very possibly preferential flow took place (see Figure 31). It is possible that the deeper aquifer is consisting of coarse sand and fine gravel which would explain the immediate reaction.
The response time to the second flood with 11 hours was slower.
It can be presumed, that due to the less erosive character of flood one and clogging silt layers at the surface as a result of the previous flood, infiltration was restricted.

The water table rise of flood two was very possibly influenced by a draw down from pumping of the production borehole. Taking into account, that the local minimum before the water table started rising was probably caused by pumping, the corrected value for the rise of the water table is estimated with approximately 8 cm.

SMIT (1978) reported a mean hydraulic conductivity of 79 m/d with a range between 161 m/d and 29 m/d for the *Kuiseb* alluvium. Within this range the water table shows a reaction.

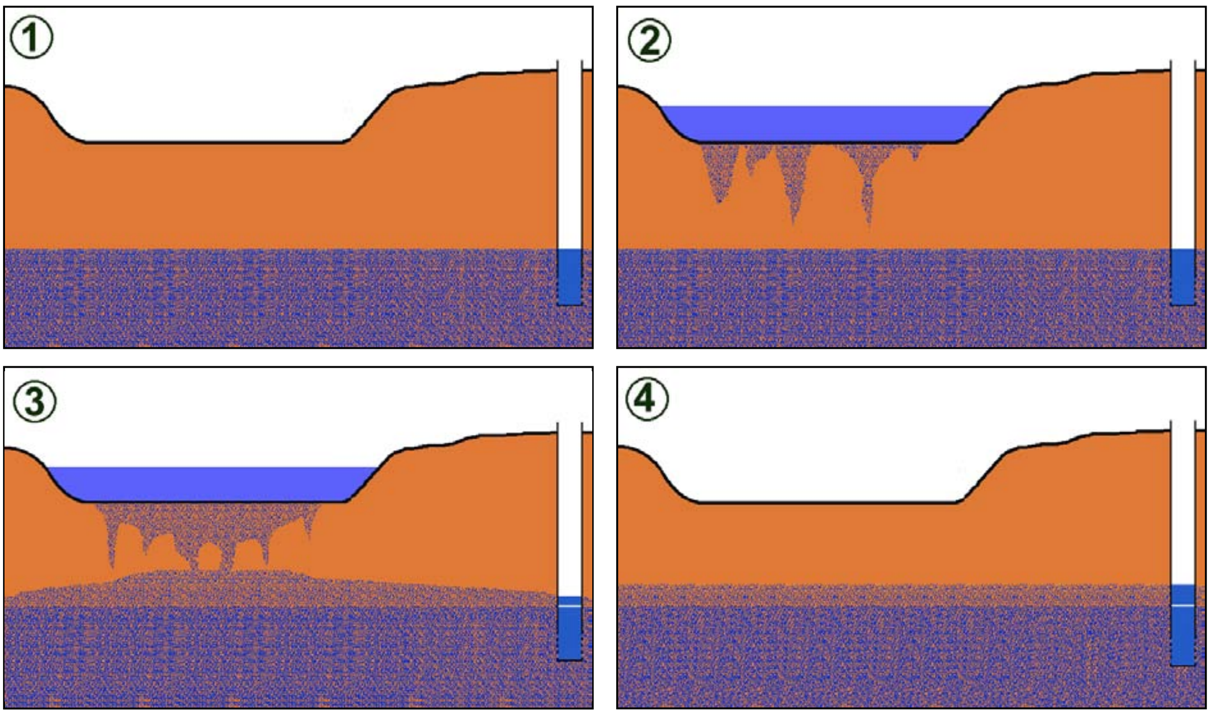


Figure 31: Scheme of groundwater recharge

The increase of the specific electrical conductivity (SC) with flood event one and 2 is probably caused by the hydraulic circumstance of water table rise. The monitoring borehole is only filtered in the deeper part of the aquifer (SEIMONS 2004). With a rising groundwater table the water table in the borehole is rising too. It is assumed that the diver was situated in a mixed water layer, before the water level started rising (Figure 32). After the increase of the water table the more saline water from the bottom of the borehole reached the diver.

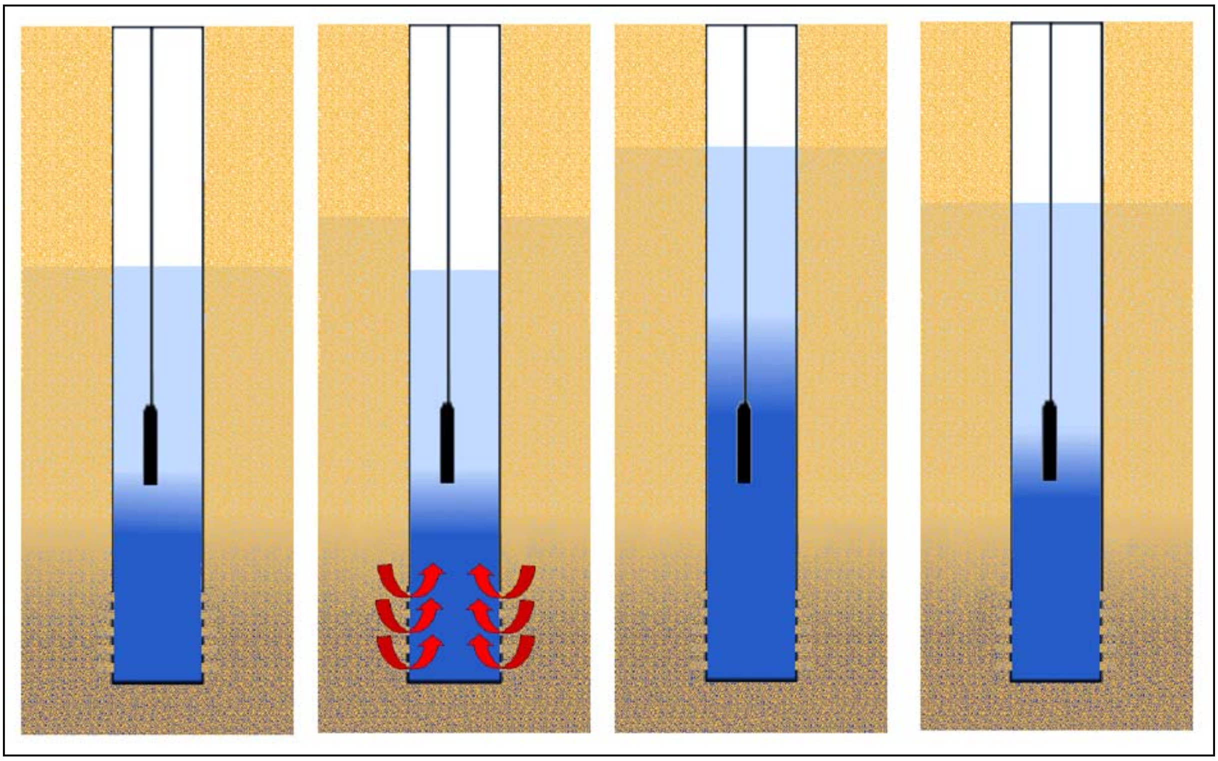


Figure 32: Scheme of increasing specific conductivity
The light blue colour shows fresh water, the dark blue colour shows dense saline water

The highest values of SC appeared with the maximum of the water table. The assumed layering would also explain the flashy distribution in the first days. It can be argued, that the layers were disturbed while installing the diver in the monitoring hole. Pulling out the diver for downloading the data apparently caused disturbance, which is visible in Figure 30 at p. 46.

Conclusion:

The aquifer responded with a rise of water table of 89 cm to flood one and with 8 cm to flood two.
A recharge of 95,630.5 m^3/km river length for flood one and of 8,596.0 m^3/km river length for flood two was calculated. These calculations are considered as a rough estimate due to the fact that the exact extent of the aquifer is not known.
No change in temperature was notified.
A significant rise of the specific electrical conductivity (SC) with flood event one and 2 was observed and is probably caused by the hydraulic circumstance of water table rise. The highest values of SC appeared with the maximum of water table. The monitoring borehole is only filtered in the deeper part of the aquifer (SEIMONS 2004). With a rising groundwater table the water table in the borehole is rising too. It is assumed that the diver first was situated in mixed layer and with the increasing water table the denser water from the deep reached the diver.

4.5 *Major ions*

Floodwater samples for the analysis of major ions were taken at *Gobabeb Research Station*, while groundwater samples were collected from several sites.

4.5.1 **Floodwater**

<u>Flood event one</u>

Sampling period: 18.01. – 21.01.2004

The ion concentration of chloride (Cl^-), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) is showing (see Figure 33) a maximum in the flood front and then sharply decrease. After the river was flowing for two hours the ion concentration was more then half of the initial ion concentration.

Only nitrate (NO_3^-) and sulfate (SO_4^{2-}) differ from this pattern. The whole range of ion concentration is shown in Table 8.

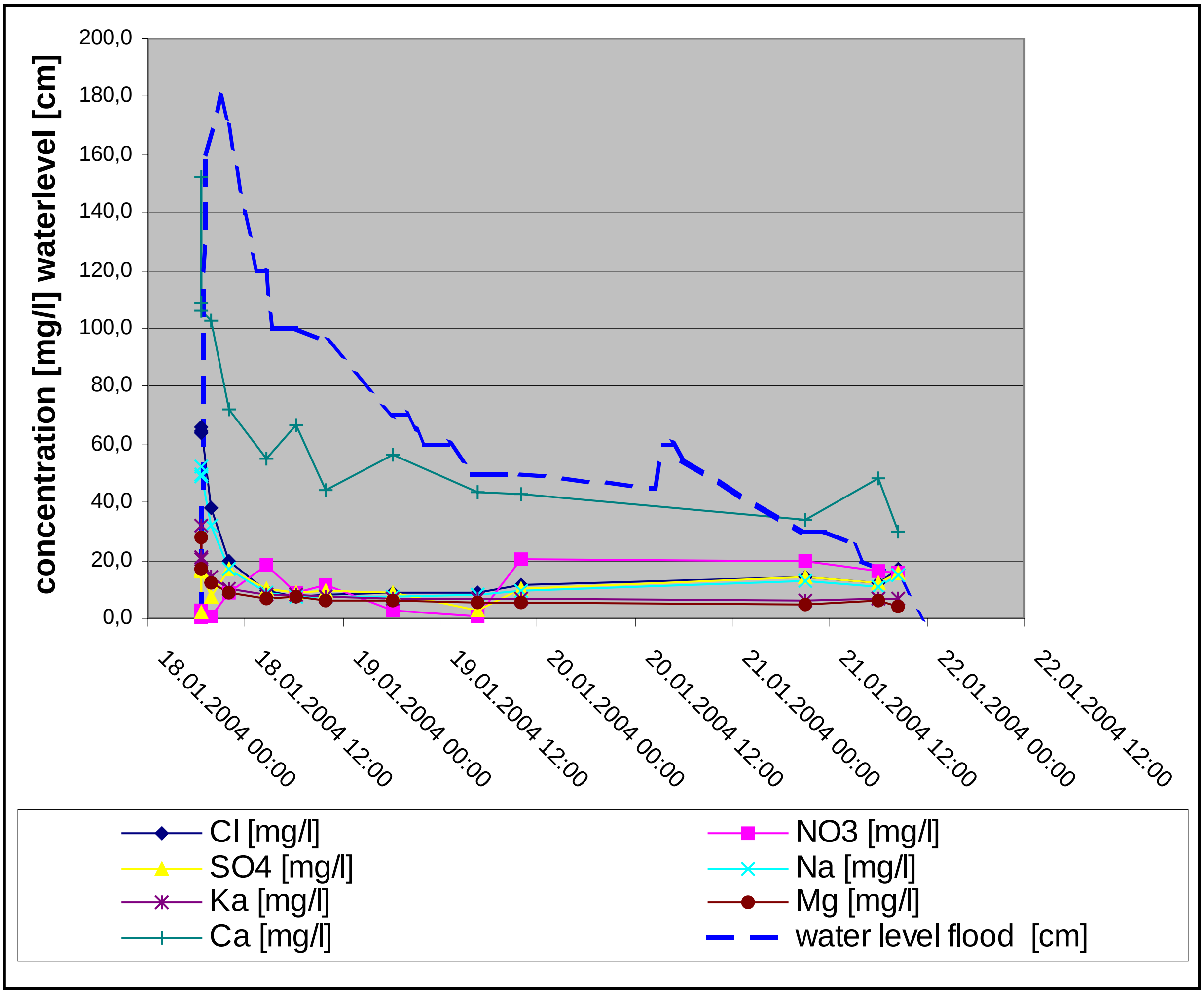


Figure 33: Distribution of the major ion concentration in the flood water of flood one at Gobabeb Station.

Table 8: Range of ion concentration of flood water from flood event one

Ion	Maximum [mg/l]	Minimum [mg/l]
Cl^-	66.1	7.8
NO_3^-	20.1	0.2
SO_4^{2-}	17.2	1.8
Na^+	52.7	7.5
K^+	32.2	6.4
Mg^{2+}	27.8	4.3
Ca^{2+}	152.2	29.8

Discussion:

The higher concentration of ions in the beginning of the flood is possibly caused by dilution of dry deposits while flood generating in the upper catchment and also by dilution of dry deposits of the dry river bed.

Flood event two

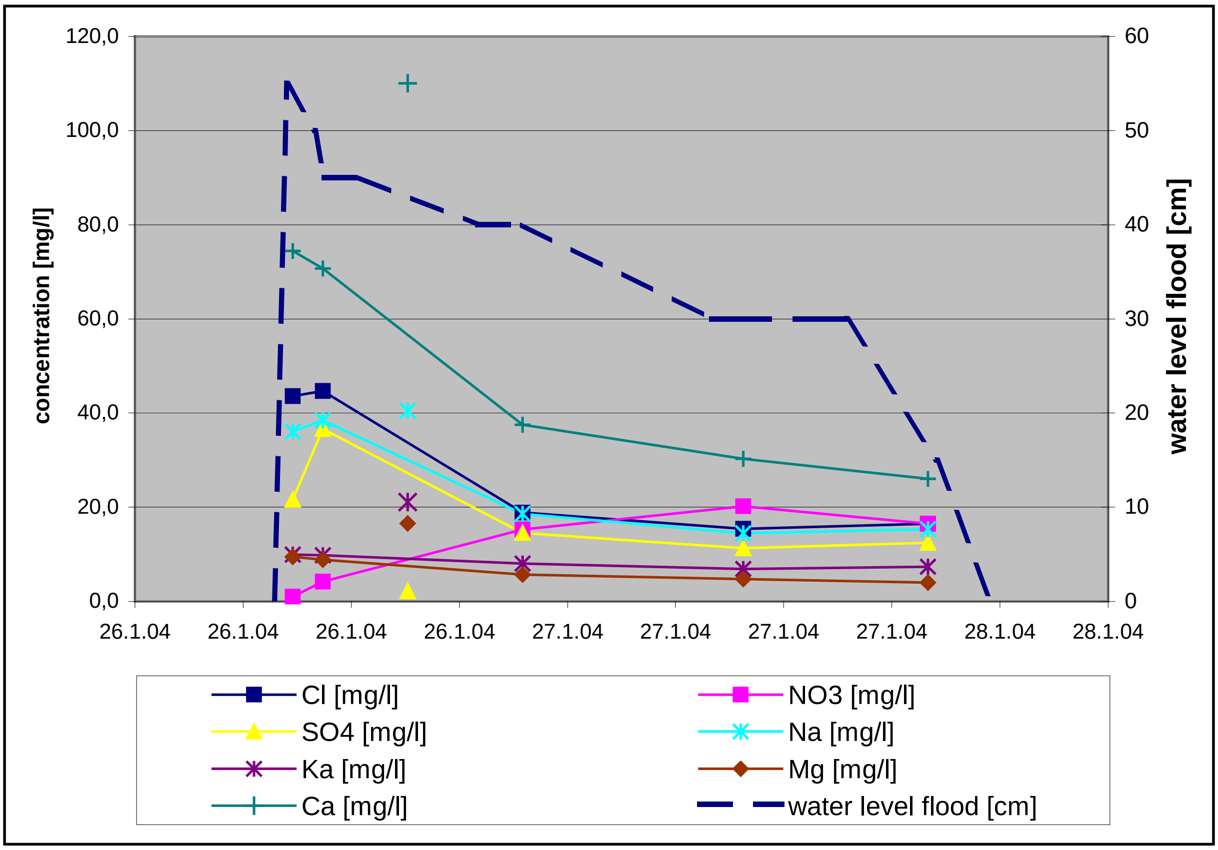


Figure 34: Distribution of the major ion concentration in the flood water of flood two at Gobabeb Station and of the flood front 15 km downstream (single points).

