Investigation of the Groundwater Resources in the Eiseb Graben in Namibia with TEM Soundings

Christopher Stadtler[1], Armin Margane[1], Friedrich Schildknecht[1], Uwe Schäffer[1] & Jens Wrabel[2]

Abstract: Within the framework of the Namibian-German Technical Cooperation, funded by the German Government, extensive geophysical and hydrogeological investigations were conducted from 2002 to 2005 in the Eiseb Graben in the Namibian Kalahari. The objective was to delineate the aquifer system and to assess its exploitation potential. The investigation comprised time-domain electromagnetic (TEM) soundings, tectonic interpretations of satellite images as well as a drilling program with borehole geophysics and water sampling, followed by a water analysis. A total of 77 TEM soundings were carried out in two field campaigns. The soundings were highly successful to delineate the before unknown extent of the Eiseb Graben, and the resistivity distribution accurately displays its internal structure. A promising area for groundwater exploitation was located at the northern graben flank, possibly bound to a paleo-channel filled with relatively coarse sediments. Based on the TEM results, locations for 7 exploration boreholes were recommended and drilled with a maximum drilling depth of 378 m. The main aims of the drilling program were to establish an interpretation basis for the TEM soundings and to delineate the alluvial aquifer system within the graben. The results reveal that at the northern edge of the graben the alluvial Kalahari filling reaches more than 378 m thickness and contains sections of high permeability. The yield of one of the boreholes was determined to reach 120 m³/h, which exceeds by far formerly achieved yields in this area of max. 3 m³/h. Since the knowledge about the extent of the Eiseb Graben aquifer system is still rather limited, the exploitation potential can presently not be assessed precisely.

1. Introduction

The project 'Investigation of Groundwater Resources and Airborne-Geophysical Investigation of Selected Mineral Targets in Namibia', a cooperation between the Namibian Department of Water Affairs (DWA) and the Federal Institute for Geosciences and Natural Resources (BGR), started in October 2002 and ended in March 2005. The program was based on the findings of two desks studies carried out several years before (BIWAC, 1999; FIELITZ, 1999). Three exploration areas in Eastern Caprivi, in the Oshivelo area and in the eastern part of the Namibian Kalahari in Omaheke were defined for detailed studies on the available groundwater resources. Concerning the Omaheke region, the project chose the Eiseb Graben, a tectonic graben at the border with Botswana (Fig. 1), as investigation target.

Due to the lack of infrastructure and the low availability of water resources, the Omaheke region, a traditional settling area for the Hereros, is only sparsely populated. The total population presently is about 80,000 (AFRICON, 2002), but for the survey area a total number of less then 3,000 people were counted. The development of the local groundwater resources is difficult because of unfavourable geological conditions. The success rate of boreholes drilled in the area was therefore less than 10 % and a lot of money had been wasted for the drilling of dry boreholes in areas known for its generally low exploitation potential. Long-term averages of rainfall and potential evaporation are around 400 mm/a and 3,000 mm/a, respectively. Therefore generally limited possibilities for groundwater recharge may exist.

[1] Federal Institute for Geosciences and Natural Resources (BGR), P.O. Box 510153, 30631 Hannover, Germany, e-mail: c.stadtler@bgr.de
[2] Department of Water Affairs (DWA), Private Bag 13193, Government Office Compound, Windhoek, Namibia

The Omaheke target area was integrated into the DWA-BGR project on an initiative of the former German President Roman Herzog. Accepting the German responsibility for the eviction of the Hereros from their traditional tribal land in the course of the Herero War, Herzog promised Germany's help in a resettlement project planned by the Ministry of Lands Resettlement and Rehabilitation in 1993. It was planned to develop 862,000 ha of grazing land in a region north of the Eiseb Graben with the purpose to resettle about 4,000 Hereros and Mbanderus that were to be repatriated from Botswana. The estimated water supply requirement would be about 900,000 m³/a. The plan, however, had to be given up due to the lack of available groundwater resources.

