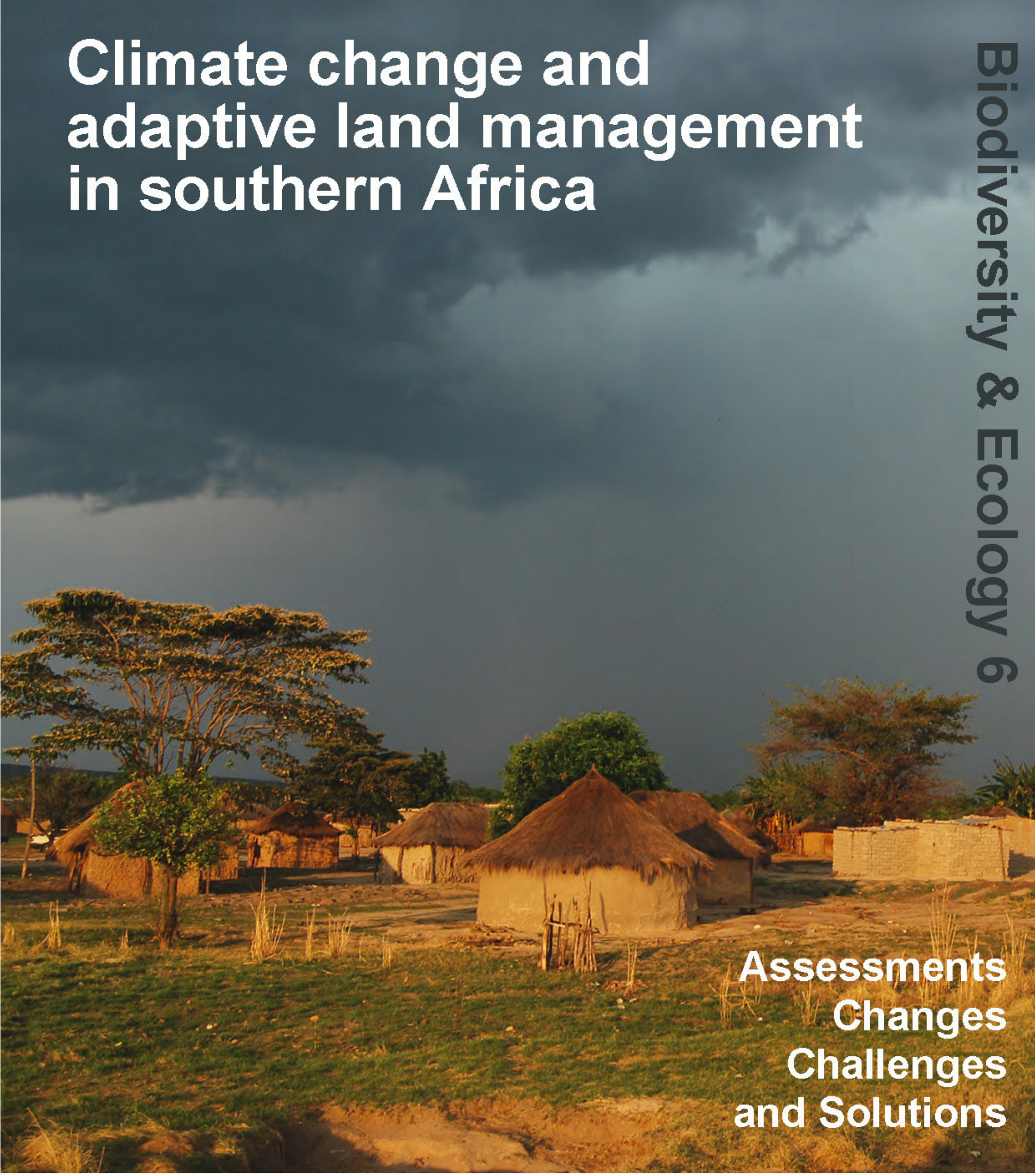
Climate change and adaptive land management in southern Africa

Biodiversity & Ecology 6



Assessments
Changes
Challenges
and Solutions

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Climate change and adaptive land management in southern Africa

Assessments, changes, challenges, and solutions

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Water resources

Deep, semi-fossil aquifers in southern Africa: A synthesis of hydrogeological investigations in northern Namibia

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Abstract: Groundwater is a key resource throughout southern Africa. Shallow aquifers are generally easy to access, but are often saline and highly vulnerable to contamination. Deep, semi-fossil groundwater resources are difficult to investigate and explore (e.g., spatial extent, volume of stored water, recharge volume, location) but potentially contain large volumes of water of excellent quality. Within SASSCAL, the opportunity to investigate a newly discovered deep aquifer in northern Namibia opened up. This article provides a summary of key findings emerging from research within SASSCAL and previous investigations. In summary, the main findings of these investigations are as follow:

i) Fresh-water in the deep Ohangwena 2 (KOH-II) aquifer is not of fossil origin (i.e., recent recharge exists).
ii) The recharge area of the KOH-II is located in the foothills of the Angolan highlands.
iii) The volume of recharge is low (less than 1 percent of mean annual precipitation).

Although these findings need to be confirmed by further scientific studies and additional drillings, especially to determine the exact extent of the aquifer system, the lessons learnt from more than three decades of investigations in this area allow the formulation of a new strategic orientation for groundwater prospecting in southern Africa: Rather than carrying out extensive drilling, the exploration strategy should be carried out similarly to the exploration for hydrocarbons, where first the tectonical boundary conditions and the sedimentological features are determined. This requires transboundary coordination and extensive planning, but it is the only way to systematically investigate deep, supraregional aquifer systems.

Resumo: As águas subterrâneas representam um recurso-chave em toda a África Austral. Aquíferos pouco profundos são geralmente fáceis de aceder, mas são muitas vezes salinos e altamente vulneráveis à contaminação. Os recursos de águas subterrâneas profundas e semi-fósseis são dificeis de investigar e explorar (e.x.: extensão espacial, volume de água armazenada, volume de recarga e localização), mas contêm potencialmente grandes volumes de água de excelente qualidade. No contexto do SASSCAL, surgiu a oportunidade de investigar um aquífero recentemente descoberto no Norte da Namíbia. Este artigo fornece uma síntese das descobertas chave provenientes da investigação do SASSCAL, bem como de estudos anteriores. Em resumo, as descobertas principais destes estudos são as seguintes:

i) A água doce no aquífero profundo de Ohangwena 2 (KOH-II) não é de origem fóssil, i.e., existem recargas recentes.
ii) A área de recarga do KOH-II localiza-se no sopé das Terras Altas de Angola.
iii) O volume de recarga é baixo (menos de 1 porcento da precipitação média anual).