Sampling period: 26.01. – 27.01.2004

The ion concentration of chloride (Cl^-), sulfate (SO_4^{2-}), sodium (Na^+), potassium (K^+), magnesium (Mg^{2+}) and calcium (Ca^{2+}) is showing a maximum in the flood front / in the first two hours of the flood and afterwards a decrease of concentration (Figure 34). After the river was flowing for about 13 hours the ion concentration was more then half of the maximum ion concentration.

Only nitrate is showing a different pattern. The whole range of ion concentration is shown in Table 9.

Table 9: Range of ion concentration of flood water from flood event two

Ion	Maximum [mg/l]	Minimum [mg/l]
Cl^-	50.4	15.4
NO_3^-	20.2	not detectable
SO_4^{2-}	36.7	2.1
Na^+	40.5	14.4
K^+	21.1	6.9
Mg^{2+}	16.6	4.7
Ca^{2+}	110.1	26.1

Including values from the flood front 15 km downstream from Gobabeb Station

Discussion:

Similar to the first flood, comparatively high concentration of ions in the beginning of the occurred flood is possibly caused by dilution of the dry deposits while flood was generated in the upper catchment. This theory is corroborated by the fact, that concentrations during the second flood event were lower than during the first one

4.5.2 Groundwater

Gobabeb Station

Sampling period 15.01. – 15.04.2004

The minima of ion concentration for chloride, sulfate, sodium, potassium, magnesium and calcium were measured right at the beginning, on the 15.01.2004 and 18.01.2004 (Figure 35).

The ion concentration of chloride, sulfate, sodium, potassium, magnesium and calcium shows a significant increase on the 20.01.2004 (third day of the first flood) and an maximum concentration on the 21.01./ 23.01.2004.

The nitrate concentration shows also a maximum on the 23.01.2004, but its minimum was at the end of the measurement period on the 07.04.2004. The whole range of ion concentration is shown in Table 10.

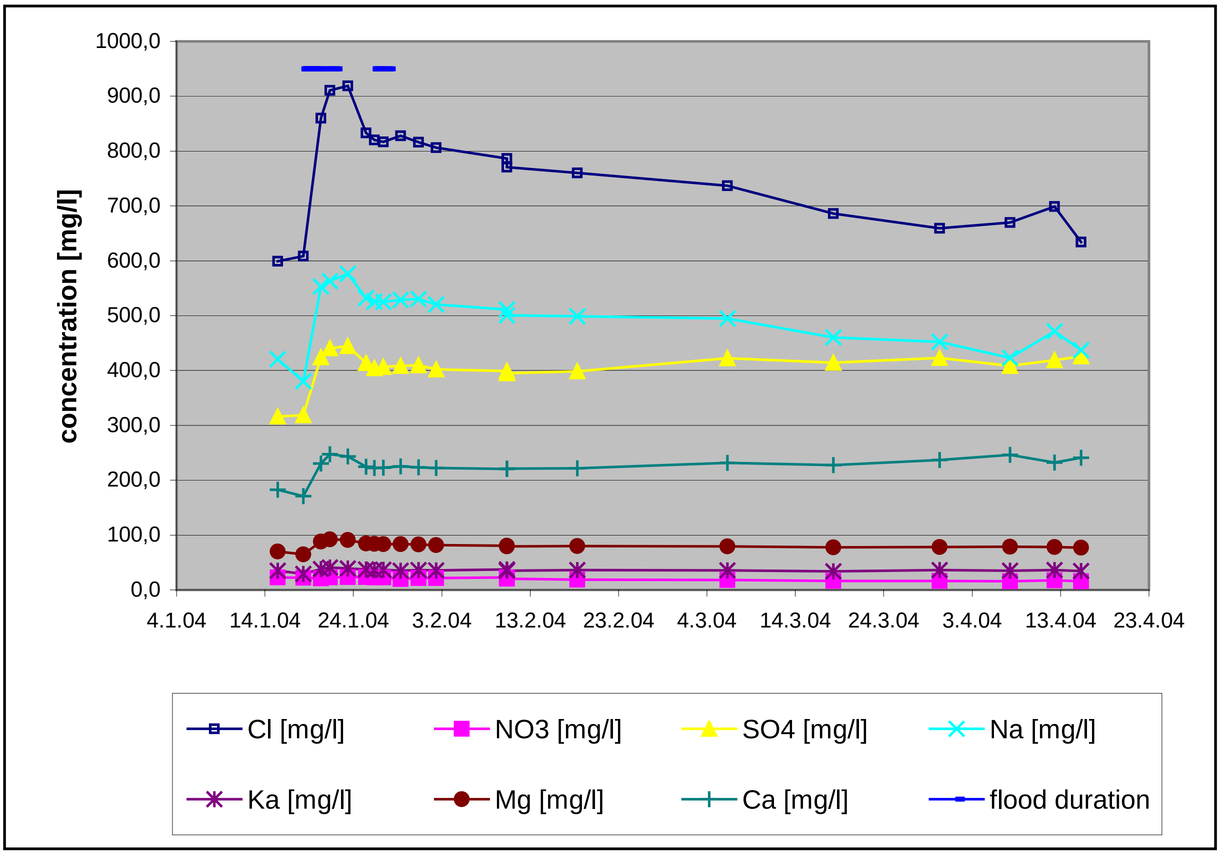


Figure 35: Distribution of the major ion concentration in the groundwater of Gobabeb Station production borehole

Table 10: Range of ion concentration of groundwater from the production borehole at Gobabeb Station

Ion	Maximum [mg/l]	Minimum [mg/l]
Cl^-	919	599
NO_3^-	23,6	15,8
SO_4^{2-}	444,8	316,4
Na^+	576.6	380.4
K^+	40.7	29.3
Mg^{2+}	91.9	65
Ca^{2+}	247.5	171.1

Discussion

A mixing of groundwater with floodwater could not be observed. It is assumed, that the significant increase of ion concentration during flood one is caused by hydraulic circumstances of water table rise. The borehole is only filtered in the deeper part of the aquifer (SEIMONS 2004). With a rising groundwater table the water table in the borehole was rising too, with the more denser water from the deeper aquifer reaching the pump.

Homeb

Sampling period: 17.02. – 07.04.2004
The ion concentration of nitrate, potassium, magnesium does not show a significant change in concentration (Figure 36).
Only the concentrations of chloride, sodium, calcium and sulphate show a slight falling tendency whereas chloride is showing the "strongest" tendency. But this tendencies are all inside of the error range. The whole range of ion concentration is shown in Table 11.

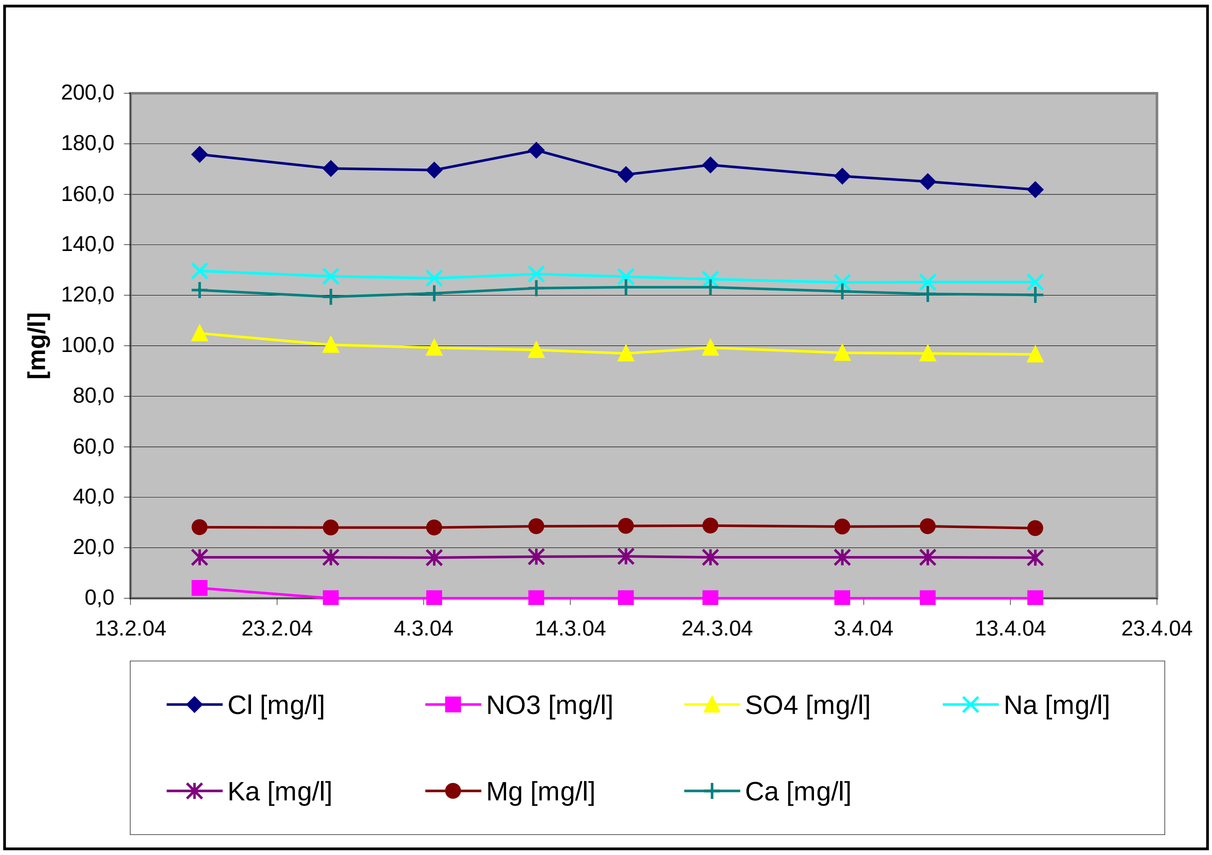


Figure 36: Distribution of the major ion concentration in the groundwater at Homeb

Table 11: Range of ion concentration groundwater at Homeb

Ion	Maximum [mg/l]	Minimum [mg/l]
Cl^-	177.4	161.8
NO_3^-	4	not detectable
SO_4^{2-}	105	96.6
Na^+	129.7	125.1
K^+	16.5	16.1
Mg^{2+}	28.8	27.8
Ca^{2+}	123.2	119.4

Discussion: A dilution of groundwater with flood water could not be observed.

Soetrevier

Sampling period: 16.02. – 07.04.2004 (Figure 37)
The chloride, sulphate and calcium concentration is significantly increasing right from the beginning of the sampling period. Sodium, magnesium and potassium show a light increasing of concentration from the beginning, but this increase is inside of the error range. The whole range of ion concentration is shown in Table 12.

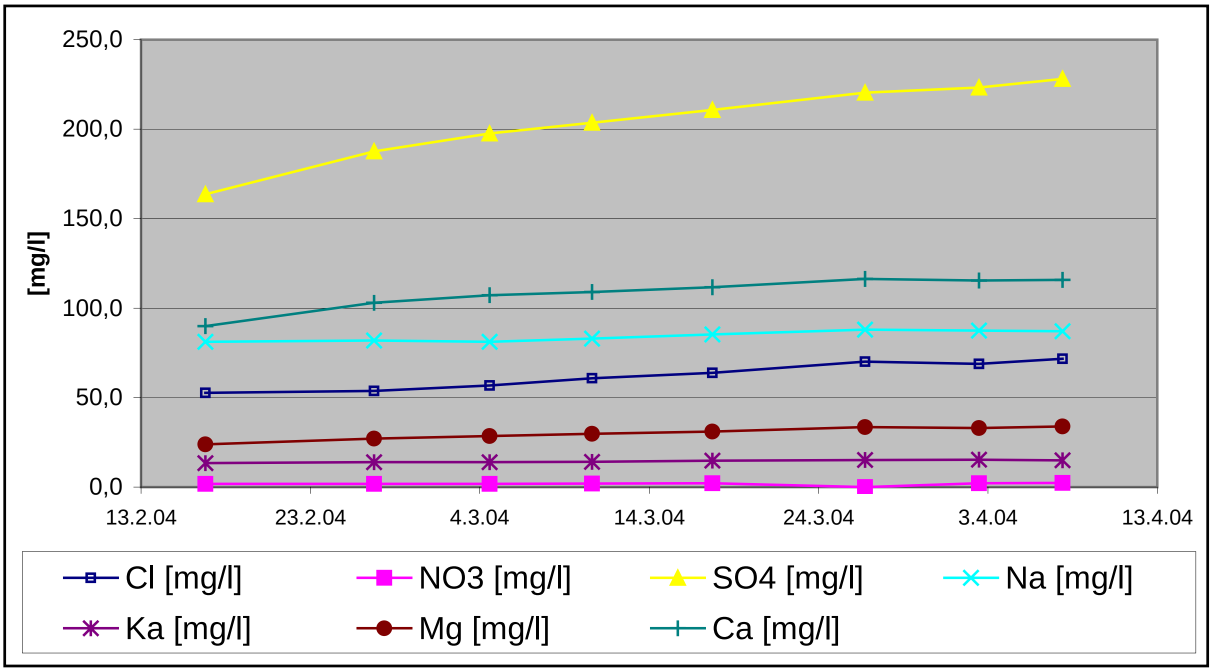


Figure 37: Distribution of the major ion concentration in the groundwater at Soetrevier

Table 12: Range of ion concentration of groundwater at Soetrevier

Ion	Maximum [mg/l]	Minimum [mg/l]
Cl^-	71.7	52.7
NO_3^-	2.4	not detectable
SO_4^{2-}	228	163.6
Na^+	87.9	81.2
K^+	15.4	13.3
Mg^{2+}	33.9	22.8
Ca^{2+}	116.4	90

Discussion:
A dilution of groundwater with flood water could not be observed. It might be that the first samples of the measuring period were influenced by flood water, but due to a lack of groundwater samples on this site before the floods, it can't be proved. Furthermore sulfate concentrations have to be considered carefully due to the fact that sulfate is a non conservative ion.