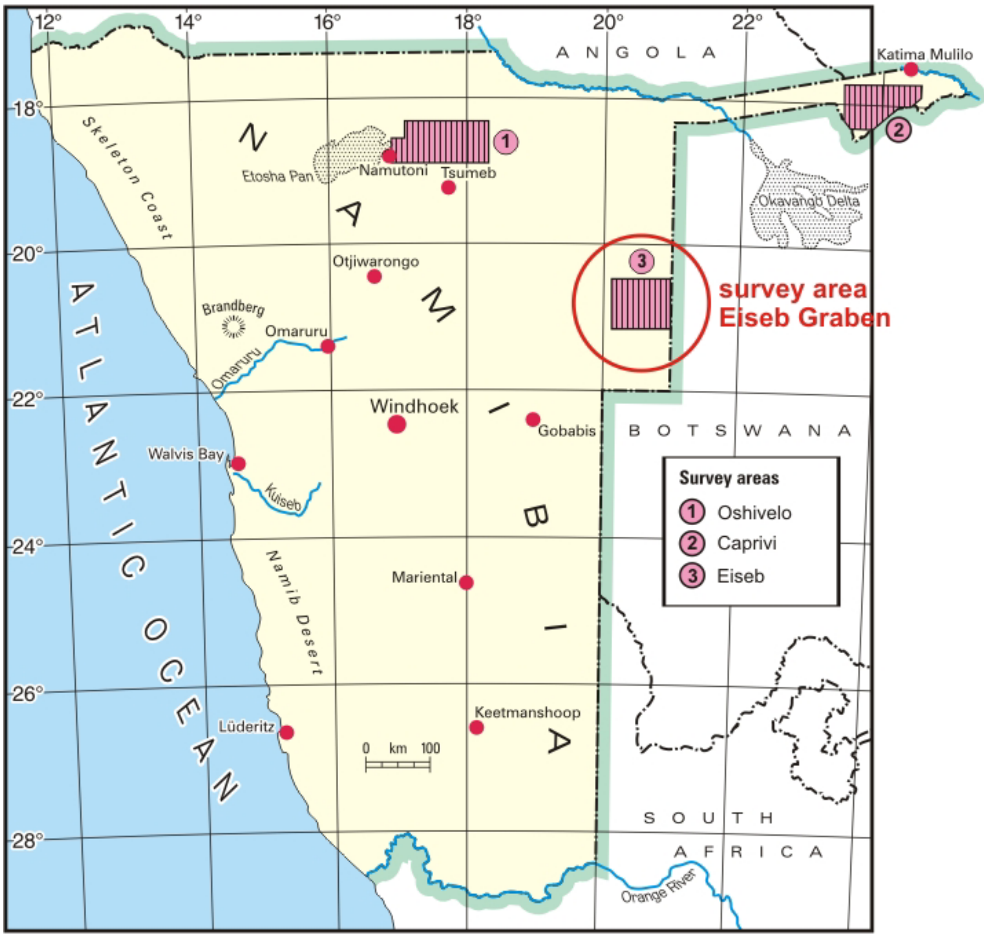

Figure 1: DWA-BGR survey areas in Namibia

The resettlement project area was then shifted towards the Eiseb Graben area where an extensive primary aquifer was assumed according to earlier studies. The evaluation of drilling reports and geoelectrical soundings carried out at the Eiseb lineament indicated a graben structure in this area. Exploration boreholes drilled to depths between 160 and 200 m yielded between 1 and 3 m³/h. The groundwater reserves in the area assumed on this experience were not considered sufficient for the requirement of the repatriation project, and the resettlement plan was abandoned. Nevertheless, it developed a steady flow of Hereros resettling from Botswana to their former grazing area in the Kalahari of Namibia and after the conclusion of the repatriation programme, a total of about 3,000 people with an estimated 12,000 head of cattle were registered as new Namibian citizens.

For the supply of the growing population, the aim of the DWA-BGR project in the Eiseb Graben was to verify groundwater reserves with a yield of 300,000 m³/a and to improve the success rate of drilling activities.

The Eiseb Graben was exclusively selected as survey area because it was considered a promising target. While in most parts of the region around the Eiseb Graben the sedimentary cover is relatively thin and the groundwater table is encountered within the bedrock formations, it was expected from earlier activities that in the Eiseb Graben a deep freshwater aquifer might exist within Kalahari or Karoo sedimentary layers. Since freshwater in bedrock formations is constrained to fractures and voids, a detection of favourable drill sites by geophysical methods is notoriously difficult, particularly if the water table is encountered at greater depths (approx. 150 m below surface). A successful geophysical groundwater survey was considered to be by far more promising in the porous aquifer conditions within the Eiseb Graben than in the bedrock formations outside. Furthermore the Graben was believed to drain the surrounding areas, leading to a regional groundwater flow towards east into the swamps of the Okawango Delta in Botswana. Hence, it was planned to delineate the alluvial aquifer system in the Graben by analyzing the resistivity distribution of its sedimentary fill.

In the survey area, the terrain gently descends from about 1,300 m in the west to about 1,000 m in the east. The satellite image (Fig. 4) clearly reveals the presence of W-E stretching longitudinal dunes. Geologically, the area is dominated by Kalahari sediments. KLOCK (2001) differentiates the Tsumkwe, Eiseb, Otjinene and Aeolian units (from bottom to top). Alluvial breccias of the Tsumkwe Formation form the base of the Kalahari. They are overlain by the Eiseb Fm., which is made up of massive or laminated limestones, pebbly sandstones and silcretes. Both formations are only partly consolidated.

The project started in October 2002 with geophysical measurements in order to facilitate the establishment of geological and hydrogeological concept models for the investigation areas. Time-domain electromagnetic measurements (TEM) were conducted along profiles perpendicular to the graben axis (Fig. 2). In a first phase, TEM measurements along four profiles with 54 soundings were conducted in 2003 (FIELITZ et al., 2004). They were extended by another 23 TEM soundings along three profiles in a second phase in early 2005 (SCHILDKNECHT et al. 2005). The intention of this second campaign was to verify the existence of the detected freshwater aquifer, to delimit its extent and to improve the horizontal resistivity resolution by additional soundings in area of special interest.

