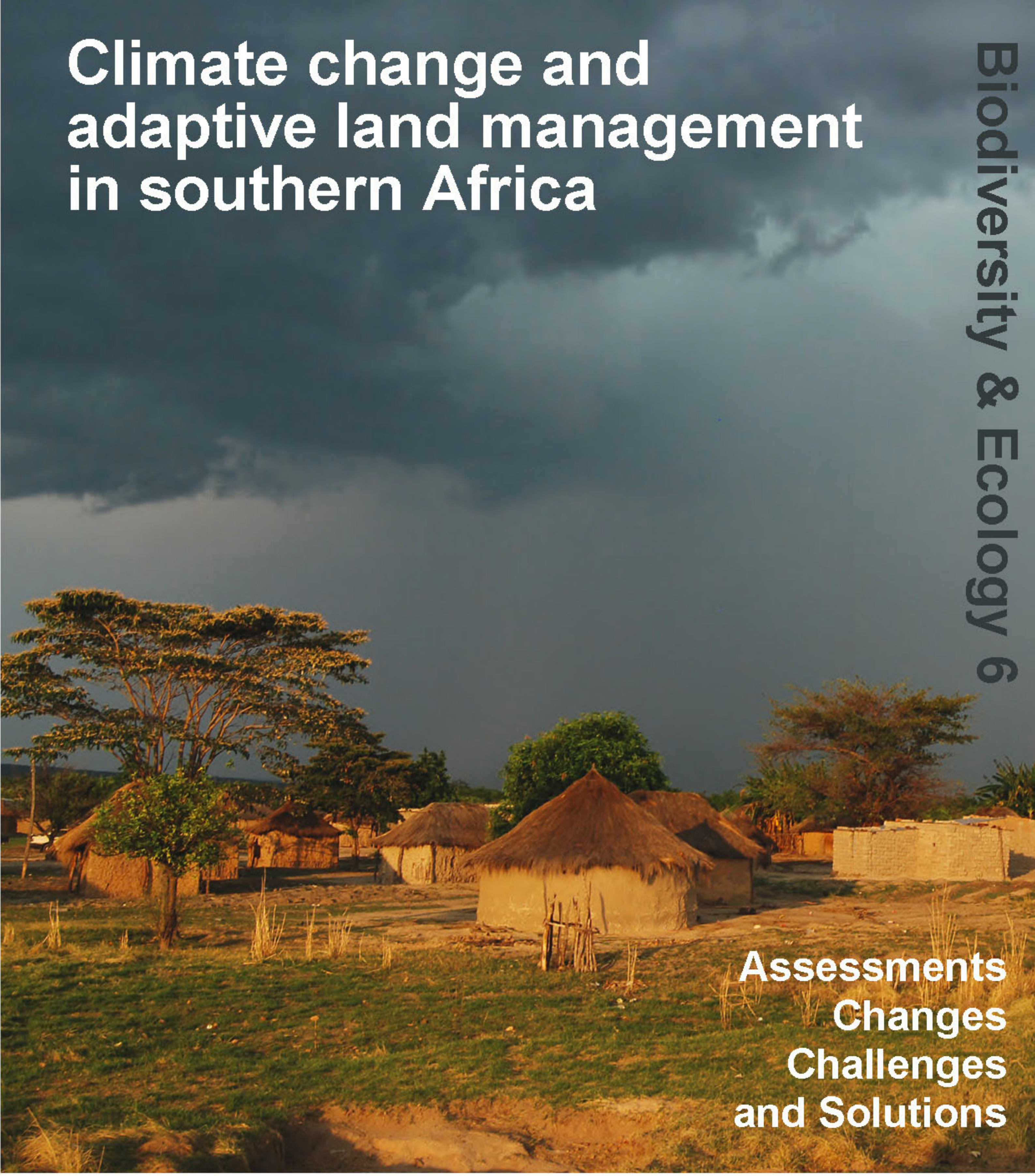
Climate change and adaptive land management in southern Africa

Biodiversity & Ecology 6



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Climate change and adaptive land management in southern Africa

Assessments, changes, challenges, and solutions

Edited by

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Water resources

The long road to sustainability: integrated water quality and quantity assessments in the Cuvelai-Etosha Basin, Namibia

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Abstract: Many arid and semi-arid regions of Southern Africa experience pressure on water resources as a result of limited rainfall, droughts, high population growth, and poor infrastructure. To satisfy domestic, agricultural, and livestock demands, multiple water sources are used, but the scientific and local knowledge on both the quality and quantity of these is limited for the study area. As part of SASSCAL Tasks 007, 010 and 014, numerous field campaigns (2013–2017) were carried out in the transboundary Cuvelai-Etosha Basin (CEB) with the aim of providing a comprehensive description of surface and groundwater resources.

The investigations reveal that sound management and coordinated use of water resources in the CEB need to be introduced. This could include, for example, adding further responsibilities to water point committees and developing management strategies based on a thorough understanding of hydrologically relevant processes. Sufficient water exists, but its quality and quantity are highly variable. Simple actions at a local scale (e.g., rainwater harvesting, fencing off wells, use of perched aquifers) could improve the situation substantially.

Resumo: Muitas regiões áridas e semi-áridas da África Austral sofrem pressão sobre os recursos hídricos, devido à precipitação limitada, às secas, ao elevado crescimento populacional e às infraestruturas precárias. De modo a satisfazer as necessidades domésticas, agrícolas e pecuárias, são utilizadas múltiplas fontes de água, mas o conhecimento científico e local sobre tanto a qualidade como a quantidade das mesmas é limitado para a área de estudo. Inseridas nas Tarefas 007, 010 e 014 do SASSCAL, foram realizadas várias campanhas de campo (2013-2017) na Bacia Cuvelai-Etosha (CEB) transfronteiriça, com o objectivo de oferecer uma descrição detalhada dos recursos hídricos superficiais e subterrâneos.

