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Effect of oil exploration and production on the salinity of a marginally permeable aquifer system in the Thar Jath-, Mala- and Unity Oilfields, Southern Sudan

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With 10 f gures

Abstract: The study area, located in the Subtropics west of the East African Rift, is characterized – on the basis of its hydrology – by an alluvial aquifer system that is made up of predominantly fine-grained early Tertiary and Quaternary sediments. These sediments were deposited by the River Nile in large lakes. Nowadays, there is little natural new water recharge from seeping precipitation, due to marginal permeability and the formation of extensive wetlands. In order to search for possible links between an increasingly high salinity in drinking water and the exploration and production of oil in Unity State, South Sudan, a total of 90 water samples from 76 different sampling sites were taken, 74 have been analysed in detail. The samples were taken from the surface water of swamps, from boreholes in various settlements in the area, from produced water storage basins, from production facilities of the oil industry and from mud pits at abandoned as well as from still active exploration drilling sites.

Results of these analyses facilitated the identification of six water types that were hydrochemically distinguishable, and that were characterized by significantly variable ionic relationships and salt contents. Waters unaffected by human activity are characterized by prograde quality development, controlled by water-rock reactions, and they range from a hydrogen carbonate type to a sulphate type. The total dissolved content increases only gradually with the geogenic, prograde evolution of groundwater close to the surface, and ranges in terms of electrical conductivity from < 400 µS/cm to about 800 µS/cm. However, by comparison, contaminated well waters show a substantially increased salt content (> 6,000 µS/cm) with simultaneous dominance of chloride and sulphate contents. This anion dominance occurs also partially in produced water storage basins of oil production facilities, especially in mud pits of exploration operations. Due to the direction of groundwater flow, the spatial distribution of salt contamination and the hydro-geological boundary conditions found in low water permeable alluvial deposits, the cause of high conductivities in drinking water wells can only be attributed to selective seepage of salt-containing water from the basins and mud pits of those three oilfields operating in the study area. Other sources of salt contamination, e.g. deepwater rises or groundwater affected by evaporation, were not identified.

In order to guarantee the supply of drinking water for the population in the region, initially two deep wells were sunk (down to 280 m and 300 m depth respectively), and drinking water was pumped from the deepest aquifer, which had not yet been explored and developed. The latter has sulphate-dominated water of low to medium conductivity, which circulates in thin lenses of sand as well as in predominantly silty, fine sand layers. A clay layer, approximately 50 m thick, separates the first partly salinized aquifer from the underlying newly explored groundwater horizon. This horizon is supplied only by very slow processes of new accumulation (re-charge) processes, extending over decades. With

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reasonable exploration and proper well construction, the natural protection against any shift of saltwater contamination into deeper layers, will be assured by the clay layer.

Kurzfassung: Zur Untersuchung eines möglichen Zusammenhangs von zunehmend hohen Salz- und Gesamtlösungsinhalten im Trinkwasser und der Exploration und Produktion von Erdöl im Unity State, Südsudan, wurden insgesamt 90 Wasserproben an 76 unterschiedlichen Entnahmestellen analysiert. Sie wurden aus Oberflächengewässern der Sümpfe, aus Trinkwasserbrunnen der Siedlungen, aus Prozesswasserbecken der Produktionsanlagen und aus Spülgruben an ehemaligen und aktiven Explorationsbohrstellen entnommen. Das in den Randtropen gelegene Untersuchungsgebiet ist hydrogeologisch durch ein alluviales Grundwasserleitersystem westlich des Ostafrikanischen Grabens charakterisiert, das durch gering wasserdurchlässige Sedimente des Nils aufgebaut ist und aufgrund der eingeschränkten Permeabilität nur keine signifikante natürliche Neubildung durch versickernde Niederschläge erfährt. Die Analyse der Wässer erfolgte nach der deutschen Trinkwasserverordnung und nach WHO Richtlinien. Die Ionenbilanzen führten zur Abgrenzung von fünf Wassertypen, die sich durch unterschiedliche Ionenrelationen und Salzgehalte auszeichnen. Die anthropogen unbeeinflussten Wässer zeichnen sich durch eine prograde, von Wasser-Gesteins-Reaktionen gesteuerte Qualitätsentwicklung vom Hydrogenkarbonat-Typ zum Sulfat-Typ aus. Dabei steigt der Gesamtlösungsinhalt nur mäßig an. Die belasteten Wässer aus den Brunnen weisen dagegen einen im Vergleich dazu stark erhöhten Salzgehalt (> 6.000 µS/cm) auf bei gleichzeitiger Dominanz der Chlorid und Sulfat-Anteile. Diese Ionenrelationen finden sich auch in den Prozesswasserbecken der Erdölproduktionsanlagen und Spülgruben der Erdölexploration. Aufgrund der Grundwasserfließrichtungen, der räumlichen Verteilung der Salzbelastungen und der vorgefundenen hydrogeologischen Randbedingungen in den geringdurchlässigen Alluvionen kann die Ursache der hohen Leitfähigkeiten in den Trinkwasserbrunnen nur auf die Versickerung von salzhaltigen Wässern aus Becken und Spülgruben der drei nahegelegenen Ölfelder zurückgeführt werden. Andere Quellen der Salzbelastungen, wie z.B. Tiefenwasseraufstiege oder verdunstungsbeeinflusste Wässer, wurden nicht identifiziert.

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Zur Sicherung der Trinkwasserversorgung der Bevölkerung in der Region wurden zunächst zwei Tiefbrunnen (280 m und 300 m Tiefe) gebohrt und Trinkwasser aus dem nächst tieferen, zweiten Grundwasserleiter gefördert. Bei diesem handelt es sich um ein Sulfat-dominiertes Wasser mit geringer bis mittlerer Leitfähigkeit, das in Sandlinsen und schluffig-feinsandigen Lagen unter einem Tonhorizont zirkuliert. Es handelt sich um einen gespannten Grundwasserleiter, der nur durch sehr langsame Neubildungsprozesse über Dekaden gespeist werden kann. Eine ca. 50 m mächtige Tonschicht trennt den ersten, punktuell versalzenen Grundwasserleiter von dem darunterliegenden, neu erschlossenen

Grundwasserhorizont. Durch diese Tonschicht bleibt bei einer angemessenen Förderung und fachgerechtem Brunnenausbau der natürliche Schutz vor der Verlagerung der Salzwasserkontamination in die Tiefe gewährleistet.

Keywords: Drinking water supply, well sinking, groundwater salinization, South Sudan

Schlüsselwörter: Trinkwasserversorgung, Brunnenbau, Salinität im Grundwasser, Südsudan

1. Introduction

The economy of South Sudan is currently characterized by subsistence farming, as well as by fisheries in extensive wetlands, the so-called *Sudd*, the largest wetland area on earth. Cattle rearing takes place on grazing land along mostly dry, high plateaus within floodplains of the River Nile (Fig. 1).

Since 1999 at the *Unity Oilfield* and since 2006 in the oilfields of *Thar Jath* and *Mala* (Unity State), oil is being produced from "Nubian Sandstone", underlying early Tertiary and Quaternary alluvial sediments of the former River Nile Delta (Abdalla 2009).