2. TEM soundings

The TEM measurements were carried out by Poseidon Geophysics Limited, Botswana. All soundings were completed using Zonge GDP-32 equipment, manufactured by Zonge Engineering and Research Organization, Tucson, USA. The system uses an air cored TEM/3 sensor with an effective coil area of 10,000 m². For the current supply a Zonge GGT10 was available, producing a ramped square wave from DC to 8 kHZ.

The transmitter loop size for all soundings was 200 m x 200 m, with a single turn wire of 10 ga. Soundings were recorded with the receiver coil axle oriented vertically and located in the centre of the transmitter loop. Three base frequencies of 1 Hz, 4 Hz and 16 Hz were used for each station. Single readings were averaged (stacked) with 64, 256 and 512 cycles for 1, 4, and 16 Hz respectively. Transmitter currents of 20 A for the 1 Hz frequency base, 15 A for the 4 Hz and 5 A for the 16 Hz base frequency were used.

Because of the large transmitter loop size of 200 m x 200 m, the resistivity distribution at shallow depths is rather uncertain. Additional soundings with smaller transmitter loop sizes to resolve shallow layers were rejected in favour of a denser sounding grid with 200 m x 200 m transmitters, in view of the limited budget and because of the great depth of the groundwater table.

Delay time corrections and averaging of readings from repeated soundings were done by the standard Zonge software SHRED and TEMAVG. TEMAVG was additionally used to provide quick look plots for data quality control in the field. Interpretation of the soundings was accomplished with the software TEMIX from Interpex, USA, which executes a 1-dimensional inversion (ridge regression).

Figure 2 shows the locations of the TEM soundings. The sites and numbers of the phase I measurement campaign are marked in black; the soundings of phase II in red. Some of the new soundings fill gaps in the phase I profiles 2 and 4. Additional short profiles (5, 6 and 7) were placed near the northern graben flank.