As investigações revelam ser necessário introduzir uma gestão sólida e uma utilização coordenada dos recursos hídricos na CEB. Isto poderia incluir, por exemplo, a adição de responsabilidades aos comités das fontes de água, bem como estratégias de gestão de base baseadas num conhecimento profundo dos processos hidrologicamente relevantes. Existe água suficiente, mas a sua qualidade e quantidade são altamente variáveis. Simples acções a uma escala local, como, por exemplo, colher água da chuva, vedar poços e utilizar água de lençóis suspensos, poderão ajudar a melhorar substancialmente a situação.

Introduction

Water scarcity is nothing new to the people in arid and semi-arid regions of Southern Africa. For centuries, they have learned to cope with erratic and limited rainfall, droughts, and dry wells. Human adaptability has its limits, however, and these seem to have been reached and exceeded in some places. The pressure on water resources is higher than ever before. Some rural communities are facing particularly severe difficulties managing their water resources sustainably thanks to a growing population, changing climate, or the wish for better standards of living.

An excellent example is the Cuvelai-Etosha Basin (CEB; Fig. 1), a transboundary river basin shared almost equally by Angola in the north and Namibia in the south, which is home to approximately 40% of the Namibian population. A detailed description of the study area is given in Beyer et al. (2018).

For sustainable management of groundwater resources – whether taken from shallow, hand-dug wells or pumped from deep aquifers – not only the quality of the water but also the pathways (e.g., direct infiltration of rainfall or indirect through lakes or rivers) and the amount by which the aquifer is recharged (groundwater recharge) need to be known. In the highly heterogeneous CEB, with its complex geological history and structure (Lindenmaier et al., 2014; Miller et al., 2010),

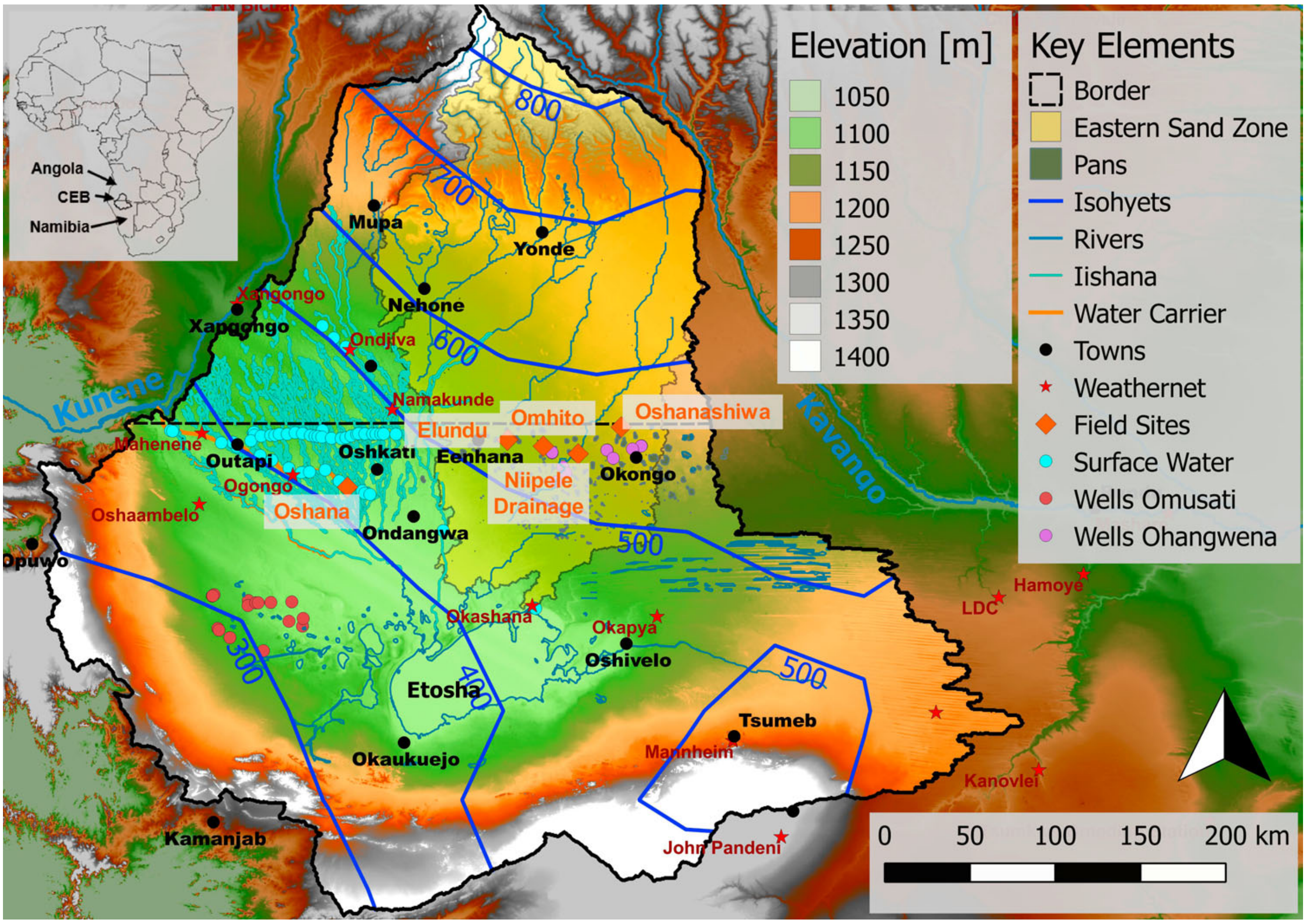


Figure 1: The Cuvelai-Etosha Basin (CEB). The figure shows a digital elevation model (SRTM) of the CEB, isohyets, and important hydrological features of the basin. Furthermore, the investigated sites for surface (turquoise circles) and groundwater (purple circles – Ohangwena Region; red circles – Omusati Region) sampling and recharge estimations (orange diamonds) are depicted. The yellow highlighted area represents the Eastern Sand Zone.

groundwater recharge–related processes are currently not well understood. In addition, there are a number of distinctive landforms present throughout the basin (e.g., *iishana*, *pans*, ephemeral riverbeds, deep Kalahari sands, shallow soils underlain by calcrete), which adds another dimension to an already complicated issue.