Klipneus

Sampling period: 16.02. – 07.04.2004 (see Figure 38)
The sodium concentration is showing a slightly decreasing tendency while chloride, calcium, sulphate and magnesium show a slightly increasing tendency, but the tendencies are inside of the error range. Potassium and nitrate are showing no tendency. The whole range of ion concentration is shown in Table 13.

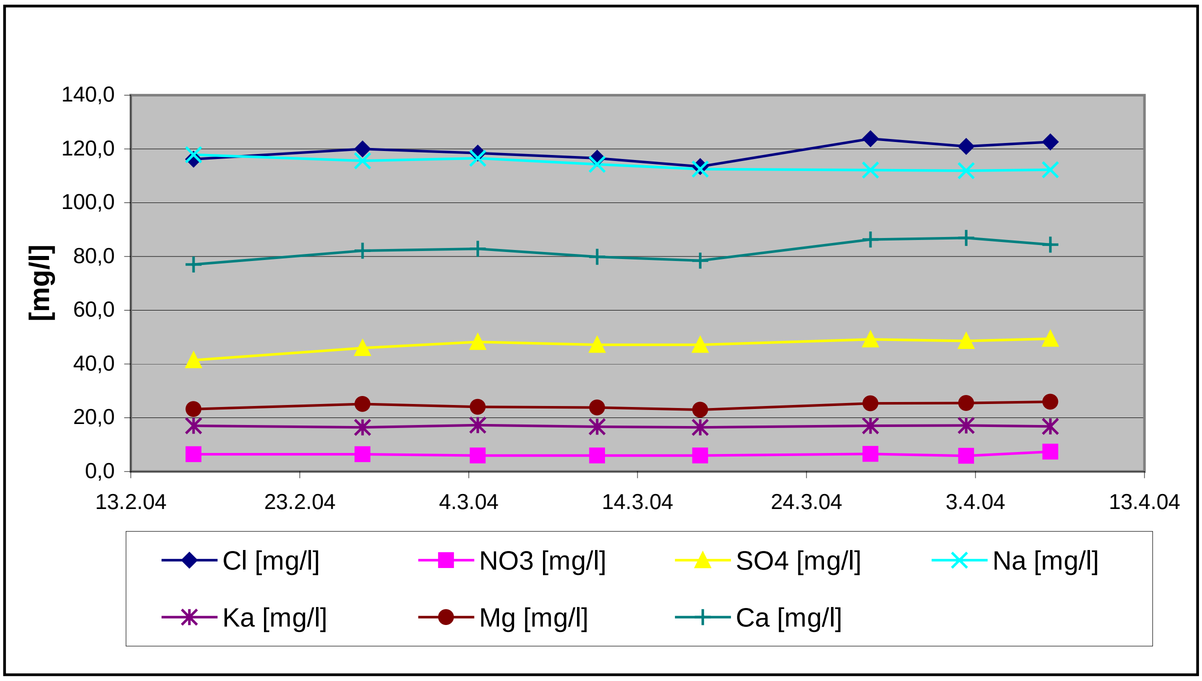


Figure 38: Distribution of the major ion concentration in the groundwater at Klipneus

Table 13: Range of ion concentration of groundwater at Klipneus

Ion	Maximum [mg/]	Minimum [mg/l]
Cl^-	123.8	113.4
NO_3^-	7.4	5.8
SO_4^{2-}	49.4	41.4
Na^+	117.9	112
K^+	17.3	16.4
Mg^{2+}	25.9	22.9
Ca^{2+}	86.9	77

Discussion: A dilution of groundwater with flood water could not be observed.

Swartbank tap

Sampling period 26.02. – 07.04.2004 (Figure 39)
The concentration of chloride is significantly increasing from 26.02.2004 to the 04.03.2004 with about 39 mg/l. Later on no tendency is visible. Sulfate is also increasing in the same period but not as pronounced as chloride. The increase is in the error range and later on no tendency is visible. Calcium shows a light increase in the period from 26.02.2004 to the 04.03.204. Furthermore no tendency is visible. Sodium is slightly increasing from the beginning to the end of the measuring period but this is also in the error range.
Magnesium, potassium and nitrate are showing no tendency in concentration change. The whole range of ion concentration is shown in Table 14.

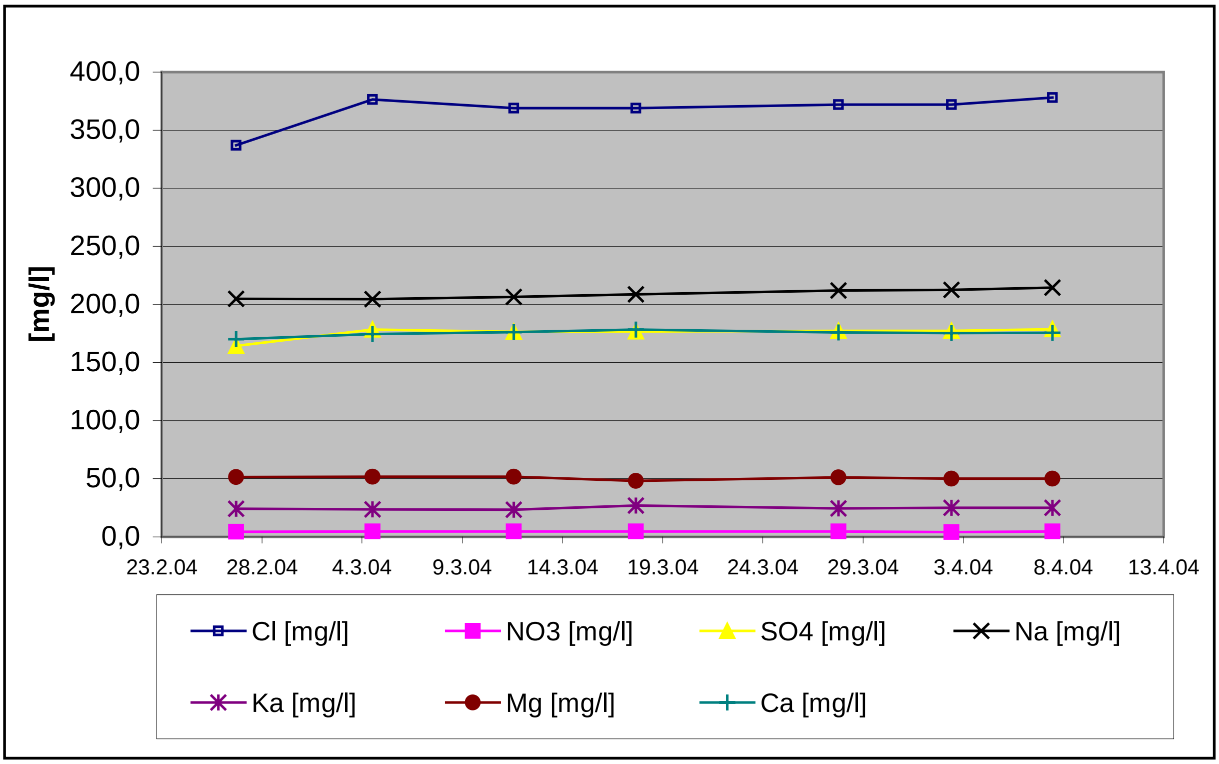


Figure 39: Distribution of the major ion concentration in the groundwater at Swartbank tap

Table 14: Range of ion concentration of groundwater from Swartbank tap

Ion	Maximum [mg/l]	Minimum [mg/l]
Cl^-	378	337
NO_3^-	4.8	4
SO_4^{2-}	178.6	164.4
Na^+	214.5	204.4
K^+	27	23.4
Mg^{2+}	51.8	48
Ca^{2+}	178.3	170.2

Swartbank hand pump

Sampling period 16.02. – 07.04.2004
Nitrate was only detected in one sample, on 11.03.2004.
Remarkable is the strong minimum of all other ion concentrations on 26.01.2004. After this minimum the concentration was increasing again. The whole range of ion concentration is shown in Table 15.

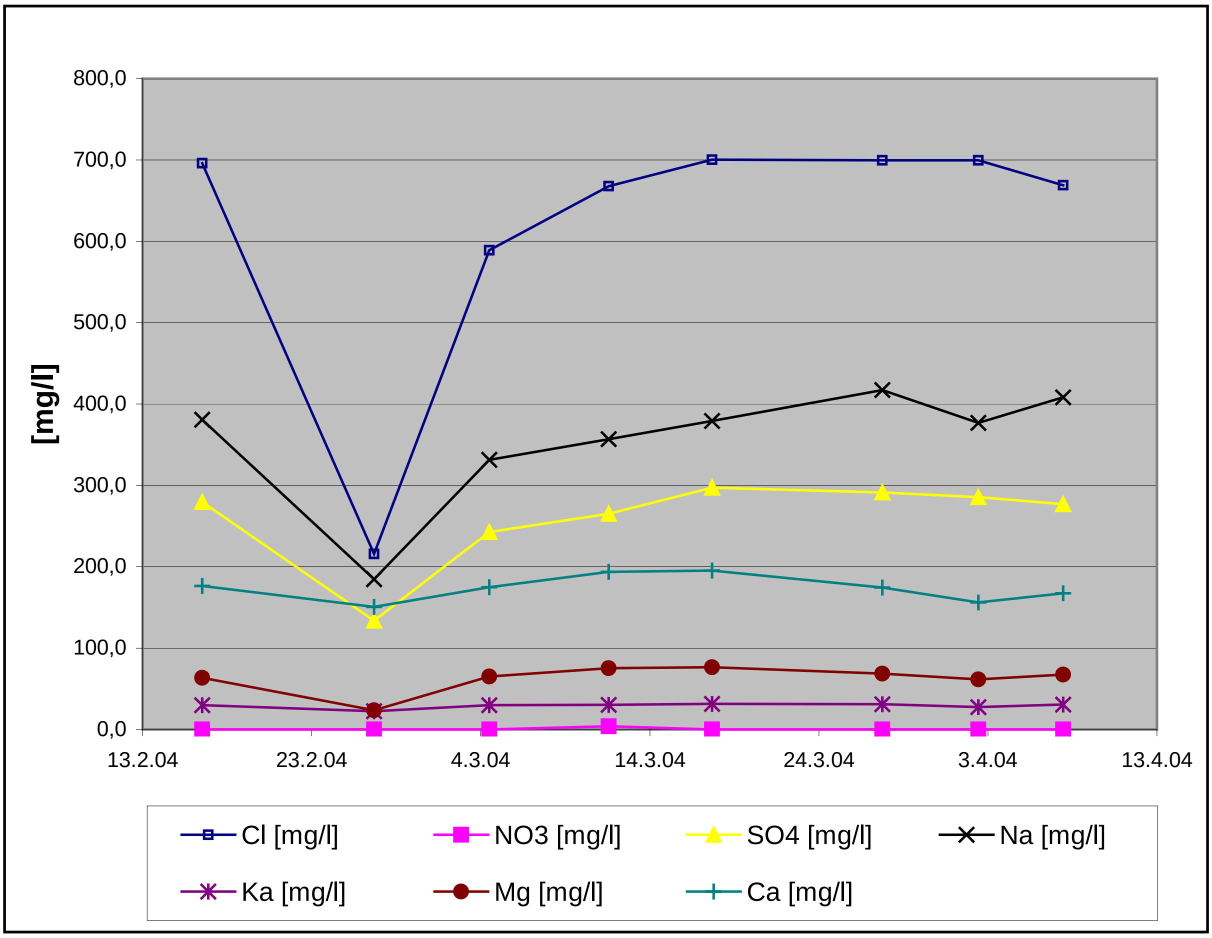


Figure 40: Distribution of the major ion concentration in the groundwater at Swartbank hand pump

Table 15: Range of ion concentration of groundwater from Swartbank hand pump

Ion	Maximum [mg/l]	Minimum [mg/l]
Cl^-	700.2	215.8
NO_3^-	not detectable	4
SO_4^{2-}	297.4	133.8
Na^+	417.2	184.8
K^+	31.5	22.5
Mg^{2+}	76.4	23.4
Ca^{2+}	195.3	150.6

Discussion:

The strong minimum of ion concentration on the 26.01.2004 is possible caused by a drawdown by pumping in the new borehole which is in direct neighbourhood.

It can be presumed, that the “hand pump bore hole” is filtered in the deeper, denser, more saline aquifer, while the new borehole is possibly mainly filtered in the upper fresh water aquifer. A significant drawdown in the new borehole would cause a fresh water intrusion. It is assumed that this happened due to the fact that the pump of the new borehole was just fixed in this period and the residents of *Swartbank* reported that the pump was running continuously for several days.

A dilution of groundwater with flood water could not be observed.

The whole results of the laboratory analysis for the major ions are in annex III.

Conclusion

Due to the fact that the ion concentration of floodwater was relative low compared with the concentration of the major ions in the groundwater of the different sites, it is assumed that a mixing of groundwater with flood water would have been visible.

Due to the lack of groundwater samples from *Homeb, Soetrevier, Klipneus* and *Swartbank* before the flood events, it is not known how the ion concentration was before the flood at this sites. Hence, such information could not be considered. The groundwater might be influenced by floodwater but this could not be proved.

The significant change of hydrochemistry, the sharp increase of ion concentration, in the groundwater at *Gobabeb* with flood event one, might be considered as an aquifer response to a flood event and as an indirect evidence of groundwater recharge. However the groundwater recharge could not be quantified on the basis of ion concentration.

4.6 Stable isotopes

4.6.1 **Floodwater**

Figure 41 shows the flood water level and the distribution of Deuterium and ^{18}O during flood one and flood two.

