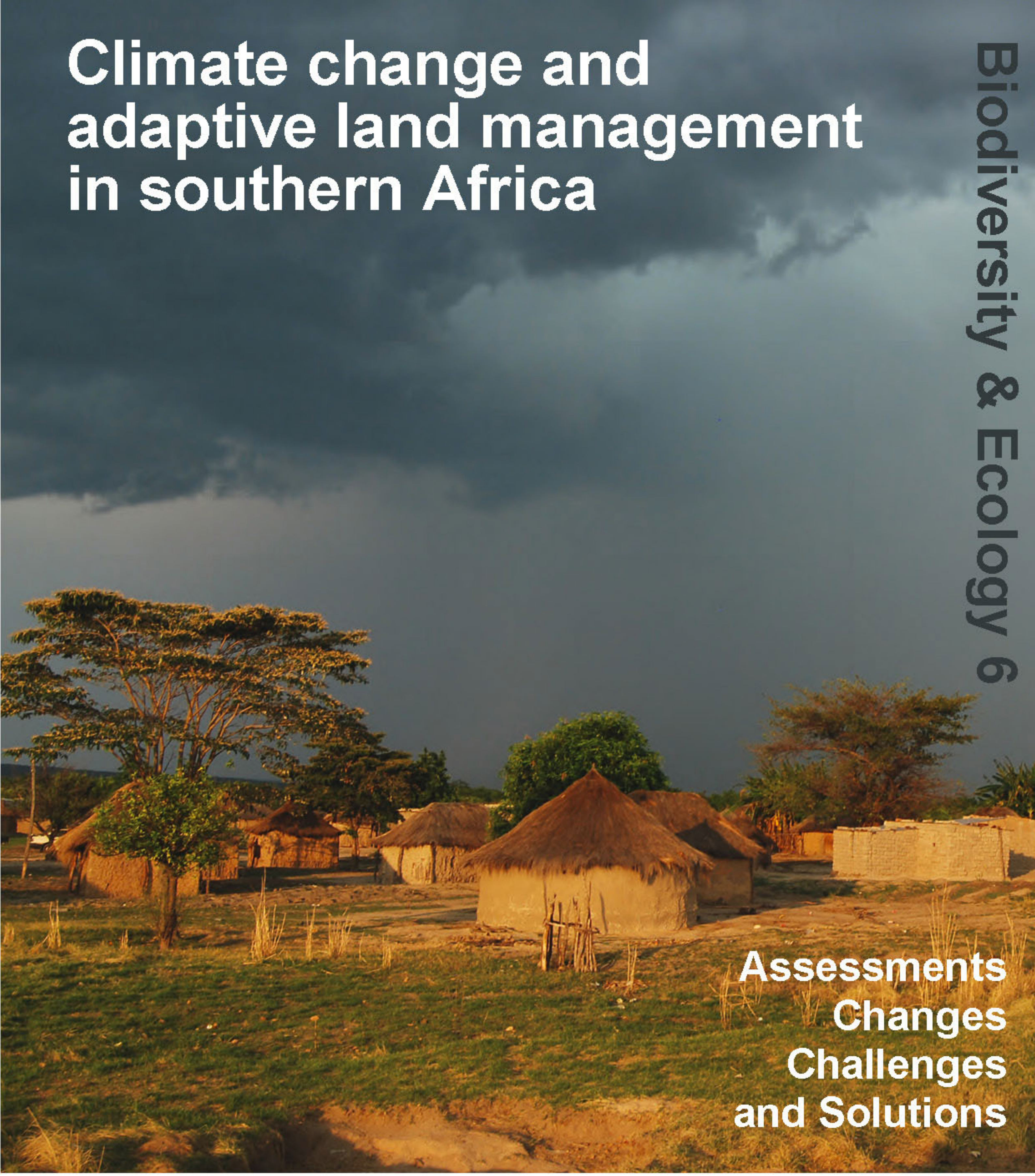
Climate change and adaptive land management in southern Africa



Biodiversity & Ecology 6

Assessments
Changes
Challenges
and Solutions

Product of the first research portfolio of

SASSCAL 2012–2018

Southern African
Science Service Centre for
Climate Change and
Adaptive Land Management

SPONSORED BY THE

Federal Ministry
of Education
and Research

Klaus Hess Publishers
Göttingen & Windhoek
www.k-hess-verlag.de

ISBN: 978-3-933117-95-3 (Germany), 978-99916-57-43-1 (Namibia)

Language editing: Will Simonson (Cambridge), and Proofreading Pal
Translation of abstracts to Portuguese: Ana Filipa Guerra Silva Gomes da Piedade
Page desing & layout: Marit Arnold, Klaus A. Hess, Ria Henning-Lohmann
Cover photographs:
front: Thunderstorm approaching a village on the Angolan Central Plateau (Rasmus Revermann)
back: Fire in the miombo woodlands, Zambia (David Parduhn)
Cover Design: Ria Henning-Lohmann

ISSN 1613-9801

Printed in Germany

Suggestion for citations:
Volume:
Revermann, R., Krewenka, K.M., Schmiedel, U., Olwoch, J.M., Helmschrot, J. & Jürgens, N. (eds.) (2018) Climate change and adaptive land management in southern Africa – assessments, changes, challenges, and solutions. *Biodiversity & Ecology*, **6**, Klaus Hess Publishers, Göttingen & Windhoek.

Articles (example):
Archer, E., Engelbrecht, F., Hänsler, A., Landman, W., Tadross, M. & Helmschrot, J. (2018) Seasonal prediction and regional climate projections for southern Africa. In: *Climate change and adaptive land management in southern Africa – assessments, changes, challenges, and solutions* (ed. by Revermann, R., Krewenka, K.M., Schmiedel, U., Olwoch, J.M., Helmschrot, J. & Jürgens, N.), pp. 14–21, *Biodiversity & Ecology*, **6**, Klaus Hess Publishers, Göttingen & Windhoek.

Corrections brought to our attention will be published at the following location:
http://www.biodiversity-plants.de/biodivers_ecol/biodivers_ecol.php

Biodiversity & Ecology

Journal of the Division Biodiversity, Evolution and Ecology of Plants,
Institute for Plant Science and Microbiology, University of Hamburg

Volume 6:

Climate change and adaptive land management in southern Africa

Assessments, changes, challenges, and solutions

Edited by

Rasmus Revermann[1], Kristin M. Krewenka[1], Ute Schmiedel[1],
Jane M. Olwoch[2], Jörg Helmschrot[2,3], Norbert Jürgens[1]

1 Institute for Plant Science and Microbiology, University of Hamburg
2 Southern African Science Service Centre for Climate Change and Adaptive Land Management
3 Department of Soil Science, Faculty of AgriSciences, Stellenbosch University

Hamburg 2018

Please cite the article as follows:

de Clercq, W., Helmschrot, J., de Witt, M., Himmelsbach, T., Kenabatho, P., Kralisch, S., Liehr, S., Ferreira Baptista, L., Mogobe, O., Mufeti, P., Müller, I., Nyambe, I., Sichingabula, H.M., Teixeira-Pinto, A., Teixeira Pires, G.J.P., Hipondoka, M. & Wanke, H. (2018) Water research in southern Africa: Data collection and innovative approaches towards climate change adaptation in the water sector. In: *Climate change and adaptive land management in southern Africa – assessments, changes, challenges, and solutions* (ed. by Revermann, R., Krewenka, K.M., Schmiedel, U., Olwoch, J.M., Helmschrot, J. & Jürgens, N.), pp. 54-65, *Biodiversity & Ecology*, **6**, Klaus Hess Publishers, Göttingen & Windhoek. doi:10.7809/b-e.00305

Water resources

Water research in southern Africa: Data collection and innovative approaches towards climate change adaptation in the water sector

Willem de Clercq[1]*, Jörg Helmschrot[1,2], Marlene de Witt[1], Thomas Himmelsbach[3], Piet Kenabatho[4], Sven Kralisch[5], Stefan Liehr[6], Lopes Ferreira Baptista[7], Oarabile Mogobe[4,8], Pauline Mufeti[9], Inken Müller[10], Imasiku Nyambe[11], Henry M. Sichingabula[12], Amandio Teixeira-Pinto[13], Gabriela J.P. Teixeira Pires[14], Martin Hipondoka[15], Heike Wanke[15]

1 Stellenbosch University Water Institute, Private Bag X1, Matieland, Stellenbosch, 7602, South Africa

2 Southern African Science Service Centre for Climate Change and Adaptive Land Use, 28 Robert Mugabe Avenue, Windhoek, Namibia

3 Federal Institute for Geosciences and Natural Resources, Groundwater & Soil Science, BGR, Hannover, Stilleweg 2, 30655 Hannover, Germany