Embora estas descobertas necessitem de ser confirmadas por novos estudos científicos e perfurações adicionais, em especial para determinar a extensão exacta do sistema de aquíferos, as lições recolhidas ao longo de mais de três décadas de investigação nesta área permitem a formulação de uma nova orientação estratégica para a exploração das águas subterrâneas no Sul de África: Em vez de se realizarem perfurações extensivas, a estratégia de exploração deverá ser realizada de forma semelhante à da exploração de hidrocarbonetos, onde são primeiro determinadas as condições dos limites tectónicos e as características sedimentológicas. Isto requer coordenação transfronteiriça e planeamento extensivo, porém, é a única forma de investigar sistematicamente sistemas de aquíferos profundos e supra-regionais.

Introduction

Namibia is a country of hydrological extremes. Hyperarid climatic conditions dominate at its coasts and in the desert, while other regions experience devastating floods almost every year. From almost no rainfall in the Namib Desert, annual precipitation increases towards the interior of the country, reaching values of around 600 mmy^{-1}, and even 800–900 mmy^{-1} further north (Fig. 1;

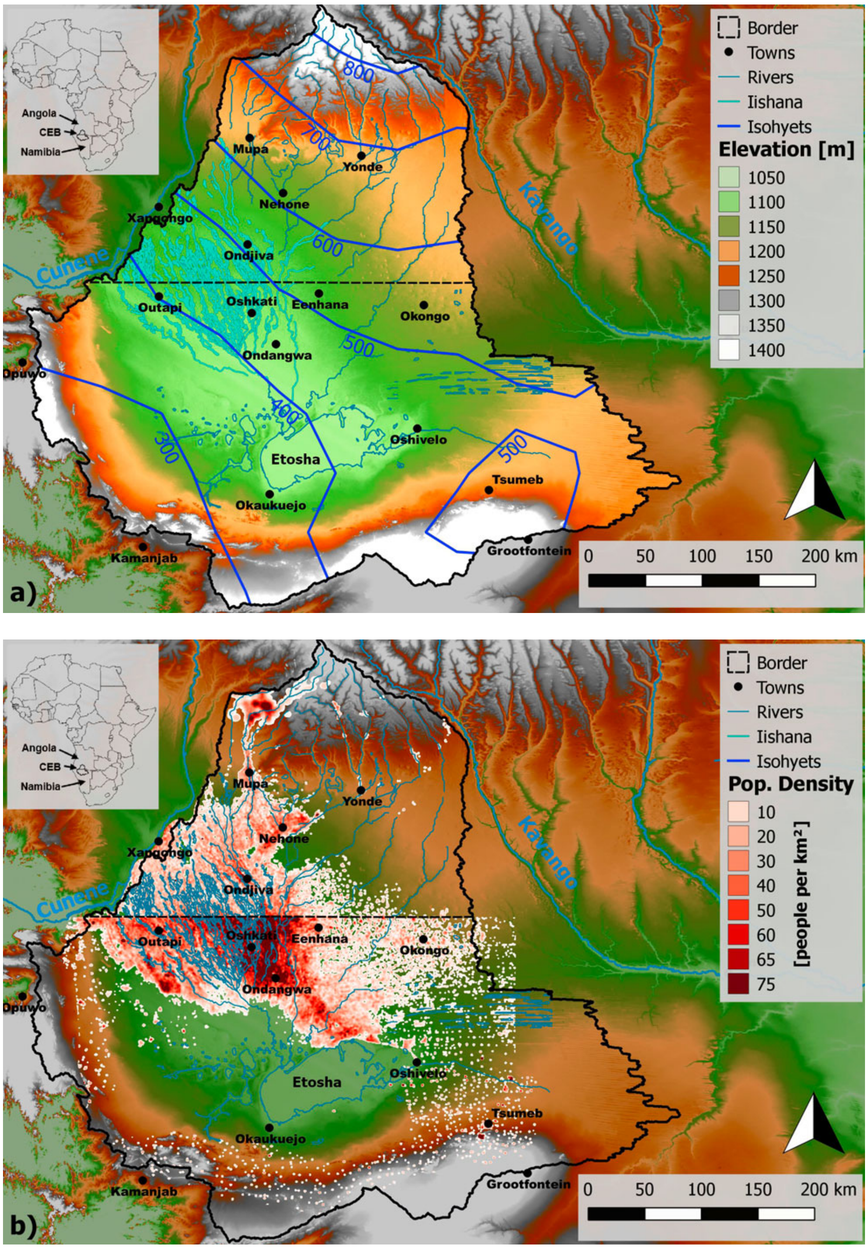

Figure 1: The Cuvelai-Etosha Basin (CEB) and its location within Africa: (a) digital elevation model (DEM) of the CEB, river network, and isohyets; (b) population density (unit: number of people per km²)

Mendelsohn & Weber, 2011). Although these values appear comparable to those of central Europe at first glance, potential evapotranspiration is five to six times higher than rainfall in Namibia because of the higher annual average temperatures and lower relative humidity (Mendelsohn et al., 2013; Mendelsohn & Weber, 2011). A water balance approach would leave little or no remainder for groundwater recharge (Hendrickx et al., 2005). Indeed, the genesis of recharge in such environments is commonly limited to extreme events or flooding, and its amount must be very low (< 5% of annual precipitation; Healy, 2010; Koeniger et al., 2016; MacDonald et al., 2012; Taylor et al., 2012).

In addition, the character of the rainy seasons is highly variable (e.g., with regard to the beginning and end of the rainy season, the number of extreme events), creating an additional challenge for water resources management (Beyer et al., 2016b). The southern winter is characterised by long dry periods lasting several months, during which there is little precipitation (May–October). Spring and summer are the rainy months, with a minor wet season (November–December) and the core rainy season (January–March). In this period, the shallow aquifers are recharged, and most of the rivers show flowing surface water for a few weeks or days. Over a time span of approximately 10 to 15 years, longer periods of aridity and low annual precipitation alternate with wetter, "good" periods (Mendelsohn & Weber, 2011; Mendelsohn et al., 2013). In addition to this periodical behaviour, the year-to-year variability is also vast (Beyer et al., 2016b). The years 1992 and 1993, for instance, were characterised by extreme aridity, which led to a decline in harvests and a loss of livestock (up to one third). On the other hand, repeated periods of extreme precipitation also occur, causing widespread flooding, particularly in the northern parts of the country. This is expected to persist – or even worsen – in the future (e.g., Beyer et al., 2016b). The northern central part of Namibia is home to more than 40% of the Namibian population (Fig. 1) (Mendelsohn et al., 2013; Mendelsohn & Weber, 2011). Strong population growth, which goes hand in hand with increasing urbanisation, a growing agricultural sector, and notable rise in tourism, increases the risk of water shortages.