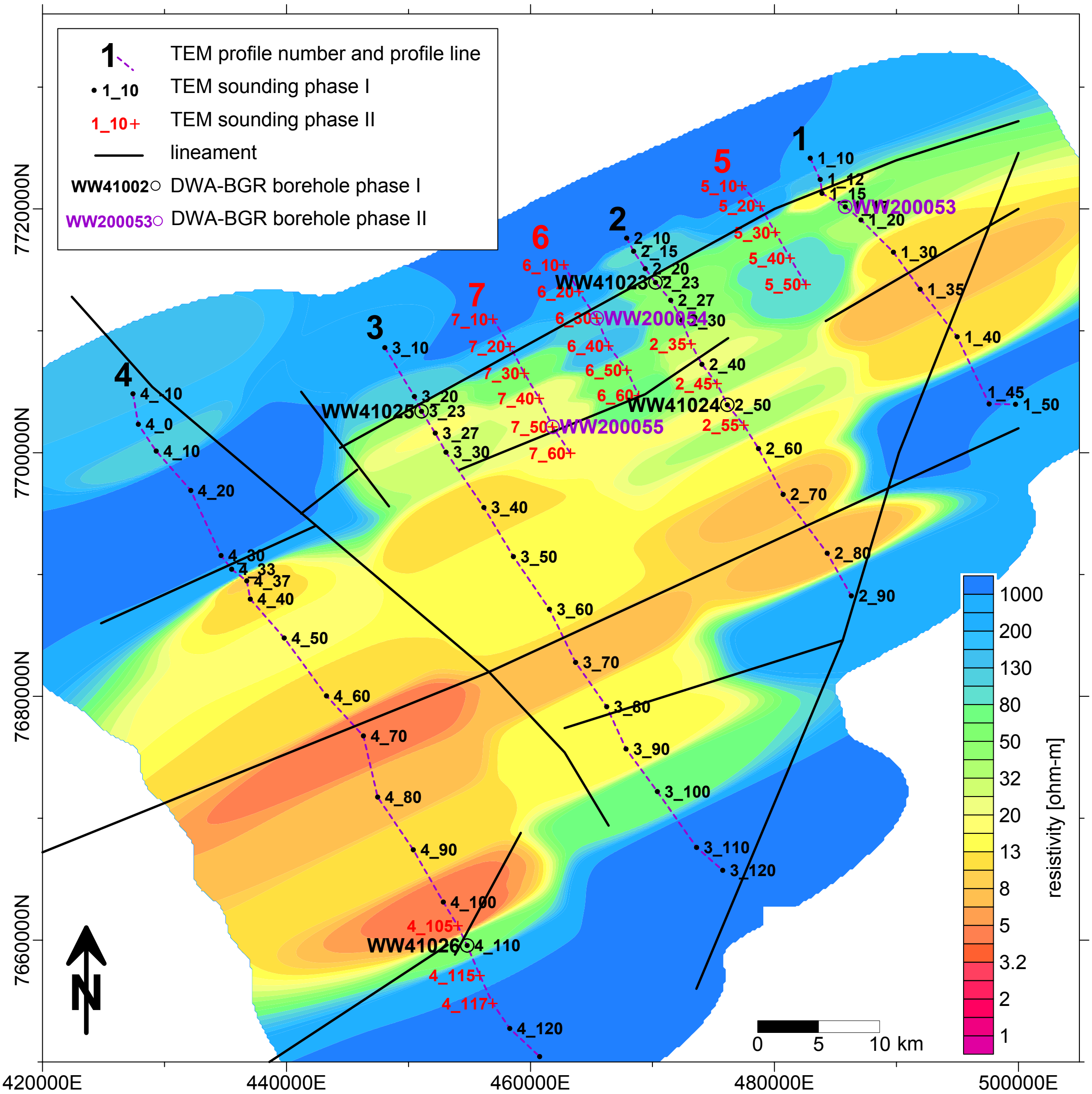

Figure 2: Distribution of averaged resistivities between 150 and 200 m depth in the Eiseb Graben area based on TEM soundings, together with TEM sounding positions, groundwater exploration wells and lineaments

In the TEM soundings in the Eiseb Graben area, two archetypes of TEM apparent resistivity curves prevail. Curve type 1 is a bowl shaped form, typical for soundings on the graben shoulder (Fig. 3a). The very curve presents the northernmost sounding of profile 2. The curves of type 1 are characterized by high resistivities (250 Ωm and more) in depths which are caused by consolidated rocks and the basement rocks of the graben shoulder. Generally, late time readings of the transient of type 1 soundings on the graben shoulder are disturbed by noise caused by weak signals from the low induction inside the high resistive basement. Noisy data points were deleted during data processing.

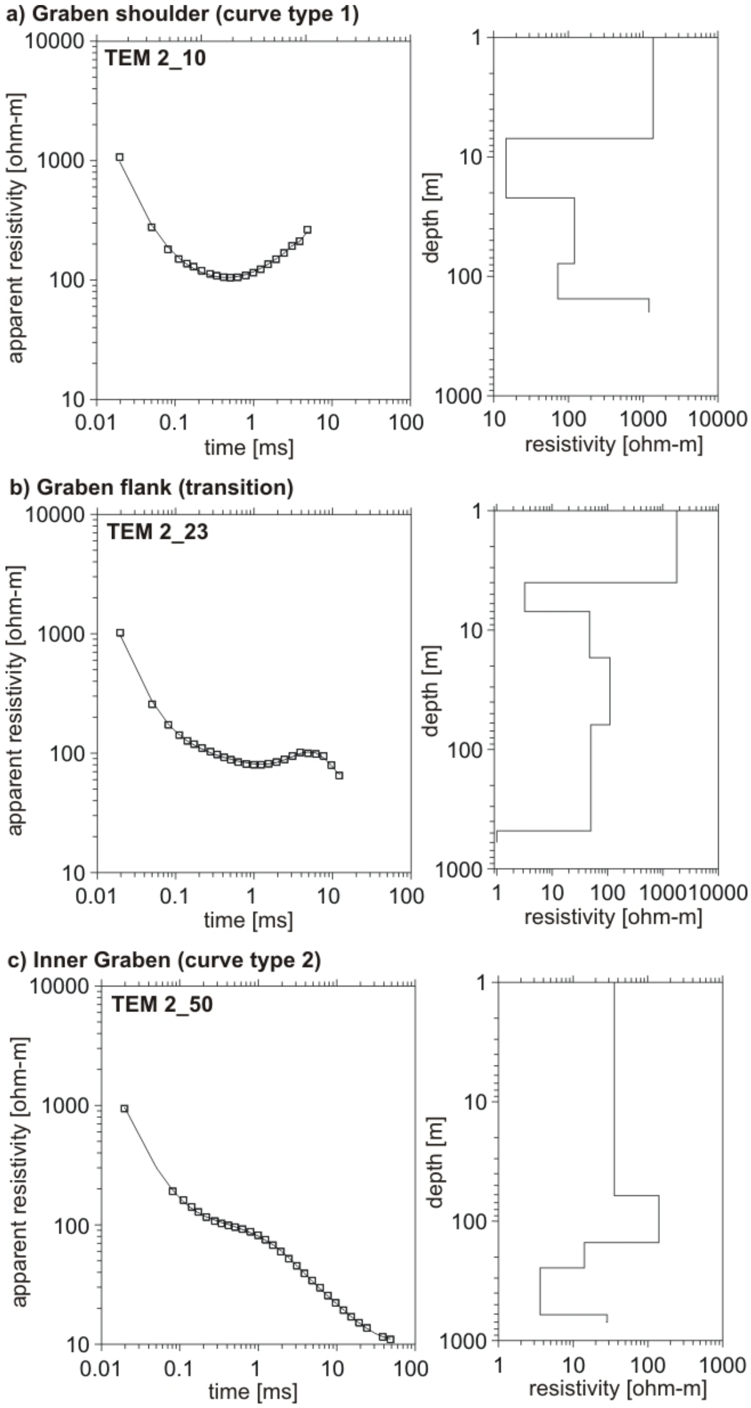

Figure 3: TEM sounding and 1d inversion model of profile 2 a) on the graben shoulder, b) at the graben flank and c) in the inner graben

Type 2 soundings present a double descending curve-type, typical for locations inside the inner graben (Fig. 3c). From moderate to high values above the water table (150 m depth), the resistivity decreases to moderate and low values at greater depths. Particularly in the eastern part of the Eiseb Graben, the depth to the highly conductive layer decreases with distance to the northern graben flank. This conductive layer represents higher water salinity in connection with higher clay contents (see Chap. 4, borehole WW41024).