It is therefore the aim of this study to provide a comprehensive description of water resources in the Namibian part of the CEB. In particular, the goals are to (1) examine the quantity and quality of surface water, using the 2017 flooding events as proxy; (2) characterize

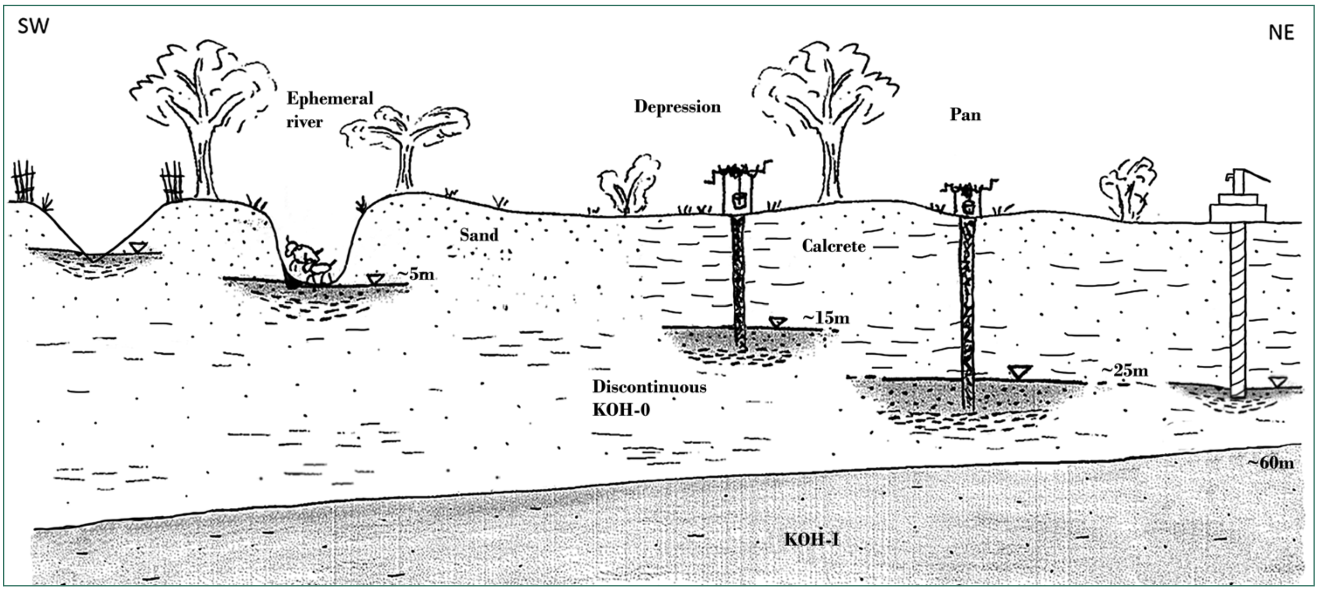


Figure 2: Schematic and vertically exaggerated view of the groundwater storeys in the study area. The graphic shows the perched aquifer Ohangwena-0 (KOH-0; 0–20 m below surface) and the regional aquifer Ohangwena-1 (KOH-1) below.

the quantity and quality of groundwater in shallow aquifers (i.e., KOH-0 and KOH-1; refer to Fig. 2); and (3) investigate recharge mechanisms and quantify groundwater recharge rates of different landforms present within the CEB.

Methods

The 2016/17 rainfall data were collected from five SASSCAL weather stations (SASSCAL Weathernet, http://www.sasscalweathernet.org/index.php) located within the basin. Fieldwork in the basin during the 2016/17 rainy season was carried out at three intervals – namely, in February at the onset of the core rainy season (60 samples), during the peak of the flood in mid-March (42 samples), and during the post-flooding stage at the beginning of April (36 samples). Sampling in both February and March included the upstream section (in Angola) of the CEB. As a result, only 22 water bodies on the Namibian side were sampled in all three field visits to permit a constant, site-specific temporal profiling. Measured parameters included flow velocity using an OTT C20 current meter with an OTT Z400 signal counter set and an impeller mounted on a 20 mm diameter steel rod; the same rod, marked with a ruler, was used to measure water depth. Turbidity (in FAU), pH, and electrical conductivity (EC) were measured onsite using Hach portable instruments. Water samples were collected for isotope measurement and analysed using a laser spectrometer (Los Gatos Research Inc., LGR DLT 100) at the University of Namibia.

To determine the quality of the shallow/local groundwater, samples were collected from 50 hand-dug wells (originating from shallow and deep hand-dug wells in small, circumscribed areas in the Ohangwena and Omusati regions, respectively; refer to Fig. 1). Ten sampling campaigns were carried out between November 2013 and May 2017, usually in the months of March (rainy season), June (early part of the dry season), August/September (peak of the dry season), and November (start of the rainy season). In the field, physico-chemical parameters – namely, pH, electrical conductivity, turbidity (in NTU), oxidation-reduction potential, oxygen content and temperature – were measured with Hach portable instruments. Samples for the determination of cations and anions were taken from each well, and the analyses were performed by Analytical Laboratory Services in Windhoek, Namibia, and at the hydrochemistry laboratory of the Federal Institute for Geosciences and Natural Resources in Hanover, Germany. The reliability of the analyses was checked by calculating the ion charge balance error on all samples. Quality was subsequently assessed using World Health Organization (WHO, 2011) guidelines.