The Ovambo Basin and its groundwater

The investigated surface water catchment, known as the Cuvelai-Etosha Basin (CEB), is a sedimentary, intracontinental endorheic basin in which the Etosha Pan – with its numerous salt lakes – represents the lowest point. The northern part of the catchment extends over parts of southern Angola up to the Angolan highlands in the southeast (Fig. 1). The subsidence and sedimentation zone of the tectonically formed Owambo Basin (as the basin is commonly known) covers almost the same area as the CEB but extends farther to the east (Fig. 2) (Lindenmaier et al., 2014). The Owambo Basin became part of the larger Kalahari Basin during the Cretaceous with the opening of the South Atlantic. Both the sedimentation and subsidence rates accelerated from the Cretaceous-Tertiary boundary, ultimately giving rise to a sedimentary thickness of almost 400 m to 600 m in the centre of the basin (Miller et al., 2010, Miller 2008).

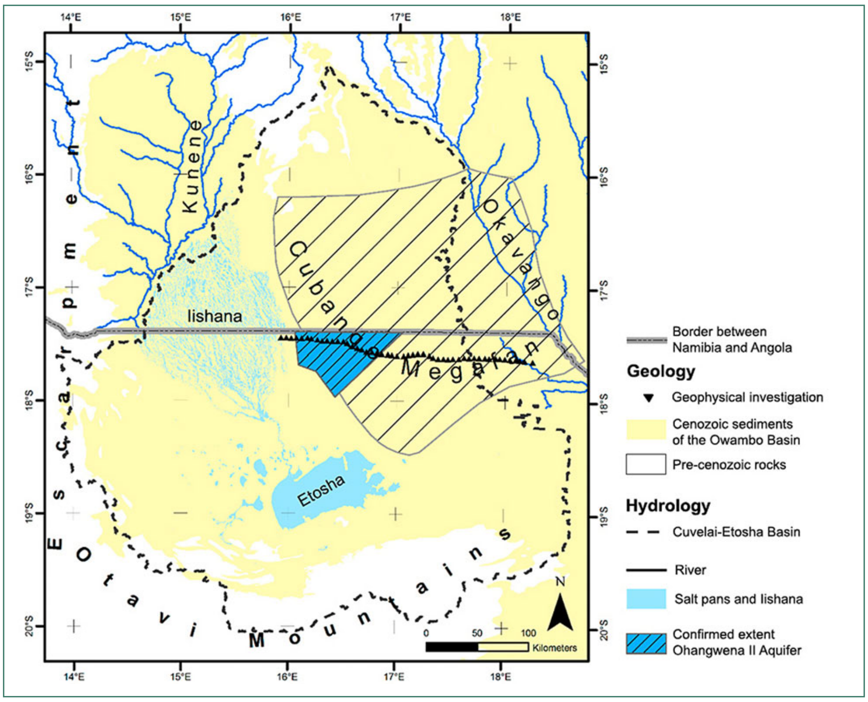

Figure 2: The CEB (surface water catchment) and the Cubango Megafan in Angola and Namibia and the current (confirmed) extent of the Ohangwena 2 (KOH-II) Aquifer.

Whereas shallow groundwater from the perched aquifers (Ohangwena 0, KOH-0) is suitable for drinking in most areas (electrical conductivity [EC] ranges of 52–296 µS/cm), the first continuous upper aquifer (Ohangwena 1, KOH-I) has only limited potential for drinking water (EC ranges of 500–1200 µS/cm) (Hamutoko et al., 2017; Wanke et al., 2018). Salinity is still tolerable in the eastern parts of the CEB, but increases markedly towards the west. In these regions, groundwater is not suitable for drinking, for livestock, or for irrigation of agricultural areas. Water supply has, therefore, for many decades depended on open canals and a dendritic system of small-diameter pipelines supplied from the Caleque Dam in Angola. Despite this water supply scheme, growing demand and the water losses from the existing system, as a result of seepage and evaporation, create a challenge for supplying the population with drinking water.

To find solutions for the ever-increasing pressure on water resources, several groundwater projects in the north of Namibia were undertaken during the last 18 years, with the ultimate discovery of a deep-seated, freshwater-containing aquifer.

Initially an opportunistic discovery, then focus of targeted exploration: A brief history of the Ohangwena 2 (KOH-II) aquifer

Drilling in the Ohangwena region in the northeast of the CEB in the 1970s and 1980s, as part of the governmental water development and drilling programme, rarely went deeper than 100 m. This situation changed, more or less by accident, when drilling an exploration well near Eenyama as part of a government programme to ameliorate the consequences of a drought. The well was drilled beyond the conventional depth of 150 m, down to a total depth of 259 m. After penetrating a sequence of silts and claystone, an aquifer containing freshwater of good quality was encountered below approximately 240 m in depth. Although this well did not reach the base of the aquifer, it quickly became clear that this new, confined aquifer with a pressure level higher than that of the brackish upper aquifer (i.e., subartesian) might represent a valuable new water resource. At this time, however, nothing was known about the geological setting and the hydrological parameters of this aquifer (in particular for the Angolan part), or even its hydrogeological connection to recent or subrecent recharge areas. About a dozen deep monitoring and pumping wells were drilled and two of them were cored. The aquitard separating KOH-I and KOH-II consists of fine sandy and silty sediments with a high clay content. Clay-mineralogical investigations showed that the presence of swelling clay minerals in the pore spaces is responsible for the strong hydraulic sealing effect of the aquitard (Dill et al., 2013). The low permeability was confirmed by hydraulic tests on water-saturated and triaxially pressurised sediment samples (Dill et al., 2013; Lindenmaier et al., 2014). Although the dry core material appeared to be of high porosity, the hydraulic tests carried out under the aforementioned conditions showed that swelling of the clay minerals caused very low hydraulic conductivities on the order of 10^{-9} m s^{-1}. This finding emphasizes the sensitivity of the aquitard with respect to external influences: Such swelling clays are difficult to drill, and therefore have to be penetrated carefully and covered by a strong and continuous casing string. Additionally, the annular space needs to be sealed to prevent flow between the aquifers, especially of brackish water downwards. It is of utmost importance that the pressure level of the deep aquifer must not fall below the bottom of the aquitard during pumping.