The apparent resistivity curve of sounding 2_23 in Figure 3b represents a transition from curve type 1 to type 2, hence the transition at the graben flank from the shoulder to the inner graben. It is characterized by a distinctive maximum, here at 8 ms.

The described characteristics of the curve types on the graben shoulder, at the flank and in the inner graben are observed at each profile at the northern flank of the Eiseb Graben but with different clarity. The characteristics are also evident at the southern graben flank, although the transition is less pronounced probably due to the greater spacing of the TEM soundings.

Due to the characteristic resistivity distribution in the survey area, the resistivity measurements were particularly suitable to delineate the before unknown extent of the Eiseb Graben, to investigate the internal structure of the graben sediments and to give an idea of the prevailing water salinity. The horizontal resistivity section in Fig. 2 shows the distribution of the average resistivity between 150 m and 200 m depth. The section comprises the upper part of the water saturated sediments within the graben. The graben shoulders are clearly displayed by high resistivities (blue colours), caused by consolidated rock and basement rocks at shallow depth. Since the water table lies within the hardrock, water in the area of the graben shoulder is completely constrained to fractures and therefore difficult to locate by resistivity measurements.

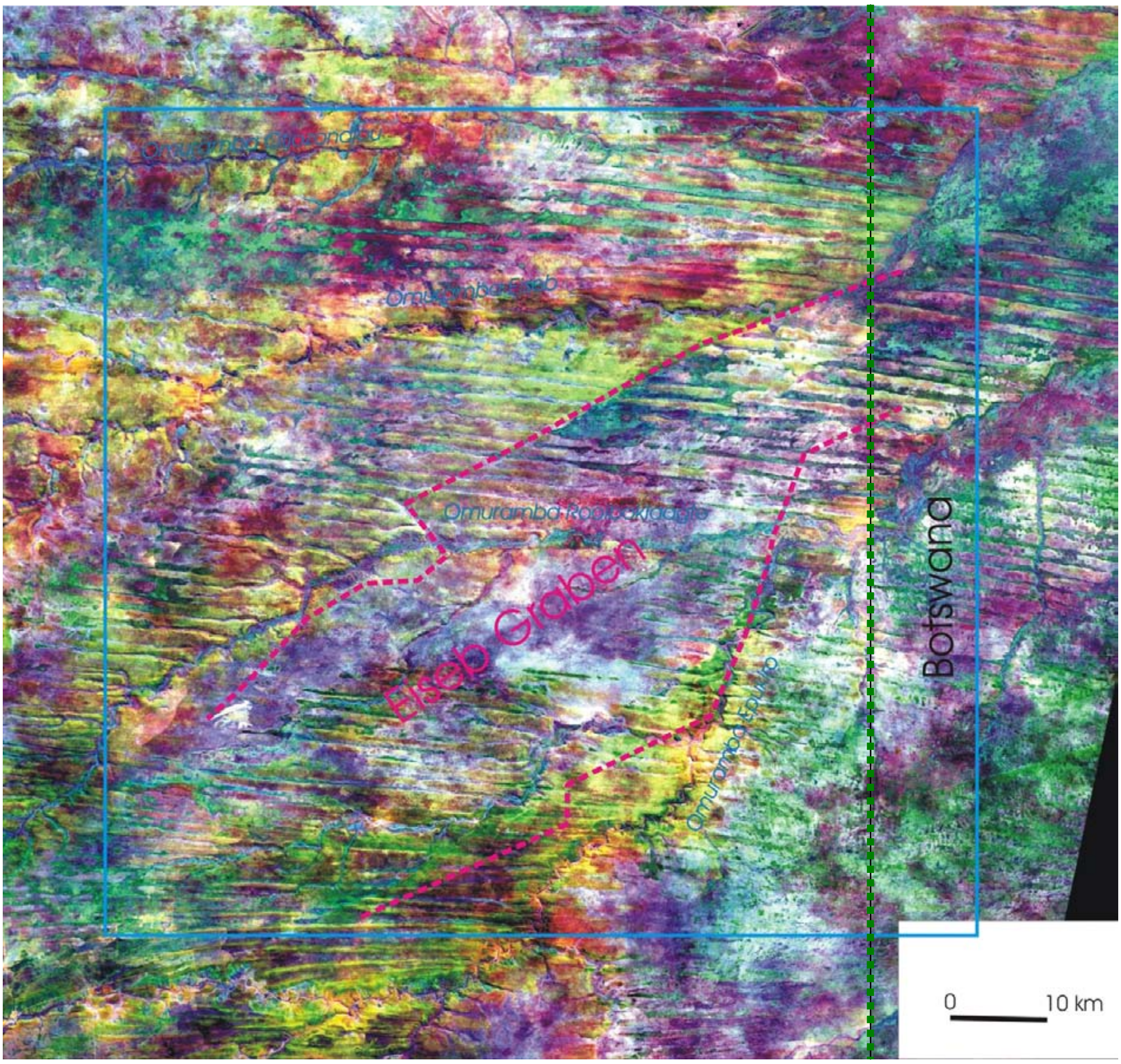

Figure 4: Satellite image of the project area with assumed extent of the Eiseb Graben