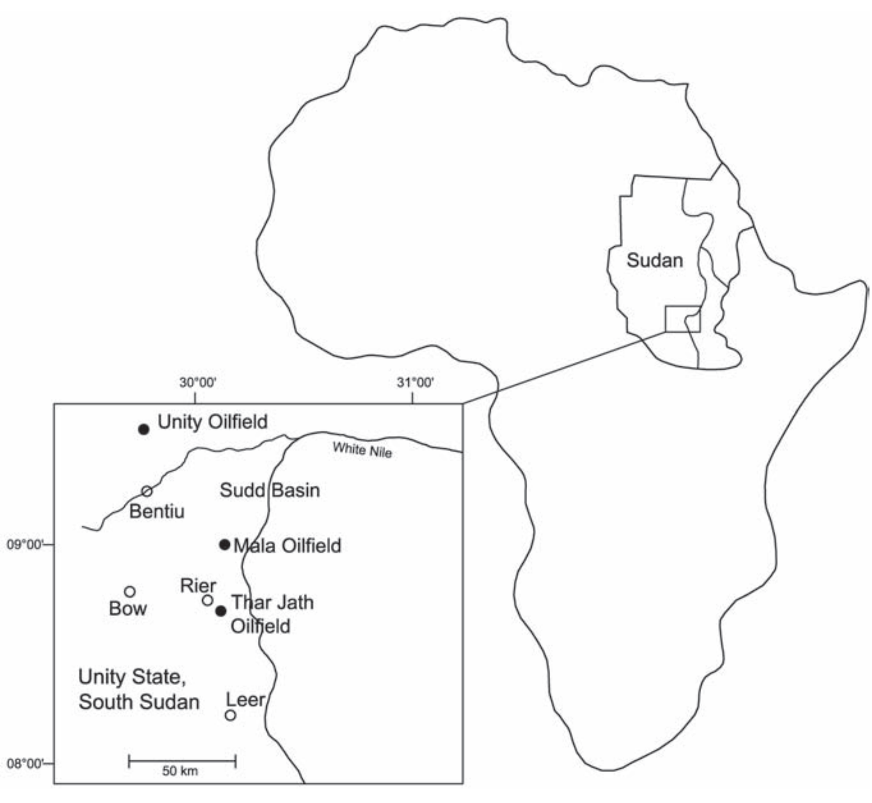


Fig. 1. Overview map of the study area in Unity State, South Sudan.

Fig. 2. Handpump water well for the local rural water supply, Type *Ajay, India-Mark II.*

Because of oil exploration and – production, the original, rural infrastructure of this region is changing. The **C**omprehensive **P**eace **A**greement – CPA on January, 9th, 2005 terminated the long-standing civil war between the north and the south. Since the peace agreement the population density in the former war regions is increasing again due to influx of returnees.

Usually, drinking water is supplied from an aquifer close to the surface, by means of shallow wells drilled down to maximally 80 m below the surface, using hand pumps of Type *Ajay, India-Mark II* (Fig. 2). A water distribution system does not exist; consequently, new wells are sunk in order to meet the growing demand for drinking water.

For several years now the population has complained about high salt content and related incompatibilities in drinking water. There are also abnormal rise in livestock mortalities. The causes of rising salinity and its chronological development were not known due to the civil-war-related unavailability of data.

Within the framework of a humanitarian aid project, unpolluted, healthy drinking water was to be made available to the population; also the causes of the increasing deterioration of drinking water quality were to be researched, in order to ensure quality drinking water supply for the future.

It was the objective of these studies initially to identify and explore possible factors that influence groundwater conditions in aquifers close to the surface. In a subsequent step, the existence and suitability of aquifers at lower geological levels was investigated. In order to map groundwater conditions close to the surface, water samples were taken from the surface of wetlands in the area, from hand-pump operated wells in surrounding villages and from produced waters, as well as from remnants of mud flushes from abandoned wells and from mud pits that were still in use. Exploratory flights prior to any site visits formed the basis for the determination of respective routes that were to be taken. All-in-all, 90 samples were taken from 76 sites during 5 field trips. At selected sampling sites, repeated water samples were taken, always following the rainy season and the dry season, in order to include possible changes in water quality. The samples underwent complete analysis according to WHO-guidelines and German Drinking Water Standards, performed always in internationally accredited German and Kenyan laboratories. Determination of ion balances and the interpretation of salt contents in these water samples were then used for the determination of possible geogenic or anthropogenic causes in groundwater aquifers close to the surface, which had been noted by the population.

Exploration of deeper aquifers commenced in regions where drilling in the same aquifer took place in order to replace wells, which were not producing water of satisfactory quality. Details about a succession of sediments in deeper aquifers and groundwater reservoirs in the study area are so far unknown, or have not been published. Studies by Goni (2008) in the adjacent Chad Basin in the west, as well as by MacDonald et al. (2008) in the Sub-Saharan Basin were initially the bases for the development of a first hydro-geological representative model of the groundwater circulation system and for the mechanisms of water recharge expected in the study area. Within the framework of humanitarian aid projects, two exploratory drillings were made in the villages *Rier* and *Bow* to assess deeper aquifers hydro-geologically and hydro-chemically by sinking bore holes, which were then structurally completed as drinking water wells. These wells can be used as an evaluation basis of a new exploration concept for the future drinking water supply for settlements in the area.

2. Geological and hydrogeological setting

The project area is located in South Sudan, in Unity State (Fig. 1). It extends over approximately 15,600 km². The northern-most point is at N 09° 51’37”, the southern-most point is at N 07° 42’55”. The eastern-most point is located at E 30° 13’22” and the western-most point is at E 29° 34’47”. The study area is about 380 to 400 m above sea level and has a balanced relief. Extensive wetlands are formed in the low-lying areas that are interrupted by islands of grazing areas and scattered settlements. These higher areas are widely flooded during the rainy season. Climatically this area is part of the zone of equatorial monsoons in the outer Tropic Zone (Sub-tropics). The mean annual temperatures are typically > 18°C with an annual precipitation > 1000 mm (Geiger 1954).

Supra-regionally, the study area belongs to the sedimentary basin structures along the western boundary of the East African Rift System and the Ethiopian Highland (Fig. 3). Close to the surface there are several hundred meters of successive early Tertiary and late Pleistocene unconsolidated sediments. These are river- and lake deposits from the White Nile and its tributaries that were formed among hard rock breakup of crystalline basements in the upper Nile Delta.

The underlying stratum of the sedimentary Nile Basin is followed by bed- and reservoir rocks of oil deposit layers that originated during the Cretaceous Period. They were formed in reef structures near the Sudanese Shear Zone (Abdalla 2009). Below that follows, the Pre-Cambrian basement rocks of East Africa.