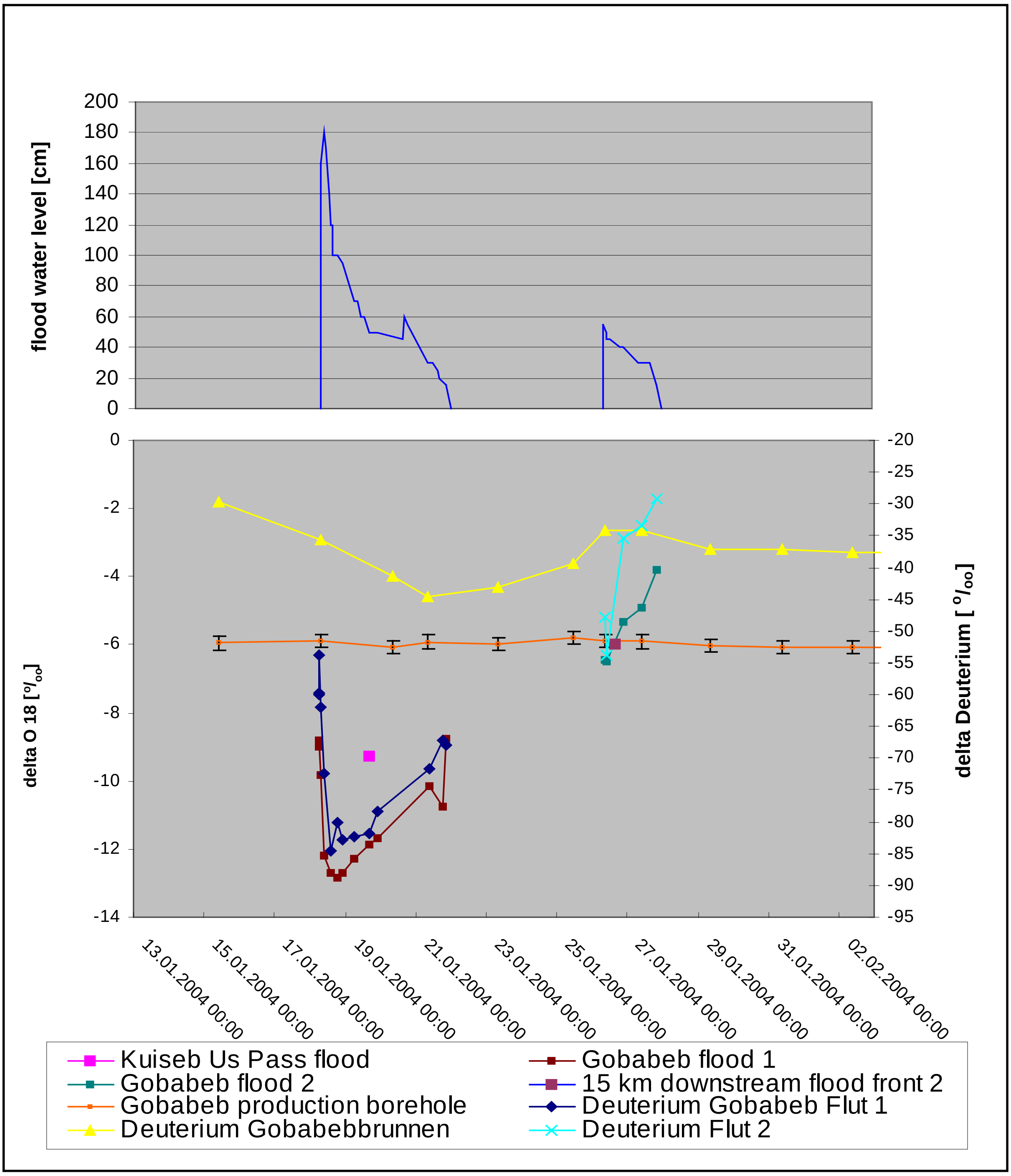


Figure 41: Distribution of Deuterium and Oxygen 18 during flood one and flood two in flood water and in groundwater of Gobabeb production borehole

Flood one

^{18}O:
The range of ™ ^{18}O was between – 8.8 ‰ and – 12.9 ‰.
Two maxima were measured, one just in the beginning of the flood, the other at the end of the flood.
In beginning of the flood the concentration was - 8.8 ‰ and decreasing then to a minimum of - 12.9 ‰ and increasing again to – 8.8 ‰ at the end of the flood.

Deuterium:
The range of ™ Deuterium was between – 53.8 ‰ and – 84.6 ‰.
The Deuterium distribution of concentration in flood one shows a similar pattern as ^{18}O ‰ with the highest concentrations in the beginning (– 53.8 ‰) and in the end (- 67.2 ‰) of the flood.

Flood two

^{18}O:
The range of ™ ^{18}O was between – 3.8 ‰ and – 6.5 ‰.
The minimum concentration was in the beginning of the flood from there on it was increasing to the maximum concentration at the end of the flood.

Deuterium:
The range of ™ Deuterium was between – 29.1 ‰ and – 53.8 ‰.
The Deuterium distribution of concentration in flood two shows a similar pattern as ^{18}O ‰, with the minimum concentration in the beginning and increasing further more to the highest concentration at the end of the flood.

4.6.2 Groundwater

Gobabeb Station

Figure 41 shows the distribution of Deuterium and Oxygen 18 during flood one and flood two in flood water and in groundwater of *Gobabeb* production borehole and Figure 42 is showing the distribution of ^{2}H and ^{18}O over the whole measurement period.*

^{18}O:
The range of ™ ^{18}O in the measurement period was between – 5.8 ‰ and – 6.4 ‰.
The measurements are not showing a significant change in concentration.

---

*From the 26.02. to the end of the measurement period the deuterium values have to be considered very carefully or better have not to be considered due to an instrument failure of the mass spectrometer. Due to this they were not furthermore analyzed but for the sake of completeness they are shown

Deuterium:

The range of ™ Deuterium in the measurement period was between– 29.6 ‰ and – 46.4 ‰.

The concentration of Deuterium is decreasing significantly to 44.6 ‰ while the first flood was flowing afterwards the ^{2}H content is increasing again up to -34 ‰ and after the second flood slightly decreasing to – 37.1 ‰ and furthermore fluctuating between – 33.5 and – 46.4 ‰.

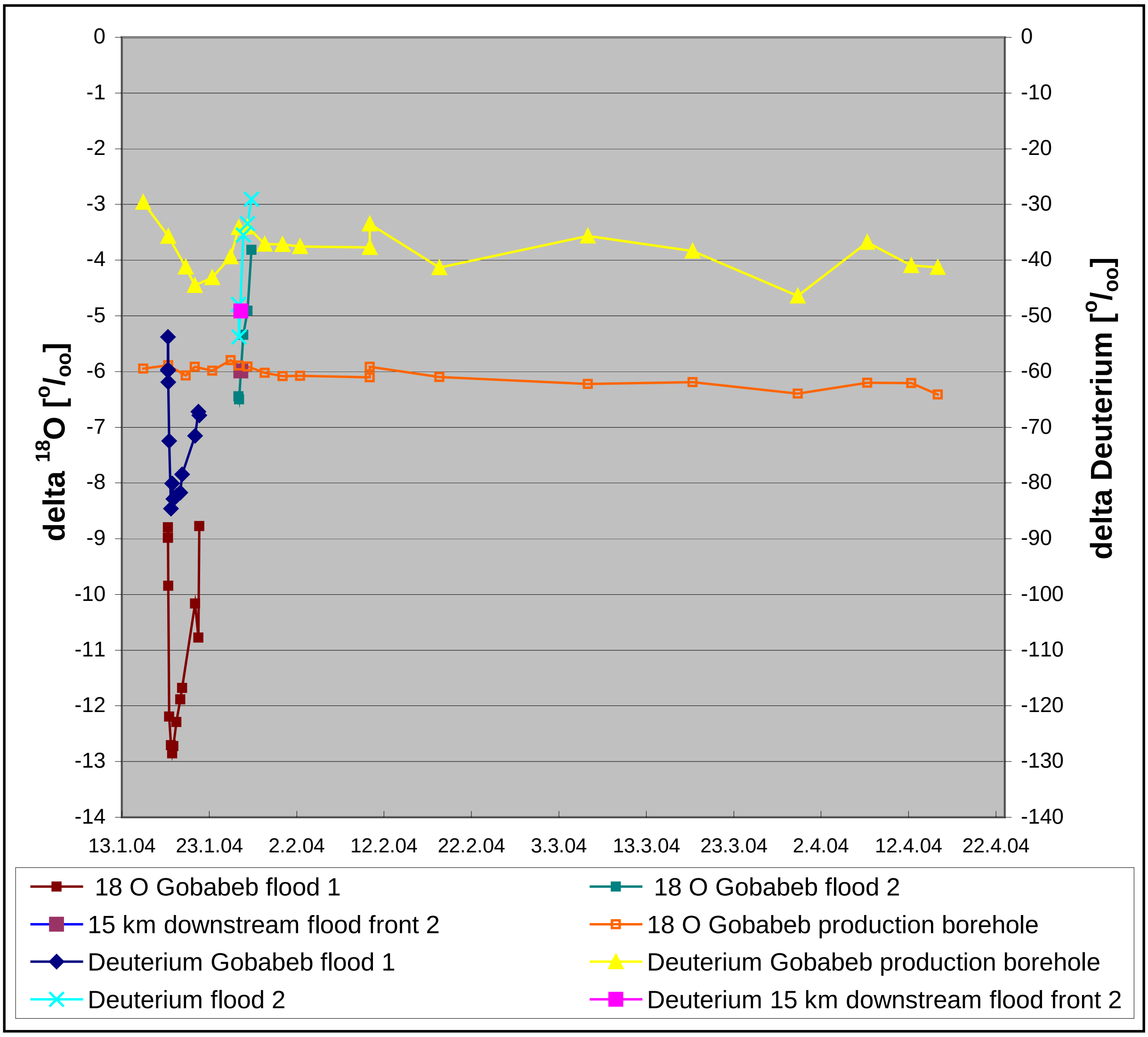


Figure 42: Distribution of Deuterium and Oxygen 18 during flood one and flood two in flood water and in groundwater of Gobabeb production borehole while the whole measurement period

Homeb

Figure 43 shows the distribution of Deuterium and Oxygen 18 over the whole measurement period.

^{18}O:

The range of ™ ^{18}O in the measurement period was between – 5.0 ‰ and – 5.4 ‰. The measurements are not showing a significant change in concentration, the slight increasing which is visible, is within the error range.

Deuterium:

The range of ™ Deuterium in the measurement period was between– 26.5 ‰ and – 33.8 ‰ .

The concentration of Deuterium is fluctuating in the range.

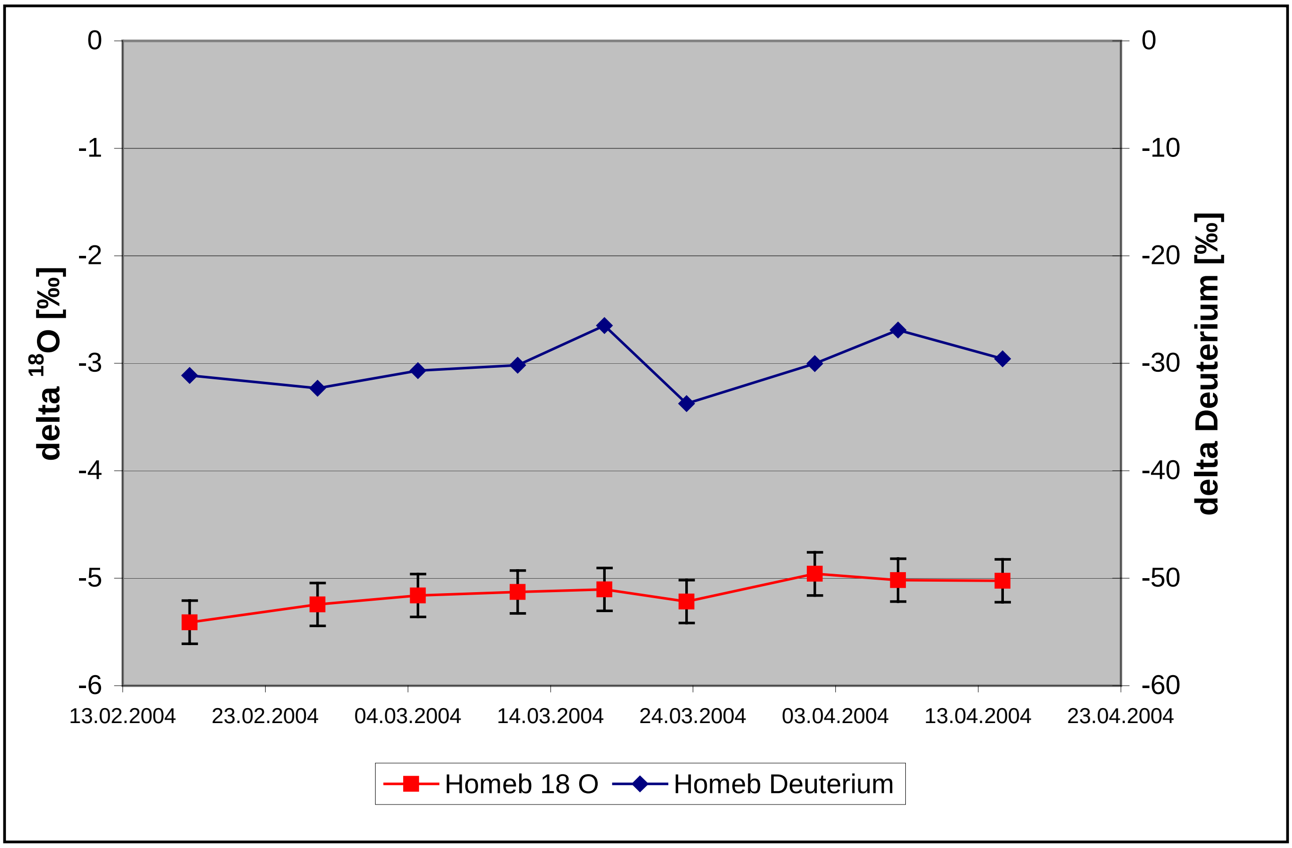


Figure 43: Distribution of Deuterium and Oxygen 18 over the whole measurement period in the groundwater at Homeb

Soetrevier

Figure 44 shows the distribution of Deuterium and Oxygen 18 in the groundwater at Soetrevier over the whole measurement period.

^{18}O:

The range of ™ ^{18}O in the measurement period was between – 6.7 ‰ and – 6.9 ‰. The measurements are not showing a significant change in concentration.

Deuterium:

The range of ™ Deuterium in the measurement period was between– 30.9 ‰ and – 51.7‰.

The concentration of Deuterium is fluctuating in this range.