An interpretation of the Landsat TM 7 scene (Fig. 4) was conducted by BGR (SCHAEFFER, 2004). It shows several lineaments with SW-NE (around 50°) direction and few lineaments striking in a more or less perpendicular direction. This interpretation does not coincide with that performed by INTERCONSULT (1996), based on similar data. The lineaments of the BGR interpretation are plotted in Fig. 2. This lineament interpretation was derived entirely independent from the TEM interpretations. The lineaments and the horizontal resistivity distribution correspond surprisingly well and provide a plausible image of the graben structure.

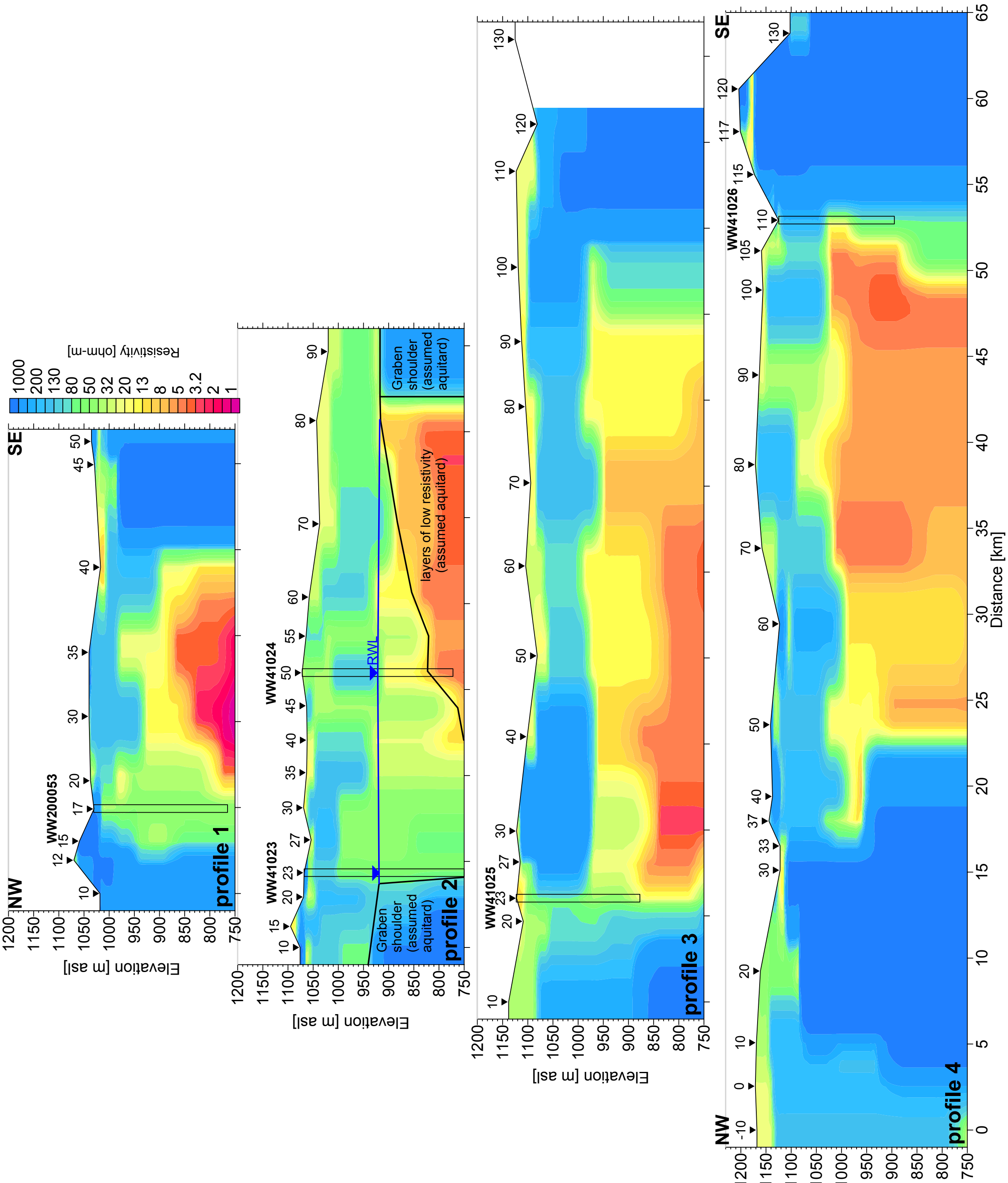

Figure 5: Vertical resistivity sections crossing the Eiseb Graben along TEM profiles 1 to 4, together with locations of the DWA-BGR boreholes. Profile 2 with hydrogeological interpretation