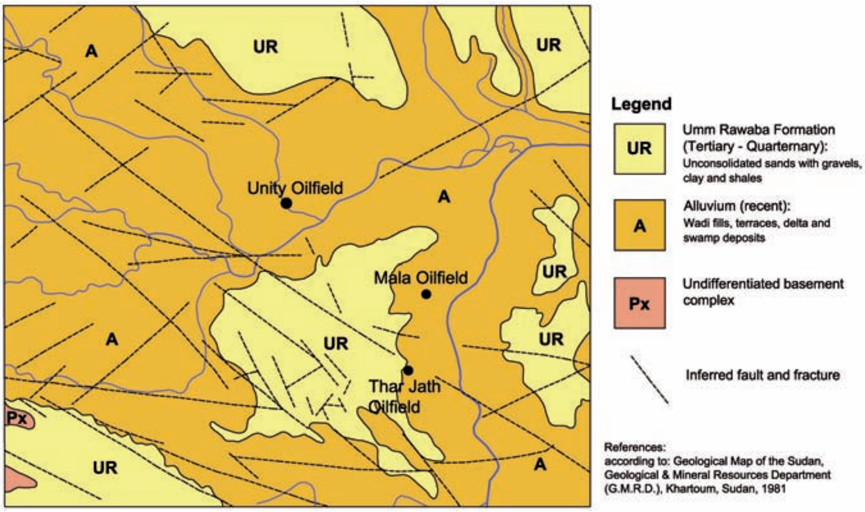


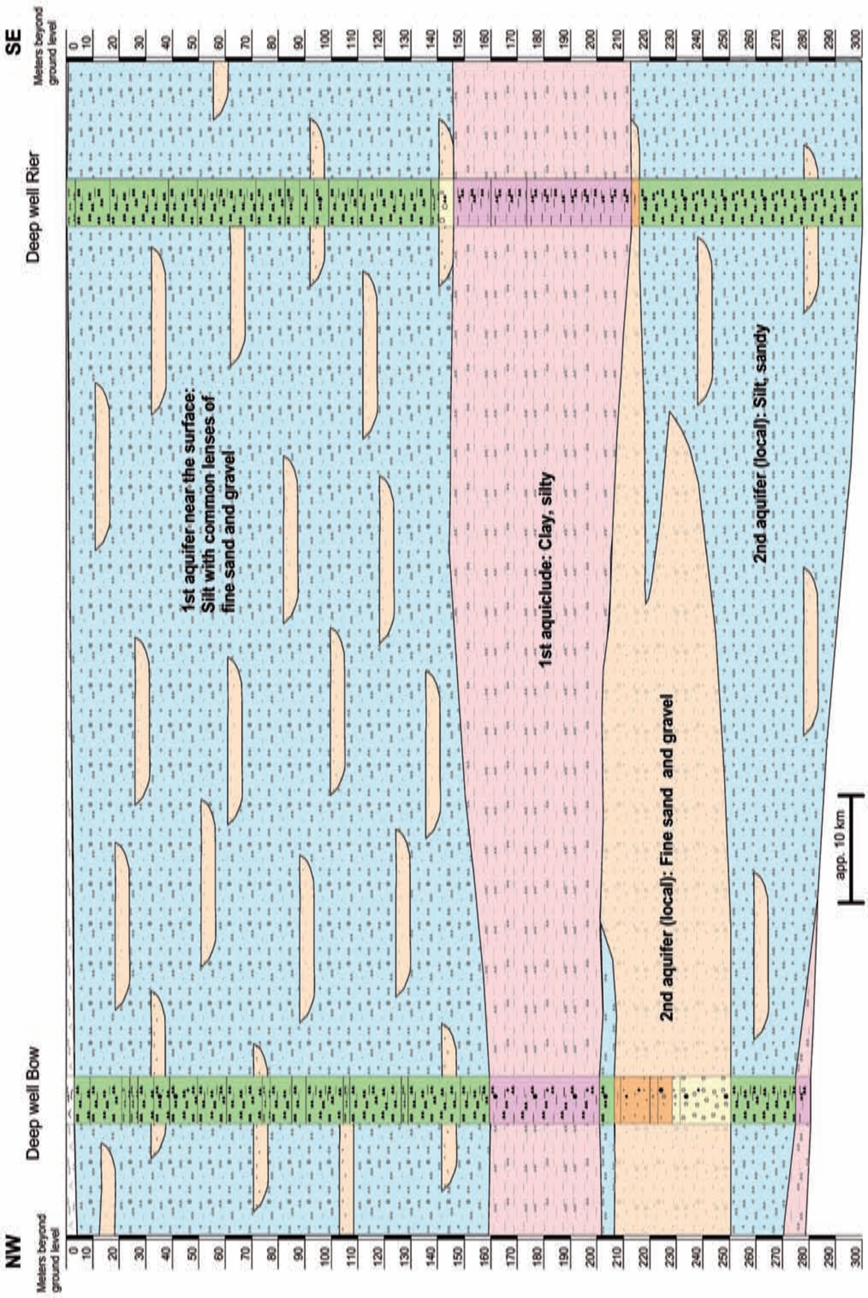
Fig. 3. Simplified geological map of the study area in the White Nile Basin, Sudd swamplands.

The southern Sudanese Basin of the upper Nile Valley continued to sink further during the Tertiary Period, so that rubble- and erosion products from the surrounding basement rocks could accumulate into thick estuarine deposits in a lake formed during the early Tertiary- to late Pleistocene period. The supply region for sediments found in the study area needs to be looked for among Precambrian hard rock breakouts along the southern and eastern margin, as well as in volcanic formations of the East African Rift System. The last mentioned rocks are responsible for the geogenic heavy-metal enrichments and elevated fluoride content (> 1.5 mg/l) in sediments close to the East African Rift (MacDonald et al. 2008).

Recharge of groundwater (20 mm to 100 mm) in the upper Nile Basin results from precipitation > 1000 mm per year (Struckmeier 2008). Since the Pleistocene Period most of the precipitation runs off to the northwest and the north via tributaries up to the White Nile or evaporates in distinctly lower plains of the upper Nile Basin. Recharge of groundwater in aquifers close to the surface in the project area is essentially from precipitation seepage in *wadis* and depressions of the lowland basin, as well as by means of oozing from perennial rivers.

In the study area groundwater presumably follows – with very gentle gradients – the course of rivers and depressions, which drain from southeast to northwest,

Fig. 4. Simplified hydrogeological schema according to the profiles of the two well drillings in Bow and Rier.


NW
SE
Meters beyond ground level
Deep well Bow
Deep well Rier
1st aquifer near the surface: Silt with common lenses of fine sand and gravel
1st aquiclude: Clay, silty
2nd aquifer (local): Fine sand and gravel
2nd aquifer (local): Silt, sandy
app. 10 km

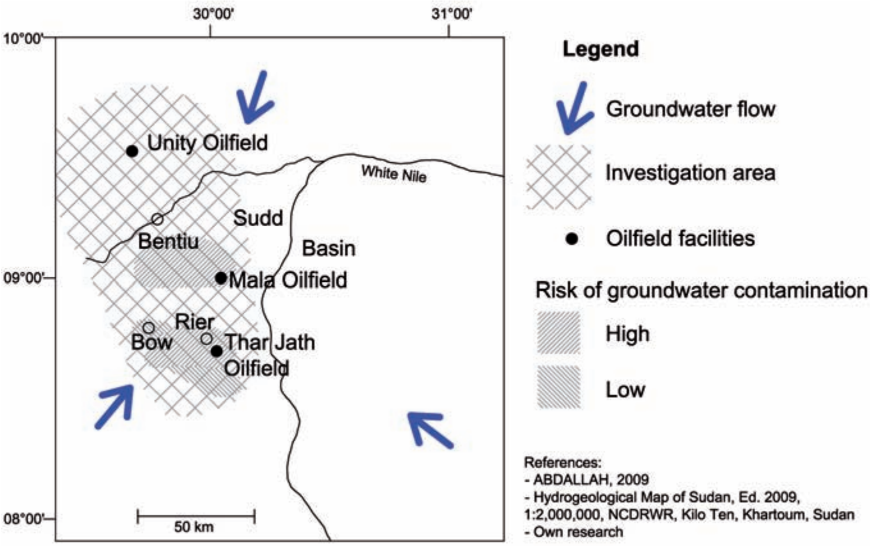


Fig. 5. Simplified groundwater flow map with areas of high and low risk of water contamination.

or from northwest to southeast, respectively, towards the River Nile (Fig. 5). According to Vrbka et al. (2008) the sedimentary basins of the Northern, Central and Southern Sudan form the most important and widest developed principal aquifers of the country. The Precambrian bedrock and the Mesozoic sediments/volcanic rocks have only minor aquifer functions. According to hydro-geological modelling by Abdalla (2009), there are different directions of local groundwater flow in the study area (Fig. 5). From the southeast, groundwater flow occurs in aquifers close to the surface, following the relief of hard rock outcrops along the margins of alluvial deposits in the directions of the White Nile. From the northeast, groundwater generally follows the strike direction (northwest – southeast) of the Southern Sudan Rift (SSR) and of the tributaries of the White Nile. Consequently, two groundwater flow directions meet in the study area close to the arch of the Nile, east of *Bentiu*. East of the Nile, the groundwater flow follows the course of the river.