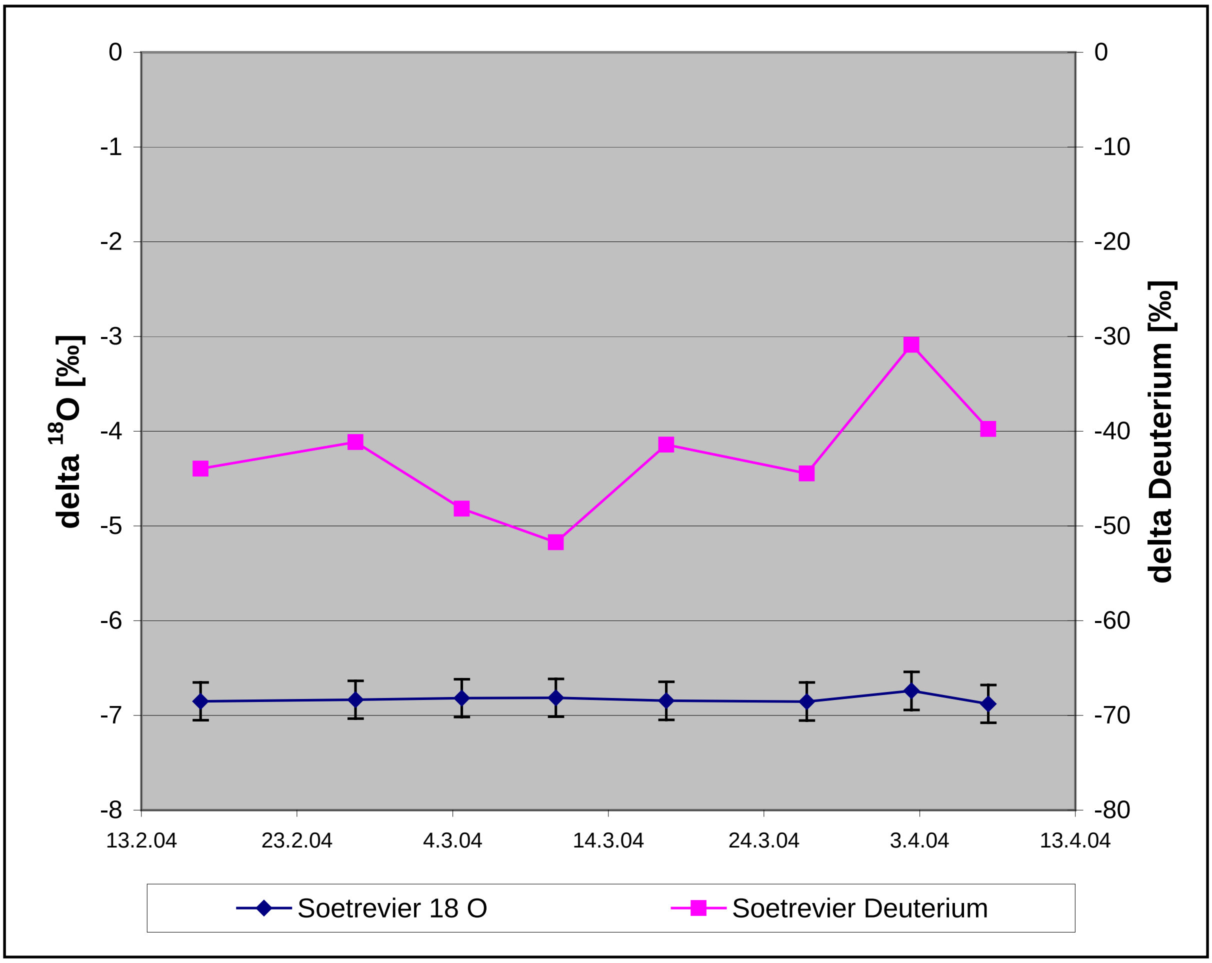


Figure 44: Distribution of Deuterium and Oxygen 18 over the whole measurement period in the groundwater at Soetrevier

Klipneus

Figure 45 shows the distribution of Deuterium and Oxygen 18 in the groundwater at Klipneus over the whole measurement period.

^{18}O:

The range of ™ ^{18}O in the measurement period was between – 7.3 ‰ and – 7.9 ‰. The measurements are showing a slight increasing tendency.

Deuterium:

The range of ™ Deuterium in the measurement period was between– 34.7 ‰ and – 54.5 ‰.

The concentration of Deuterium is showing an unstable trend.

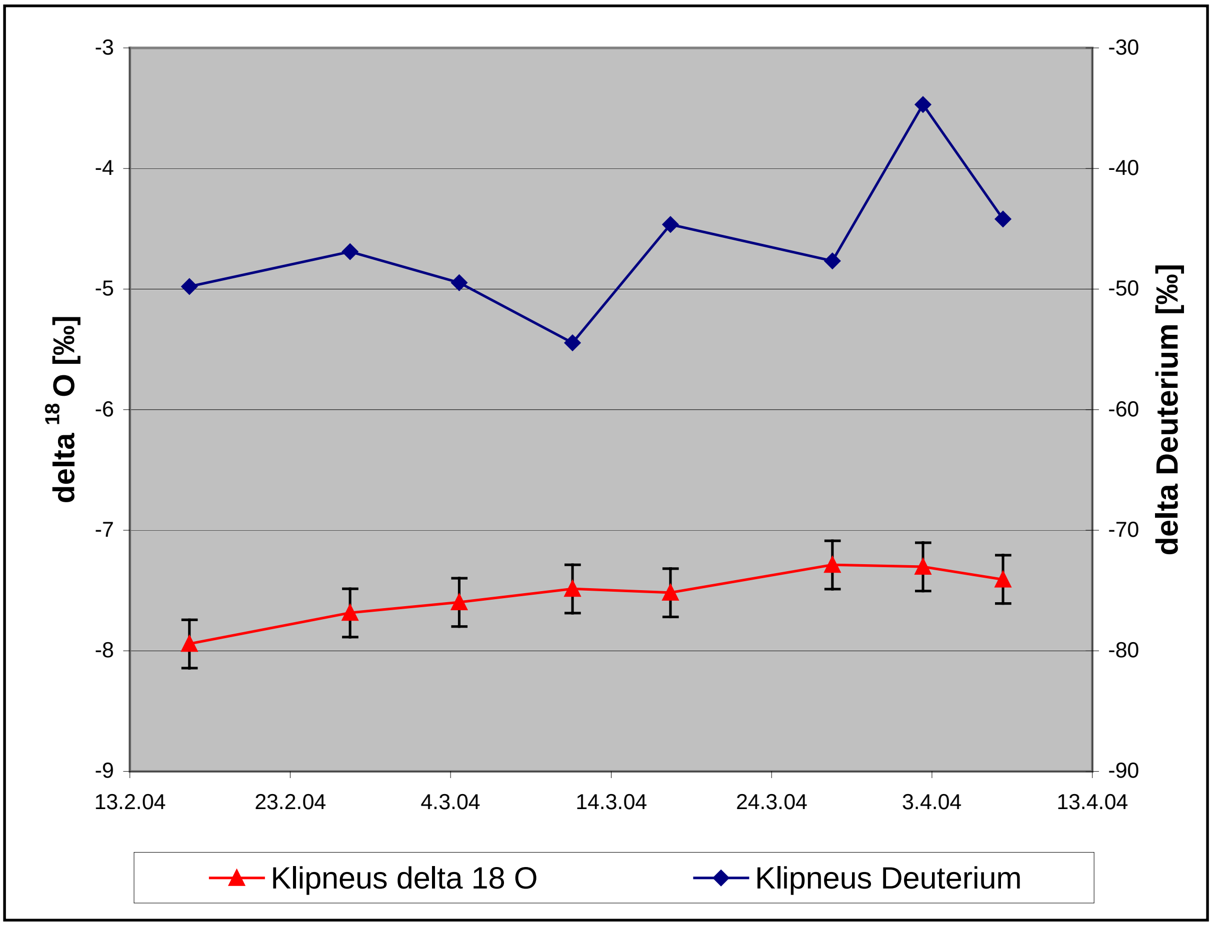


Figure 45: Distribution of Deuterium and Oxygen 18 over the whole measurement period in the groundwater at Klipneuss

Swartbank

Figure 46 shows the distribution of Deuterium and ^{18}O in the groundwater at Swartbank over the whole measurement period.

Swartbank hand pump

^{18}O:

The range of ™ ^{18}O in the measurement period was between – 6.7 ‰ and – 7.2 ‰.
A minimum in concentration is on the 26.02.2004 visible, but this minimum is just in the error range. Furthermore the measurements are not showing a significant concentration change.

Deuterium:

The range of ™ Deuterium in the measurement period was between– 55.9 ‰ and – 43.2 ‰.
The concentration of Deuterium is fluctuating in this range over the time.

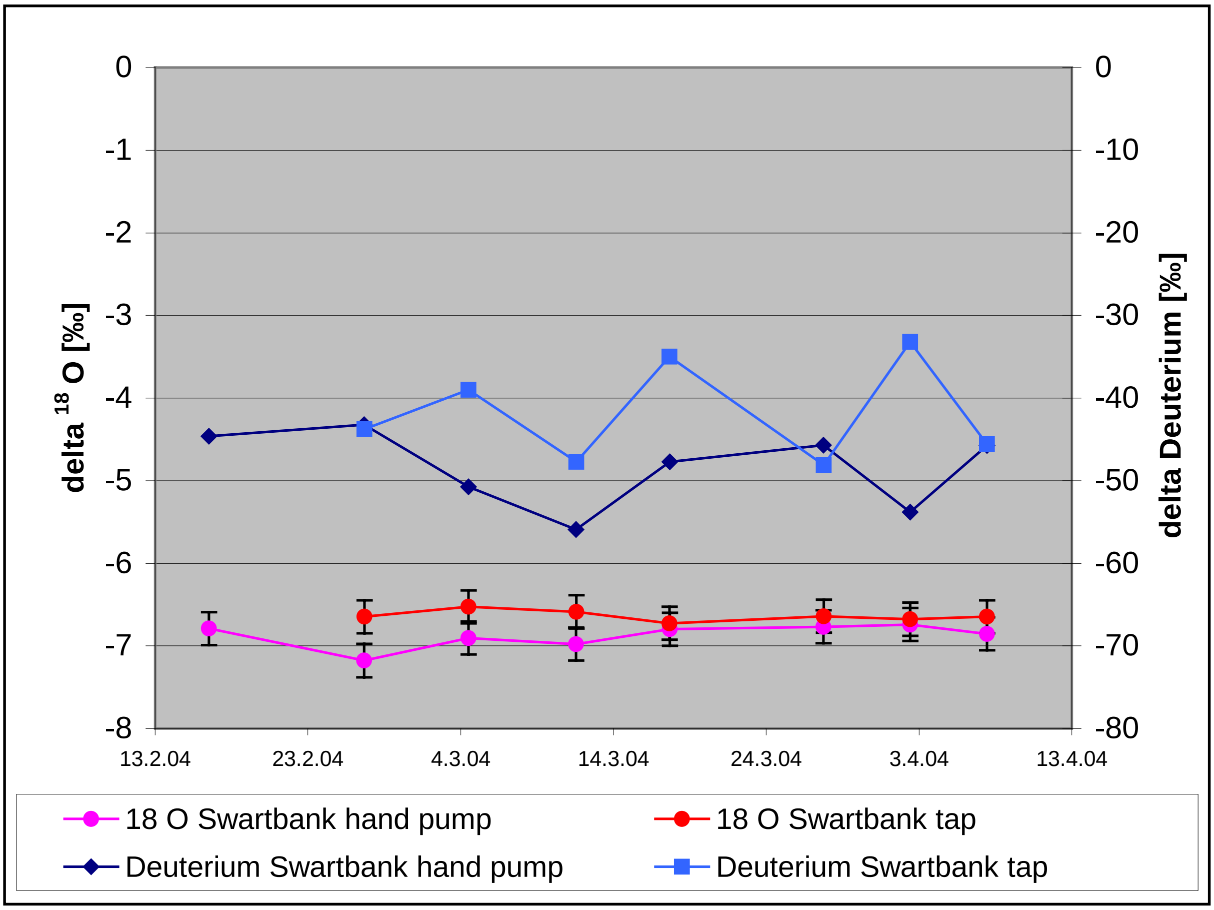


Figure 46: Distribution of Deuterium and Oxygen 18 over the whole measurement period in the groundwater at Swartbank

Swartbank tap

^{18}O:
The range of ™ ^{18}O in the measurement period was between – 6.7 ‰ and – 6.5 ‰.
The measurements are not showing a significant change in concentration.

Deuterium:
The range of ™ Deuterium in the measurement period was between– 33.2 ‰ and – 48.1 ‰.
The concentration of Deuterium is strong fluctuating in this range (see Figure 46, p. 66).

Discussion

From the 26.02.2004 to the end of the measurement period the Deuterium values were not considered and discussed due to an instrument failure of the mass spectrometer. But for the sake of completeness they are reported.
There was a significant difference in the concentration of stable isotopes in the groundwater compared to the range of concentration in the floodwater of flood one, while the water of flood two had a similar concentration. According to the results describing soil moisture dynamics and the reaction of the water table, flood one was significant higher contributing the groundwater.
Therefore it is assumed that a mixing of groundwater with floodwater would be noticeable if happens.
The groundwater from *Gobabeb* production borehole showed a significant decrease of deuterium concentration during flood one, whereas the concentration of ^{18}O did not change.
Based on this observation, it is assumed that the decrease of Deuterium is not caused by a dilution with floodwater, but rather caused by another water layer.
The borehole is only filtered in the deeper part of the aquifer (SEIMONS 2004). With a rising groundwater table the water table in the borehole was rising too, with the more denser water from the deeper aquifer reaching the pump. It is assumed that this water has coincidentally the same concentration of ^{18}O but a different concentration of Deuterium.
The groundwater at the settlements *Homeb, Soetrevier, Klipneus,* and *Swartbank* was not showing a significant change in concentration of ^{18}O.
Due to the lack of groundwater samples from *Homeb, Soetrevier, Klipneus* and *Swartbank* prior the floods, for this places it is not known how the concentration of stable isotopes was before floods and hence can not be considered. Furthermore it is assumed that all boreholes are mainly filtered in the deeper aquifer. The groundwater might be influenced by floodwater but this could not be proved. A significant groundwater recharge could not be proved by data from stable isotopes.

Conclusion

There was a significant difference in the concentration of stable isotopes in the groundwater compared to the range of concentration in the floodwater of flood one, while the water of flood two had similar concentrations. According to the results of soil moisture dynamics and the response of the water table, flood one was contributing significantly higher to the groundwater. According to this it is assumed that a mixing of groundwater with floodwater would be visible.

The groundwater at the settlements *Homeb, Soetrevier, Klipneus*, and *Swartbank* were not showing a significant change in concentration of ^{18}O

The ^{18}O concentration of groundwater at *Gobabeb* did also not change, where as the deuterium concentration decreased significantly while flood one, but it is assumed that this decrease was not caused by mixing floodwater with groundwater.

A mixing of groundwater with floodwater could not be proved on the basis of stable isotope concentration.

5 Conclusion

The aim of the present study was to examine experimentally the soil moisture dynamics and the aquifer response to a flood in the alluvial fill of the *Kuiseb River* in Namibia. Based on the measurements and data analysis transmission losses and groundwater recharge were to be estimated.
This research study focuses on understanding the processes and rates of infiltration during flood events at a site specific scale.

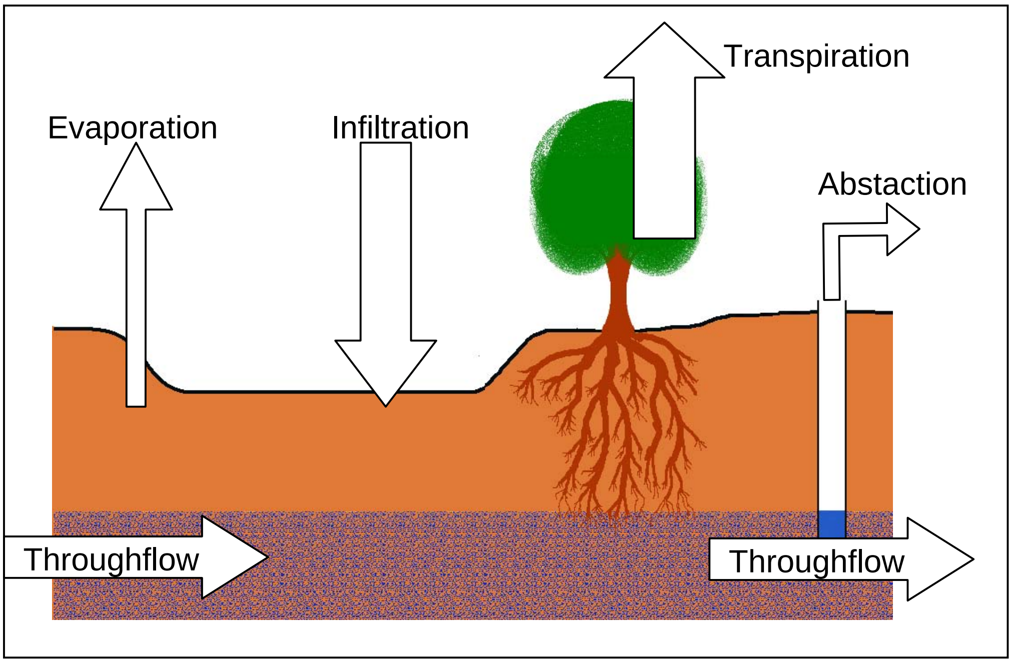


Figure 47: Water household scheme of Kuiseb alluvial aquifer

The stratigraphy shows a distinct spatial variability, sand stratified with layers of clay and or silt of different thickness and silt layer of different thickness on the surface of the active channel. The layers of silt and clay are possibly reducing the infiltration.
Two floods were observed:

- Flood one had a peak discharge of approximately 90 m^3/s and a flood duration of four day
- Flood two, occurring four days after the river stopped flowing, had an approximately peak discharge of 8m^3/s and a flood duration of 2 days.