Figure 5 displays the vertical resistivity distribution the TEM profiles 1 to 4, crossing the graben. The sections are arranged on top of each other in order to provide a view along the axis of the graben. The vertical sections demonstrate that in most parts of the inner graben low resistivities, unfavourable for groundwater exploitation, prevail below the water table. These low resistivities are probably caused by cohesive to clayey formations in combination with brackish to saline groundwater. Moderate resistivities, ranging from 30 to 80 Ωm, indicating freshwater conditions, were detected within an elongated strip along the northern rim of the graben. This resistivity structure was interpreted as a narrow water bearing structure, eventually representing a paleo-channel.

Based on the results of the phase I survey, four locations for groundwater exploration boreholes were recommended. Rather then to achieve high water yields, the boreholes were sited to establish an interpretation basis for the TEM soundings. Nevertheless, the first borehole at the northern Graben flank, drilled into the supposed paleo-channel revealed a water yield unusual for the area under investigation (see Chap. 3). Due to this excellent drilling result, the second TEM campaign was decided and carried out in early 2005 with soundings measured along short profiles crossing the detected channel near the northern graben flank. Based on the new results locations for three additional exploration boreholes were recommended. The borehole locations of phase I and II are marked in Figure 2.

3. Results of drilling campaigns and hydrogeological investigations

The drilling program for the four selected borehole sites, based on the interpretation results of the first TEM campaign, was conducted between July and August 2004 (MARGANE et al., 2004; MARGANE & WRABEL, 2004; WIERENGA et al., 2004). A second drilling campaign for another three boreholes followed in September and October 2005 (BEUKES et al., 2005). Simultaneously to the drilling the following activities were carried out: hydrogeological survey to improve the information basis for the overall interpretation, borehole geophysics, step- and constant discharge pumping tests with corresponding interpretation and hydrochemical- and isotope geochemical sampling with analysis.

The Eiseb Graben is the westernmost extension of the Linyanti-Gomare Fault. The existence of the graben has been assumed since the mid 1970s (SCHOLZ et al., 1976) but only now its horizontal and vertical dimensions could be determined by the project activities. For the delineation of the graben and its internal structure the TEM measurements have been essential. The interpretation of these data, combined with borehole data and lithological logs from boreholes of the project area show that the graben is bound by rocks of high resistivity (gneiss) to the north and south and that outside the graben area the chances of finding groundwater are slim. The yields of boreholes previously drilled in the graben area have been comparatively low with values between 1 and 3 m³/h (INTERCONSULT, 1996). In the first drilling campaign conducted by this project, 4 boreholes were drilled. Two of them were sited at the northern margin of the graben, one at the central graben and another at the southern margin. The boreholes gave evidence that at the northern graben margin a narrow part of the graben floor may have been deeply downlifted (trench with a Kalahari sequence filling of supposedly more than 380 m).

With a recommended yield of around 120 m³/h, borehole WW41023, drilled at the northern graben rim, exceeds all groundwater-expectations. It encountered coarse, freshwater bearing horizons at greater depths. The borehole in the central part (WW41024, Fig. 6) penetrated clay at greater depths, as was predicted by the geophysical measurements. The borehole at the southern margin could not confirm the assumption of another freshwater filled trench here. With the second TEM and drilling campaign the position of the trench at the northern margin of the graben was confirmed. Packer tests, conducted in two boreholes, showed that the inflow into the wells occurs mainly at depths below 200-250 m.

As water from the shallow part of the aquifer system mostly exhibits electric conductivities between 1,000 and 1,500 µS/cm, the low electric conductivities around 500 µS/cm encountered in the three very productive boreholes WW41023, WW200053 und WW200054, point to a different groundwater recharge mechanism in the lower part of the aquifer system. It cannot be excluded that groundwater in the lower part of the aquifer system is of relatively old age and was recharged under different climatic conditions than the shallow groundwater. However, isotopic and hydrochemical analyses are not yet conclusive concerning this matter.

The exploitation potential in the Eiseb Graben is currently estimated at 0.7 MCM/a. The mechanism of groundwater recharge, however, is still insufficiently known so that it will be necessary to monitor water levels in case the water resources in the Eiseb Graben will be developed.

KLOCK (2001) and AQUALOGIC & WATER SURVEYS BOTSWANA (2003) suggest that a NW-SE trending structure, termed NE-Namibia Graben, enters the Eiseb Graben from the north. This hypothesis could not be confirmed by the findings of the project.