3. Scope of study

The selection of water sampling sites was done by evaluating own aerial photographs, GPS tracks of own surveillance flights as well as from information provided by villagers living in the study area. Mud pits of oil exploration drilling activities as well as water storage basins of processing plants (which separate water from crude oil) were identified as possible pollution potentials for groundwater. The general lack of central effluent treatment- and -removal systems from settlements in the area is conceivably another potential pollution hazard for drinking water

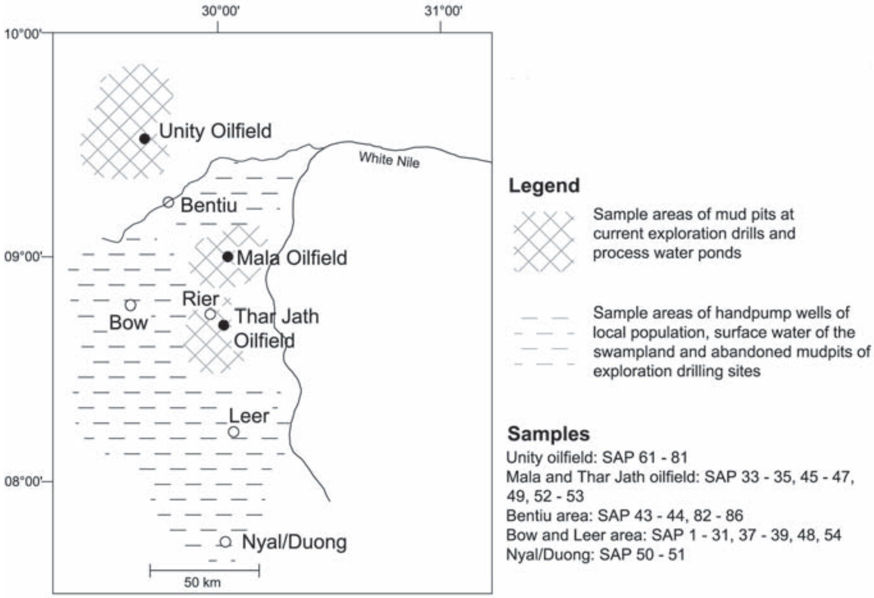


Fig. 6. Sample areas of water wells and surface lakes as well as process water and mud pits at exploration drilling sites.

wells. This also includes surface- and run-off waters close to settlements, where – for instance – villagers do their domestic and commercial activities.

Due to population growth in settlements of the area, slash-and-burn clearing takes place on a large scale, something that can also lead to changes in groundwater condition.

As a first step of the investigation, those wells, which had been identified by the population where water was deemed undrinkable, were specifically targeted for sampling. For comparisons purposes, wells that supplied drinking water of acceptable quality were also sampled. All hand-operated wells are approximately between 40 and 80 m deep and produce groundwater from the upper aquifer. The exact location of individual filter sections is not known. From details provided by locals, the filter sections are encased by locally acquired materials, the upper 3 m are filled with a concrete plug. A horizon-specific sampling of partial filter sections is therefore not possible. The analysis of surface waters from wetland was used as reference point for the natural recharge of (new) groundwater.

Due to strong seasonal variations of precipitation, the concentration of some parameters (e.g. nitrate, nitrite) was compared following every dry- and wet season (samples were always taken in October/November and March/April). Scope of the study included cations and anions as well as the heavy metals listed in Drinking Water Regulations and the WHO-Standard. Tests for odour and turbidity, pH value, temperature, TDS (total dissolved solids) and electric conductivity were

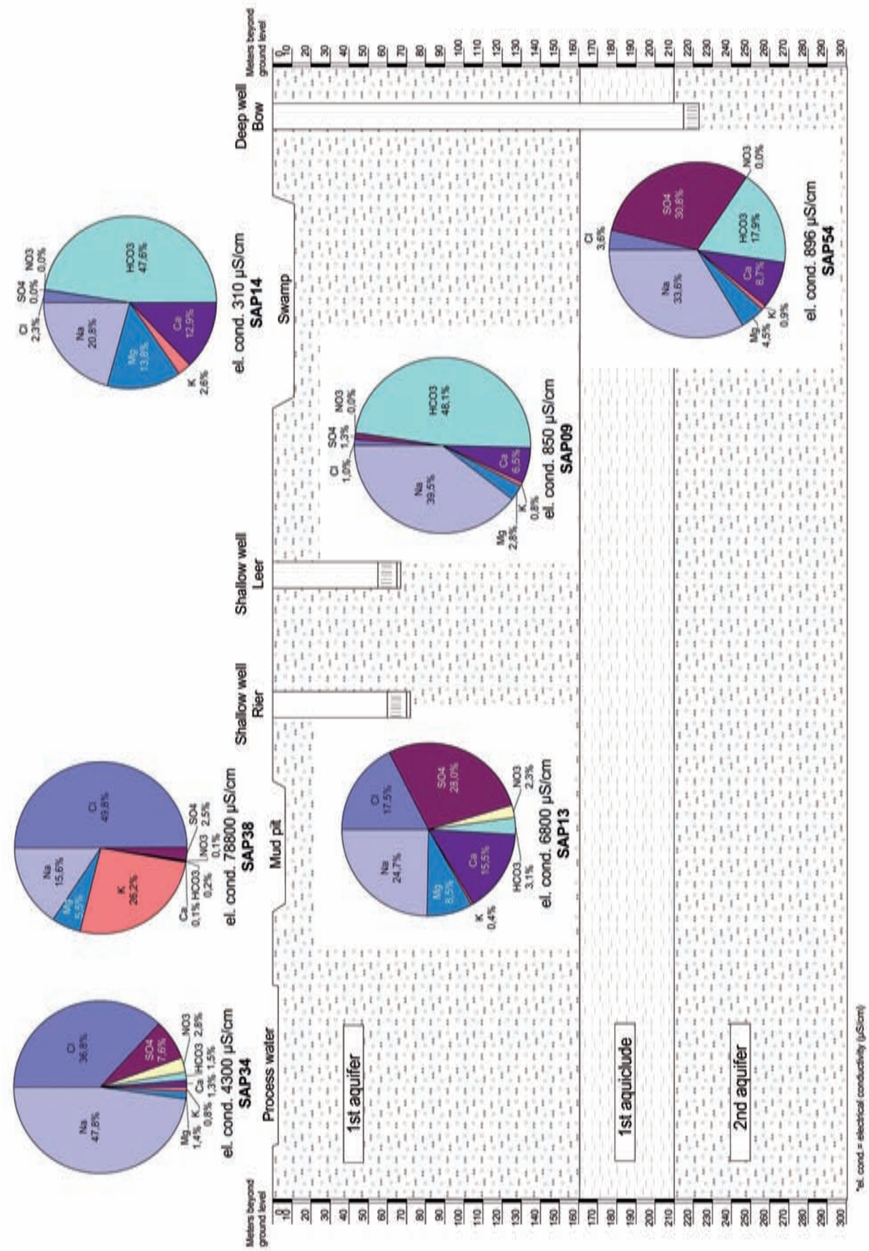

Meters beyond ground level
Process water
Mud pit
Shallow well Rier
Shallow well Leer
Swamp
Deep well Bow
1st aquifer
1st aquiclude
2nd aquifer
el. cond. 4300 µS/cm
SAP34
el. cond. 78800 µS/cm
SAP38
el. cond. 6800 µS/cm
SAP13
el. cond. 850 µS/cm
SAP09
el. cond. 310 µS/cm
SAP14
el. cond. 896 µS/cm
SAP54
*el. cond = electrical conductivity (µS/cm)