4 University of Botswana, Private Bag UB 0022, Gaborone, Botswana

5 Friedrich Schiller University Jena, Geographic Information Science, Loebdergraben 32, D-07743 Jena, Germany

6 ISOE – Institute for Social-Ecological Research, Hamburger Allee 45, 60486 Frankfurt am Main, Germany, and Senckenberg Biodiversity and Climate Research Centre, Senckenberganlage 25, 60325 Frankfurt am Main, Germany

7 Universidade Agostinho Neto, Rua Direita da Camama and Rua do Estádio 11 de Novembro, Luanda-Sul, Angola

8 Okavango Research Institute, University of Botswana, Private Bag 285, Shorobe Road, Sexaxa, Maun, Botswana

9 Ministry of Agriculture, Water and Forestry, Private Bag 13184, Windhoek, Namibia

10 Deutsches Zentrum für Luft- und Raumfahrt e.V., Deutsches Fernerkundungsdatenzentrum, Georisiken und zivile Sicherheit, Oberpfaffenhofen, 82234 Weßling, Germany

11 Integrated Water Resources Management Centre, School of Mines, University of Zambia, Great East Road Campus P.O. Box 32379, Lusaka, Zambia

11 Department of Geography and Environmental Studies, University of Zambia, P.O. Box 32379, Lusaka, Zambia

13 Instituto Superior Politécnico Tocoista, Av. Pedro de Castro Van-Dúnem Loy, Luanda, Angola

14 Universidade Agostinho Neto, Rua Direita da Camama and Rua do Estádio 11 de Novembro, Luanda-Sul, Angola

15 University of Namibia, Private Bag 13301, Windhoek, Namibia

* Corresponding author: wpdc@sun.ac.za

Abstract: Water availability continues to hamper southern African nations' economic and societal development efforts. Highly variable rainfall; observed and projected rainfall decrease; and the inability of governments to keep up with infrastructure provision for fast-growing populations and urban, agricultural, and industrial sectors; as well as a lack of sufficient information and monitoring are some of the factors that limit the ability of decision-makers to manage water resources sustainably to promote social and economic development. Proper planning and management of water resources are not possible without a sufficient understanding and assessment of interacting drivers and processes controlling and/or affecting the water system. Against this background, the water theme of the SASSCAL programme aimed to significantly contribute to the knowledge base of southern African water resources, providing decision-makers with additional means to inform their planning efforts and thereby improve access to water, water resources management, and sustainable water use. Extensive research was conducted in Angola, Botswana, Namibia, South Africa, and Zambia, as well as across national borders. The focus was on improving monitoring and hydro-climatic data generation; gaining a better understanding of groundwater and surface water dynamics; and exploring the interdependency of water resources, water-use patterns, and vulnerabilities of society; as well as improving modelling techniques for advanced (transboundary) water resources assessment and management. This paper provides an overview of the SASSCAL water-related tasks to highlight some of the outcomes achieved under the SASSCAL water theme. Some key outcomes include: new methods for groundwater prospecting developed in

Namibia; socioeconomic studies to enhance integrated drought management in Namibia and Angola; improved accuracy in modelling in South Africa; a better understanding and monitoring of water quality in the Okavango Delta; updated digital geological maps in Angola; comprehensive river basin assessments; and significantly improved knowledge of groundwater and surface water resources and the effects of climate and land use change thereon.

Resumo: A disponibilidade de água continua a dificultar os esforços de desenvolvimento económico e social das nações do Sul de África. A elevada variabilidade da precipitação, a diminuição da precipitação observada e projectada, a incapacidade dos governos em manter a disponibilização de infraestruturas para as populações em crescimento e os sectores urbano, agrícola e industrial, bem como a falta de informação e monitorização suficientes, são alguns dos factores que limitam os decisores na gestão sustentável dos recursos hídricos para o desenvolvimento social e económico. O planeamento e a gestão adequados deste recurso complexo não é possível sem uma compreensão suficiente destes factores. Neste contexto, o tema da água do programa SASSCAL teve como objectivo contribuir significativamente para a base de conhecimento dos recursos hídricos da África Austral, fornecendo aos decisores meios adicionais para informar os seus esforços de planeamento e, assim, melhorar o acesso à água, a gestão dos recursos hídricos e o uso sustentável da água. Investigação extensiva foi realizada na África do Sul, Botswana, Namíbia, Angola e Zâmbia, bem como além fronteiras. O objectivo foi melhorar a monitorização e produção de dados hidro-climáticos, obter uma melhor compreensão das dinâmicas das águas subterrâneas e superficiais, explorar a interdependência dos recursos hídricos, padrões do uso da água e vulnerabilidades da sociedade, bem como melhorar técnicas de modelação para a avaliação e gestão avançada (transfronteiriça) dos recursos hídricos. Este artigo fornece uma visão geral das tarefas do SASSCAL relacionadas com a água, de modo a destacar alguns dos resultados alcançados sob este tema no SASSCAL. Alguns dos principais resultados incluem: novos métodos para a prospecção de águas subterrâneas desenvolvidos na Namíbia; estudos socioeconómicos para melhorar a gestão integrada da seca na Namíbia e Angola; maior precisão na modelação na África do Sul; uma melhor compreensão e monitorização da qualidade da água no Delta de Okavango; mapas geológicos digitais actualizados em Angola; avaliações abrangentes de bacias hidrográficas; melhoria significativa do conhecimento dos recursos hídricos subterrâneos e superficiais, e dos impactos do clima e uso das terras nos mesmos.

Introduction

The impact of climate change on water resources in southern Africa is already being experienced. Climate change, with a projected temperature increase of between 1.5°C and 3°C by 2050 (Niang et al., 2014), changes in rainfall patterns, and an intensification of climate extremes, will severely affect agricultural practices and food security in the region. The rapidly increasing intensity and severity of droughts and floods are catching the governments of these nations off guard. Never has this been more evident than in the current multiple-year drought that has been affecting southern African countries since 2014. The Southern African Development Community (SADC) declared the region a disaster area in 2016, due to nations being “overwhelmed” by the severity of the drought in 2015-2016 (SADC, 2016). As reported by the 2016 SADC Drought Fact Sheet, about 21.3 million people in the SADC region needed humanitarian assistance after losing their harvests to climate extremes and are now exposed to hunger, famine, and displacement. Moreover, Cape Town, South Africa, is currently fighting to not become the first coastal city in the world to run out of water (e.g., Schlanger, 2018). Ageing infrastructure, polluted water sources, a general lack of understanding of the hydrological response to climate change in catchments, and poor adaptive capacity are some of the factors that exacerbate the effects of below-average rainfall (Callaway, 2004; IPCC, 2007; Kusangaya et al., 2014). This interplay of natural hazards with inadequate infrastructure exposes the livelihoods of those in the region to ever-increasing risks (Taubenböck et al., 2018)—risks that demand improved management strategies. The coupling of technical-social perspectives towards risk management have been emphasised in the approach followed in SASSCAL (Taubenböck et al., 2009). The current drought has emphasised the urgent need to better understand the surface and groundwater resources of the region and their interaction with natural and human systems, as well as the pressures on these resources in terms of quality and quantity (Fig. 1), in order to support better planning and decision-making at the national and transboundary scales.

Weather and the atmosphere ignore national boundaries, as do fluxes of water, food, migrating people, and the spreading of animals and plants. Due to manifold ecological and socioeconomic processes and mechanisms of interaction, neighbouring countries are functionally interlinked at varying spatial and temporal scales. People living along watercourses are particularly affected. For instance, downstream riparian communities may depend on decisions taken by upstream users in a different country. Sustainable

Figure 1: Uncontrolled use of open water for domestic purposes with effects on water quality for downstream users in Menongue, Angola. (Photo: J. Helmschrot, 2013)

water resources management must consider trigger mechanisms, tipping points, and cascading effects at a regional or even larger scale. Numerous transboundary and regional agreements, institutions, commissions, and governance instruments have been or need to be established to jointly manage important water-related ecosystem resources and services and to develop novel, innovative utilisation options. All these examples strengthen the notion that, in addition to the local grassroots level and the national priority of informed political decision-making, it is essential to address the regional dimension of environmental change with validated, knowledge-based information.

All African SASSCAL countries have expressed the need for improved monitoring and enhancement of data collection network densities to increase water quality and quantity information to support improved decision making. However, such improved data needs to be supported by a better understanding of the drivers and processes of the water cycle controlling water-related ecosystem services. Additionally, more attention must be given to the role that groundwater resources at different depths could play as a strategic contingency resource during long-lasting droughts. Groundwater recharge estimation plays a crucial role for any sustainable management. Thus, water-related research activities in SASSCAL have been aimed at improving our knowledge of the complex interaction and feedback between surface and groundwater dynamics and resources, as well as land-surface processes in selected regions of SADC.

The main objective of this joint and integrated research effort of 17 water tasks was to develop reliable hydrological, hydro-climatic, and hydrogeological baseline data, along with a set of analytical methods to strengthen the research capacity of the water sector of the southern African region. With this in mind, the SASSCAL programme aimed to contribute to the implementation of integrated water resources management strategies for improved transboundary river management and resource usage in the context of global climate and land management changes.