The hydraulic pump tests carried out in the aquifer system revealed permeability coefficients on the order of 10^{-6} to 10^{-5} m s^{-1} (Dill et al., 2013). This range corresponds approximately with the permeability deduced from granulometric and hydraulic tests. Because of the thickness of the sediments, combined with the high porosity and relative homogeneity, this aquifer is considered highly productive. An example of a well and sedimentological log from one of the deep drillings from northern Namibia is shown in Figure 3.

The crucial question: Fossil groundwater body or current groundwater recharge?

The key question to be answered with respect to the future use of this new water resource is whether it is a fossil deposit or whether the aquifer receives recent groundwater recharge. Even with low recharge rates, the enormous size of the

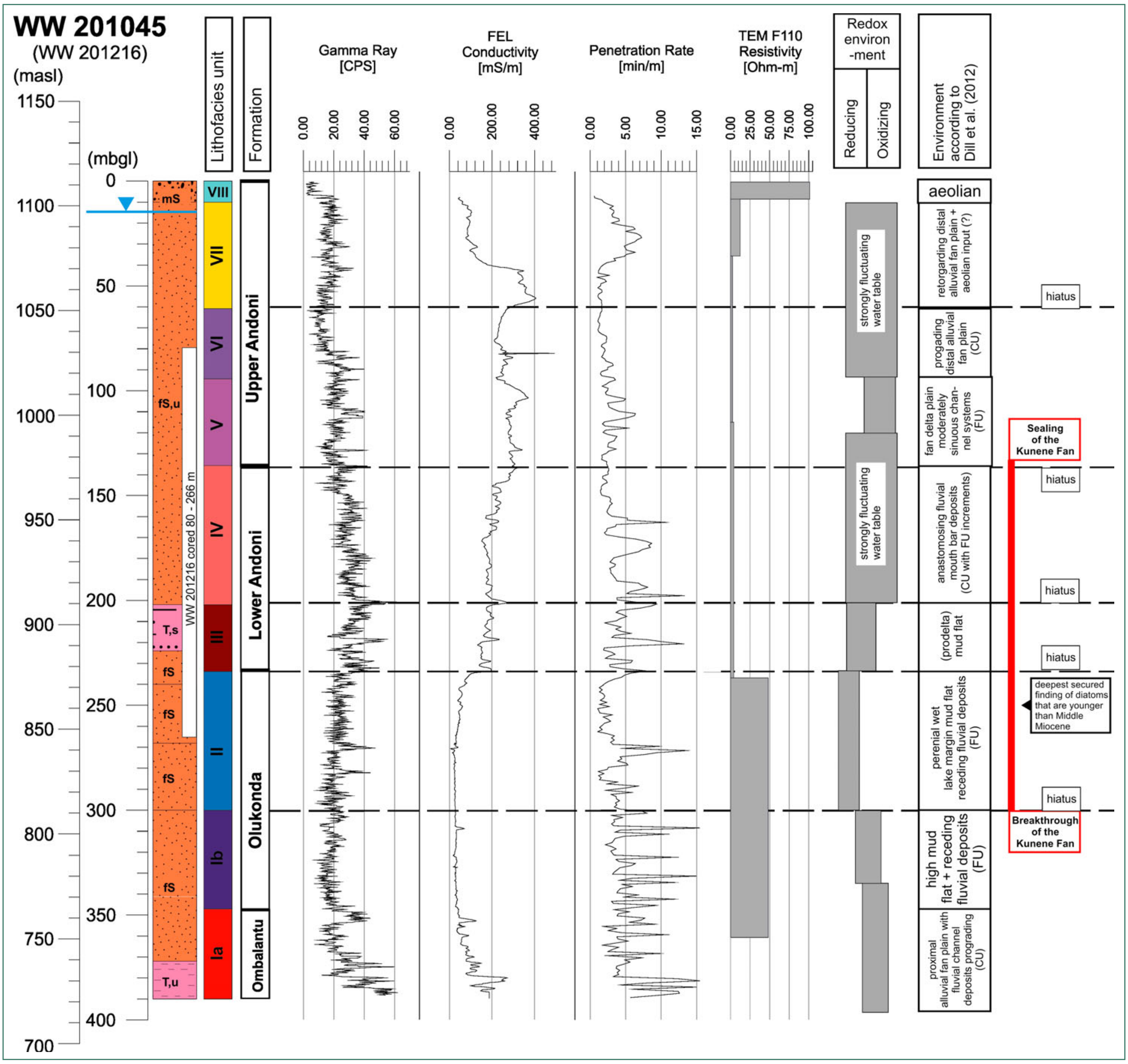

Figure 3: Example of sedimentological and well log as well as geophysical tests from one of the deep drillings in northern Namibia (modified after Lindenmaier et al., 2014)

potential recharge area means that large volumes of water could be involved; hence, knowing the approximate amount of recharge – if existent – might open up an avenue for developing sustainable extraction schemes. If the KOH-II were a fossil aquifer, no sustainable management would be possible in principle. In that case, the new groundwater deposit would have to be seen mainly as a strategic resource for use during extreme droughts. The presence of potential groundwater recharge areas was suspected previously from an initial analysis of satellite images in the neighbouring outcrops of the Angolan highlands. However, only sparse hydrogeological information is available from this area. The Angolan part of the CEB is hardly accessible, even years after the end of the civil war in Angola in 2002, because it has not yet been completely cleared of mines. The part of the Cubango Megafan (Fig. 2) located in this area, as well as the neighbouring Angolan highlands, however, are the key for understanding this transboundary groundwater system.

Within SASSCAL, the opportunity to carry out scientific research on the deep aquifer system emerged. Together with a local partner, the University of Namibia (UNAM), and with the support of the German Aerospace Center (DLR), key questions related to the deep Ohangwena 2 aquifer (KOH-II; Lindenmaier et al., 2014) were investigated:

- Is there recent groundwater recharge, or is the water in KOH-II solely of fossil origin?
- Where does the recharge originate?
- What is the approximate rate of current recharge?