Fig. 7. Ion balances of the six identified water types and their associated water sources.

made while sampling and also under laboratory conditions. For technical reasons, refrigerating of the samples was not possible. Therefore, quality assurance of test results could only be ensured through the ion balance. GPS data for all sample sites were recorded and the details are summarized in Table 1 - Results. The sampling sites were grouped within three areas, shown in Fig. 6. On one hand, these are the two oilfields *Unity* and *Thar Jath/Mala*, and on the other hand it includes the widely dispersed settlements between *Lalop* in the North and *Nyal* in the South.

Within the framework of exploring the deeper aquifers, two boreholes were sunk in *Bow* and *Rier* (Fig. 4). Penetration reached a depth of 280 m and 300 m respectively. The boreholes were drilled using a *Salzgitter RB 225* in direct mud rotary drilling and then built as regular wells. A sediment sample was taken from the drilling mud every 3 m, to map the geological profile. The filter section in *Bow* is fitted between 215 m and 223 m within a layer of sand, in *Rier* between

Table 1. Results of water analysis of selected samples.

Sample No.	SAP 09	SAP 13	SAP 14	SAP 34	SAP 38	SAP 54
N	08.18.23,3	08.46.59,9	08.45.55,1	08.44.18,4	08.38.08,0	08.18.26,0
E	30.08.15,7	30.06.06,0	30.06.42,0	30.08.39,4	29.58.49,9	30.08.16,9
pH@20°C	8,1	7,03	7,44			
pH@25°C				9,58	7,95	8,2
TDS (mg/l)				2570	47200	
el.Con.(µS/cm)	850	6.800	310	4.300	78.800	896
F	0,3	ND	0,54	5,9	0,31	< 0,2
HCO3	571	372	225	60	240	227
Cl	7	1.200	6	870	42.389	26,7
SO_4	12	2.600	ND	244	2.877	308
NO_3	ND	63,00	ND	25,80	47,28	< 0,5
NH_3	ND	ND	0,03	1,62	2,62	0,23
CN	ND	ND	ND	2,5	12,5	ND
Mn	0,1	0,002	0,06	ND	0,72	1,5
Mg	7	200	13	12	1591	12
Na	177	1.100	37	731	8.631	161
Ca	25	600	20	17	26	36,2
Fe	0,32	0,21	0,43	ND	2,48	1,4
K	6	29	8	22	24569	7,2
Al	0,17	ND	0,17	ND	ND	0,11
Cr	ND	0,036	ND	ND	0,45	ND
Pb	ND	0,012	ND	ND	2,15	ND
Cu	ND	0,007	ND	ND	0,21	ND
Ni	ND	ND	ND	ND	0,956	ND
Cd	ND	0,001	ND	ND	0,53	ND
B	ND	ND	0,06	ND	50,8	ND
Se	ND	ND	ND	ND	ND	ND
As	ND	ND	ND	ND	0,08	ND
Ba	0,052	0,009	0,093	0,650	140	0,054
Sr	0,33	6,40	0,27	0,56	58,00	0,31
(C10-C40)	ND	ND	ND	ND	ND	ND
Tetrachloroethene,	ND	ND	ND	ND	ND	ND
Trichloromethane,	ND	ND	ND	ND	ND	ND
Total Trihalomethane	ND	ND	ND	ND	ND	ND
Benzene	ND	ND	ND	ND	ND	ND
Toluene	ND	ND	ND	ND	ND	ND
Total detected PAH	ND	0,020	0,070	0,030	0,040	ND

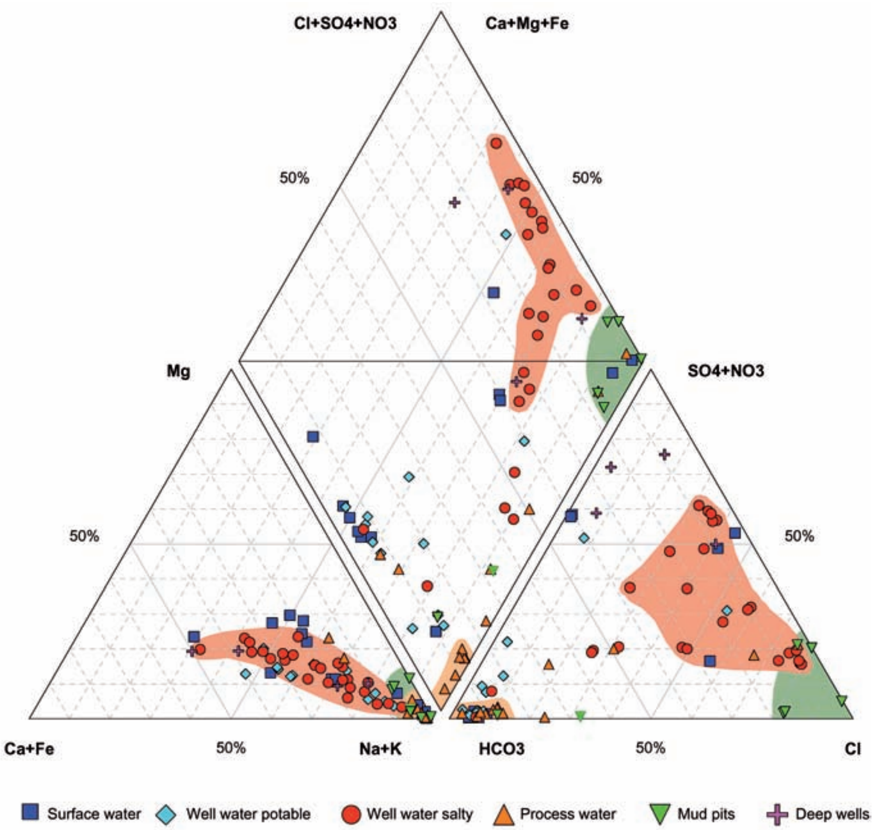


Fig. 8. Piper diagram of all samples, showing the six different water types of well water, surface water, salty wells, produced water, mud pits and deep well water.

205 m and 217 m in alternating layers of silt/fine sand. The annular space in both wells was sealed off with clay pellets. Afterwards, the wells were developed hydraulically, tested and hydro-chemically analysed.