The research activities within the water theme can be grouped into three key research areas:

- Baseline data observation/monitoring in Angola (new monitoring infrastructure establishments in the Rio Giraul Basin), Botswana (expansion of existing monitoring infrastructure in the Notwane Basin), Namibia (expansion of monitoring coverage in the Cuvelai-Etosha and Zambezi basins), and South Africa (continuation and extension of long-term observations in four catchments);
- Basic research in the fields of water quantity and quality assessments and modelling (with strong focus on the Barotse floodplain, Zambia, and the Okavango Delta), erosion and sedimentation assessments, and evaluation of land use/climate change impacts in selected river basins across the region; and
- Integrated and interdisciplinary research in the fields of groundwater mapping, water quality and quantity assessments and use, flood mapping, monitoring, risk assessments, and large-scale drought impacts, as well as analyses of water demand and water-related vulnerabilities of households.

In agreement with tasks from the other thematic areas, five regional hotspots were identified as locations for water research in the SASSCAL research portfolio (Fig. 2), while some studies used Earth-Observation (EO)-based products to monitor floods and droughts for the entire region (e.g., Müller et al., 2018). These locations were:

i. Northern Namibia/southern Angola (e.g., Cuvelai-Etosha Basin, Cunene Basin, Rio Giraul Catchment)
ii. Central Angola (Lusaka Province, Kwanza River Basin)
iii. The broader KAZA transboundary region, including the upper Zambezi River Basin, upper Congo River Basin, Okavango River Basin, and Chobe River Basin
iv. Southern Botswana (Notwane River Basin and upper Limpopo River Basin)
v. South Africa (Heuningnes, Verlorenvlei, and Sanspruit catchments in the Western Cape Province, Cathedral Peak in KwaZulu-Natal Province, and Letaba in Limpopo Province).

As a hypothesis for the SASSCAL water research, it is stated that improved monitoring and modelling will enhance the capacity in SADC to deal with water-related issues in a responsible manner. This paper primarily takes stock of the SASSCAL water research portfolio in the SASSCAL partner countries and provides a platform for ongoing and future research initiatives.

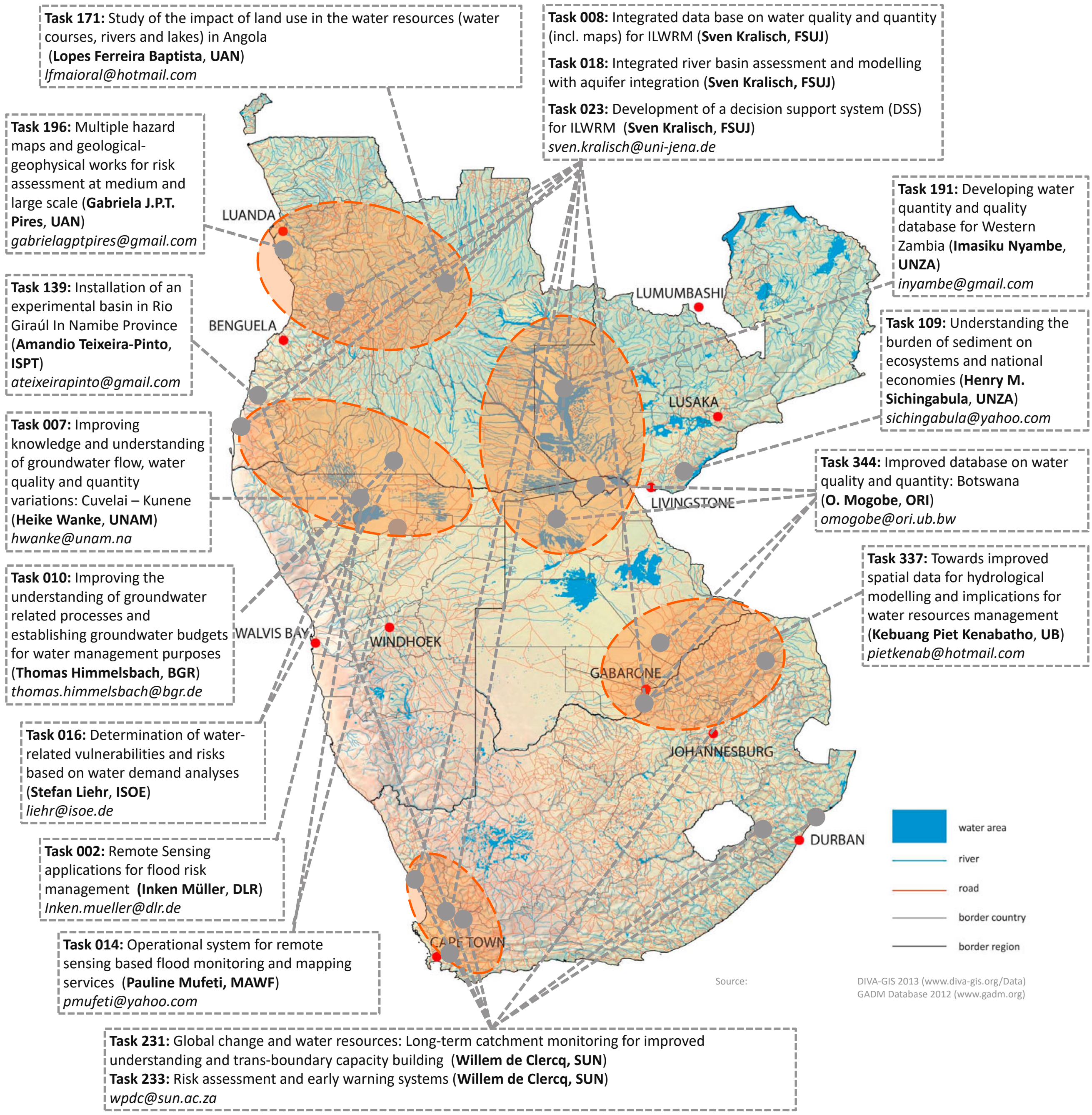


Figure 2: The locations of the SASSCAL water research sites.

Namibia

Groundwater will play an increasingly important role in ensuring water security for populations in arid and semi-arid regions amidst surface water decline due to climate change and population growth (Scanlon et al., 2006; Stadler et al., 2010). This is certainly the case for semi-arid southern Africa (MacDonald et al., 2012). Although it is recognised that southern Africa has significant potential for groundwater use (MacDonald et al., 2012), it is still critical to obtain sufficient information on the groundwater resources and impacts thereon to understand recharge patterns and ensure proper management of this finite resource. The complex interaction between land-use practices and groundwater quality needs to be understood before aquifers are intensively explored and utilised for human consumption or agriculture (Stadler et al., 2010; Bann & Wood, 2011) (Fig. 3).

Namibia is one of the driest countries in the world, which forced it to diversify its water sources and reduce dependency on surface water (Lahnsteiner & Lempert, 2007). Groundwater has long been in use and has occasionally been augmented by infiltration of treated waste water (Lahnsteiner & Lempert, 2007). Shallow aquifers are widely used because of their ease of access, but these are also often saline or contaminated due to land-use impacts. Himmelsbach et al. (2018) focused their research on exploring deep aquifer systems in Namibia in an attempt to improve the responsible use of groundwater resources in this country. The deeper, semi-fossilised systems present a more secure source of water

Figure 3: Extraction of shallow groundwater by wells with grazing livestock affecting groundwater quality in the Cuvelai region, Namibia. (Photo: J. Helmschrot, 2016)

for human use but studying these is as complex as accessing them for use. With their research, Himmelsbach et al. (2018) provide valuable insights into the methodology for groundwater prospecting in southern Africa. The focus was on creating a holistic strategy for groundwater exploration that is largely based on methods of oil and gas exploration. New scientific findings based on interdisciplinary research suggest the existence of further strategic groundwater resources that are related to large tectonic features on the continent, as well as intra-continental and coastal river deltas.

A second Namibian study provided an integrated assessment of the surface and groundwater quality and quantity in the Cuvelai-Etosha Basin. Wanke et al. (2018) conducted several field campaigns between 2013 and 2017 to obtain much-needed data required for more informed decision making in this transboundary catchment. Hydrological and microbiological sampling and analyses have shown that water quality and quantity in this region is highly variable, both in space and time. Knowledge of recharge conditions and recharge rates are indispensable key parameters for appropriate resource management, but only a few methods are applicable in arid environments. Stable isotope methods were intensively applied to quantify infiltration rates and evaporation loss and to better estimate recharge via the unsaturated zone (Beyer et al., 2016; Gaj et al., 2016). The complex interrelation of vegetation, soil structure, microclimate, and spatio-temporal heterogeneity were described as main regulators that govern deeper infiltration and net water fluxes. Both studies make practical recommendations for the implementation of corrective measures at a local scale that will improve water security in the region.