The rate of advance of the wetting front was 0.3 m/h for flood one and 0.15 m/h for flood two.
The infiltration rates were 0.89 mm/min and 0.26 mm/h, respectively. The rates of infiltration as well as the advance of the wetting front are lower than the results of other arid research areas published by other authors. It is assumed that the smaller rates are mainly caused by a thick silt layer on the surface, which reduced the infiltration.

A lateral movement of the wetting front towards the dry overbank area could not be measured up to a depth of 130 cm and in a distance between 230 cm and 570 cm to the active channel.

The examination of soil moisture dynamics indicates transmission losses via infiltration of 2957 l/m^2 for flood one and 250 l/m^2 for flood two. However, these infiltration rates were only measured at a single point in the active channel and are not representative to the whole channel. It is assumed that due to the heterogeneous character of the stratigraphy the infiltration is possibly higher at places with less silt or clay layers. At places with more or thicker silt or clay layers lesser infiltration could be possible.

The aquifer responded with a rise of water table of 89 cm to flood one and with 8 cm to flood two.

A recharge of 95,630.5 m^3/km river length for flood one and of 8,596.0 m^3/km river length for flood two was calculated. These calculations are considered as a rough estimate due to the fact that the exact extent of the aquifer is not known. The significant smaller amount of infiltration during flood two and as a result the significant smaller amount of groundwater recharge can be explained as follows:

- The surface of the active channel was during flood two mostly sealed by the wet silt cover deposited by the flood one four days before.
- A scour of this clogging layers didn‘t take place due to the less erosive character of flood two.

It is further assumed that the deeper alluvium was still at field capacity when flood two occurred and most of the infiltrated water could percolate to the aquifer, resulting in recharge despite the sealed surface.

Also the fact that despite of significant different amounts of runoff, both floods were flowing approximately the same distances indicates that during flood two significant less transmission loss took place.

The water losses by evapotranspiration from the upper alluvium are restricted to the water content at field capacity (approximately 30 V%) after flood due to the fact that the groundwater level is at about 6 m below ground. These losses are compared with the estimated annually transpirational loss (by BATE & WALKER 1991) by all the vegetation with 2.02×10^5 m^3 per km river length. Using the rough recharge calculation (assuming the same aquifer width as BATE & WALKER 1991) it is indicated, that the groundwater recharge from the two floods is not sufficient to supply the vegetation for one year time.

With the analysis of the major ions a recharge could not be evidenced directly. A mixing of groundwater with floodwater could not be proved. Only the groundwater from the *Gobabeb* production borehole showed a significant change of hydrochemistry in a significant increase of ion concentration to flood one.

However, the groundwater recharge could not be quantified on the basis of ion concentration.
Similar, the analysis of the stable isotopes does not give evidence to mixing of groundwater with floodwater after flood events.
It has to be considered that water samples were not available from all bore holes prior to the floods. In addition most of the boreholes are screened in the deeper aquifer and therefore the water samples are not representative for the shallow alluvium aquifer.
Overall it seems that the main limiting factors for transmission losses are the existing silt layers on the surface of the active channel as well as the silt and clay layers within the stratigraphy.

Considering the results of this study, though measuring the water table reaction and soil moisture dynamics are the most appropriate of the applied methods for estimating transmission losses and groundwater recharge in short term studies in arid areas, the analysis of the processes of the alluvial fill of the *Kuiseb* need further investigations applying other methods i.e. a long term investigation about ion and isotope concentrations.

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ANNEX

ANNEX I: PROFILES

Profile No.: 1
Location: next to site four, active channel

Depth [cm]	Description	Specification
Cover	3 cm silt layer	Ut 2 lu u
0 - 95	medium sand stratified with fine sand	mS ss s
95 - 105	fine gravel	fine gravel
1o5 -135	medium sand	mS ss s

Profile No.: 2
Location: south site active channel

Depth [cm]	Description	Specification
Cover	0,5 - 1 cm clayey silt	Ut3 lu u
0 -140	medium sand stratified with fine sand	mS ss s

Profile No.: 3
Location: active channel 1m distance to river bank south site

Depth [cm]	Description	Specification
Cover	thin cover of clayey silt , thin enrolled borders with max: 0,5 cm thickness	Ut2 lu u
0 - 51	medium sand	mS ss s
51 - 70	sand - stratified with silt and pats of clay and fine pebbles	mixed layer
70 - 77	up to 5 x 10 X 7 cm pebbles surrounded by medium sized sand	pebbles
77 - 79	medium sand	mS ss s
79 - 110	silty sand	Su4 us s
110 - 120	medium sand	mS ss s
120 - 130	medium sand, stratified with very fine silty clayey layers	mix mS ss s , clay, silt
130 -150	medium sand	mS ss s

Profile No.: 4A
Location: Gobabebpipeline active channel (erosion line)

Depth [cm]	Description	Specification
Cover	thin clayey silt cover	Ut2 lu u
0 -13	silty sand	Su 4 us s
13 - 17	sandy silt containing organic material (roots, plant remains)	Us su u
17 - 24	sandy silt	Us su u
24 - 37	medium sand	mS ss s
37 - 48	clayey silt with very thin sandlayer in between	Ut3 lu u
48 - 52	fine sand	fS ss s
52 - 54	clayey silt	Ut3 lu u
54 - 67	fine sand	fS ss s
67 -75	sandy loam at the lateral extension sandy clay	Ls 2 ll l - Ts lt t
75 -175	medium sand	mS ss s

Profile No.: 4 B
Location: active channel, (erosion line riverbed)

Depth [cm]	Description	Specification
Cover	very thin clayey silt cover	Ut2 lu u
0 - 11	medium sand	mS ss s
11 - 27	sandy clay	Ts 2 lt t
27 - 150	medium sand	mS ss s

Profile Number 5
Location: active channel, next to rock 2.

Depth [cm]	Description	Specification
Cover	enrolled very thin clayey silt layer	Ut2 lu u - Ut3 lu u
0 - 150	medium sand	mS ss s

Profile Number 6
Location: active channel, south site, driving path to dunes

Depth [cm]	Description	Specification
Cover	0.5 cm silt layer (smooth)	Uu su u
0 -73	medium sand with pebbles up to 5 x 2 x 3cm	mS ss s
73 - 90	coarse sand	gS ss s
90 - 120	medium sand	mS ss s
120 -130	coarse sand containing fine gravel	gS ss s
130 - 150	medium sand	mS ss s

Profile Number 7
Location: active channel

Depth [cm]	Description	Specification
Cover	0.5 cm clayey silty cover	Ut2 lu u
0 - 9	medium sand	mS ss s
9 -10	silty sand	Su3 su u
10 - 80	medium sand	mS ss s
80 - 81	medium sand containing pats of clay	mix
81 - 150	medium sand	mS ss s

Profile No.: 8
Location: ~1,5 km downstream pipeline
active channel

Depth [cm]	Description	Specification
Cover	very thin silt cover	Uu su u
0 - 34	medium sand	mS ss s
34 - 40	silty clay containing roots and stratified with fine sand layers	Tu 2 lt t
40 - 60	medium sand	mS ss s
60 - 83	sandy silt	Su 4 us s -Us su u
83 - 150	medium sand	mS ss s
150 -163	medium sand containing pats of clay	mS ss s
163 -180	medium sand	mS ss s

Profile No.: 9
Location: 200m upstream of second rock directly at northern riversite (research station site)
active channel

Depth [cm]	Description	Specification
Cover	1 -2 cm clayey silt cover	Ut 2 lu u
0 - 20	silt	Uu su u
20 - 40	medium sand	mS ss s
40 - 50	coarse sand	gS ss s
50 - 67	medium sand	mS ss s
67 - 72	sandy loamy silt	Uls lu u
72 - 120	medium sand	mS ss s

Profile No.: 10
Location: Beginning of over bank

Depth [cm]	Description	Specification
Cover	very thin silt cover	Uu su u
0 - 4	fine sand	fS ss s
12 - 20	medium sand with a thin layer of coarse sand	mS ss s
20 - 31	silt stratified with fine layers of sand	Uu su u
31 - 70	medium sand - coarse sand	mS ss s
70 - 117	medium	mS ss s
117 - 123	clayey silt	Ut2 lu u

Profile No.: 11
Location: Middle of riverbed
active channel

Depth [cm]	Description	Specification
Cover	0.5 cm silt cover	Uu su u
0 - 38	fine sand	fS ss s
38 - 45	sandy loam	Ls 2 ll l
45 -120	medium sand	mS ss s
120 - 170	left site medium sand (orange colour), other site coarse sand with	mixed layer
	fine gravel with pebbles up to 3x5x4 cm and some pats of clay	

Profile No.: 12
Location: Entrance of driving path into riverbed upstream
active channel

Depth [cm]	Description	Specification
Cover	max. 0.5 cm clayey silt	Ut 2 lu u
0 - 15	fine sand	fS ss s
15 - 33	medium sand	mS ss s
33 - 60	clay silt and sand penetrated by little roots	mixed layer
33 - 39	Su 4 us s stratified with Slu	
39 - 49	Su 3 us s	
49 - 59	Us s su stratified with Ut2 lu u - Tu2	
59 - 100	medium sand	mS ss s

Profile No.: 13 a
Location: Erosion line near well

Depth [cm]	Description	Specification
Cover	max 0.5 cm silt layer	Uu su u
0 - 30	medium sand	mS ss s
30 - 38	silty sand	Su 2 ls s
38 - 100	medium sand	mS ss s

Profile No.: 13 b
Location: Erosion line near well — Direcly beneath 13 a

Depth [cm]	Description	Specification
Cover	max 0.5 cm silt layer	Uu su u
0 - 100	medium sand	mS ss s

Profile No.: 14
Location: middle active channel

Depth [cm]	Description	Specification
Cover	1 cm silty clay	Tu 2 lt t
0 - 20	medium sand	mS ss s
20 - 24	sandy clay	Ts 2 lt t
24 - 100	medium sand	mS ss s

Profile No.: 15
Location: active channel near rock 1

Depth [cm]	Description	Specification
Cover	0.5 - 1cm silty clay with "Glimmer"	Tu 3 ut t
0 - 10	fine sand containing organic material (plant remains)	fS ss s
10 - 20	silty sand containing organic material (plant remains)	Su 3 ls s
20 - 26	medium sand	mS ss s
26 - 30	coarse sand	gS ss s
30 - 100	medium sand	mS ss s

Profile No.: 16 A
Location: 2km downstream south site
active channel

Depth [cm]	Description	Specification
Cover	2cm silty clay with "Glimmer"	Tu 2 lt t
0 - 10	fine sand	fS ss s
10 - 120	medium sand	mS ss s

Name:
Profile No.: 16 B
Location: 2km downstream south site, middle of active channel

Depth [cm]	Description	Specification
Cover	1 cm clayey silt	Ut3 lu u
0 - 20	medium sand	mS ss s
20 - 37	medium sand, stratified with thin layers silty clay	mS ss s
37 - 44	medium sand	mS ss s
44 - 66	medium sand containing medium gravel	mS ss s
66 - 120	medium sand	mS ss s

Profile No.: 16 C
Location: 2km downstream north site , middle of active channel

Depth [cm]	Description	Specification
Cover	1 cm clayey silt cover	Ut3 lu u
0 - 43	medium sand	mS ss s
43 - 47	coarse sand	gS ss s
47 - 62	medium sand	mS ss s
62 - 76	coarse sand and fine gravel, some pebbles	mixed
76 - 80	medium sand	mS ss s
80 - 92	silt layer containing large nuggets of silty clay (Tu 3 ut t)	Uu su u
92 - 120	medium sand	mS ss s

Profile No.: 16 D
Location: 2km downstream north site , active channel

Depth [cm]	Description	Specification
Cover	0.5 cm clayey silt cover	Ut 3 lu u
0 - 10	fine sand	fS ss s
10 - 20	medium sand containing organic material (plant remains)	
20 - 50	medium sand	mS ss s
50 - 70	medium sand stratified with coarse gravel, containing small pebbles	
70 - 80	coarse gravel containing pebbles up to 10x7x4cm	
80 - 92	silty sand heavily penetrated by roots	Su2 sl s
92 - 96	coarse sand containing fine gravel	gS ss s
96 - 120	medium sand	mS ss s
120	boulder/ rockbasement	

Profile No.: 17
Location: Close to 16 er Profil 16 (south site, near dunes)
over bank

Depth [cm]	Description	Specification
0 - 5	medium sand	mS ss s
5 -16	silty sand containing some organic material	Su 3 us s
16 - 26	medium sand	mS ss s
26 - 31	silt	Us su u
31 - 40	medium sand	mS ss s
40 - 57	silt penetrated by roots	Uu su u
57 - 73	silty sand	Su 2 ls s
73 - 78	medium sand (red)	mS ss s
78 - 87	silty, loamy sand Slu sl l in layers	Slu sl l
	in between the layers fine sand	
87 - 130	medium sand	mS ss s

Profile No.: 18
Location: site 1 active channel Riverbed, 1m deep, after flood 90 cm

Depth [cm]	Description	Specification
Cover	~ 3cm clayey silt cover	Ut3 lu u
0 - 10	clayey silt plattig gelagert in between the plates very fine sand layers,	mainly Ut4 tu u
	and organic material	
10 - 27	silty sand	Su 2 ls s
27 - 50	medium sand	mS ss s
50 - 90	silty sand penetrated by roots with a diameter of up to 10 cm	Su 3 us s
	and small roots (thin roots)	
90 - 100	silty clay in layers, in between the plates very fine sand layers,	Tu 4 ut t

Profile No.: 19
Location: Anatee middle over bank

Depth [cm]	Description	Specification
Cover	fine sand and mulch	
0 - 20	silty sand	Su 3 us s
20 - 55	silty clay very hard , containing a few roots	Tu 4 ut t
55 - 80	clayey silt containing more roots	Ut 3 lu u
80 - 120	sandy silt densely bedded	Su 3 us s - Us su u
120 - 140	sandy silt containing dead roots	Su 2 ls s
100	root with a diameter of 6 cm	