Results of water analysis data from the study area revealed six different types of water, as per Furtak & Langguth (1967) (Fig. 7 and 8):

Type 1: Surface water in wetlands, Na-Mg-Ca-HCO_3-Water
Type 2: Well water of potable quality: Na-HCO_3-Water
Type 3: Well water of insufficient drinking water quality: Na-Ca-SO_4-Cl-Water
Type 4: Produced water from crude oil processing: Na-Cl-Water
Type 5: Mud pit of exploratory drilling sites: K-Na-Cl-Water
Type 6: Groundwater from 2nd aquifer: Na-SO_4-HCO_3-Water

Wells with low water quality show distinctly increased chloride- and sulphate components, in comparison to surface waters and well waters (based on German

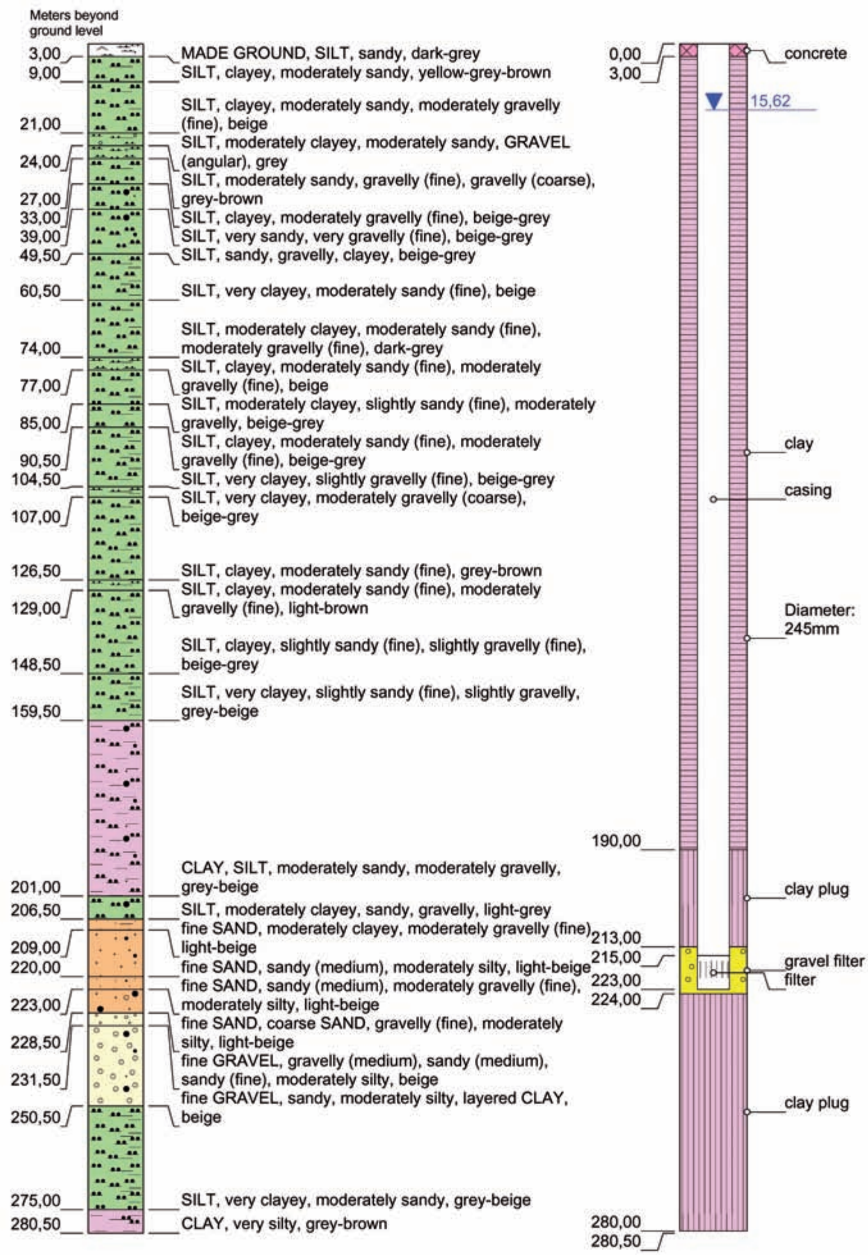


Fig. 9. Geological profile and well building in Bow.

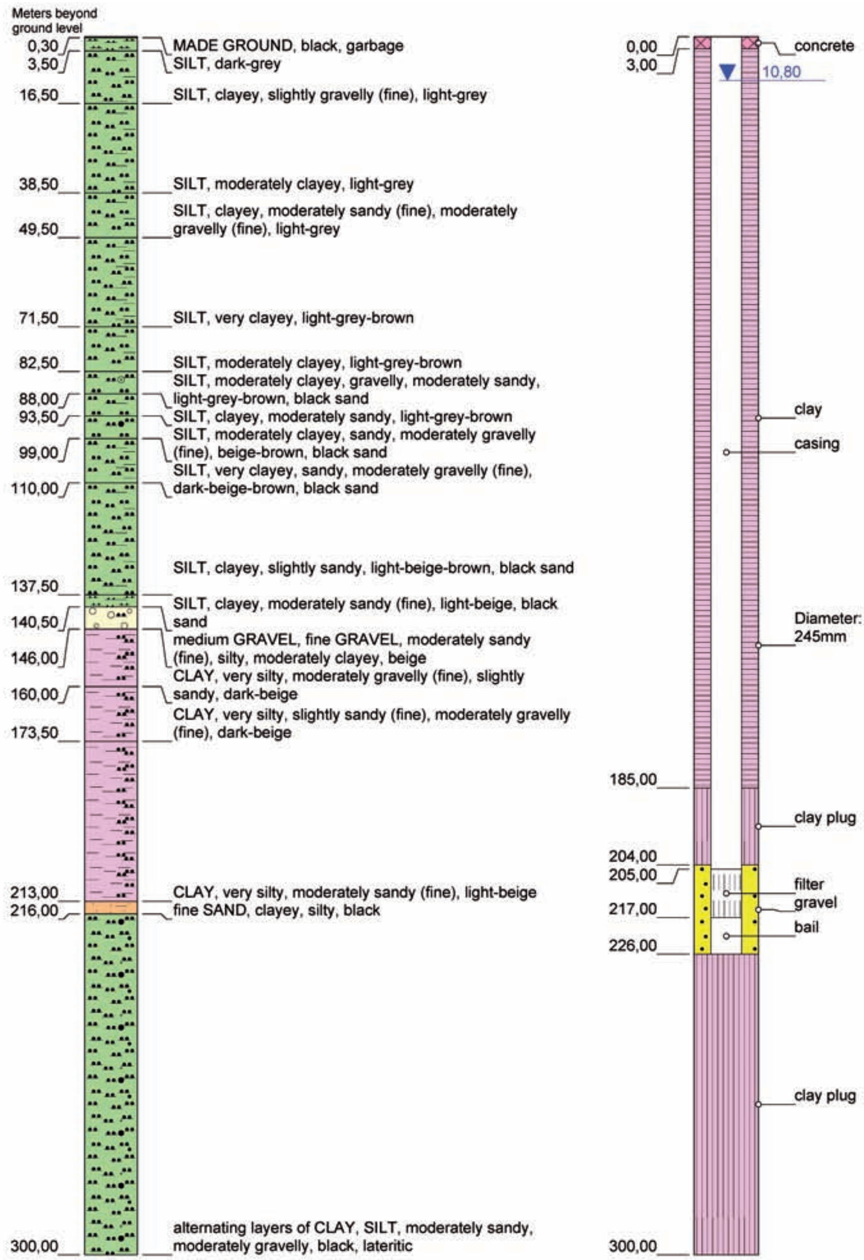
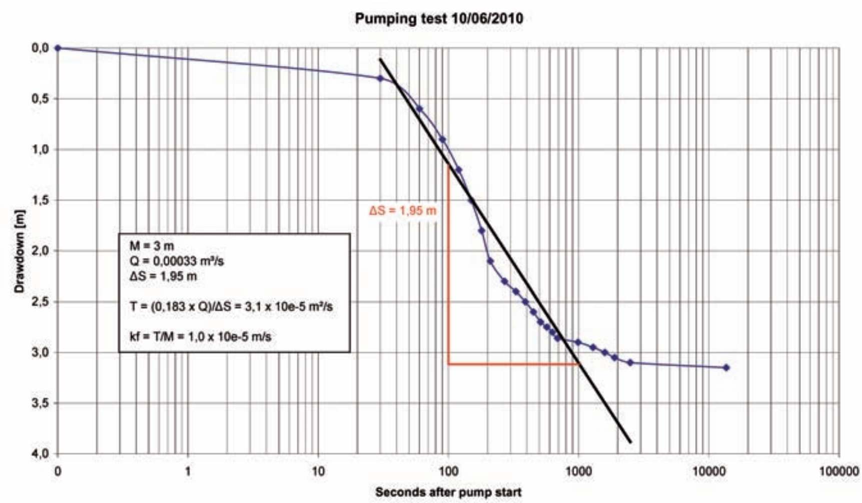