Luetkemeier & Liehr (2018) adopted a social-ecological perspective on water and food security and assessed the sensitivity of households to drought in the Cuvelai-Etosha Basin in Namibia and Angola (also see Luetkemeier et al., 2017). They conducted structured socioeconomic surveys in 2014 and 2015 among 461 households in urban and rural areas to assess seasonal water and food consumption patterns. The study found significant alterations of people's consumption patterns that serve as an entry point for drought sensitivity analyses. These insights contribute to an enhanced decision base for integrated drought risk management in both countries. The incorporation of the population's vulnerability is the key to upgrade common drought hazard assessments to integrated risk assessments. The study shows that people's coping capacities have to be assessed and evaluated against the specific drought hazard conditions.

The Hydrology Division in the Ministry of Agriculture, Water, and Forestry in Namibia uses a variety of systems for early flood warning and monitoring. These systems include telemetry gauges for rainfall and river levels, weather and rainfall forecasting systems, remote sensing for rainfall and river flow estimations, and satellite images for flood mapping and rapid assessments—all combined in empirical flood forecasting. Research was undertaken to improve the scientific basis for the implemented monitoring and observational systems. This was done by integrating EO technologies and hydrological and hydraulic modelling to determine surface water balances and conduct flood risk and vulnerability mapping in the target basin and floodplains. Results were combined in a scientifically sound flood model for the Cuvelai-Etosha Basin and the Namibian Zambezi floodplains. This was supported by field studies that analysed the target communities' vulnerability to floods caused by the possible impacts of increased climate variability and change. This was done to improve the ability to develop sound early warning and disaster risk management systems that will support local communities to cope with climate extremes. During the rainy season, early warning and flood forecasting information is disseminated through the Daily Flood Bulletin, which is provided to more than 600 stakeholders (Fig. 4).

With respect to short-term events such as floods, EO data, and particularly radar data, have been applied for the detection of surface water and thus, in exceptional circumstances, flooded areas (Müller et al., 2018). The developed object-based approach provides decision makers with mapping products of flooded areas 45 minutes after satellite data have been received. The combination of the spatial extent of the natural hazard and the exposed elements allows an assessment of people at risk (Müller et al., 2018).

South Africa

South Africa has a rich history in hydrological research concerning surface–groundwater interactions, rainfall-runoff modelling, the establishment of water resource databases, ecological reserve

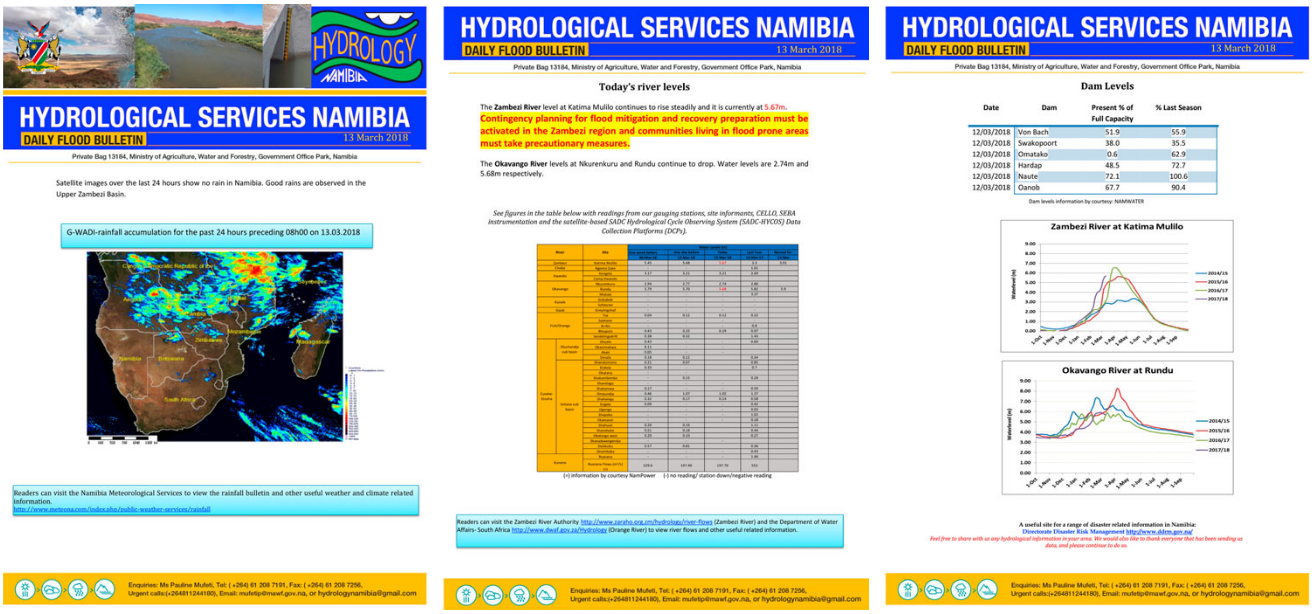


Figure 4: Daily Flood Bulletin of the Hydrology Division, Ministry of Agriculture, Water, and Forestry, serving more than 600 subscribers (MAWF, 2018).

determinations, and climate change impacts (Hughes, 2007). Nevertheless, there is lack of long-term monitoring in catchments, database systems for catchment water resources are scattered amongst different institutions and for different components of the water cycle, and there is a strong need to build capacity in the use of predictive hydrological models.

In South Africa, infrastructure related to water quantity and quality monitoring is the responsibility of the state. This infrastructure, for various reasons, started to become less important during the implementation phase of the new water legislation in South Africa, as the new law made room for Catchment Management Agencies (CMA) to be defined by the public and industry (Stein, 2005). The authority to monitor water was therefore increasingly transferred to the public domain, and during this period, the impacts of climate change and related problems in water became more topical. To make matters worse, at the onset of the SASSCAL research, South Africa also found itself in a crisis situation related to water supply and accountability related to mitigation of the ongoing drought (De Clercq et al., 2010).

Three universities, namely Stellenbosch, Western Cape and KwaZulu-Natal, together with the Council for Scientific and Industrial Research (CSIR), were identified as water centres of excellence in the NEPAD Southern African Network of Centres of Excellence. These centres were also included in the SASSCAL water research themes. All four centres were involved in long-term research in specific locations and were also actively collaborating with international partners.

The SASSCAL water research in South Africa had two domains, both of which were embedded in the idea of continued hydrological research related to long-term monitoring and advances in methodology to better the prospects of being a living laboratory and enhance the prospects of modelling related to the idea of twinning (Flugel, 2012). The two categories were: (1) hydrological and hydro-geological baseline data and modelling, and (2) risk assessment with the possibility of generating early warning information. This research concept was aimed at setting standards for monitoring and mitigating the drought conditions originating from climate change.

The major research locations in South Africa were Cathedral Peak in KwaZulu-Natal Province; the Sandspruit, Verlorenvlei, and Heuningnes catchments in the Western Cape Province; and the Klein-Letaba system in the Limpopo Province. These catchments have been chosen primarily because long-term monitoring of some water components is already taking place and because they are located in climatically different regions of the country. Data on climate, streamflow, and groundwater depths were collected in the catchments.

Miller et al. (2018) studied the complex interaction between recharge rates, salinity, and suitability of use of groundwater in the Verlorenvlei area on the West Coast of South Africa. By using groundwater and weather measuring equipment and applying groundwater modelling, Miller et al. (2018) provided an improved understanding of the interdependence of domestic, agricultural, and ecological water requirements. The improved understanding of hydrology of the West Coast supports planning for the effects of climate change, and the lessons from this work will now be applied beyond this area.

Malan (2016) evaluated the possibility of using geomorphons to produce improved digital geomorphic and soil maps. This approach allows the inclusion of human knowledge in terrain classification, thereby improving the topographic and landscape analysis. This was done through redefining mapped soil properties by making use of elevation models and a process of land form identification and mapping using GIS.

As gully erosion is recognised as a major land degradation process to natural and farmland, especially in the Western Cape Province, Olivier et al. (2018) investigated the current dynamics and impact of gully erosion on agricultural

Figure 5: Fishery structures in the Okavango Delta, Botswana. (Photo: J. Helmschrot, 2015)

systems in the Western Cape. The field-based case study of a classic, discontinuous gully system in the Swartland quantified sediment movement at hillslope scale and related it to rainfall and field observations of gully activity. This showed that the gully system is not only an active sediment source, but also a conduit for sediment from hillslopes. It was further noted that agricultural practices such as ploughed contour banks are causing the expansion of the gully network, in addition to delivering sediment from hillslope sources to the gully system. Vegetation cover was found to reduce gully erosion temporally by up to 91.6%.