Table 1: Summary of drilling results of both drilling campaigns

IDN	TEM	Elevation (SRTM)	TD (m)	Started	Completed	Sceens/open	Recommended Yield (m³/h)	T (m²/d)	EC (µS/cm)
		m	*m*	*dd.mm.yyyy*	*dd.mm.yyyy*	*m*	*m³/h*	*m²/d*	*µS/cm*
WW41023	2_23	1068	378	29.06.2004	05.07.2004	148.2-218.6, 226.30-378	123	553	430
WW41024	2_50	1072	300	09.07.2004	17.07.2004	147.31-206.43, 229.23-251.75	2.5	52.1	1380
WW41025	3_23	1122	244	17.07.2004	27.07.2004	145.16-203.31, 203.31-226.56	< 1	-	960
WW41026	4_110	1125	230	30.07.2004	06.08.2004	not installed	< 1	-	750
WW200053	1_17	1039	267	08.09.2005	29.09.2005	133-196, 199-267	40	34	520
WW200054	6_30	1084	302	14.09.2005	06.10.2005	156-240, 246-302	35	177	480
WW200055	7_50	1093	249	13.10.2005	20.10.2005	151-175, 181-249	3.5	8	720

4. Comparison of litho-log, γ-ray, resistivity log and TEM model

In all of the projects exploration boreholes γ-ray logs (GR) and focused electric logs (FEL) were run with an ANTARES logging system using an ANTARES GR/FEL-combi-probe (ANTARES Datensysteme GmbH, Germany). In order to compare resistivities from borehole logs with TEM resistivities from surface measurements, logging results and corresponding TEM model are plotted together with a lithological log in Figure 6.

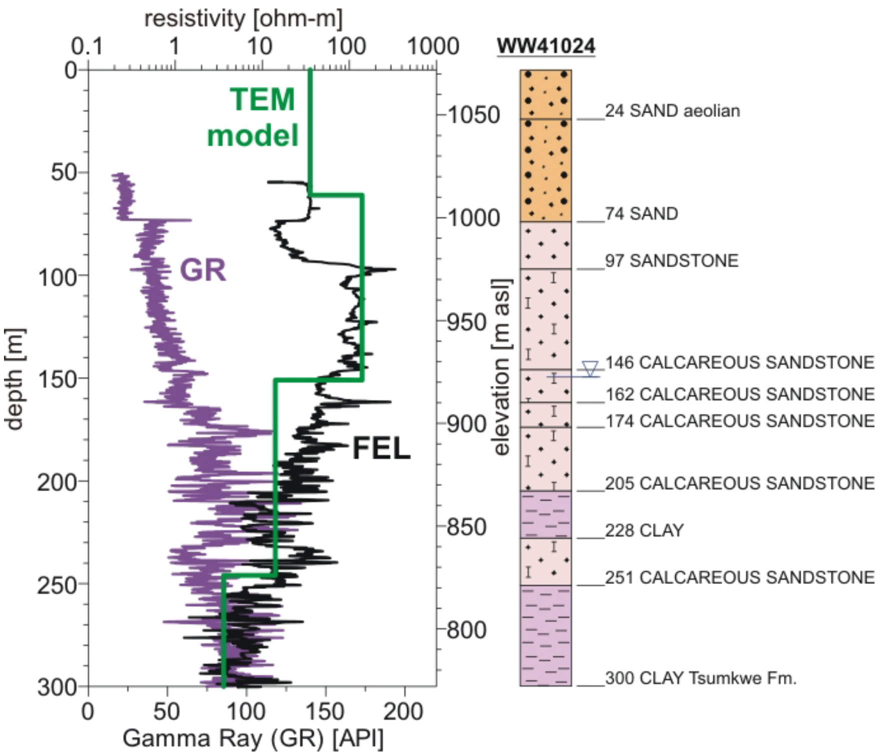

Figure 6: Litho-log, γ-log and resistivity log (FEL) of borehole WW41024 and TEM model of sounding 2_50

The logging results (GR, FEL) from borehole WW41024 and the resistivity models from TEM sounding 2_50 demonstrate a good correlation with respect to resistivity values as well as interface depths. Furthermore they are in good agreement with the geologists' litho-log of the borehole. This fact can be observed in all of the boreholes of the first drilling campaign. The borehole logs of the second drilling campaign are not yet available. In Figure 6 the FEL-resistivities below 150 m depth show a general decrease with depth which is also reflected in the TEM model. Above 90 m depth the correlation is weak, which probably is attributed to the insufficient resolution of shallow layers by TEM soundings.

5. Conclusions and recommendations

The TEM measurements proved to be highly successful for delineating the extent of the Eiseb Graben and the main freshwater bearing zone at its northern margin. The latter consists of a deep reaching trench with a filling of semi-consolidated Kalahari sediments of more than 380 m thickness. Three boreholes drilled into this zone have recommended yields and transmissivities by far exceeding previously encountered yields. Already the first drilled well exceeded the yield which was aimed by the project. The main groundwater inflows to these wells occur at depths below 200 to 250 m. They are particularly related to coarse grained sedimentary sections in the lower part of the Kalahari sequence.

The encountered water is of a good quality and is suitable for drinking purposes. The exploitation potential of this aquifer is currently estimated at 0.7 MCM/a. However, the groundwater recharge mechanism is not yet well understood. It is recommended to monitor the impact on water levels and groundwater quality during an eventual exploitation of the aquifer.

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