Answering these questions is an essential step to determine the sustainable extraction rate, a prerequisite for sustainable management of groundwater resources.

Methods

Indicators of recent groundwater recharge?

Satellite radar interferometry (InSAR) has been shown previously to be a useful

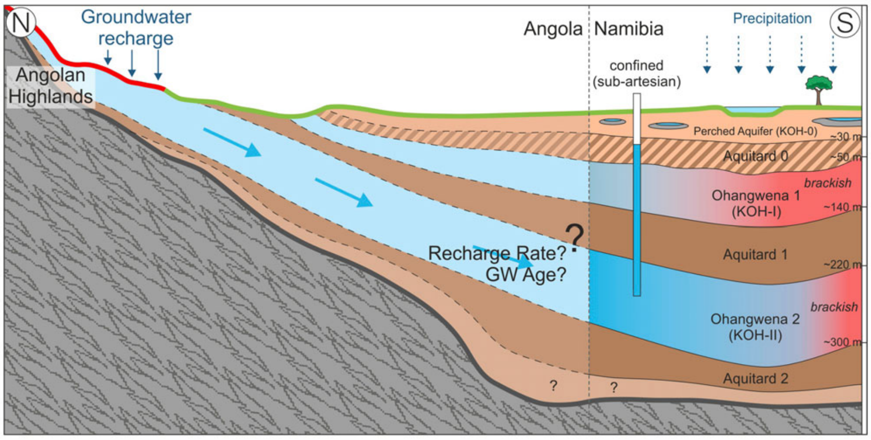

Figure 4: Schematic, vertically exaggerated section of the aquifer system showing the perched aquifer Ohangwena 0 (KOH-0; 0–30 m below surface); brackish Ohangwena 1 (KOH-I; 30–50 m below surface) and the deep, semi-fossil aquifer Ohangwena 2 (KOH-II; ca. 220–300 m below surface (Lindenmaier et al., 2014; Wallner et al., 2017). Also highlighted is the potential recharge area in Angola.

tool for the analysis of ground uplifts and subsidence processes on a regional scale, which can be used to study groundwater recharge or aquifer depletion (i.e., Bell et al., 2008; Ferretti et al., 2014, Hanssen 2001, Lu & Danskin, 2001). Here, we apply the concepts of InSAR to evaluate the possibility of infiltration at the foothills of the Angolan highlands to the outcrops of the KOH-II aquifer (Lindenmaier et al., 2014). The method can – in brief – be described as follows:

A satellite sends radar waves to the land surface and detects the signal reflected by the ground surface (e.g., in 3 m x 3 m pixels).

This procedure is repeated in time intervals (e.g., every two weeks).

The phase difference for each pixel between subsequent overflights is compared between the images. In this way, uplift or subsidence processes at an extremely high resolution can be identified.

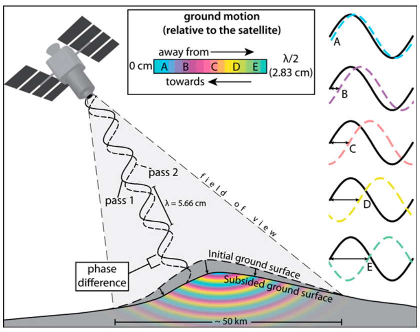

Figure 5: Principles of radar interferometry (InSAR) for the detection of changes in the land surface. [Source: http://volcano.si.edu/volcanoes/region13/hawaii/maunaloa/3705mau2.jpg]

The principle of radar interferometry is depicted in Figure 5.

Within SASSCAL task 010, the DLR provided a strip survey (interval ca. two weeks; temporal coverage between July 2015 and February 2016) using the TerraSAR-X satellite, with a horizontal resolution of 3 m x 3 m and a vertical resolution of a few millimetres. For a pilot area located in the Angolan part of the CEB (Fig. 6), TerraSAR-X data were processed and interpreted as explained above. In addition, the thermal bands of Landsat and MODIS imagery were used for the pilot area (Fig. 6) to detect characteristic features (e.g., wetlands).

Where does current recharge originate? What is the approximate magnitude of current recharge?

The satellite image evaluation formed the basis for the development of a conceptual regional numerical groundwater model (for details of the model set-up, see Wallner et al. (2017). It covers the upper CEB and includes all existing hydrological, hydraulic, sedimentological, and hydrogeological information. Measured groundwater level fluctuations in the KOH-II revealed a seasonal signal, pointing at seasonal groundwater recharge. An initial geological analysis showed that the KOH-II crops out into the foothills of the Angolan highlands. The recharge area has thus to be sought there. However, the exact location and size of the recharge area was unclear. Theoretically,

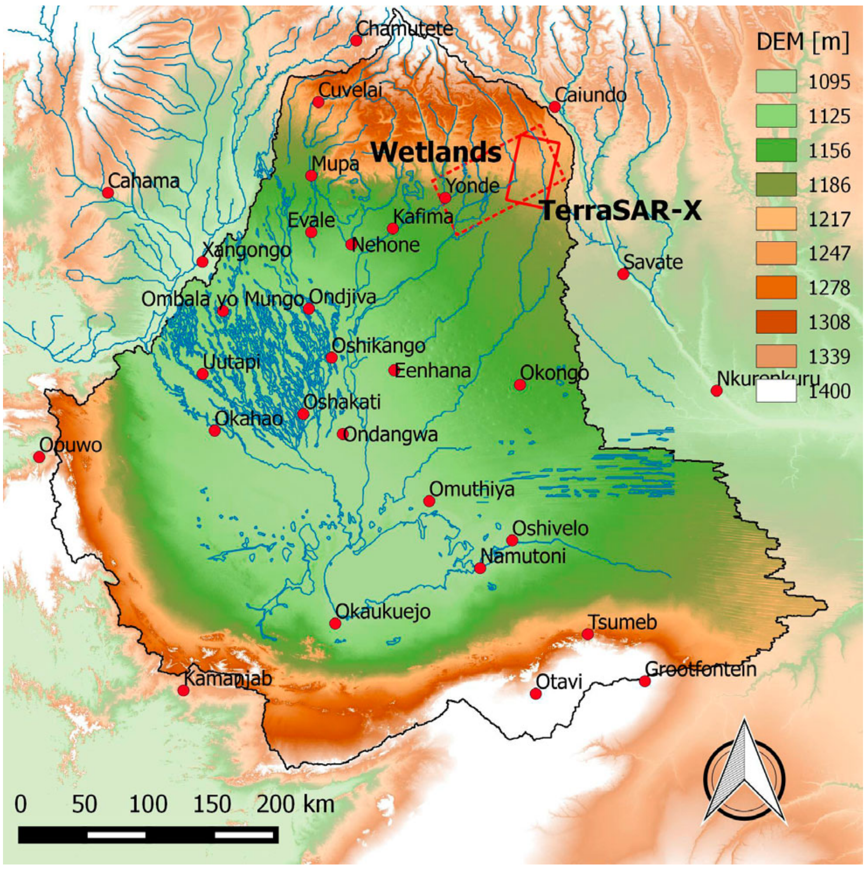

Figure 6: Pilot area chosen for the analysis of vertical ground movement using TerraSAR-X data.