Data collection and the enhancement in monitoring were part of a capacity-building programme during the research. The use of field equipment, along with its calibration and long-term maintenance and monitoring, became key activities in the development programme, a feature that also contributes to the idea of living labs. Capacity building in terms of training also formed part of the twinning idea with catchments in the rest of the SASSCAL countries. The South African team is consequently busy building this capacity in the other SASSCAL countries, and this infrastructure will support these activities. It is also important to mention the standardised monitoring infrastructure generated, with the ability to duplicate this in other SASSCAL countries. The key items in capacity building are related to the various methods of groundwater monitoring, flow measurement and monitoring (e.g., distinguishing between surface runoff, subsurface flow, and deep drainage), and climate monitoring.

Botswana

Research in Botswana focused on two aspects of the water tasks: increasing baseline data collection and understanding the complex interaction between natural and human systems with a specific focus on the Okavango Delta and the upper Limpopo.

The Okavango Delta in Botswana is one of the most famous wetland systems in the world and is mostly protected, but land use and population growth around the delta affects water quality (Kolawole et al., 2017). Apart from its ecological importance, the delta is a key source of drinking water (Mogobe et al., 2014). One key challenge in managing the delta is finding a balance between eco-tourism (i.e., environmental protection) and agriculture (i.e., food security) (Kolawole et al., 2017) (Fig. 5). Another challenge is small farmers' varying levels of knowledge regarding sustainable use of fertilisers and access to appropriate products, leading to chemical pollution of the streams flowing to and from the delta (Kolawole et al., 2017).

The SASSCAL research conducted by Mogobe et al. (2018) provided much-needed monitoring equipment and data to better understand the level of water pollution in the Upper Okavango Delta. The study area was in the Okavango Panhandle, the main watercourse that flows into the delta in Botswana, and therefore an important monitoring point. The researchers continuously monitored water quality between 2014 and 2017 using physio-chemical parameters. A positive research outcome of acceptable ionic composition shows that wetland systems have thus far been successful in keeping the delta's water quality at acceptable levels, in spite of the human impact from diversifying land uses in the Upper Okavango Delta.

The Notwane catchment in Botswana is a strategic catchment for water resources in Botswana. Gaborone's water supply is primarily based on water from the Gaborone Dam, which receives its inflow from the Notwane catchment. The continuous water supply to Gaborone and surrounding areas is a concern to water managers, given the variability of rainfall in the catchment and uncontrolled water uptake in tributary areas. It has experienced declining water levels in recent years due to a variety of causes, including the effects of climate variability and change, as well as the impact of more than 300 farm dams located upstream of Gaborone Dam.

Despite these environmental issues, the catchment does not have sufficient hydro-meteorological stations to adequately assist in addressing key water resources issues in the catchment. Utilising innovative modelling and EO-based mapping tools, a modelling study undertaken in the Notwane catchment (Meinhardt et al., 2018) has documented how up-to-date technologies can be used to analyse water level dynamics in the dam in the context of rainfall variability and human activities in the basin.

In support of improving data availability and water management in semi-arid environments with highly variable rainfall conditions, Moalafhi et al. (2018) utilised an experimental set of automated weather stations over Notwane catchment to improve the understanding of the predictive capacity of the monitored variables. The study has shown that observed hydro-climatic time series can be notably improved in quality and length when coupling Artificial Neural Networks (ANNs) with different modelling approaches to describe and validate inherent relationships with precipitation. It is also revealed that simulated precipitation exhibits a similar mean and variability with the observations, despite poor simulations for low and high precipitation events.

Zambia

Water research in Zambia focused on the surface water quality of the upper Zambezi, the resilience of floodplains along the Zambezi River, and the role and economic implications of sedimentation in wetlands and reservoirs in the central and southern parts of Zambia.

Spatial and temporal changes may serve as valuable indicators of the level of change in a wetland system, such as the Barotse Floodplain in the Western Province of Zambia (Zimba et al., 2018). The pressures on this floodplain are particularly high, with more than 80% of the inhabitants owning livestock that graze on the communal lands (Turpie & Barnes, 2003). The Barotse Floodplain is a key economic driver for Zambia, but growing and conflicting uses are threatening the ecosystem's functioning (Turpie & Barnes, 2003). Nyambe et al. (2018), through SASSCAL, set out to determine the seasonal variation in water quality parameters in the Barotse Floodplain, through which inferences could be made into spatio-temporal variation. Water samples were collected across the floodplain and tested for their physical, bacteriological, and chemical characteristics. Sediment samples were tested for their chemical elements. Through the analyses of these samples, the surface water quality and sediments of the Barotse Floodplain were characterised during low and high flows.

The researchers found that the floodplain may play a critical role in being a natural sink of some elements, although a high spatio-temporal variability of parameters was observed. It was concluded that the mechanisms and drivers for the variability and varying loads could be attributed to both anthropogenic and natural processes. Anthropogenic effects resulting from deforestation and increased agricultural production in the surrounding areas of the floodplains led to high sedimentation and high nutrient loading, low dissolved oxygen, and bacteriological contamination of water, especially in settled water courses. Nyambe et al. (2018) expect that future economic pressures in western Zambia due to population growth and limited resource availability may exacerbate these effects. The study further revealed that the observed change in water quality parameters is also related to natural processes, such as low and high flooding patterns. These processes are critical in the 'renewal' of biogeochemical processes and ecological balance of the floodplain. Drawing on their results, the authors emphasise that ensuring proper management of the floodplain is essential to ensure climate change resilience and thereby protect the economic value of this system. The work was supported by modelling studies in the Luanginga catchment, which revealed that a decrease in rainfall and higher temperatures cause lower water quantities, resulting in a reduction of flood extent (35%) and duration and, thus, alteration and damage to the highly productive and valuable wetland ecosystem (Meinhardt et al., 2018). The authors conclude that this will increase risks and vulnerability for the people who depend on the flooding pattern in the wetlands.

A second study focused on mapping and quantifying the extent of sedimentation and erosion in Lusaka and the country's southern provinces. This exercise focused on the storage capacity of small reservoirs and sedimentation from agricultural fields and its impact on both ecosystems and the economy of the agricultural and water sectors at the national level. The aim was to approach rural communities to raise awareness regarding sedimentation and the problems that it creates, and to provide guidance on optimised land and farm dam management. The study provided bathymetric surveys and mapped more than 500 farm dams. This is the most thorough inventory of manmade dams and reservoirs in SADC. The study was supported by case studies, such as one presented by Chomba and Sichingabula (2015), who determined sedimentation rates and their effects on four small reservoirs in the eastern parts of the Lusaka district. The results showed that reservoir capacity storage losses were in two to three orders of magnitude, indicating how serious sedimentation was on small reservoirs. The study called for dam owners to begin regularly dredging the deposited sediment, which will increase storage capacity and ensure sustainable use of the water resources in small reservoirs for local communities. The status of sedimentation on small reservoirs in central Zambia is similar to that in southern parts of the country, as reported by Muchanga (2017). Muchanga et al. (2017) determined concentration levels and the distribution of selected physicochemical parameters of water in the Makoye Reservoir and their implications for livestock. Their findings indicate that chemical sedimentation might be detrimental to reservoir water quality but may still be useful to domestic animals given that most analysed chemical and physical parameters were found to be within acceptable limits recommended for livestock watering.

Angola

Water research is an evolving discipline in Angola. Given the data scarcity and lack of monitoring infrastructure, the focus is still very much on collecting baseline data and establishing monitoring systems in the country. Three studies were conducted in Angola to support data collection and to strengthen research capacities in hydrological monitoring and assessment.

In the Rio Giraul Basin, an experimental monitoring system was established to observe runoff dynamics and sediment transport during the rainy season—a process that repeatedly causes severe damage to infrastructure. The basin is located in the Province of Namibe, in southwest Angola, and characterises the transition between the high plateau of Chela Mountain, which is approximately 2 300 m above sea level. Here there is a sudden change of height from 2 200 m to 950 m above sea level in only 5 km—from the Tundavala Ridge where the Giraul River (there known as Munhino River) starts, to the mean heights of Bibala. The middle reaches of the river cross the Angolan part of the Namib Desert, defining the arid conditions in large parts of the catchment. The river drains into the Atlantic Ocean near the city of Namibe. The catchment covers an area of about 4 500 km². Given the area's remoteness and difficulties in accessing wider parts of the catchment, the installation and operation of 10 Automatic Weather Stations (AWS), as well as three runoff stations to provide consistent and reliable data, is considered a successful step towards the establishment of the experimental catchment. However, vandalism poses constant challenges. The lack of actual data records was addressed by re-analysing data, including EO-based rainfall information and historical observations. The combined analysis of the available data set led to the conclusion that the upper areas receiving higher rainfall, i.e., 650 mm/year between 1962 and 1972, are well covered by all products, while rainfall for the middle reaches varies between 140 mm and 400 mm/year and in the coastal areas, it ranges between 100 mm and 280 mm/year. This showed the uncertainty in data for this sparsely covered area. Further analysis is needed to better understand atmospheric conditions, which will eventually control the runoff generation mechanisms. Addressing this demand, a process-based, spatially distributed rainfall-runoff model was implemented, providing the basis for model-driven analyses of recent and future hydrological process dynamics.