Four independent methods for estimating groundwater recharge through the unsaturated zone were applied and improved within SASSCAL:

- The well-documented chloride mass balance (e.g., Gaye & Edmunds, 1996; Huang et al., 2017; Scanlon, 1991) as a reference method for estimating mean recharge: This method uses the relationship between chloride entering the system (through precipitation and dry deposition) and chloride in the deep unsaturated zone or groundwater to infer recharge.
- The peak-shift method using deuterium as an artificial tracer (e.g., Beyer et al., 2015; Blume et al., 1967; Saxena, 1984; Zimmermann et al., 1966): A tracer (in the present case, deuterated water, ^2H_2O) is artificially inserted into the soil and its downward displacement monitored over time. Recharge is then estimated by combining the information of water content with the distance of displacement over time (e.g., one rainy season).
- An empirical method based on soil water isotope depth profiles (e.g., Allison et al., 1984; Barnes & Allison, 1988; Gaj et al., 2016): When plotting soil water isotopes of the deep unsaturated zone in sandy areas and groundwater isotopes in dual-isotope space, a parallel shift of the former is often observed. The degree of this displacement can be used to obtain a crude estimate of recharge (Allison, 1988; Barnes & Allison, 1988).
- Groundwater level fluctuations from six shallow boreholes drilled in Ohangwena at the villages of Omboloka (2 sites, 23 and 20 m deep), Ohameva (26 m deep), Okamanya (31 m deep), Epumbalondjaba (10 m deep) and Oshanashiwa (30 m deep) (indicated in Fig. 1 as part of Wells Ohangwena) and equipped with Solinst Leveloggers: Water level fluctuations were recorded daily during the 2016/17 rainy season and measured with a water level meter in October 2016 and May 2017. Recharge rates for this specific year were obtained by multiplying the increase in water level with effective porosities obtained during a vulnerability study by Hamutoko et al. (2016). The resulting recharge value is to be seen as a conservative estimate, as water withdrawal was not considered in this simple approach.

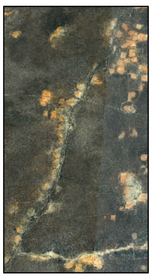
All of these methods require extensive fieldwork and deliver a point estimate of recharge. Therefore, several sites with distinct characteristics (geology, morphology, soil type, and vegetation) were chosen in order to identify landforms comprising potential recharge areas for the near-surface aquifer KOH-0. The selected landforms are summarized in Tab. 1, together with a brief description (also refer to Mendelsohn et al., 2013; Mendelsohn & Weber, 2011). For comparing these point estimates with large-scale approximations of groundwater-storage changes, a remote-sensing approach using GRACE gravity field satellite data was applied (Chen et al., 2016; Longuevergne et al., 2013; Rodell et al., 2007; Yeh et al., 2006). Recharge pathways to the deep KOH-2 aquifer were investigated by means of a groundwater model (Wallner et al., 2017) but are not the focus of this research (we refer to Himmelsbach et al., 2018).

Results

Rainfall and discharge

To characterize the discharge in relation to precipitation amount, corresponding 2016/17 monthly rainfall data from five SASSCAL weather stations situated within the alluvial plains are presented in Fig. 3. Although Mahenene station is

Table 1: Main landforms and representative sites investigated in this study.

Landform / Site	Characterization	Image
Deep sheet sands of the Eastern Sand Zone / *Elundu Forest*, *Omhito, Omboloka 1*	Characteristic landform of the Eastern Sand Zone. The unsaturated zone is dominated by sand covered by a medium-dense forest. The perched aquifer is not present here. Major (potentially deep-rooting) tree and shrub species are *Baikiea plurijuga, Acacia erioloba, Collinum combretum, Salacia luebertii, Terminalia sericea,* and *Colophospermum mopane.*	  
Dune sands and local depressions underlain by calcrete / *Oshanashiwa, Okamanya, Omboloka*	Alternating reddish sand dunes and depressions, found mainly in the Okongo region. Underlain by a thick (up to 20 m) of calcrete. Often, perched aquifers are present in this region. Vegetation is less high because of the calcrete. Depressions are often covered by hand-dug well fields.	 
Iishana / *Oshana Oshakati*	Old river channels. Flooded in the rainy season, creating an interconnected channel system in years with significant flooding. Swellable clay minerals, highly saline. Very low permeability. Grasses in the rainy season; otherwise only Makalani Palms present.	 
Pans / *Deflation Pan Elundu*	Local pans which are present throughout the Eastern Sand Zone. Winds have blown out fine material from the pans that was deposited on the leeward side, creating favourable conditions for farming. The pan itself is filled during the rainy season and used for livestock watering. Mainly carbonate-rich sands, silt, and clay fractions. Low permeability.	 
Ephemeral riverbeds / *Niipele Drainage, Epumbalondjaba*	Remainders of an old river system. Can carry surface water in years with high rainfall. In dry years and during the dry season, water is flowing below the soil surface. Coarse sand of high permeability. The filled-up river channels decrease evaporation. Often hand-dug wells near the riverbeds.	 

missing data from March 9, 2017, onwards, western Cuvelai received comparatively higher rainfall than central Cuvelai. Ogongo, in central Cuvelai, received the lowest amount, with 372 mm (17% below the long-term average of approximately 450 mm y^{-1}) for the entire season. Rainfall at Ondjiva was 24% below the long-term average of approximately 600 mm y^{-1}. All other stations received rainfall above or around their respective long-term averages. Except at Oshaambela, where rainfall