recharge could stem from infiltration at the foothills of the Kunene highlands in the northwest and the Angolan highlands in the north. Potentially, an exfiltration from the Cubango River to the northeast is also possible. Since correct boundary conditions, especially for water inflow, are essential for any model analysis, the boundary conditions had to be identified by modelling itself. In a heuristic modelling approach, a set of 143 physically realistic boundary conditions were defined and implemented in the subsequent calculations. The least-squares measure was used to identify plausible and physically realistic model runs realisations that gave the best match to (a) the groundwater levels measured in the observation wells, (b) the flow direction inferred from the groundwater contour maps, and (c) the age of the groundwater determined using the radiocarbon method (^{14}C). The latter was assigned a lower weighting than the previous two. We refer to Wallner et al. (2017) for a detailed description of methods and data.

Results

The satellite data were employed to evaluate whether seasonal infiltration at the foothills of the Angolan highlands might occur. In Figure 7, the relative changes in the soil surface for the dry season (period of analysis: June 12–September 30, 2015; Fig. 7a) and the rainy season (November 13, 2015–February 20, 2016; Fig. 7b) are shown. During the dry season, a clear subsidence in the northeast of the analyzed strip can be identified. The subsiding area is bounded by a sharp edge (black, dotted line in Fig. 7a), which represents the zone of transition between Quaternary sediments in the centre of the basin to Neogene sediments on the edge of the basin. This area is also located at the foothills of the Angolan highlands (recharge area)—that is, where the surface area becomes flat.

South of this edge, an uplift of up to 10 mm is clearly visible. This uplift is present across different vegetation forms (not shown here; see Mendelsohn et al., 2013; Mendelsohn & Weber, 2011). There are several possible causes for uplift and subsidence. One involves swelling processes of the soil clay minerals, whilst other factors can be attributed to hydromechanical effects in the pore spaces of the aquifer itself. Because no salt crusts or similar features were identified during the dry season in the satellite images of the uplifted areas, and because these areas are wetlands, one can assume that the uplift taking place during the rainy season must be caused by the infiltration and/or transport of water. This confirms the hypothesis that water indeed percolates towards the deeper aquifer layers at the foothills of the Angolan highlands where the deep aquifer crops out (i.e., towards KOH-II). Because Figures 7a and 7b indicate uplift during both the wet and dry seasons, one might interpret that this process is occurring seasonally. However, this hypothesis needs to be investigated further and confirmed by ground-truthing. Currently, the preliminary results from the radar interferometry are complemented