A second study aimed to contribute to the updating of multiple hazard maps and geological-geophysical risk assessments at the medium and large scales, with a primary focus on the Province of Luanda. Various geophysical and geotechnical surveys utilising refraction seismics, Standard Penetration Tests (SPT), and the Manual Light Dynamic Penetrometer (PDL) Test have enabled researchers to produce updated digital geological maps at scale 1:50 000, as well as various digital diagnosis maps (e.g., topography, lithology, tectonics, hydrological and hydrogeological, land-use maps, etc.) for the Province of Luanda. In addition, geological hazard maps characterising zones of mass movements (e.g., erosion, landslides, and falling of materials) and floods were produced. All data were integrated in the GIS GEOURBE system—a computer platform that allows managing and updating all the geological and geotechnical information for the city of Luanda and its surroundings. The system will be made available to the relevant authorities and the wider public.

Baptista et al. (2018) conducted a study in the eastern provinces of Angola (Lunda Norte and Lunda Sul) where exhaustive mining activities, such as industrial and artisanal diamond exploitation, and other land-use activities take place in order to assess their impact on water resources and the environment. The authors found mining to be a major driver of environmental impact, severely affecting surface water and groundwater quality, but also changing landscape features through deforestation, erosion, and sedimentation dynamics. These practices also affect the area's floral and faunal biodiversity, all leading to environmental changes including altered flow conditions and groundwater recharge mechanisms. The study has shown that replanting of vegetation, the construction of sedimentation basins for capturing mining waste, as well as the creation of waste water treatment facilities may reduce the environmental impact of mining in the region.

Transboundary hydrological assessments and modelling

Using the data gathered and monitoring efforts made in the country-specific studies summarised above, SASSCAL researchers also aimed to develop a comprehensive river basin assessment using further hydrological assessments and modelling. A river basin assessment is an essential part of integrated land and water resources management (ILWRM) in transboundary basins. It is based on an integrated system analysis to identify hydrological process dynamics related to landscape features and socioeconomic development. Interlinked, these components control the regeneration of (sub-) surface water resources and river runoff contribution.

Integrating observed data, assessment and modelling tools, and an advanced understanding of hydrological systems allowed some projects to focus on transboundary basin assessments. Research was conducted on the Gabarone Dam Catchment in Botswana and South Africa; the Okavango Basin in Angola, Namibia, and Zambia; and the Luanginga

Catchment in the upper Zambezi River Catchment in Angola and Zambia. Meinhardt et al. (2018) and Baumberg et al. (2014) used the Integrated Landscape Management System (ILMS) and its hydrological model system, JAMS, to develop the basin assessment and model hydrological process dynamics in these catchments. Because of improved simulation components developed by the research team, the study could more precisely predict the impact of both climate change conditions and human activity (e.g., informal farm dams, contour farming, irrigation agriculture, etc.) on the three catchments. Overall, results of this research showed that climate is the dominant driver of change for runoff generation in the investigated basins. Consequently, management actions need to focus on improved water distribution and water-use efficiency.

The result is a comprehensive database of all information pertinent to the study areas, with information stored in the River Basin Information System (RBIS), which is also part of the ILMS developed at the University of Jena (Germany). The database includes information in the form of time series data, geospatial data, documents, model results, and others, and will serve the purpose of collating inputs for hydrological models in the SASSCAL context. Given the operability of the system, the hydrological database was integrated with the SASSCAL Data and Information Portal (Helmschrot et al., 2018), providing data, models, and model simulations to a wider research community, decision makers such as the Okavango Basin Commission (OKACOM) or the Zambezi River Basin Commission (ZAMCOM), and local and national water authorities in the respective countries.

Another approach targeted the location and severity of droughts at large scale. Droughts are conceptually defined as an extended period of deficit rainfall related to the long-term average condition for a specific region. Using a monitoring period from the year 2000 until 2016, the severity of droughts was assessed for the entire SASSCAL region using vegetation indices as proxies. The results provided insights into spatial patterns of drought severity and, in combination with exposure data (settlements/population), revealed the impacts of drought in the region (Müller et al., 2018).

Conclusion and outlook

This paper summarises the results of 17 SASSCAL research projects that were conducted in the water sector in southern Africa over the past five years. The research was done at a critical time for the southern African nations, as each is experiencing significant drought conditions that have severe social and economic effects. This situation, which is still ongoing in some parts of the SASSCAL countries, highlighted the urgent need for improved knowledge of water resources, as well as improved data for predictive and preventative hydrological modelling, to support the resilience of SADC countries to the effects of climate change. Each research project featured in this section of the SASSCAL research book produced results and findings that governments can use henceforth.

The studies conducted under this SASSCAL research portfolio successfully contributed to the Initiative's mission to produce scientific knowledge products that can inform decision making on climate change in southern Africa. Aiming to improve knowledge on groundwater and surface water and their interaction and to develop more reliable hydrological and hydrogeological data and tools to support (transboundary) water resources management and planning in the region, the presented studies and their outcomes demonstrate that the Initiative's mission has been largely achieved. The goal of notably contributing to and strengthening water research by providing water-related, up-to-date data, information, and knowledge and making these available to stakeholders ranging from academia and decision makers to the wider public across the region has been achieved. Furthermore, some results—particularly those related to modelling—are relevant in an international context beyond the southern African region.

Based on the achieved results, which were presented to the relevant scientific and decision-making communities, SASSCAL has identified gaps in regional water research, particularly in support of ensuring water security in the region. In addressing the identified regional gaps in the water sector, future SASSCAL research activities will build on the achievements of the first phase and place additional focus on:

- improving monitoring capabilities by reviewing and integrating existing networks and, in collaboration with water authorities, automating data restoration and recycling, collection platforms, and stations;
- supporting the development of comprehensive databases through mapping of the nature and extent of both the quantity and quality of surface and underground water resources in the region;
- improving integrated water resource assessments to establish catchment water balance estimations using modelling approaches, spatial and temporal variations in flows and water availability, long-term variations, trends and projections in water availability, and water use and demands, as well as aquifer recharge estimations;
- improving the understanding of surface/subsurface interactions through process-based studies and modelling of changing ecosystems with a strong focus on groundwater recharge mechanisms;
- improving the protection of water resources by assessing the impact of previous and future extreme events (floods and droughts) and urbanisation, conducting vulnerability assessments of water resources to hydrologic extremes, conducting assessments of river flows and aquifer water quality, conducting sediment transport assessments, and identifying and assessing the impact of source and non-source pollutants;
- supporting ecosystems- and catchment-based transboundary water resource management through Transboundary Diagnostic Analysis (TDA) and catchment/basin-wide environmental flow assessments;
- supporting the strengthening of limited regional institutional capacities in

water management and water governance at the national and regional levels; and
- conducting detailed socioeconomic analyses aimed at enhancing the understanding of the inter-linkages between water-based ecosystem services and human well-being to support water authorities in formulating appropriate policies and strategies for poverty alleviation.

Acknowledgements

The research was carried out in the framework of SASSCAL and was sponsored by the German Federal Ministry of Education and Research (BMBF) under promotion numbers 01LG1201E, 01LG1201I, 01LG1201K, 01LG1201 L, and 01LG1201M.

References

Bann, C. & Wood, S.C. (2012) Valuing groundwater: A practical approach for integrating groundwater economic values into decision making—A case study in Namibia, Southern Africa. *Water SA,* **38**(3). *International Conference on Groundwater Special Edition*.

Baumberg, V., Helmschrot, J., Göhmann, H., Steudel, S., Fischer, C. & Flügel, W-A. (2014) Assessing basin heterogeneities for rainfall-runoff modelling of the Okavango River and its transboundary management. *Evolving Water Resources Systems: Understanding, Predicting, and Managing Water–Society Interactions* (ed. by A. Castellarin, S. Ceola, E. Toth, and A. Montanari). Proceedings of ICWRS2014, Bologna, Italy, June 2014. *IAHS*, **364**, 320-325.

Beyer M., Koeniger P., Gaj M., Hamutoko J., Wanke H., & Himmelsbach T. (2016) A deuterium-based labelling technique for the investigation of rooting depths, water uptake dynamics, and unsaturated zone water transport in semiarid environments. *Journal of Hydrology*, **533**, 627–643.

Callaway, J.M. (2004) Adaptation benefits and costs: How important are they in the global policy picture and how can we estimate them? *Global Environmental Change*, **14**, 273–284.

Chomba, I. C. & Sichingabula, H. M. (2015) Sedimentation and its effects on selected small dams east of Lusaka, Zambia. *Modern Environmental Science and Engineering,* **1**, 325–340.

De Clercq, W.P., Jovanovic, N. & Fey, M.V. (2010) Land use impacts on salinity in Berg River water. *Water Research Commission Report nr 1503/01/10.*

Ferreira-Baptista, L., Aguiar, P.F., Pereira, M.J. & Manuel, J. (2018) Impact of mining on the environment and water resources in northeastern Angola. This volume.