Profile No.: 20
Location: Anatree direct over bank — 130 cm probe

Depth [cm]	Description	Specification
Cover	mulch and fine sand	
0 - 10	silty sand	Su 4 us s - Us su u
10 - 20	silty sand containing organic material (remats plants)	Su 4 us s
	Fraktion	
20 - 40	clayey silt compact layers, between this	Ut 2 lu u
	thin layers of fine sand	
40 - 60	clayey silt containing fine roots	Ut3 lu u
60 - 70	silty sand containing fine roots	Su 4 us s
70 - 90	silty sand containing fine roots	Su 4 us s
90 - 120	silty sand	Su 4 us s
120 - 130	silty sand containing a root of 10 cm diameter	Su 2 ls s

Profile No.: 21
Location: Rock site, where starter probe was positioned

Depth [cm]	Description	Specification
"cover"	clogging mixture from clay silt sand and organic matter	
	(plant remains, roots)	mixed layer
35 - 50	same mixture as above but a bit more medium sized sand	mixed layer
50 - 100	medium sand	mS ss s

Profile No.: 22
Location: active channel, pure evaporation area with tree, 1m

Depth [cm]	Description	Specification
Cover	1 cm silty clay cover	Tu 2 lt t
0 - 10	silty sand	Su 4 us s
10 - 24	silty sand	Su 2 ls s
24 - 40	clayey silt	Ut 3 lu u
40 - 46	sandy silt containing organic matter (plant remains)	Us su u
46 - 56	silty sand with a high content of organic matter (plant remains)	Su4 us s
56 - 100	medium sand	mS ss s
100 - 110	pebbles inserted in fine gravel to coarse sand	
110 - 120	medium sand	mS ss s

Profile No.: 23
Location: active channel pure evaporation area without vegetation, 1m

Depth [cm]	Description	Specification
Cover	max 0.5 cm clayey cover	Ut3 lu u
0 - 40	medium sand	mS ss s
40 - 60	fine sand	fS ss s - su2 ls s
60 - 100	medium sand	mS ss s
100 - 110	medium sand with pebbles	mS ss s
110 - 120	medium sand	mS ss s

Name: site 4, 1m
Profile No.: 24
Location: active channel

Depth [cm]	Description	Specification
Cover	alluvial sand cover	
0 - 5	clogging silt clay and organic matter	
5 - 15	silty sand	Su 2 ls s
15 - 36	medium sand	
36 - 40	medium sand containing organic matter (remains plants roots)	mS ss s
40 - 58	medium sand containing medium gravel	mS ss s
58 - 120	fine sand	fS ss s
70	3 cm thick root without fine roots	
87	1 cm thick root without fine roots	

Profile No.: 25
Location: active channel site 4, 2m

Depth [cm]	Description	Specification
Cover	thin silt layer	
0 - 60	fine sand	fS ss s
60 - 70	fine sand more "Glimmer"	fS ss s
70 - 80 upstream rechts	fine sand with very high content ~ 30% Glimmer	fS ss s
70 - 80 upstream links	silty sand	Su 4 us s
80 - 90	coarse sand containing small pebbles (3x3x4mm)	gS ss s
90 - 97	silty sand	Su 3 us s - Su 2 ls s
97 - 117	fine Sand	fS ss s
117 - 170	fine Sand more "Gimmer"	fS ss s
170 - 210	silty sand well penetrated by small roots	Su 4 us s

Profile No.: 26
Location: Niedersachsen active channel

Depth [cm]	Description	Specification
0 - 70	medium sand	mS ss s
70 - 80	coarse sand and fine gravel	gS ss s

Profile No.: 27
Location: Gobabeb/ Soetrevier active channel

Depth [cm]	Description	Specification
Cover	thin silt cover	
0 - 100	medium sand	mS ss s

Profile No.: 28
Location: Gobabeb downstream active channel

Depth [cm]	Description	Specification
Cover	0.5 cm silt cover	Ut 3 lu u
0 - 75	medium sand	mS ss s

Profile No.: 29
Location: over bank

Depth [cm]	Description	Specification
0 - 120	medium sand	mS ss s

Profile No.: 30

Location: over bank

Depth [cm]	Description	Specification
Cover	mulch	
0 - 100	medium sand	mS ss s

ANNEX II: DILUTION

Sample site	Dilution Anions	Dilution Cations
Flood water	no dilution	no dilution
Deelie farm	10:100	10:100
Van der Merve	10:100	10:100
Homeb	5:100	5:10
Gobabeb production bore hole	5:100	5:10
Gobabeb abandoned bore hole	1:100	1:100
Soetrevier	10:100	5:10
Saltwater springs	1:1000	1:1000
Klipneus	5:100	5:10
Swartbank hand pump	5:100	5:20
Swartbank new borehole	5:100	5:20
Brunnen No 11, NAMWATER	no dilution	10:100
Brunnen No 2, NAMWATER	no dilution	5:100
Brunnen No 3B, NAMWATER	no dilution	5:20
Brunnen No 6, NAMWATER	no dilution	10:100
NAM DNA 1	no dilution	5:10
NAM BG 20165	no dilution	no dilution
NAM BG 20152	no dilution	no dilution
NAM BG 21606	no dilution	no dilution
NAM BG 20196	no dilution	no dilution
NAM BG 20200	no dilution	no dilution
NAM BG 21527	no dilution	no dilution
NAM BG 20143	no dilution	no dilution
NAM BG 20146	no dilution	no dilution
NAM BG 20147	no dilution	no dilution
NAM BG 20171	no dilution	no dilution

ANNEX III: ANALYSIS OF MAJOR IONS

Date / Time	Location	ANIONS Cl [mg/l]	ANIONS NO3 [mg/l]	ANIONS SO4 [mg/l]	CATIONS Na [mg/l]	CATIONS Ka [mg/l]	CATIONS Mg [mg/l]	CATIONS Ca [mg/l]
19.01.2004 16:35	Kuiseb Us Pass flood	7,4	8,0	3,8	5,9	5,1	2,4	9,4
02.03.2004 14:42	Us Pass Kuiseb flood left over	55,3	0,2	15,3	42,1	9,1	8,9	37,7
06.04.2004 14:00	Kuiseb Us Pass flood front	41,5	0,9	11,9	31,7	7,9	6,2	25,7
02.04.2004 15:08	Kuisebbridge after Gamsbergpass flood	38,3	9,2	52,5	40,0	12,6	8,3	49,0
13.01.2004 16:05	Niedersachsen flood	5,4	1,8	8,2	6,3	6,3	4,6	39,9
18.01.2004 06:31	Gobabeb flood 1	64,2	2,9	16,7	48,9	20,9	17,3	108,8
18.01.2004 06:31	Gobabeb flood front 1	64,5	0,2	1,8	52,7	32,2	27,8	152,2
18.01.2004 06:36	Gobabeb flood 1	66,1	1,2	16,3	49,9	20,2	16,7	106,3
18.01.2004 07:52	Gobabeb flood 1	38,3	0,6	7,6	31,7	14,3	12,4	102,9
18.01.2004 10:05	Gobabeb flood 1	19,5	8,7	17,2	16,7	10,5	8,6	72,3
18.01.2004 14:37	Gobabeb flood 1	9,2	18,5	10,2	8,8	8,3	7,1	54,9
18.01.2004 18:20	Gobabeb flood 1	7,8	8,7	9,0	7,8	8,2	7,4	66,5
18.01.2004 21:57	Gobabeb flood 1	7,9	11,8	9,2	7,5	7,3	6,2	44,5
19.01.2004 06:17	Gobabeb flood 1	8,9	2,9	8,6	7,6	6,9	6,4	56,5
19.01.2004 16:44	Gobabeb flood 1	9,0	0,7	2,9	8,2	7,1	5,2	43,4
19.01.2004 22:00	Gobabeb flood 1	11,3	20,1	10,4	9,3	6,9	5,7	42,9
21.01.2004 09:00	Gobabeb flood 1	14,6	19,9	14,1	13,3	6,4	5,0	34,3
21.01.2004 18:00	Gobabeb flood 1	12,3	16,4	12,2	11,1	7,0	6,0	48,1
21.01.2004 20:30	Gobabeb flood 1	17,0	15,8	15,7	14,7	7,0	4,3	29,8
26.01.2004 15:08	15 km downstream floodfront 2.flood	50,4	0,0	2,1	40,5	21,1	16,6	110,1
26.01.2004 08:45	Gobabeb flood 2	43,6	1,0	21,6	36,1	10,0	9,4	74,4
26.01.2004 10:25	Gobabeb flood 2	44,7	4,2	36,7	38,4	9,8	8,9	70,7
26.01.2004 21:30	Gobabeb flood 2	18,8	15,3	14,5	18,6	8,1	5,7	37,5

Date / Time	Location	ANIONS				CATIONS			
		Cl [mg/l]	NO3 [mg/l]	SO4 [mg/l]		Na [mg/l]	Ka [mg/l]	Mg [mg/l]	Ca [mg/l]
27.01.2004 09:45	Gobabeb flood 2	15,4	20,2	11,3		14,4	6,9	4,7	30,3
27.01.2004 20:00	Gobabeb flood 2	16,5	16,5	12,5		15,4	7,4	4,0	26,1
15.01.2004 10:30	Gobabeb production borehole	599,0	22,6	316,4		420,9	34,9	70,2	182,7
18.01.2004 07:46	Gobabeb production borehole	608,8	22,4	318,4		380,4	29,3	65,0	171,1
20.01.2004 07:50	Gobabeb production borehole	859,8	21,2	424,2		553,3	37,9	88,0	230,5
21.01.2004 08:00	Gobabeb production borehole	911,0	22,6	440,6		562,9	40,7	91,9	247,5
23.01.2004 08:30	Gobabeb production borehole	919,0	23,6	444,8		576,6	38,9	90,9	243,0
25.01.2004 10:40	Gobabeb production borehole	833,2	23,2	413,4		532,0	37,5	84,6	224,4
26.01.2004 09:00	Gobabeb production borehole	820,4	23,0	404,4		525,7	35,9	84,1	222,0
27.01.2004 09:30	Gobabeb production borehole	816,8	23,0	406,8		524,8	36,9	83,5	222,7
29.01.2004 08:30	Gobabeb production borehole	827,8	19,8	408,6		528,5	35,2	83,6	225,1
31.01.2004 09:00	Gobabeb production borehole	816,4	21,8	409,4		530,4	36,2	82,7	223,2
02.02.2004 09:10	Gobabeb production borehole	806,4	21,8	401,8		520,7	35,6	81,9	222,0
10.02.2004 09:00	Gobabeb production borehole	786,4	22,6	399,0		511,2	37,4	80,8	220,6
10.02.2004 09:00	Gobabeb production borehole	770,6	20,2	395,2		500,4	35,2	79,5	221,1
18.02.2004 08:20	Gobabeb production borehole	760,4	18,6	398,6		498,6	36,0	80,2	221,7
06.03.2004 07:30	Gobabeb production borehole	737,0	17,8	422,4		494,7	35,8	79,5	231,9
18.03.2004 07:05	Gobabeb production borehole	686,4	16,6	414,0		460,6	33,9	77,5	227,3
30.03.2004 07:50	Gobabeb production borehole	659,4	16,4	423,0		452,0	35,9	77,9	236,9
07.04.2004 06:30	Gobabeb production borehole	669,6	15,8	408,6		422,8	34,8	78,7	246,4

Date / Time	Location	ANIONS				CATIONS			
		Cl [mg/l]	NO3 [mg/l]	SO4 [mg/l]		Na [mg/l]	Ka [mg/l]	Mg [mg/l]	Ca [mg/l]
12.04.2004 07:30	Gobabeb production borehole	698,8	17,6	419,0		471,7	35,9	78,1	232,2
15.04.2004 08:00	Gobabeb production borehole	634,2	15,8	426,0		436,9	34,3	76,8	240,7
23.03.2004 11:31	Gobabeb abandoned borehole	7249,2	26,0	1672,0		3146,0	142,0	314,0	504,0
23.03.2004 11:31	Gobabeb abandoned borehole	7350,2	26,6	1683,0		2987,0	136,0	294,0	456,0
17.02.2004 17:00	Homeb tap	175,8	4,0	105,0		129,7	16,2	28,1	122,1
26.02.2004 15:45	Homeb tap	170,2	0,0	100,4		127,5	16,2	28,0	119,4
04.03.2004 16:53	Homeb tap	169,6	0,0	99,2		126,8	16,1	28,0	120,8
11.03.2004 16:30	Homeb tap	177,4	0,0	98,4		128,4	16,5	28,6	122,8
17.03.2004 18:42	Homeb tap	167,8	0,0	97,0		127,4	16,5	28,6	123,2
23.03.2004 13:08	Homeb tap	171,6	0,0	99,2		126,4	16,3	28,8	123,2
01.04.2004 13:00	Homeb tap	167,2	0,0	97,2		125,1	16,2	28,4	121,6
07.04.2004 09:07	Homeb tap	165,0	0,0	97,0		125,2	16,2	28,5	120,5
14.04.2004 17:00	Homeb tap	161,8	0,0	96,6		125,2	16,1	27,8	120,1
16.02.2004 17:00	Klipneus tap	116,2	6,4	41,4		117,9	17,0	23,2	77,0
26.02.2004 17:17	Klipneus tap	120,0	6,4	46,0		115,6	16,4	25,1	82,1
04.03.2004 13:00	Klipneus tap	118,4	6,0	48,2		116,5	17,3	24,0	82,8
11.03.2004 14:30	Klipneus tap	116,6	6,0	47,2		114,2	16,7	23,8	79,8
17.03.2004 17:00	Klipneus tap	113,4	6,0	47,2		112,5	16,5	22,9	78,5
27.03.2004 19:00	Klipneus tap	123,8	6,6	49,2		112,2	17,0	25,4	86,3
02.04.2004 10:45	Klipneus tap	121,0	5,8	48,6		112,0	17,1	25,4	86,9
07.04.2004 10:13	Klipneus tap	122,6	7,4	49,4		112,3	16,8	25,9	84,4
16.02.2004 12:35	Swartbank hand pump	696,2	0,0	279,8		381,0	29,6	63,7	176,4
26.02.2004 16:30	Swartbank hand pump	215,8	0,0	133,8		184,8	22,5	23,4	150,6
04.03.2004 12:00	Swartbank hand pump	589,0	0,0	242,8		331,2	29,7	65,2	174,8
11.03.2004 13:23	Swartbank hand pump	667,8	4,0	265,0		356,7	30,1	75,4	193,6
17.03.2004 16:15	Swartbank hand pump	700,2	0,0	297,4		379,0	31,5	76,4	195,3
27.03.2004 18:00	Swartbank hand pump	699,6	0,0	291,2		417,2	31,2	68,5	174,6
02.04.2004 10:15	Swartbank hand pump	699,6	0,0	285,4		377,0	27,3	61,8	156,1
07.04.2004 10:42	Swartbank hand pump	669,2	0,0	277,0		408,0	30,7	67,5	167,3