Fig. 10. Geological profile, well building and first results of a pump test in Rier.



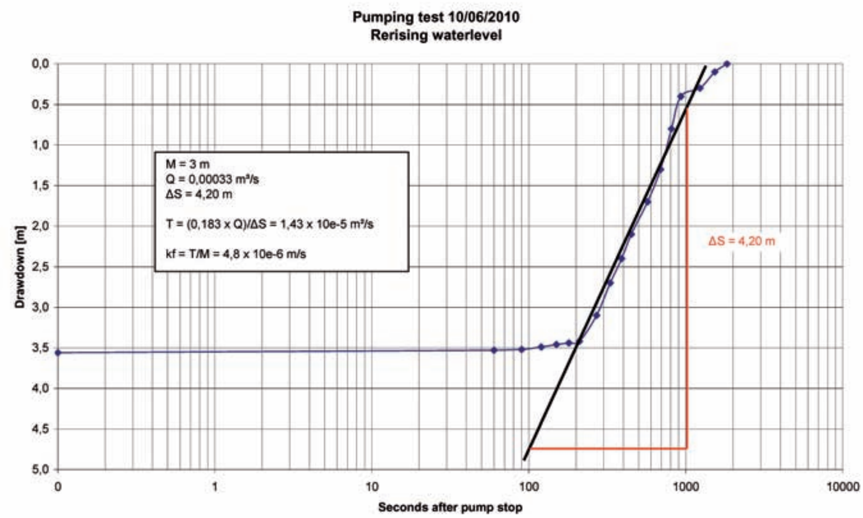


Fig. 10. continue

Drinking Water Guidelines [Trinkwv 2001 and WHO 2004]). These ions can also be shown to be present in dominant proportion in the total ion composition of produced waters from oil processing and in mud pits of abandoned exploration drilling sites. Further potential sources of saltwater could not be found in the study area.

In addition to the salt contents, organic compounds were also analysed, which are to provide answers in respect to possible contamination by fossil hydrocarbon deposits, or for the contamination of harmful substances from crude oil production, respectively. These indicators include, among others, free-flowing, halogenated hydrocarbons and aliphatic hydrocarbons.

Polycyclic aromatic hydrocarbons (PAHs) also occur naturally in crude oil. They also develop during incomplete burning of fossil fuels, organic materials (e.g. slash-and-burn clearing) and during crude oil distillation (Killops & Killops 1997).

BTX (benzene, toluene, xylene and ethyl-benzene) are solvents, which also belong to the aromatic hydrocarbons. They are often connected to crude oil processing and they are – similarly to free-flowing, halogenated hydrocarbons – potential groundwater contaminants (Brassell et al. 1980).

Apart from heavy metals listed in the Guidelines, the samples were also analysed for their content of strontium and barium, since these elements often contributed through the inflow of drilling additives from exploration drilling sites (Arnold 1993).

4. Results of well drilling

The boreholes (Fig. 9 and 10) in the study area showed a sequence of silt and fine sand, as well as layers of fine-grained gravel, between surface and approximately 140 to 160 m depth. The geological facies of this upper aquifer consists of an irregular sequence of fluvial and lacustrine sediments of low permeability. The embedded fine sands are predominantly black and the intermediate fine-grained gravel layers are of lateritic composition, with a gradual transition into layers of silty sand and silty clay. In its entirety this must be considered as a 'semi-confined' aquifer. The static water level is at 10 to 12 m below surface. Underneath the first aquifer there is a layer of clay, approximately 50 m thick. Below that starts another confined aquifer, which has – in contrast to the upper aquifer – layers of lens shaped, light-beige, fine to medium-grained sand. The water level of this aquifer is at the same geodetic level as in the upper aquifer (approximately 10 to 14 m below surface). According to results of the pumping tests, the permeability factor (kf-Value) of the fine-grained facies of the lower aquifer is at 10–6 and 10–7 m/s, in result marginally permeable.

The well at *Bow* achieved a specific yield of .67 m^3/h with a lowering of 1 m, the well at *Rier* achieved .34 $m^3/h/m$.

5. Discussion of drilling results

For the first time, the geological sequence of layers in the study area could be described on the basis of sediments and hydrology, from test results obtained from both drillings. The basin sediments are characterized vertically and horizontally by a quick change of facies of fine-grained lakustrine sediments and alluvial deposits, so that the retention time of groundwater can be very high.

The upper part of the formation, from which drinking water for the local population is being recovered, consists of an alternating sequence of silt and fine-grained sands with local intercalation of lateritic gravel beds. Their thickness is on the scale of decimetres. The principal water pathway for accessible groundwater is presumably tied to intermediate layers of sand and gravel. The hydrological model developed from drilling data (Fig. 4) is based on a confined aquifer system with low permeability and annual recharge. Surface tests, like those from mud pits and process water storage basins, have revealed that the local hydraulic lead horizons could be connected to each other by vertical dessication cracks in proximity of the surface. Therefore, any recharge of groundwater occurs primarily along these pathways. The possibility for recharge of the upper aquifer level is possible mainly at areas of alluvial deposits located higher up. In permanently water-covered, morphologically lower located swamp areas, these vertical pathways are presumably closed off by clogging, so that the pressure relationship between surface water level and groundwater space is controlling any recharge of groundwater. By comparison to higher areas located outside the swamp areas, this is considered to be very low.

From a depth level of approximately 140 m downward, the base of the upper aquifer forms a thick layer of clay (about 52 m) that can be considered as a hydraulic aquiclude. The sand lenses below alternate at the same geodetic levels with silty, fine sands, which are similar to the facies of the upper aquifer. These layers of the second aquifer were found in both drinking water bore holes (Fig. 4). The hydraulic permeability of this aquifer is dependent on characteristics of facies and must also be categorized as marginally permeable. The recharge of groundwater at this level is presumably controlled exclusively by means of seepage processes.

The low vertical and horizontal permeability of the sediments causes a slow groundwater flow speed, extensive recharge time frames and a low water turnover. Most of the precipitation evaporates quickly due to high temperatures, according to Struckmeyer (2008) only 5 to 10% of annual precipitation can seep into aquifers close to the surface and to those at deeper levels. Rising waters from greater depths (> 300 m) could not be found, since the hydraulic head of the second aquifer is nearly congruent to the one of the upper aquifer. So far precise measurements for the determination of pressure differences do not exist, and have also not been possible due to reasons relating to the drilling technology employed for establishing these two deep wells.