Flügel, W.A. (2011). Twinning European and South Asian river basins to enhance capacity and implement adaptive integrated water resources management approaches–results from the EC-project BRAHMATWINN. *Advances in Science and Research*, **7**, 1–9.

Gaj M., Beyer M., Koeniger P., Wanke H., Hamutoko J., & Himmelsbach, T. (2016) In-situ unsaturated zone stable water isotope (2H and 18O) measurements in semi-arid environments using tunable off-axis integrated cavity output spectroscopy. *Hydrology and Earth System Sciences*, **20**, 715–731.

Helmschrot, J., Thompson, S., Kralisch, S, & Zander, F. (2018) The SASSCAL Data and Information Portal. This volume.

Himmelsbach, T. Beyer, Wallner, M. Grünberg, I. & Houben, G. (2018) Deep, semi-fossil aquifers in southern Africa: A synthesis of hydrogeological investigations in northern Namibia. This volume.

Hughes, D.A. (2007) South African research in the hydrological sciences: 2003-2006. *South African Journal of Science*, **103**, 415–418.

IPCC. (2007) Summary for policymakers. Climate change 2007: The physical science basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller). Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Kolawole, O.D., Mogobe, O. & Magole, L. (2017) Soils, people, and policy: Land resource management conundrum in the Okavango Delta, Botswana. *Journal of Agriculture and Environment for International Development,* **111**(1), 39–61.

Kusangaya, S., Warburton, M.L., Van Garderen, E.A. & Jewitt, G.P.W. (2014) Impacts of climate change on water resources in southern Africa: A review. *Physics and Chemistry of the Earth*, **67–69**, 47–54.

Lahnsteiner, J. & Lempert, G. (2007) Water management in Windhoek, Namibia. *Water Science & Technology*, **55**, 441–448.

Luetkemeier, R. & Liehr, S. (2018) Drought sensitivity in the Cuvelai Basin: Empirical analysis of seasonal water and food consumption patterns. This volume.

Luetkemeier, R., Stein, L., Drees, L. & Liehr, S. (2017) Blended Drought Index: Integrated drought hazard assessment in the Cuvelai Basin. *Climate* **5**, 51.

MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.E.O. & Taylor, R.G. (2012) Quantitative maps of groundwater resources in Africa. *Environmental Resources Letters*, 024009.

Malan, G.J. (2016) Investigating the suitability of land type information for hydrological modelling in the mountain regions of Hessequa, South Africa. *MSc thesis.* Stellenbosch University, Stellenbosch.

Meinhardt, M., Fleischer, M., Fink, M., Kralisch, S., Kenabatho, P., De Clercq, W., Zimba, H., Phiri, W., & Helmschrot, J. (2018) Semi-arid catchments under change: Adapted hydrological models to simulate the influence of climate change and human activities on rainfall-runoff processes in southern Africa. This volume.

Miller, J.A., Watson, A.P., Fleischer, M., Eilers, A., Sigidi, N.T., Van Gend, J., Van Rooyen, J., Clarke, C.E. & De Clercq, W.P. (2018) Groundwater quality, quantity, and recharge estimation on the west coast of South Africa. This volume.

Moalafhi, D.B., Kenabatho, P.K., Parida, B.P. & Matlhodi, B. (2018) Predictability of precipitation using data from newly established automated weather stations over Notwane catchment in Botswana. This volume.

Mogobe, O., Masamba, W.R.L., Mosimanyana, E. & Mosepele, K. (2014) Occurrence of aluminium and beryllium in the Okavango Delta, Botswana: Human health risks. 3rd International Conference: Water resources and wetlands. 8-10 September, 2014 Tulcea (Romania). pp. 270–277.

Mogobe, O., Masamba, W.R.L., Mosimanyana, E. & Mosepele, K. (2018) Monitoring water quality of the Upper Okavango Delta. This volume.

Muchanga, M. (2017) Understanding sedimentation process in the Makoye Reservoir of Southern Zambia. *Journal of Geography and Earth Sciences,* **5**, 77–96.

Muchanga, M., Sichingabula, H.M., Chisola, M. Chomba, I.C., Sikazwe, H. & Kalapula, S. (2017) Concentration levels and distribution of selected physico-chemical parameters in the Makoye Reservoir and their implications on livestock. Unpublished paper presented at ZAWAFE Conference, June 2017.

Müller, I., Hipondoka, M., Winkler, K., Geßner, U., Martinis, S. & Taubenböck, H. (2018) Monitoring flood and drought events – earth observation for multi-scale assessments of water-related hazards and exposed elements. This volume.

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J. & Urquhart, P. (2014) Africa. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White), pp. 1199–1265. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Nyambe, I., Chabala, A., Banda, K., Zimba, H. & Phiri, W. (2018) Determinants of spatio-temporal variability of water quality in the Barotse Floodplain, Western Zambia. This volume.

Olivier, G. Helmschrot, J. & de Clercq, W.P. (2018) Are large classical gully systems inactive remnants of the past: A field-based case study investigating sediment movement. This volume.

SADC. (2016) SADC launches a US$2.4 billion appeal to assist millions hit by El Nino-induced drought. *Southern African Development Community*. https://www.sadc.int/news-events/news/sadc-launches-u24-billion-appeal-assist-millions-hit-el-nino-induced-drought/.

Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gaye, C.B., Edmunds, W.M. & Simmers, I. (2006) Global synthesis of groundwater recharge in semi-arid and arid regions. *Hydrological processes*, **20**, 3335–3370.

Schlanger, Z. (2018) This major city could be the first to run out of water. *World Economic Forum.* https://www.weforum.org/agenda/2018/01/this-major-city-may-be-the-first-to-run-out-of-water

Stadler, S., Osenbrück, K., Suckow, A.O., Himmelsbach, T. & Hötzl, H. (2010) Groundwater flow regime, recharge, and regional-scale solute transport in the semi-arid Kalahari of Botswana derived from isotope hydrology and hydrochemistry. *Journal of Hydrology*, **388**(3-4), 291–303.

Stein, R. (2005) Water law in a democratic South Africa: A county case study examining the introduction of a public rights system. *Texas Law Review*, **83**, 2167–2183.

Taubenböck, H., Goseberg, N., Setiadi, N., Lämmel, G., Moder, F., Oczipka, M., Klüpfel, H., Wahl, R., Schlurmann, T., Strunz, G., Birkmann, J., Nagel, K., Siegert, F., Lehmann, F., Dech, S., Gress, A. & Klein, R. (2009) Last-mile preparation for a potential disaster: Interdisciplinary approach towards tsunami early warning and an evacuation information system for the coastal city of Padang, Indonesia. *Natural Hazards & Earth Systems Science*, **9**, 1509–1528.

Taubenböck, H., Müller, I., Geiß, C. & Lütkemeier, R. (2018) Managing Hazards: A conceptual foundation. This volume.

Turpie, J.K. & Barnes, J.I. (2003) Balancing ecology and economics in the multiple use of wetlands on communal lands. Proceedings of the VIIth International Rangelands Congress, Durban, South Africa, 26 July – 1 August 2003. pp. 1932–1941.

Wanke, H., Beyer, M., Hipondoka, M., Hamutoko, J., Gaj, M., Koenigerand, P. & Himmelsbach, T. (2018) The long road to sustainability: Integrated water quality and quantity assessments in the Cuvelai-Etosha Basin, Namibia. This volume.

Zimba, H., Kawawa, B., Chabala, A., Phiri, W., Selsam, P., Meinhardt., M. & Nyambe, I. 2018. Assessment of trends in inundation extent in the Barotse Floodplain, upper Zambezi River Basin: A remote sensing-based approach. *Journal of Hydrology: Regional Studies*, **15**, 149–170.

