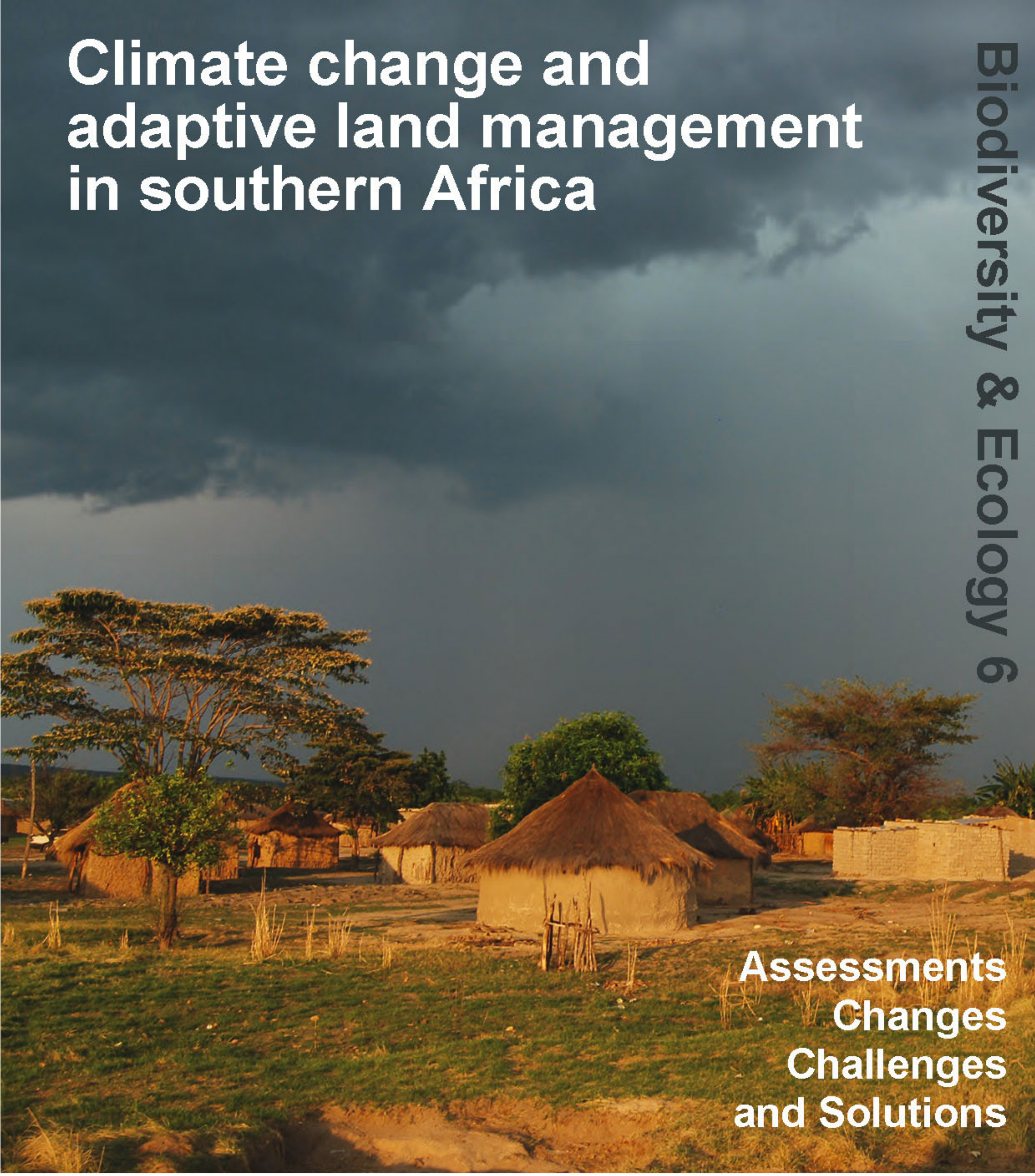
Climate change and adaptive land management in southern Africa

Biodiversity & Ecology 6



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Changes
Challenges
and Solutions

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Climate change and adaptive land management in southern Africa