6. Interpretation and discussion of hydro-chemical data

Water analyses from the study area showed that the groundwater circulation system encountered in wells in the area surrounding *Bentiu*, can be categorized hydro-chemically into different zones. Stuyfzand (1989, 1993, 1999) refers to the hydro-chemical zonation in a groundwater flow system in the direction of the groundwater flow, as a prograde change of water quality. Using the Dutch dune aquifers along the North Sea coastline as an example, this author describes the groundwater body on the basis of its water composition. He categorizes this according to explicit origins, such as recharge of groundwater through precipitation, river water infiltration or artificial groundwater enrichment. With increasing distance from the point of origin of its hydro-chemical character, the prograde change of groundwater exhibits a decline in seasonal variation of the ion content. Thereby, a stable chemical water composition is controlled through filtration, buffering, sorption or degradation with increasing groundwater age. Connected with this is an increase in alkalinity and a change from oxic conditions to an anoxic environment.

In similar climatic zones an upward rise of groundwater (Marshall et al. 1996) can lead to an increase of salinity in groundwater close to the surface due to strong evaporation rates during the dry season in the unsaturated zone.

Connected with this vertical transport is an increase in mineralization and a displacement of dominat anions from hydrogen carbonate through sulfate to chloride. The causes of such evolution of groundwater chemistry are, when applying the model assumptions of Stuyfzand (1999), the increasing evapotranspiration and CO_2-production on the ground, a slowing down of groundwater circulation with increasing depths and a more intensive water-rock-reaction. In combination with such proven, low permeability and low recharge rates, there are reduced exchange- and washout rates in the aquifer (Shipovalov 1984). This prograde development of water conditions, described in the literature as a displacement of ionic conditions (Appelo & Postma 2005) from water close to the surface to lower groundwater levels, cannot be confirmed in this study area.

In groundwater close to the surface (Type 2), the conductivity rises from 310 to 850 μS/cm, in contrast to surface water from wetlands (Type 1). The sodium component in groundwater close to the surface increases through ion exchange to the disadvantage of alkaline earth elements, from about 31 mmol % to about 40 mmol %. This ion exchange indicates very slow transport of newly accumulated water and a very long residence time in pore spaces of the saturated and unsaturated zone. Only a very slight increase of total dissolved content is linked to this ion exchange, whereby the hydrogen-carbonate character of the water is maintained. This process of ion exchange and the upward concentration of water can be considered (for the study area) as the defining geogenous – by humans uninfluenced – character.

Water quality in the groundwater circulation system changes with increasing pressure and temperature. Under these conditions, higher temperatures lead to potassium and magnesium excess through recrystallization- or compaction processes in pore spaces (Muller 1967), hyper-filtration (Freeze & Cherry 1979) and to a general increase in salinity due to a decline of cation exchange capacity (Schoeller 1955). In the aquifer (Type 6), the anion components in particular are being displaced in favour of sulphate content. The sulphate component increases from < 2 mmol % to 30 and 38 mmol % respectively. At the same time, the hydrogen-carbonate component declines to approximately 20 mmol %. However, chlorides are usually below 5 mmol %; nitrate, as a component of groundwater close to the surface, was not detected.

With decreasing permeability of the aquifer and with increasing depth, this prograde process in the study area, manifests itself in an increasing sulphate- and chlorite component. It increases due to longer residence times and with that more intensive water-rock-reactions to the disadvantage of hydrogen carbonate. However, this development in the lower aquifer is not uniform. This can be demonstrated by the difference of ion components of drillings at *Bow* (more favourable permeability in sand layers) and *Rier* (lower permeability in silty, fine sand layers) (Fig. 4).

In some well waters of the upper aquifer (Type 2) there were ion relationships and concentrations that deviated from developments described in the literature. These were characterized by the dominance of the chloride- and sulphate component, and at the same time by very high electrical conductivities of > 6000 μS/cm. Such ion distributions and conductivities are comparable to water samples from some produced water storage basins; yet, in mud pits a total conductivity in excess of 80,000 μS/cm and a distinctly higher potassium concentration was shown to be present (26 mmol %). The difference in conductivity between these two waters influenced by human factors can probably be explained in that there is permanent water inflow in to produced water storage basins from the production line. In the mud pits, however, there is an added concentration of salts from the drilling process and from evaporation, upon completion of drilling. During the rainy season these storage basins are being re-filled and the precipitated salts as well as the remnant salt concentrations are being diluted again.

The high potassium contents in mud pit waters are presumed to be a consequence of potassium chloride as drilling additive (Arnold 1993). But these potassium enrichment can also originate in water from pore spaces of deeper water accumulations below the alluvial groundwater circulation system (Muller 1967).

These ion balances and electrical conductivities were neither observed in surface waters nor in deeper natural groundwater. The contamination by chlorides and sulphates of drinking water wells close to the surface, can be related to selected entries of water from mud pits and produced water storage basins (based on the hydro-geological framework and the hydro-chemical evolution of waters in this climatic zone). The high salt loads have so far not been found in deeper aquifers. Other sources of saline waters, as for instance the rise of saline water from lower levels, were also not found in the alluvial sediment sequence so far explored down to approximately 300 m. Considering the groundwater flow directions (Figs 5 and 6), there can be possible entries of saline waters in the upper aquifer from the *Unity* oilfield in the North and the *Thar Jath/Mala* oilfields in the South.

7. Conclusions

The upper aquifer is selectively polluted by slowly seeping, saline waters from crude oil production, supplied regularly via storage basins and mud pits during the rainy season, as well as by constantly re-supplying produced waters. The downstream located, drinking water wells become less contaminated with increasing distance from potential contamination sources. Wells located upstream from crude oil production facilities as well as from exploration drilling sites are less contaminated with increasing distance. Wells located upstream from crude oil production facilities as well as from exploration drilling sites reveal natural groundwater conditions of the hydro-carbonate type. Based upon local groundwater flow direction, it can be shown that drinking water wells are influenced by seepage of saline waters in the northern oilfields as well as in the southern oilfields. This indicates an improvement of water quality from the upper aquifer cannot be expected through further exploration of aquifer in this region.

Using the deeper water aquifer for water supply as in Bow and Rier, hydrogeological, hydrochemical and technical well building aspects become crucial.

A hydraulic short-circuit between different water aquifers must be avoided by propper well engineering. Existing wells have been built without paying attention to hydrogeological background. Undifferentiated filters, gravel horizons, backfilling and concrete plugs cannot ensure a hydraulic sealing. This may cause the seepage of saltwater from upper aquifer to the lower groundwater source. An increasing yield due to the population growth boosts this effect.

For the first time, filter segments and seals adapted to the geology were built at *Bow* and *Rier* (Fig. 9 and 10). This effectively prevents production-related, vertical transport of salts from the first – into the second aquifer. On the basis of water analysis, it can be shown that this separation of levels also has hydrochemical relevance. For future drinking water explorations in this area it is important to preserve the aquiclude between the two different aquifers. Moreover, the production rate from such wells must not lead to seepage from the first into the second aquifer due to high feed rates. A hydraulic overload of the second aquifer must be anticipated. Chlorides of the contamination sources will not be retarded by the above mentioned clay horizon, but leads to an increased concentration in the second aquifer.

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