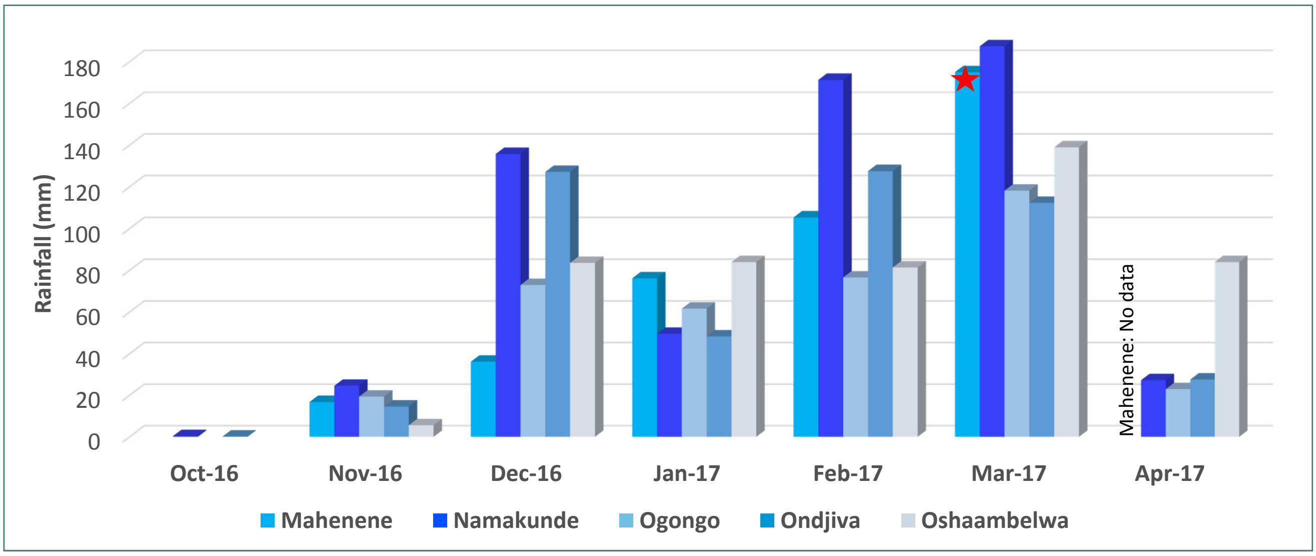


Figure 3: Distribution of rainfall for the 2016/17 rainy season. The star denotes missing data for Mahenene from March 9, 2017, onwards.

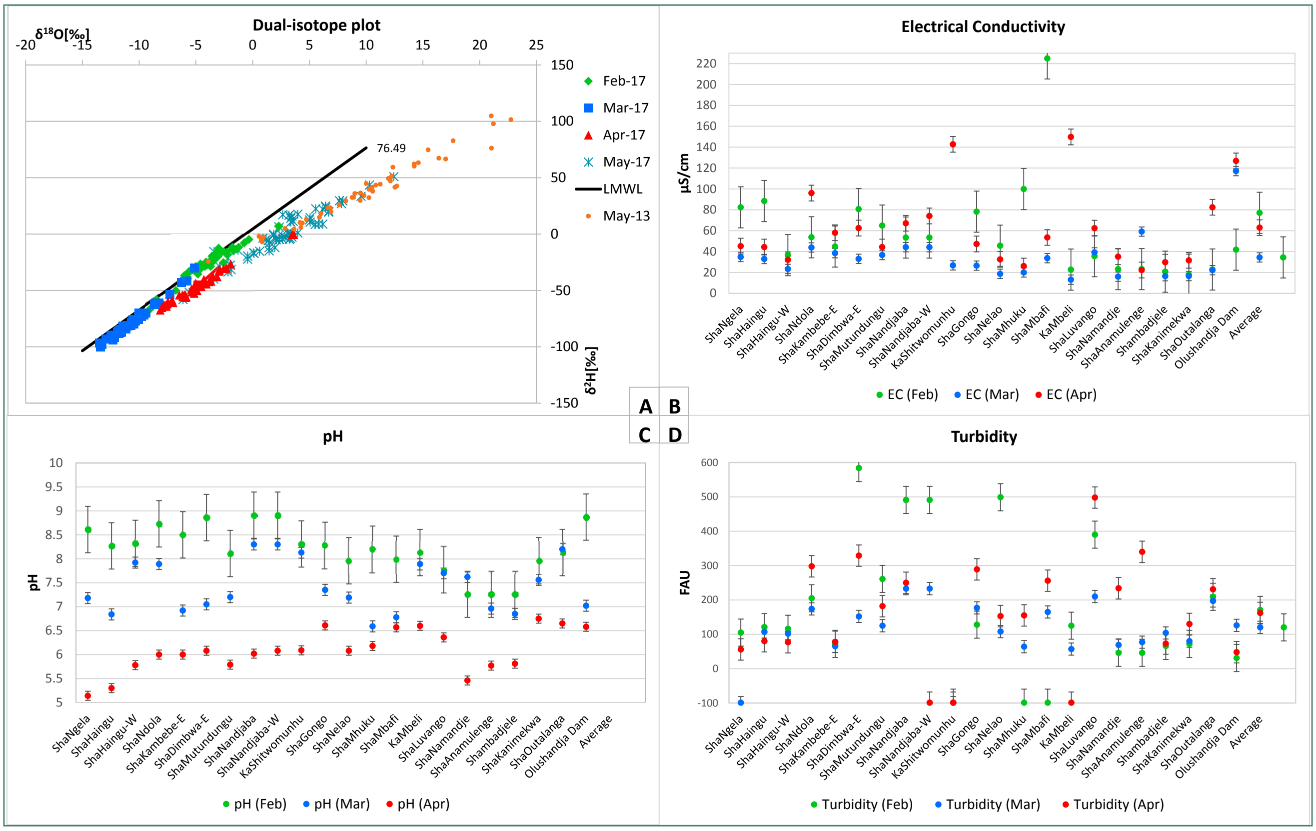


Figure 4: Stable water isotopes (A), EC (B), pH (C), and turbidity (D) following the first major rainfall (February 2017), around the flood peak (March 2017), and post-flood (April 2017) from 22 water bodies (ordered from east to west), which were consistently measured during each field visit. FAU values below 0 (-99) denote that turbidity exceeded the level of the probe. EC values of 481 µS/cm at KaShitwomunhu are not shown due to scale.

was relatively uniform from December onwards, February and March were the wettest months, accounting for more than 50% of the rainfall amount.