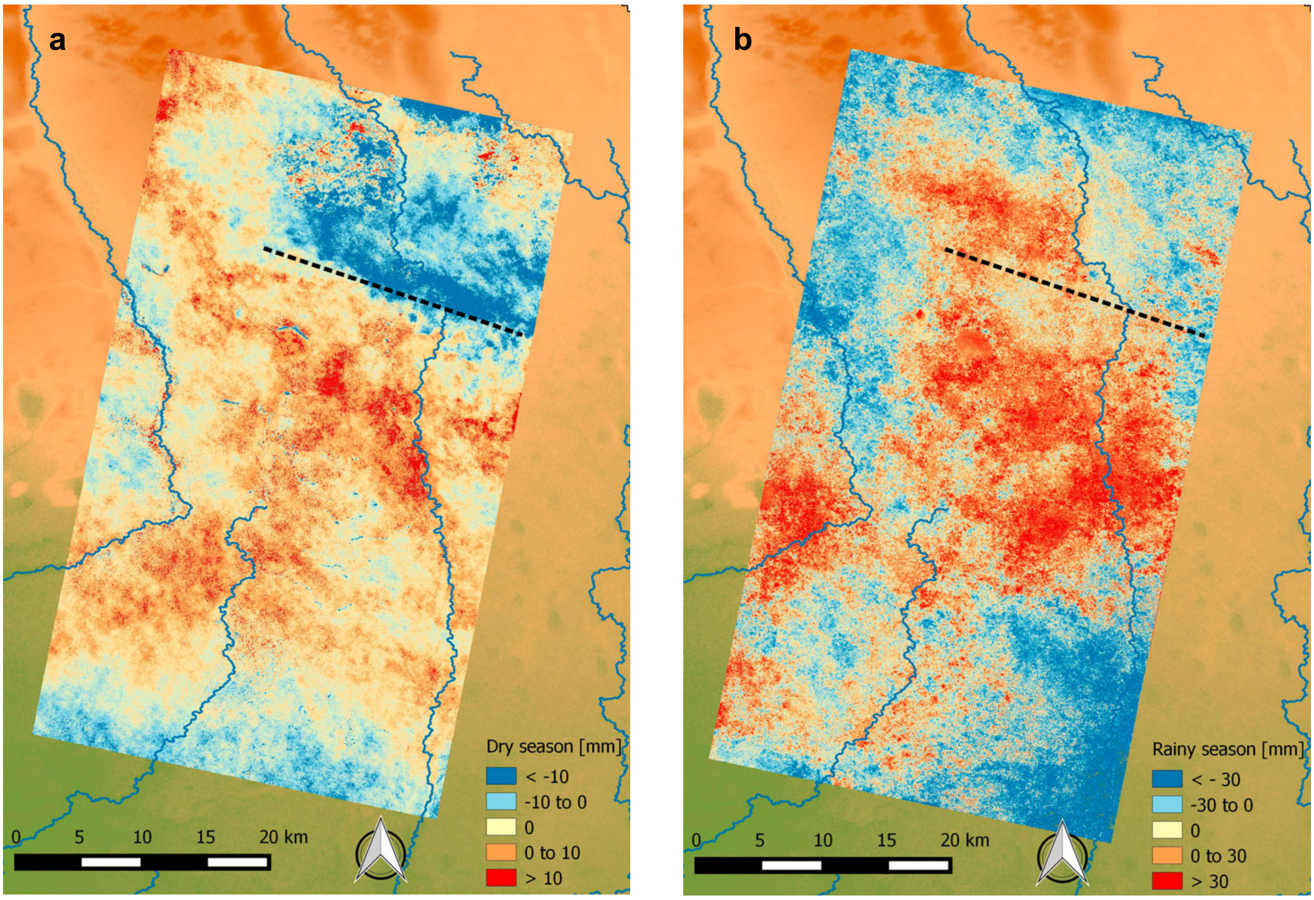

Figure 7: Processed TerraSAR-X images of the surveyed area (CEB, northern Namibia and Angola) (a) during the dry season and (b) during the rainy season. Red colour indicates uplifting, blue stands for subsidence (colour scales are not identical for (a) and (b)).

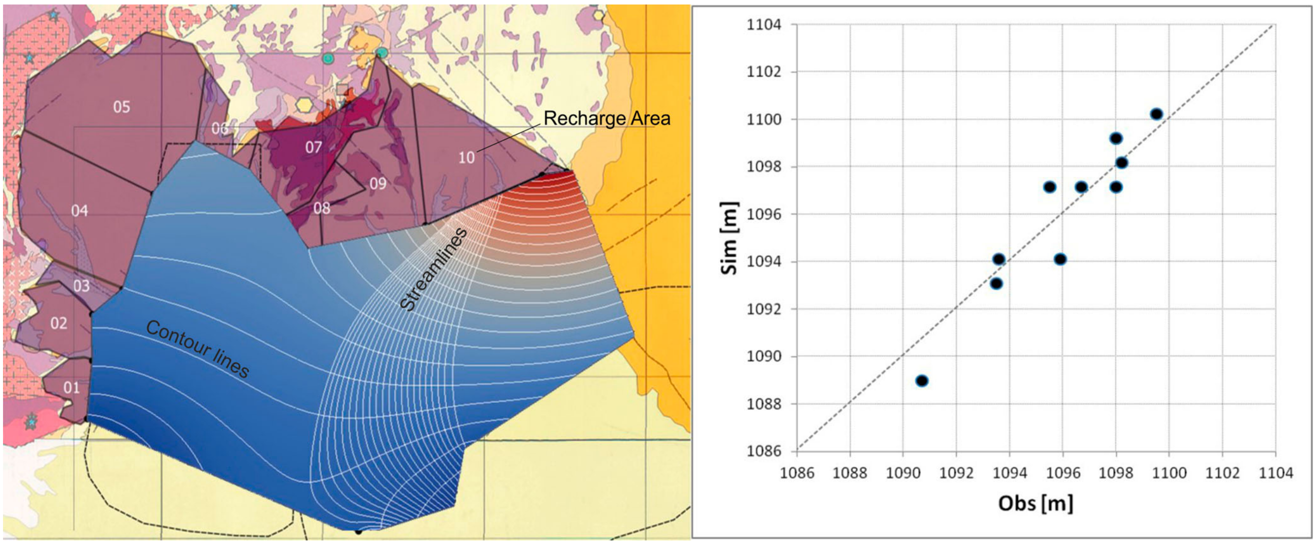

Figure 8: Potential recharge pathways to the Ohangwena 2 aquifer, groundwater contour lines, and streamlines (left); scatterplot of the simulated and observed groundwater levels based on the best realisations of numerical modelling (right) (modified after Wallner et al., 2017).

by an analysis of lineaments and further interpretation of DEMs and other satellite-derived products (e.g., Landsat, MODIS) to improve the confidence in the abovementioned findings.

The numerical flow model showed that recharge comes predominantly from the foothills of the Angolan highlands in the north of the CEB. Infiltrations from the Kunene highlands and from the Cubango River are negligible and small, respectively. Recharge rates constitute less than 1% of total rainfall, yielding recharge volumes of a few million cubic meters per year. This would be the maximum sustainable yield available for extraction. The results of the modelled scenarios, together with the measures for the goodness-of-fit for the best model realisations, are shown in Figure 8. A detailed documentation of the model results can be found in Wallner et al. (2017).

In conclusion, these – even though preliminary – findings suggest that the KOH-II is actively being recharged, but only at very low rates. Based on the numerical models (root mean square error for groundwater levels is 0.82), recharge is less than 1% of the mean annual precipitation. We explicitly state that these results need to be confirmed and reevaluated once an expanded database is available. Further scientific and technical cooperation projects, perhaps under the umbrella of a continuation of SASSCAL, involving the Angolan part of the CEB are urgently needed. Nevertheless, the confidence that recharge from Angola occurs is high based on the presented evidence.

Discussion

From exploration to utilisation

The discovery of the new groundwater resource attracted not only the national but also international media; consequently, hopes and expectations for an improved