Assessments, changes, challenges, and solutions

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Water resources

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

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Abstract: A comprehensive river basin assessment is key to integrated land and water resources management (ILWRM), which is based on an integrated system analysis to identify interacting hydrological processes that are driven by landscape features and socioeconomic development. Software toolsets like RBIS (River Basin Information System), GRASS-HRU, and the hydrological modelling system JAMS/J2000 were used and further developed for basin assessments and modelling of hydrological process dynamics and other environmental processes in selected catchments in southern Africa. These are the Gaborone Dam catchment (Botswana, South Africa), the Verlorenvlei catchment (South Africa), and the Luanginga catchment (Angola, Zambia). All of these catchments respond very sensitively to changes in climate and land management, revealing additional issues like a strong decline of inflow (Gaborone Dam) or a decline of usable groundwater resources (Verlorenvlei). Further, extensive wetland areas in the Upper Zambezi (Luanginga) respond strongly to changes in hydro-climatic conditions and land management. In this study, newly developed and improved simulation components for representing processes with a strong local impact on the hydrological conditions such as floodplain inundation, irrigation, small farm dams, and contour bank farming were used to more precisely simulate the hydrology of the respective basins. After successful model validation and an improved understanding of catchment dynamics, the models were used as a platform for different land or climate change analysis. Taking the RCP 8.5 scenario based on EC-Earth and ECHAM, downscaled by REMO, into account, the Luanginga catchment showed a strong decrease in runoff generation, inundation extent, and groundwater recharge. For the Kruismannsrivier, a sub-catchment of the Verlorenvlei, the relation between contour farming and related effects on surface/subsurface runoff processes and related parameters were revealed through modelling. These findings could also be projected to the Gaborone Dam catchment, in which the influence of small farm dams spread over the catchment could be shown by modelling.

Resumo: Uma avaliação abrangente da bacia hidrográfica é essencial para a gestão integrada dos recursos terrestres e hídricos (ILWRM), a qual é baseada numa análise integrada do sistema para identificar processos hidrológicos em interacção que são impulsionados pelas características da paisagem e o desenvolvimento socioeconómico. Ferramentas de software, tais como RBIS (River Basin Information System), GRASS-HRU e o sistema de modelação hidrológica JAMS/J2000, foram utilizadas e desenvolvidas para avaliações de bacias e modelação de dinâmicas de processos hidrológicos e outros ambientais em bacias selecionadas na África Austral. Estas são a bacia de Gaborone Dam (Botswana, África do Sul), bacia de Verlorenvlei (África do Sul) e bacia de Luanginga (Angola, Zâmbia). Todas estas bacias hidrográficas são muito sensíveis a alterações no clima e na gestão das terras, revelando problemas adicionais como um forte declínio no influxo (Gabarone

Dam) ou um declínio nos recursos hídricos subterrâneos utilizáveis (Verlorenvlei). Além disso, extensas áreas de zonas húmidas no Zambezi Superior (Luanginga) respondem fortemente a alterações nas condições hidro-climáticas e na gestão das terras. Neste estudo, foram utilizados componentes de simulação recentemente desenvolvidos e melhorados para representar processos com um forte impacto local nas condições hidrológicas, tais como inundação de várzeas, irrigação, pequenas barragens agrícolas e agricultura de contorno, para simular com maior precisão a hidrologia das respectivas bacias. Após a validação bem-sucedida do modelo e uma melhor compreensão das dinâmicas das bacias, os modelos foram usados como uma plataforma para diferentes análises da terra e das alterações climáticas. Tendo em conta o cenário do RCP 8.5, baseado em EC-EARTH e ECHAM, downscaled pelo REMO, a bacia de Luanginga mostrou uma forte diminuição na produção de escorrência superficial, extensão de inundação e recarga de águas subterrâneas. Para o Kruismannsrivier, uma sub-bacia do Verlorenvlei, a relação entre a agricultura de contorno e os impactos relacionados com os processos de escorrência superficial/subterrânea (e parâmetros relacionados) foram revelados pela modelação. Estas descobertas podiam ser também projectadas para a bacia de Gaborone Dam, na qual a influência de pequenas barragens agrícolas espalhadas pela bacia podia ser demonstrada através da modelação.

Introduction

Background

Sustainable water management in semi-arid areas is a challenge from various perspectives. Given the projected changes in climate as well as ongoing population growth and associated demands for food and energy production that result in land management changes, a key challenge in the sub-Saharan countries is to secure water at sufficient quality and quantity for both the stability of ecosystems, with their requisite functions and services, and for human use. Changing conditions will severely influence the highly variable hydrological pattern in southern African catchments, including, for example, increasing extremes, changing groundwater recharge patterns, or increasing water extraction and pollution. These effects, in turn, will create even more pressure on ecosystems, existing and future land management, socio-economic development, and biodiversity. Consequently, southern Africa is suspected to be strongly affected by global climate change and shows a high climate vulnerability and risk (Miola & Simonet, 2014), with climate extremes presumed to intensify in frequency and magnitude (SREX, 2012). Due to recent droughts resulting from an El Niño event, water managers are challenged with questions such as: Can we cope with the demands on water (e.g., water shortages in Gaborone or Windhoek; Allgemeine Zeitung, 2016; Mmegi, 2016) or can we provide enough energy to further develop southern African economies (e.g., lack of production at Lake Kariba; IGC, 2016; New York Times, 2016)? To manage such interrelated phenomena in data-scarce regions like southern Africa, innovative modelling techniques can be successfully applied.