Subsequent discharge in iishana varied significantly in space and time. In February, just under 10 of iishana sampled were running at an average of 2.5 m^3/s (maximum recorded 3.6 m^3/s). In mid-March, more than 20 iishana were running and the average discharge increased to 7 m^3/s (maximum recorded, 13 m^3/s). There were more (26) running iishana at the beginning of April, but the average discharge of 2 m^3/s (maximum 5 m^3/s) was the lowest amongst the three field visits. Considering that there are at least 34 major iishana along the traversing 140 km road between the Olushandja Dam, Outapi, Omafo, and Odibo (an average of one oshana for every 4 km in the alluvial plains), a discharge in excess of 200 m^3/s during the flood peak was generated; the nearby Kunene River had a discharge of around 500 m^3/s at Ruacana during the same period (Namibia Hydrological Services, 2017). The dual isotope plot (Fig. 4a) documents well

Table 2: Summary of recharge rates obtained with different methods and for characteristic sites for each landform. Whenever ranges are given, multiple sites for the particular landform (e.g., with different rainfall amounts) were examined and the ranges represent the variation within these.

Landform	Investigated site	Recharge pathway	Recharge rate [mm y^{-1}]
Deep sheet sands, vegetated	Elundu Forest	direct	[*1]Mean: 9–20 mm y^{-1} [*2]Mean: 11 mm y^{-1} [*3]Mean: 5 mm y^{-1} [*2]2013/14: 29 mm y^{-1} [*2]2014/15: 0 mm y^{-1} [*2]2015/16: 4 mm y^{-1}
Deep sheet sands, bare soil	Elundu Forest	direct	[*1]Mean: 9–14 mm y^{-1}
Deep sheet sands, vegetated	Omhito School		[*1]Mean: 17–25 mm y^{-1}
Deep dune sand, vegetated	Omboloka1	direct	[4]2016/17 min: 12.5 mm [4]2016/17 max: 67 mm
Depressions underlain by calcrete	Oshanashiwa	direct/indirect	[*1]2013/14: 31 mm y^{-1} [*4]2016/17 min: 13.5 mm [*4]2016/17 max: 55.8 mm
	Okamanya		[*4]2016/17 mean: 15 mm
	Omboloka2		[*4]2016/17 min: 17 mm [*4]2016/17 max: 91.8 mm
Iishana	Oshakati	indirect	[*1]Mean: 0 mm y^{-1} [*2]2013/14: 0 mm y^{-1} [*2]2014/15: 0 mm y^{-1}
Deflation pans	Elundu Pan	indirect	[*1]Mean: 3–4 mm y^{-1}
Ephemeral riverbeds	Niipele Drainage	direct/indirect	[*1]Mean: 20–56 mm y^{-1}
	Epumbaondjaba		[*4]2016/17 mean: 39.3 mm
Basin mean decadal water storage changes	CEB	direct/indirect	[*5]Mean: 11 mm y^{-1}

[*]Methods of estimation (refer to methods section): [1]chloride mass balance; [2]peak-shift method; [3]isotope depth profiles; [4]groundwater level fluctuation, [5]large-scale approximation based on remote sensing

the continual loss of water by evaporation with the shift toward more enriched isotopic ratios as times passes and evaporation proceeds.

Water quality: surface water

Results from 22 water bodies on the Namibian side of the basin that were sampled on all three occasions are summarised in Fig. 4. Surface water from local rainfall and devoid of upstream input has significantly higher pH values compared to the later sampling of water with additional precipitation and inflow from the upper catchment, when pH lowered to neutral values. Post-flood pH values are consistently below 7. Overall, the highest pH (9.09 at Epako; not shown in the figure) was recorded before the flood, while the lowest (5.14 at Engela) was recorded after the flood.

EC and turbidity values for all sites are lowest in flooding conditions (largely below 100 [average 33] µS/cm and 200 [average 120] FAU, respectively). With few exceptions, no significant difference was recorded before and after the floods for both EC and turbidity. Nevertheless, average EC and turbidity values were relatively higher before the flood than in post-flooding conditions (i.e., 88 vs. 68 µS/cm and 264 vs. 194 FAU for all sites). No distinct spatial pattern emerged from any of the measured parameters.

Water quality: groundwater

For the Ohangwena region, the physico-chemical parameters of the shallow groundwater are in general within the WHO drinking water guidelines. The average temperature was 25°C, and the lowest temperatures were recorded during mornings in winter whereas the highest temperatures were recorded on summer afternoons. EC ranges from 50 to 1,200 µS/cm, and deeper wells are generally more mineralised than shallow wells. Temporal variations in EC are minor. pH is in the neutral range of 7.1 to 7.6. However, turbidity is often problematic, especially for the shallow wells, which showed values up to 255 NTU, whereas for the deeper wells turbidity is always less than 20 NTU.