References [CrossRef]

Bann, C. & Wood, S.C. (2012) Valuing groundwater: A practical approach for integrating groundwater economic values into decision making—A case study in Namibia, Southern Africa. *Water SA*, **38**(3). *International Conference on Groundwater Special Edition*. CrossRef

Baptista, L.F., Aguiar, P.F., Pereira, M.J. & Manuel, J. (2018) Impact of mining on the environment and water resources in northeastern Angola. This volume. CrossRef

Baumberg, V., Helmschrot, J., Göhmann, H., Steudel, S., Fischer, C. & Flügel, W-A. (2014) Assessing basin heterogeneities for rainfall-runoff modelling of the Okavango River and its transboundary management. *Evolving Water Resources Systems: Understanding, Predicting, and Managing Water–Society Interactions* (ed. by A. Castellarin, S. Ceola, E. Toth, and A. Montanari). Proceedings of ICWRS2014, Bologna, Italy, June 2014. *IAHS*, **364**, 320-325. CrossRef

Beyer M., Koeniger P., Gaj M., Hamutoko J., Wanke H., & Himmelsbach T. (2016) A deuterium-based labelling technique for the investigation of rooting depths, water uptake dynamics, and unsaturated zone water transport in semiarid environments. *Journal of Hydrology*, **533**, 627–643. CrossRef

Callaway, J.M. (2004) Adaptation benefits and costs: How important are they in the global policy picture and how can we estimate them? *Global Environmental Change*, **14**, 273–284. CrossRef

Chomba, I. C. & Sichingabula, H. M. (2015) Sedimentation and its effects on selected small dams east of Lusaka, Zambia. *Modern Environmental Science and Engineering*, **1**, 325–340. CrossRef

De Clercq, W.P., Jovanovic, N. & Fey, M.V. (2010) Land use impacts on salinity in Berg River water. *Water Research Commission Report nr 1503/01/10.*

Flügel, W.A. (2011). Twinning European and South Asian river basins to enhance capacity and implement adaptive integrated water resources management approaches–results from the EC-project BRAHMATWINN. *Advances in Science and Research*, **7**, 1–9. CrossRef

Gaj M., Beyer M., Koeniger P., Wanke H., Hamutoko J., & Himmelsbach, T. (2016) In-situ unsaturated zone stable water isotope (2H and 18O) measurements in semi-arid environments using tunable off-axis integrated cavity output spectroscopy. *Hydrology and Earth System Sciences*, **20**, 715–731. CrossRef

Helmschrot, J., Thompson, S., Kralisch, S, & Zander, F. (2018) The SASSCAL Data and Information Portal. This volume. CrossRef

Himmelsbach, T. Beyer, Wallner, M. Grünberg, I. & Houben, G. (2018) Deep, semi-fossil aquifers in southern Africa: A synthesis of hydrogeological investigations in northern Namibia. This volume. CrossRef

Hughes, D.A. (2007) South African research in the hydrological sciences: 2003-2006. *South African Journal of Science*, **103**, 415–418.

IPCC. (2007) Summary for policymakers. Climate change 2007: The physical science basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller). Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Kolawole, O.D., Mogobe, O. & Magole, L. (2017) Soils, people, and policy: Land resource management conundrum in the Okavango Delta, Botswana. *Journal of Agriculture and Environment for International Development*, **111**(1), 39–61.

Kusangaya, S., Warburton, M.L., Van Garderen, E.A. & Jewitt, G.P.W. (2014) Impacts of climate change on water resources in southern Africa: A review. *Physics and Chemistry of the Earth*, **67–69**, 47–54. CrossRef

Lahnsteiner, J. & Lempert, G. (2007) Water management in Windhoek, Namibia. *Water Science & Technology*, **55**, 441–448. CrossRef

Luetkemeier, R. & Liehr, S. (2018) Drought sensitivity in the Cuvelai Basin: Empirical analysis of seasonal water and food consumption patterns. This volume. CrossRef

Luetkemeier, R., Stein, L., Drees, L. & Liehr, S. (2017) Blended Drought Index: Integrated drought hazard assessment in the Cuvelai Basin. *Climate* **5**, 51. CrossRef

MacDonald, A.M., Bonsor, H.C., Dochartaigh, B.E.O. & Taylor, R.G. (2012) Quantitative maps of groundwater resources in Africa. *Environmental Resources Letters*, 024009. CrossRef

Malan, G.J. (2016). Investigating the suitability of land type information for hydrological modelling in the mountain regions of Hessequa, South Africa. *MSc thesis.* Stellenbosch University, Stellenbosch.

Meinhardt, M., Fleischer, M., Fink, M., Kralisch, S., Kenabatho, P., De Clercq, W., Zimba, H., Phiri, W., & Helmschrot, J. (2018) Semi-arid catchments under change: Adapted hydrological models to simulate the influence of climate change and human activities on rainfall-runoff processes in southern Africa. This volume. CrossRef

Miller, J.A., Watson, A.P., Fleischer, M., Eilers, A., Sigidi, N.T., Van Gend, J., Van Rooyen, J., Clarke, C.E. & De Clercq, W.P. (2018) Groundwater quality, quantity, and recharge estimation on the west coast of South Africa. This volume. CrossRef

Moalafhi, D.B., Kenabatho, P.K., Parida, B.P. & Matlhodi, B. (2018) Predictability of precipitation using data from newly established automated weather stations over Notwane catchment in Botswana. This volume. CrossRef

Mogobe, O., Masamba, W.R.L., Mosimanyana, E. & Mosepele, K. (2014) Occurrence of aluminium and beryllium in the Okavango Delta, Botswana: Human health risks. 3rd International Conference: Water resources and wetlands. 8-10 September, 2014 Tulcea (Romania). pp. 270–277.

Mogobe, O., Masamba, W.R.L., Mosimanyana, E. & Mosepele, K. (2018) Monitoring water quality of the Upper Okavango Delta. This volume. CrossRef

Muchanga, M. (2017) Understanding sedimentation process in the Makoye Reservoir of Southern Zambia. *Journal of Geography and Earth Sciences*, **5,** 77–96. CrossRef

Muchanga, M., Sichingabula, H.M., Chisola, M. Chomba, I.C., Sikazwe, H. & Kalapula, S. (2017) Concentration levels and distribution of selected physico-chemical parameters in the Makoye Reservoir and their implications on livestock. Unpublished paper presented at ZAWAFE Conference, June 2017.

Müller, I., Hipondoka, M., Winkler, K., Geßner, U., Martinis, S. & Taubenböck, H. (2018) Monitoring flood and drought events – earth observation for multi-scale assessments of water-related hazards and exposed elements. This volume. CrossRef

Niang, I., Ruppel, O.C., Abdrabo, M.A., Essel, A., Lennard, C., Padgham, J. & Urquhart, P. (2014) Africa. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (ed. by V.R. Barros, C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White), pp. 1199–1265. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA.

Nyambe, I., Chabala, A., Banda, K., Zimba, H. & Phiri, W. (2018) Determinants of spatio-temporal variability of water quality in the Barotse Floodplain, Western Zambia. This volume. CrossRef

Olivier, G. Helmschrot, J. & de Clercq, W.P. (2018) Are large classical gully systems inactive remnants of the past: A field-based case study investigating sediment movement. This volume. CrossRef

SADC. (2016) SADC launches a US$2.4 billion appeal to assist millions hit by El Nino-induced drought. *Southern African Development Community*. https://www.sadc.int/news-events/news/sadc-launches-u24-billion-appeal-assist-millions-hit-el-nino-induced-drought/.

Scanlon, B.R., Keese, K.E., Flint, A.L., Flint, L.E., Gaye, C.B., Edmunds, W.M. & Simmers, I. (2006) Global synthesis of groundwater recharge in semi-arid and arid regions. *Hydrological processes*, **20**, 3335–3370. CrossRef

Schlanger, Z. (2018) This major city could be the first to run out of water. *World Economic Forum.* https://www.weforum.org/agenda/2018/01/this-major-city-may-be-the-first-to-run-out-of-water

Stadler, S., Osenbrück, K., Suckow, A.O., Himmelsbach, T. & Hötzl, H. (2010) Groundwater flow regime, recharge, and regional-scale solute transport in the semi-arid Kalahari of Botswana derived from isotope hydrology and hydrochemistry. *Journal of Hydrology*, **388**(3-4), 291–303. CrossRef

Stein, R. (2005) Water law in a democratic South Africa: A county case study examining the introduction of a public rights system. *Texas Law Review*, **83**, 2167–2183.

Taubenböck, H., Goseberg, N., Setiadi, N., Lämmel, G., Moder, F., Oczipka, M., Klüpfel, H., Wahl, R., Schlurmann, T., Strunz, G., Birkmann, J., Nagel, K., Siegert, F., Lehmann, F., Dech, S., Gress, A. & Klein, R. (2009) Last-mile preparation for a potential disaster: Interdisciplinary approach towards tsunami early warning and an evacuation information system for the coastal city of Padang, Indonesia. *Natural Hazards & Earth Systems Science*, **9**, 1509–1528. CrossRef

Taubenböck, H., Müller, I., Geiß, C. & Lütkemeier, R. (2018) Managing Hazards: A conceptual foundation. This volume. CrossRef

Turpie, J.K. & Barnes, J.I. (2003) Balancing ecology and economics in the multiple use of wetlands on communal lands. Proceedings of the VIIth International Rangelands Congress, Durban, South Africa, 26 July – 1 August 2003. pp. 1932–1941.

Wanke, H., Beyer, M., Hipondoka, M., Hamutoko, J., Gaj, M., Koenigerand, P. & Himmelsbach, T. (2018) The long road to sustainability: Integrated water quality and quantity assessments in the Cuvelai-Etosha Basin, Namibia. This volume. CrossRef

Zimba, H., Kawawa, B., Chabala, A., Phiri, W., Selsam, P., Meinhardt., M. & Nyambe, I. 2018. Assessment of trends in inundation extent in the Barotse Floodplain, upper Zambezi River Basin: A remote sensing-based approach. *Journal of Hydrology: Regional Studies*, **15**, 149–170. CrossRef