Precipitation in the semi-arid regions of southern Africa is highly variable; rainfall is of relatively short duration, highly localised, and often occurs with different intensities (Hughes, 2007). Various studies over the previous decades have shown that extreme rainfall events make up a significant share of the total annual precipitation (e.g., Mason et al., 1997; Güntner, 2002; van Wilgen et al., 2016). Highly variable precipitation events also cause a strong variability in the discharge behaviour of rivers in southern Africa (e.g., Mazvimavi & Wolski, 2006; Steudel et al., 2013a; Kusangaya et al., 2014). Partly due to this high variability, the runoff at the west coast of Western Cape province is most sensitive to climate change all over South Africa (Schulze, 2000). In addition, low latitudes and high radiation lead to high annual mean temperatures and therefore to a high potential evapotranspiration (e.g., Alexander, 1985; Steudel et al., 2013a, 2013b; Engelbrecht et al., 2015) which may result in severe droughts in years with only small amounts of rainfall. In areas affected by unsustainable management practices, climatic and hydrological extremes increase already existing trends towards desertification, erosion, and a related loss of biodiversity, water, and food insecurity (Meigh, 1995; Hughes, 2007; Wheater, 2008). To represent the complex interacting natural and human-induced drivers in hydrological models in an appropriate, process-oriented way, advanced and adaptive modelling tools and methods are needed (Parida et al., 2006; Wheater, 2008).

Objectives

The aforementioned challenges are predominant in the three pilot catchments investigated in this study, all located in semi-arid southern Africa (Fig. 1). The overall aim of this work, which was embedded in SASSCAL Task 18, was the development of eco-hydrological computer models that are tailored to the specific conditions in the selected river basins, both in terms of dominant processes and data availability. Further, these models were required to represent eco-hydrological and anthropogenic processes using physically based, conceptual approaches in order to make them applicable for assessing the impacts of land management and climate change, and thus to provide a basis for informed water resources management in the selected pilot catchments.

To achieve these objectives, rainfall-runoff dynamics of the often data-poor areas were reproduced by utilising the integrated, process-based, and spatially distributed modelling system JAMS/J2000 (Kralisch & Krause, 2006). The first objective was to simulate the undisturbed