Hydrochemically, most of the samples from the deeper wells are dominated by Ca^{2+}. Fewer are Na^+ dominated or have no dominant cations. For the shallow wells, Na^+ is the most prominent cation. The general order of abundance is $Ca^{2+} > Mg^{2+} > Na^+ > K^+$ for the deep wells and $Na^+ > Ca^{2+} > K^+ > Mg^{2+}$ for the shallow wells. The dominant anion in all deep wells is HCO_3^-. The same largely holds for the shallow wells; only about a third of the samples are dominated by Cl^- and SO_4^{2-}. The abundance of major anions is $HCO_3^- > NO_3^- > Cl^- > SO_4^{2-} > F$ for the deep wells and $HCO_3^- > NO_3^- > SO_4^{2-} > Cl^- > F^-$ for the shallow wells. Ca^{2+}, Mg^{2+}, Na^+, Cl^-, and SO_4^{2-} concentrations meet drinking water quality, but some samples have concentrations of K^+, NO_3^-, and F^- above permissible limits as recommended by WHO (2011). For shallow wells all cations and anions concentrations meet drinking water quality, with the exception of K^+, which is above the limit in 50% of the samples.

The physico-chemical parameters of the shallow groundwater in the Omusati region often make the water unfit for human consumption. EC ranges from 140 to 11,450 µS/cm, and seasonal variations are observed, with increasing salt content during the dry season. pH is in the range of 6.6 to 9.1 and shows larger spatial and temporal variations than for the sampling sites in the Ohangwena region. Turbidity is also often problematic here and reaches values up to 297 NTU.

Hydrochemically, most of the samples from Omusati are of a Ca^{2+}-SO_4^{2-} type; a Na^+-HCO_3^- type is seldom encountered. Ca^{2+}, Mg^{2+}, Na^+, $Fe^{2+/3+}$, K^+, and NO_3^- concentrations are within the limits of drinking water quality, but in 70% of the sampled hand-dug wells the water is unfit for human consumption because of high SO_4^{2-} concentrations. A few samples also exceed the permissible limits for Cl^- (12%), F^- (19%), and Mn^{2+} (13%) as recommended by WHO (2011).

Groundwater recharge

The estimated recharge rates for the investigated sites are summarized in Tab. 2. We refer to Beyer et al. (2015, 2016, 2017), Gaj et al. (2016, 2017), Hamutoko et al. (2017), Koeniger et al. (2016), and Shehu (2015) for detailed information on the studied sites (e.g., soil hydraulic properties, grain sizes, hydraulic conductivity, etc.), methodologies, and descriptions of results.

Discussion

The findings of the presented study are highly relevant for developing a strategy for sustainable management of water resources in the CEB. Three key points are to be pointed out explicitly:

- Surface water from iishana can potentially contribute to the supply of water for various local needs.
- The water quality of both shallow groundwater and surface water in the CEB often is not meeting drinking water quality. Hence, the water requires proper treatment before use, and awareness raising is urgently required.
- The amount of groundwater recharge is limited and its occurrence highly localized. This affects the availability of water.

Water quantity

As the current water supply situation in the basin is already constrained and the imported surface water also needs treatment, the water resources covered in this study can be considered important locally. Rainfall data for the 2016/17 rainy season revealed that an amount around or just above the average rainfall can generate runoff sufficient for triggering floods. Although runoff and subsequent floods lasted for less than three months, iishana generated at its peak flooding approximately half the discharge of the Kunene River at Ruacana (regulated for hydropower generation) during the same period (Namibia Hydrological Services, 2017) – and all this water is available in the iishana system. Existing long-term records (collected since 1941, for a total of 55 years; missing 23 years) reveal that, in addition to a third of drought or lean years, minor floods accounted for just over a third during that period, while medium (20%) and major floods (13%) made up the remaining third (Mendelsohn et al., 2013). On that basis, flood occurrence is relatively common in the basin. If the flooded water were stored in covered systems and not left unattended or in earth dams, the increase in overall salt content because of evaporation, as observed in our study, could be avoided. Practical applications of iishana water harvesting were tested in the CuveWaters project (http://www.cuvewaters.net/). Such water can be used untreated for gardening purposes and livestock watering or, after appropriate treatment, also as drinking water. In times of drought, when precipitation, surface water, and flooding are lacking, the shallow aquifers in the Ohangwena region provide a buffer because they contain groundwater recharged over many years. However, the very low level of groundwater recharge makes it a limited resource, and reliable balancing of abstraction rates against the recharge rates is of utmost importance.

Water quality

Overall, the *surface water* quality during the observation period is acceptable with regard to pH and EC but not with regard to turbidity, which in a few instances had also exceeded the 1,110 FAU limit of the probe. The parameters that make the *groundwater* unfit for human consumption are turbidity, K^+, NO_3^-, and F^- in the Ohangwena region and SO_4^{2-}, Cl^-, F^- and Mn^{2+} in Omusati. Increased SO_4^{2-} and Cl^- are to be attributed to evaporation (evaporation from the unsaturated zone during infiltration, from the very shallow aquifers, directly from the well) and/or the inwash/dissolution of accumulated salts. F^- is usually considered to be a geogenic contaminant. Wanke et al. (2013, 2015) carried out a detailed study on fluoride contamination and its implications. K^+ and NO_3^- are contaminants typically associated with agricultural activities and faecal contamination by animals. Their presence is consistent with observations during fieldwork that livestock watering happens either from a trough close to the well or by allowing livestock to walk into the broad, shallow wells. None of the wells in the study area showed a protection zone, and contaminants can enter the shallow aquifer with the infiltrating precipitation or surface runoff. Microbiological contaminants are beyond the scope of this study, and we refer to Chisenga et al. (2015) for a thorough discussion. Disinfection of the water with chlorination tablets (the most common method in the studied areas) is rather difficult, as turbidity in excess of 1 NTU (WHO, 2011) might prevent effective disinfection by shielding certain microorganisms. In addition, only 50% of the households treat water from hand-dug wells and shallow pits in the Ohangwena region (Italtrend, 2009), and awareness creation needs to be integrated into any strategy for sustainable management of water resources in the CEB.