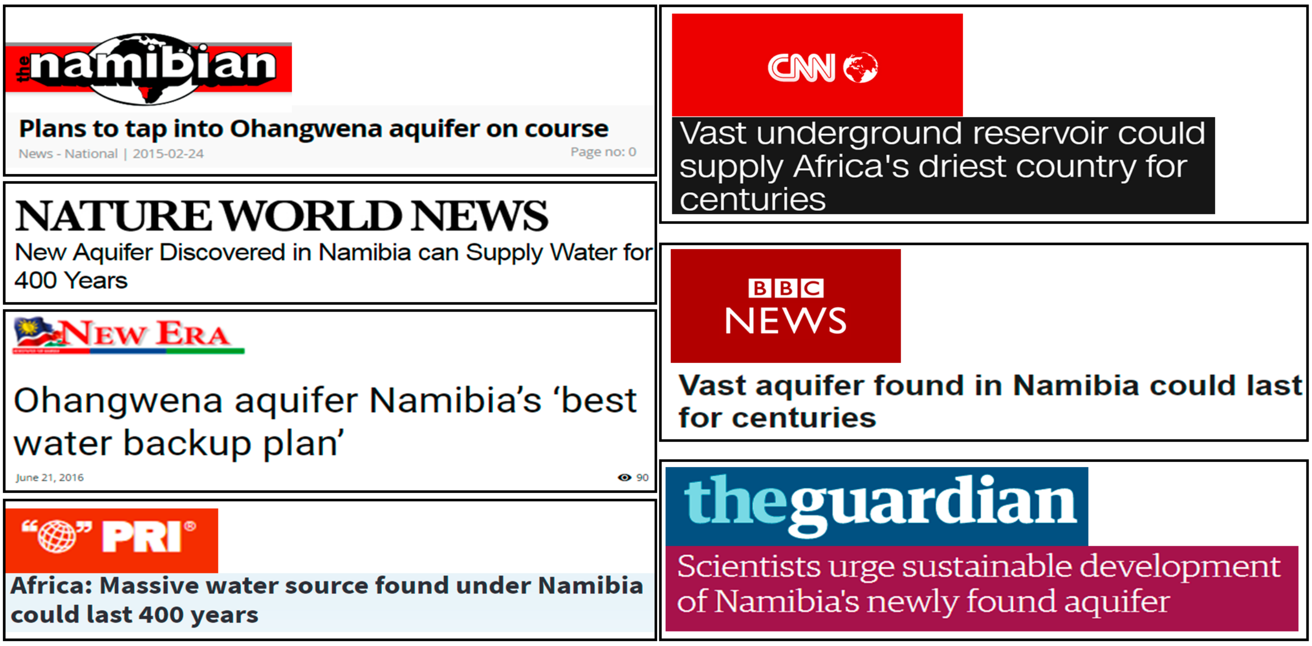

Figure 9: Media echo on the discovery of the Ohangwena 2 aquifer.

water supply for the population were great, in particular for rural communities.

The wet years 2009 to 2011 were followed by a severe drought. Many families in the CEB lost more than half of their livestock. This caused the Namibian government to consider making use of water from the new aquifer (personal communication, as of June 2016) even though neither the exact extent nor the amount by which the KOH-II is recharged is sufficiently known. This simple example demonstrates the key role the newly discovered aquifer will play in the future water supply of northern Namibia and which challenges and opportunities it poses for political decision makers in Namibia and Angola. Even though reliable data on the extent and internal structure of the aquifer are currently available for only approximately 20% of the basin and only in northern Namibia, it is clear that a regionally and strategically important groundwater resource has been found. One of the most significant implications of the findings is the importance of protecting this resource. A first step towards this was made in assigning a protected status to the aquifer as part of the country's national planning and legislation processes.

Recently (2013 to 2017), the first wells of the national water utility company have been connected to the pipeline grid and hydraulic tests have been carried out. Additional monitoring efforts in the form of groundwater level loggers are being installed to observe the hydraulic response of the aquifer. At present, only minor abstractions are taken from KOH-II. However, the long-term sustainable use of the aquifer requires the internal dynamics of the aquifer to be recorded and described by improved groundwater models. This must be undertaken in parallel to improving the efficiency of the utilisation and investing in more economical water use. This includes, for instance, reducing leaks to a minimum in the pipeline system and reducing evaporation losses in the open canals.

The numerical modelling results indicated a few millimetres of groundwater recharge per year; currently, between 1 and 3 millimetres per year are assumed (less than 1% of mean annual precipitation). Thanks to the large size of the recharge area, however, enough water could be available to allow the sustainable use of the aquifer for the drinking water supply of the local population, but only if managed very carefully. Using the aquifer to support large-scale irrigation schemes or a long-distance water supply systems (e.g., for the capital, Windhoek) should be considered with a great deal of scepticism. This could overexploit the aquifer and lead to its degradation in the long term.

The discharge area of the newly discovered aquifer remains unclear. Since there are hardly any deep wells in the eastern and sparsely populated Kalahari, one can only speculate. One of the most plausible hypotheses is that the eastern part of the aquifer is an extremely slowly flowing system, which probably leads to a groundwater residence time of 100,000 years or more. This could be addressed only with the help of age dating using radioactive noble gases since ^{14}C analysis is inadequate for this purpose. Contacts have recently been established with the International Atomic Energy Authority (IAEA) in Vienna in this regard, and such investigations could be interesting for a future continuation within SASSCAL. Another hypothesis is that the aquifer is connected to the Graben system in Botswana, which is also characterised by deep and likely fresh aquifers, draining in the direction of the Zambezi to the east. Finally, an artesian relief towards the KOH-I aquifer around the Cuvelai Pan, where artesian wells are common, is possible.

Ways forward

The findings from both SASSCAL and earlier technical cooperation projects are encouraging, but further joint research efforts and confirmation of some of the assumptions are required. Additional numerical models are being prepared based on the established groundwater model. All modelling approaches aim at incorporating the growing amount of information on the structure, and particularly on the initial and general climatic and hydrological conditions. Although the results emerging from two completed PhD projects on groundwater recharge in the CEB (Marcel Gaj and Matthias Beyer) and on the hydrogeochemical characterisation of shallow wells in rural areas (MSc Josefina T. Hamutoko; PhD in preparation) within SASSCAL have meant a great deal of progress, these parameters continue to be the ones with the greatest level of uncertainty.

The recently discovered deep KOH-II aquifer must be considered an opportunistic discovery, and not the result of systematic exploration. It is therefore necessary to adopt a new approach to groundwater development in southern Africa that incorporates a more systematic and intentional approach to investigation. Unlike previous exploration strategies that were based on randomly drilling wells in largely unknown sedimentary sequences with unknown tectonic structures and sedimentary histories, the future exploration strategy for groundwater should pursue the same approach used in oil and gas exploration. Information is first required regarding the tectonic framework, which should be used to derive tectonic structures and boundaries, and the sedimentological background. This information allows us to estimate the hydraulic parameters and, in a final step, to identify potential supraregional aquifers. The fundamental advantage of adopting this kind of approach is not only the ability to save money and avoid drilling expensive dry holes but also to deliver an important source of information for local political decision makers.

Pursuing such an approach assumes that exploration for aquifers of this kind is based on long-term planning and has access to the necessary expertise and data. It is worth repeating that projects of this kind require an interdisciplinary approach, one that SASSCAL has adopted from the beginning. It is therefore essential to incorporate regional geophysical surveys as well as satellite-based remote sensing methods from the start.

The results provide a hopeful sign that the large intercontinental basins in southern Africa may contain more, currently unknown deep aquifers. These new resources should be treated as strategic long-term resources for water supply, however, considering the rapidly growing population. Before any utilisation, sustainable monitoring and management

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strategies have to be developed. Adaptation to climate change and socioeconomic challenges will be possible only following this approach.

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