Date / Time	Location	ANIONS			CATIONS			
		Cl [mg/l]	NO3 [mg/l]	SO4 [mg/l]	Na [mg/l]	Ka [mg/l]	Mg [mg/l]	Ca [mg/l]
26.02.2004 17:00	Swartbank tap	337,0	4,4	164,4	204,7	24,1	51,4	170,2
04.03.2004 12:20	Swartbank tap	376,2	4,8	178,4	204,4	23,7	51,8	174,6
11.03.2004 13:40	Swartbank tap	368,8	4,6	176,4	206,4	23,4	51,8	176,1
17.03.2004 16:00	Swartbank tap	369,0	4,8	176,8	208,7	27,0	48,0	178,3
27.03.2004 18:25	Swartbank tap	371,8	4,8	177,4	211,8	24,5	51,2	176,0
02.04.2004 10:00	Swartbank tap	372,0	4,0	177,4	212,6	25,2	50,2	175,2
07.04.2004 11:00	Swartbank tap	378,0	4,8	178,6	214,5	25,2	50,1	175,6
07.03.2004 16:30	Us Pass Deelie production borehole				243,0	8,6	13,4	71,8
09.03.2004 16:30	Us Pass Deelie production borehole	208,1	3,3	193,4	268,8	9,1	15,5	76,1
11.03.2004 12:00	Us Pass Deelie production borehole	199,6	3,1	184,3	260,9	8,6	14,4	72,8
15.03.2004 12:00	Us Pass Deelie production borehole	202,6	2,7	186,8	266,6	8,3	14,1	79,0
18.03.2004 12:00	Us Pass Deelie production borehole	200,6	2,0	185,6	267,2	8,6	13,1	72,5
25.03.2004 12:00	Us Pass Deelie production borehole	198,3	3,1	180,2	261,6	8,4	13,3	70,0
30.03.2004 12:00	Us Pass Deelie production borehole	192,8	2,8	174,6	258,3	8,6	13,0	68,3
06.04.2004 12:00	Us Pass Deelie production borehole	191,3	2,1	173,2	231,6	25,4	29,3	77,2
06.04.2004 14:00	Us Pass Deelie production borehole	184,6	2,6	169,8	227,0	24,2	28,9	76,6
09.04.2004 12:00	Us Pass Deelie production borehole	175,8	2,7	160,2	218,5	24,8	28,6	78,0
10.04.2004 12:00	Us Pass Deelie production borehole	173,1	2,9	159,2	215,3	23,8	28,4	77,3
14.04.2004 12:00	Us Pass Deelie production borehole	170,1	0,0	159,8	216,3	24,4	27,6	71,8
07.03.2004 16:00	Us Pass van der Merve (Tank)	309,2	11,0	284,0	294,8	27,0	46,6	113,0
18.03.2004 19:00	Saltsprings Saltrevier				18280	1020,0	890,0	1580,0
18.03.2004 19:00	Saltsprings Saltrevier				17560	1090,0	830,0	1560,0

Date / Time	Location	ANIONS			CATIONS			
		Cl [mg/l]	NO3 [mg/l]	SO4 [mg/l]	Na [mg/l]	Ka [mg/l]	Mg [mg/l]	Ca [mg/l]
16.02.2004 19:05	Soetrevier Tap	52,7	1,8	163,6	81,2	13,3	23,8	90,0
26.02.2004 18:00	Soetrevier Tap	53,8	1,8	187,5	81,9	13,9	27,2	103,0
04.03.2004 14:05	Soetrevier Tap	56,8	1,8	197,5	81,2	13,8	28,5	107,3
10.03.2004 15:00	Soetrevier Tap	60,8	1,9	203,6	83,1	14,1	29,9	109,1
17.03.2004 17:30	Soetrevier Tap	63,8	2,2	210,8	85,3	14,9	31,1	111,8
26.03.2004 18:00	Soetrevier Tap	70,2	0,0	220,4	87,9	15,1	33,6	116,4
02.04.2004 11:15	Soetrevier Tap	68,9	2,2	223,3	87,5	15,4	33,1	115,4
07.04.2004 09:50	Soetrevier Tap	71,7	2,4	228,0	87,1	15,0	33,9	115,9
10.03.2004 11:25	NAM BG 20171 M165	39,6	19,3	34,5	44,4	8,5	11,7	46,7
18.03.2004 14:00	Brunnen No 11, NAMWATER	502,1	15,2	105,0	167,1	19,1	34,4	91,9
18.03.2004 14:00	Brunnen No 2, NAMWATER	5065,1		4391,2	342,4	35,2	108,0	262,4
18.03.2004 14:00	Brunnen No 3B, NAMWATER	249,7	46,8	98,9	142,8	15,0	24,6	74,7
18.03.2004 14:00	Brunnen No 6, NAMWATER	997,3	19,1	147,6	182,9	20,3	48,7	119,3
18.04.2004 11:39	NAM DNA 1	123,3	30,0	166,0	112,6	15,9	29,0	86,2
18.04.2004 11:45	NAM BG 20165	94,9	19,2	62,8	77,6	12,6	18,9	56,9
18.04.2004 11:56	NAM BG 20152	70,1	16,5	53,7	74,4	12,0	15,4	57,1
18.04.2004 12:02	NAM BG 21606	49,8	16,4	48,5	55,6	11,7	15,1	57,4
18.04.2004 12:08	NAM BG 20196	55,1	18,2	53,2	55,7	11,9	14,3	62,1
18.04.2004 12:14	NAM BG 20200	47,2	20,7	43,8	54,8	10,8	14,0	56,2
18.04.2004 12:22	NAM BG 21527	43,0	24,8	34,0	54,3	9,7	14,2	52,7
18.04.2004 12:29	NAM BG 20143	47,9	20,1	44,9	51,6	9,5	13,0	50,9
18.04.2004 12:43	NAM BG 20146	57,0	18,1	41,3	46,0	10,0	11,8	52,8
18.04.2004 12:50	NAM BG 20147	310,2	14,3	91,0	129,4	15,2	24,5	90,7

ANNEX IV: ANALYSIS OF ^{18}O AND DEUTERIUM

Date/ Time	Location	δ 18 O [‰]	δ 2 H [‰]
13.01.2004 16:05	Niedersachsen flood	-8,37	-32,97
19.01.2004 16:35	Kuiseb Us Pass flood	-9,29	-55,64
02.03.2004 14:42	Us Pass Kuiseb flood left over	-3,2	-22,55
02.04.2004 15:08	Kuisebbridge after Gamsbergpass, flood	-4,34	-35,75
06.04.2004 14:00	Kuiseb Us Pass flood front	-3,91	-23,76
18.01.2004 06:31	Gobabeb flood front 1	-8,98	-59,62
18.01.2004 06:31	Gobabeb flood front 1	-8,98	-59,86
18.01.2004 06:36	Gobabeb flood 1	-8,79	-53,79
18.01.2004 07:52	Gobabeb flood 1	-9,84	-61,9
18.01.2004 10:05	Gobabeb flood 1	-12,19	-72,46
18.01.2004 14:37	Gobabeb flood 1	-12,71	-84,57
18.01.2004 18:20	Gobabeb flood 1	-12,86	-80,11
18.01.2004 21:57	Gobabeb flood 1	-12,73	-82,84
19.01.2004 06:17	Gobabeb flood 1	-12,29	-82,29
19.01.2004 16:44	Gobabeb flood 1	-11,88	-81,72
19.01.2004 22:00	Gobabeb flood 1	-11,68	-78,46
21.01.2004 09:00	Gobabeb flood 1	-10,16	-71,55
21.01.2004 18:00	Gobabeb flood 1	-10,78	-67,23
21.01.2004 20:30	Gobabeb flood 1	-8,77	-67,88
26.01.2004 15:08	15 km downstream floodfront 2.flood	-5,99	-49,14
26.01.2004 08:45	Gobabeb flood 2	-6,44	-47,93
26.01.2004 10:25	Gobabeb flood 2	-6,5	-53,79
26.01.2004 21:30	Gobabeb flood 2	-5,34	-35,51
27.01.2004 09:45	Gobabeb flood 2	-4,91	-33,43
27.01.2004 20:00	Gobabeb flood 2	-3,82	-29,08
15.01.2004 10:30	Gobabeb production borehole	-5,95	-29,59
18.01.2004 07:46	Gobabeb production borehole	-5,89	-35,73

Date/ Time	Location	δ 18 O [‰]	δ 2 H [‰]
20.01.2004 07:50	Gobabeb production borehole	-6,07	-41,23
21.01.2004 08:00	Gobabeb production borehole	-5,92	-44,56
23.01.2004 08:30	Gobabeb production borehole	-5,99	-43,12
25.01.2004 10:40	Gobabeb production borehole	-5,8	-39,39
26.01.2004 09:00	Gobabeb production borehole	-5,9	-34,15
27.01.2004 09:30	Gobabeb production borehole	-5,91	-34,04
29.01.2004 08:30	Gobabeb production borehole	-6,02	-37,1
31.01.2004 09:00	Gobabeb production borehole	-6,08	-37,2
02.02.2004 09:10	Gobabeb production borehole	-6,08	-37,54
10.02.2004 09:00	Gobabeb production borehole	-6,1	-37,72
10.02.2004 09:00	Gobabeb production borehole	-5,91	-33,48
18.02.2004 08:20	Gobabeb production borehole	-6,1	-41,32
06.03.2004 07:30	Gobabeb production borehole	-6,23	-35,64
18.03.2004 07:05	Gobabeb production borehole	-6,19	-38,35
30.03.2004 07:50	Gobabeb production borehole	-6,39	-46,41
07.04.2004 06:30	Gobabeb production borehole	-6,2	-36,8
12.04.2004 07:30	Gobabeb production borehole	-6,21	-40,97
15.04.2004 08:00	Gobabeb production borehole	-6,41	-41,28

23.03.2004 11:31	Gobabeb abandoned borehole	-6,03	-42,12
23.03.2004 11:31	Gobabeb abandoned borehole	-6,1	-42,24

07.03.2004 16:30	Us Pass Deelie production borehole	-5,91	-39,74
09.03.2004 16:30	Us Pass Deelie production borehole	-5,66	-45,48
11.03.2004 12:00	Us Pass Deelie production borehole	-5,56	-44,51
15.03.2004 12:00	Us Pass Deelie production borehole	-5,74	-41,47
18.03.2004 12:00	Us Pass Deelie production borehole	-5,68	-38,42
25.03.2004 12:00	Us Pass Deelie production borehole	-5,7	-39,72
30.03.2004 12:00	Us Pass Deelie production borehole	-5,7	-43,57
06.04.2004 14:00	Us Pass Deelie production borehole	-5,51	-36,2
06.04.2004 12:00	Us Pass Deelie production borehole	-5,62	-25,53
09.04.2004 12:00	Us Pass Deelie production borehole	-5,69	-31,59
10.04.2004 12:00	Us Pass Deelie production borehole	-5,32	-34,86
14.04.2004 12:00	Us Pass Deelie production borehole	-5,56	-36,01

07.03.2004 16:00	Us Pass van der Merve (tank)	-6,58	-38,43

17.02.2004 17:00	Homeb tap	-5,41	-31,12

Date/ Time	Location	δ 18 O [‰]	δ 2 H [‰]
26.02.2004 15:45	Homeb tap	-5,24	-32,31
04.03.2004 16:53	Homeb tap	-5,16	-30,69
11.03.2004 16:30	Homeb tap	-5,13	-30,17
17.03.2004 18:42	Homeb tap	-5,1	-26,5
23.03.2004 13:08	Homeb tap	-5,22	-33,75
01.04.2004 13:00	Homeb tap	-4,96	-30,04
07.04.2004 09:07	Homeb tap	-5,02	-26,92
14.04.2004 17:00	Homeb tap	-5,02	-29,59

16.02.2004 17:00	Klipneus tap	-7,94	-49,79
26.02.2004 17:17	Klipneus tap	-7,68	-46,89
04.03.2004 13:00	Klipneus tap	-7,6	-49,47
11.03.2004 14:30	Klipneus tap	-7,49	-54,46
17.03.2004 17:00	Klipneus tap	-7,52	-44,63
27.03.2004 19:00	Klipneus tap	-7,29	-47,67
02.04.2004 10:45	Klipneus tap	-7,3	-34,7
07.04.2004 10:13	Klipneus tap	-7,41	-44,2

10.03.2004 11:25	NAM BG 20171 M165	-7,07	-54,44
18.03.2004 14:00	borehole No 11, NAMWATER	-6,42	-41,13
18.03.2004 14:00	borehole No 3B, NAMWATER	-6,69	-47,54
18.03.2004 14:00	borehole No 6, NAMWATER	-6,58	-45,56
18.03.2004 14:00	borehole No 2, NAMWATER	-6,83	-50,8

18.04.2004 12:43	NAM BG 20146	-7,99	-50,75
18.04.2004 12:50	NAM BG 20147	-6,72	-42,78
18.04.2004 11:39	NAM DNA 1	-6,64	-40,64
18.04.2004 11:45	NAM BG 20165	-6,62	-40,18
18.04.2004 11:56	NAM BG 20152	-6,39	-31,43
18.04.2004 12:02	NAM BG 21606	-6,02	-33,32
18.04.2004 12:08	NAM BG 20196	-6,98	-41,76
18.04.2004 12:14	NAM BG 20200	-6,3	-34,16
18.04.2004 12:22	NAM BG 21527	-6,68	-34,22
18.04.2004 12:29	NAM BG 20143	-7,49	-50,02

16.02.2004 00:00	Soetrevier tap	-6,85	-43,95
26.02.2004 18:00	Soetrevier tap	-6,83	-41,15
04.03.2004 14:05	Soetrevier tap	-6,82	-48,18
10.03.2004 15:00	Soetrevier tap	-6,81	-51,71

Date/ Time	Location	δ 18 O [‰]	δ 2 H [‰]
17.03.2004 17:30	Soetrevier tap	-6,85	-41,41
26.03.2004 18:00	Soetrevier tap	-6,85	-44,47
02.04.2004 11:15	Soetrevier tap	-6,74	-30,89
07.04.2004 09:50	Soetrevier tap	-6,88	-39,77
16.02.2004 12:35	Swartbank hand pump	-6,79	-44,62
26.02.2004 16:30	Swartbank hand pump	-7,18	-43,23
04.03.2004 12:00	Swartbank hand pump	-6,91	-50,76
11.03.2004 13:23	Swartbank hand pump	-6,98	-55,9
17.03.2004 16:15	Swartbank hand pump	-6,8	-47,71
27.03.2004 18:00	Swartbank hand pump	-6,77	-45,71
02.04.2004 10:15	Swartbank hand pump	-6,74	-53,83
07.04.2004 10:42	Swartbank hand pump	-6,85	-45,74
26.02.2004 17:00	Swartbank tap	-6,65	-43,75
04.03.2004 12:20	Swartbank tap	-6,53	-38,98
11.03.2004 13:40	Swartbank tap	-6,59	-47,74
17.03.2004 16:00	Swartbank tap	-6,73	-34,99
27.03.2004 18:25	Swartbank tap	-6,64	-48,1
02.04.2004 10:00	Swartbank tap	-6,68	-33,21
07.04.2004 11:00	Swartbank tap	-6,65	-45,58
18.03.2004 19:00	Saltsprings Saltrevier	0,92	-19,19
18.03.2004 19:00	Saltsprings Saltrevier	1,21	-15,5

Ehrenwörtliche Erklärung:

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

Freiburg, 28.09.2004

Andrea Ursula Schmitz