Groundwater recharge

With the investigations on groundwater recharge to KOH-0 being just one example, valuable insights on recharge processes and recharge amounts in the CEB that can be transferred to other areas were gained. In addition to the site-specific field approaches described herein, we calculated large-scale fluctuations of total water storage changes (i.e., integrated over all aquifers) using well-documented GRACE gravity field satellite data (Rodell et al., 2009; Swenson & Wahr, 2006; Wahr et al., 2004, 2006). The approach followed herein (we refer to Shehu, 2015, for a detailed description of methods) is that total water storage changes from the driest point of one particular year to the subsequent one provide an integrated measure of water changes across all aquifers. Mean water storage changes integrated over the complete basin and all landforms for the years 2002–2016 were estimated to be as high as 11 mm y^{-1} (or ~2% of mean annual precipitation). This – though not equal to groundwater recharge rates per se – can be seen as an indicator that the basin is receiving sufficient water, through either groundwater inflow or direct/indirect groundwater recharge. These figures are also consistent with other work conducted in the CEB (e.g., Wanke et al., 2015) or in Namibia with comparable climatic and geological conditions (e.g., Brunner et al., 2004; Gieske, 1992; Wanke et al., 2008). The site-specific investigations, however, allow a more precise characterization: Generally, the deep sheet sands of the Eastern Sand Zone provide favourable conditions for direct groundwater recharge because of their high porosity and conductivity for water. In regions where trees are abundant, however, the estimated recharge rates obtained might be significantly reduced locally as trees can take up the water from the unsaturated zone and from the groundwater itself. The reason for this is that many of the species present (e.g., *A. erioloba, C. collinum, B. albitrunca*), are capable of developing deep and potentially groundwater-tapping roots (Beyer et al., 2016). For the ephemeral riverbeds and bare soil sites, however, these factors do not apply. Based on the chloride mass balance method, net local recharge rates are the highest here (Tab. 2). The two landforms – namely, iishana and pans – where mainly indirect recharge could occur are not potential recharge areas. No significant groundwater recharge was observed with any of the applied methods. Nevertheless, these landforms are of great importance for livestock water supply after the rainy season and for fishing purposes. The landform where proper recharge estimations remain challenging is the areas underlain by thick calcrete. The numbers estimated using the peak-displacement method (see Tab. 2) can be seen as potential recharge only because the water was accumulating on top of the calcrete layer located around 1.4 m below the surface at the study site. There is potential that this water could infiltrate through preferential flow paths in the calcrete, but it might also be that all the water is lost via transpiration and evaporation. Applying the chloride mass balance method at this site is not appropriate because dissolution effects in the infiltrating and groundwater can change the estimated recharge by magnitudes. For these sites, the estimations obtained via the water-level fluctuation method are more reliable. Nevertheless, these rates are a summation of groundwater inflow (to the depressions) and direct recharge. The main implications for recharge processes and groundwater recharge can be summarized as follows:

- The areas with the highest potential for direct groundwater recharge are non-vegetated areas underlain by deep sheet sands. Recharge in vegetated areas is sporadic and highly dependent on the character of the rainy season (Bahlmann, 2016).
- Indirect groundwater recharge in the CEB is very limited and occurs only from the ephemeral riverbeds. Unlike in the iishana and pan systems, water stored in them is protected from evaporation by a thick sand layer. If local impermeable layers underneath are present (e.g., the riverbed itself), this constitutes a valuable water source for the rural population that can be accessed easily. Geophysical investigations conducted by the BGR (2006) revealed the presence of large volumes of freshwater underneath several ephemeral rivers throughout Namibia. Studies of similar areas have also confirmed increased recharge potential in the old streams (e.g., Morin et al., 2009). In contrast, both iishana and pans are exfiltration rather than infiltration areas. This is supported by field experiments conducted in this area (infiltrometer tests, isotope labelling tests), the presence of swellable clay minerals and the enhanced salinities encountered in this region. However, the importance of ponding surface water in both iishana and pans for the rural population is enormous.
- Recharge in areas underlain by calcrete, such as the Oshanashiwa site, can occur only when preferential pathways (cracks, fissures, old root channels) are present or the calcrete is discontinuous. The magnitude of recharge is highly variable (see Tab. 2) and requires further scientific attention as well as continued local monitoring efforts.

Conclusion

Water resource management in the CEB is highly complex and remains challenging, especially as no local management bodies (e.g., water point committees) for well fields or for surface water bodies exist. Hand-dug wells are and will continue to be the most important water source in remote areas during the dry season. The use of surface water is limited (dam abstractions, size of the water carrier), but further utilisation of seasonal water stored in the iishana and pans offers great potential (e.g., through innovative techniques such as flood water harvesting or construction of *omatale* [earth dams] covered by shade balls). Both surface and shallow groundwater need to be protected, and simple actions such as not washing clothes in the supply canals, fencing and keeping clean of wells, and installing flood- and rainwater harvesting systems can improve the situation substantially. The rural population has generally endured and learned how to deal with short-lived droughts, but governmental efforts are urgently required for viable interventions (i.e., more boreholes in remote areas) (cf. Luetkemeier & Liehr, 2018). Shallow, highly localized perched aquifers also offer great potential for water supply, and further efforts to detect them would be enormously valuable (e.g., use of geophysics). Deep groundwater resources can provide a strategic reserve during droughts, and future research in SASSCAL can determine their specific locations, appropriate drilling techniques, and by which amounts these aquifers are recharged.

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