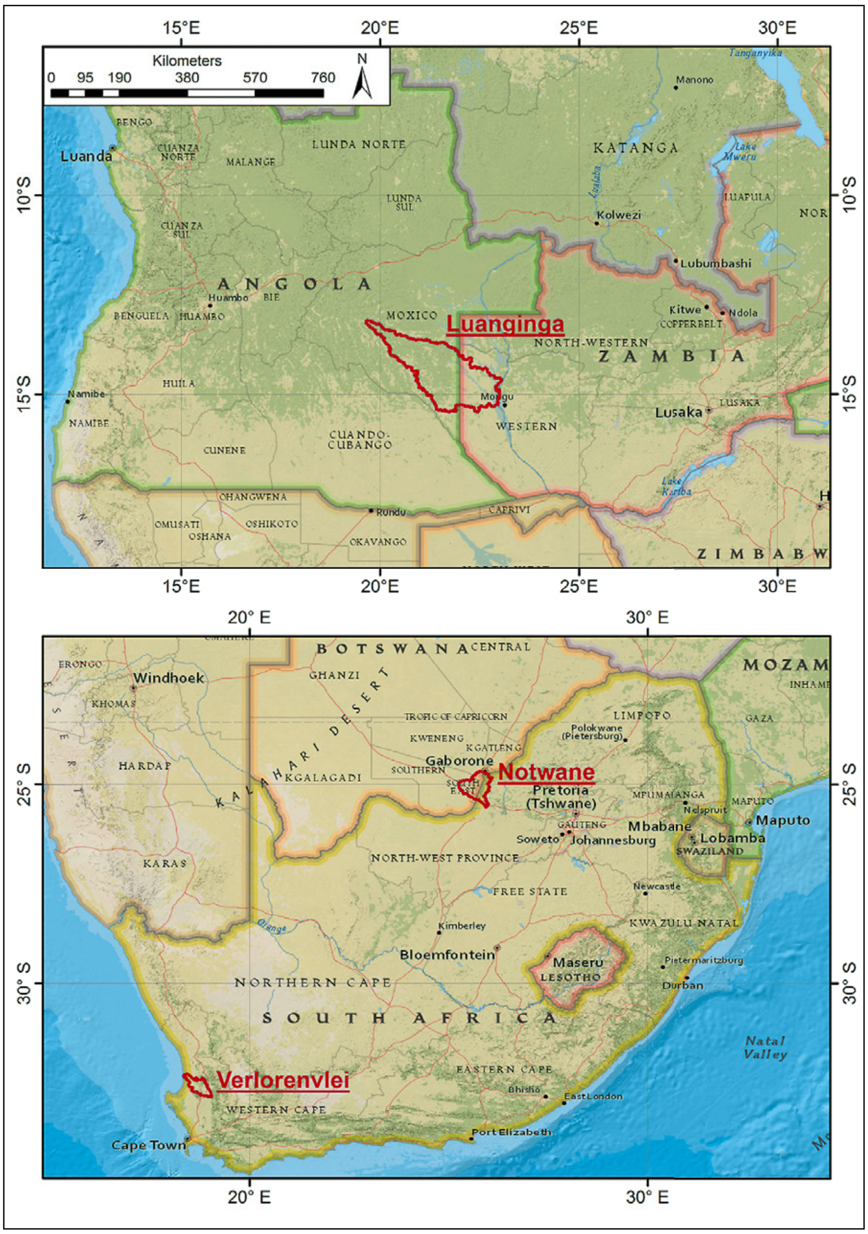


Figure 1: Location of the pilot catchments (red).

natural conditions of the hydrological systems in the three pilot catchments. The second objective focused on the representation of major anthropogenic factors apparently influencing the hydrological conditions within two of the pilot catchments, namely the Gaborone Dam and Verlorenvlei catchments. By implementing additional simulation routines, the models were adapted to more precisely reflect specific local conditions in both pilot catchments and to improve model performance (e.g., advanced routing techniques and modules simulating the influence of small farm dams, irrigation, and contour farming). The third objective was to assess the effects of climate change on the hydrological process dynamics in the other pilot catchment, the Luanginga catchment. In this catchment, the focus was on developing a model extension capable of simulating the annual flooding condition and therefore to provide a more realistic simulation of hydrological components like runoff generation, evapotranspiration, and soil moisture. Using this model, the climate change impact has been analysed up to the year 2100. Special attention was paid to investigating how the newly developed flood extension responds to climate change and how this impacts flood dynamics and extent. However, the developed model also provides the basis for follow-up assessments with more comprehensive climate projection data sets.

Study Areas

Verlorenvlei

The Verlorenvlei catchment (~1 820 km²; Fig. 1) drains into an estuarine lake, a RAMSAR-listed wetland on the west coast of South Africa within the Sandveld area; the intermittent connection between fresh and salt water is connected to a high biodiversity profile. The Sandveld region has a Mediterranean climate, characterised by cool, rainy winters and hot, dry summers (Franke et al., 2014). Precipitation is in the form of coastal fog and low and variable rainfall (Conrad & Munch, 2006). Furthermore, the area experiences wide ranging inter-annual climatic variability. The highest annual rainfall was recorded at in the upper catchment with 589 mm in 2001, whereas the coastal area received the lowest rainfall, 115 mm in 2002. Potential evapotranspiration (PET) ranges from 1 200 mm per year to 1 600 mm per year, mostly exceeding rainfall rates; even the lowest PET is in excess of the highest rainfall (Conrad & Munch, 2006).

The catchment is an important agricultural area, providing 15% of the South African potato crop (Potatoes South Africa, 2015). Some tea and fruits are also grown, but play only a minor role for the majority of the farmers (Archer et al., 2009). The catchment is exposed to several challenges, such as climate change and decreasing groundwater levels combined with an increasing irrigation agriculture, representing a hydrologically vulnerable area within the Sandveld (Conrad & Munch, 2006). The water users in Verlorenvlei area are highly dependent on groundwater, as surface water resources are scarce. Most cities and irrigation systems in the region are supplied with groundwater. The only dams used for irrigation can be found in the more mountainous headwaters. A single sub-catchment providing good quality water, the Krom-Antonies, is the system's main provider of fresh water—almost all other sub-catchments are facing salinity difficulties (Conrad & Munch, 2006). Thus, the catchment is considered as a good example of South Africa's coastal areas, where water scarcity may be a limiting factor for economic development. The correct evaluation of water resources, as well as their

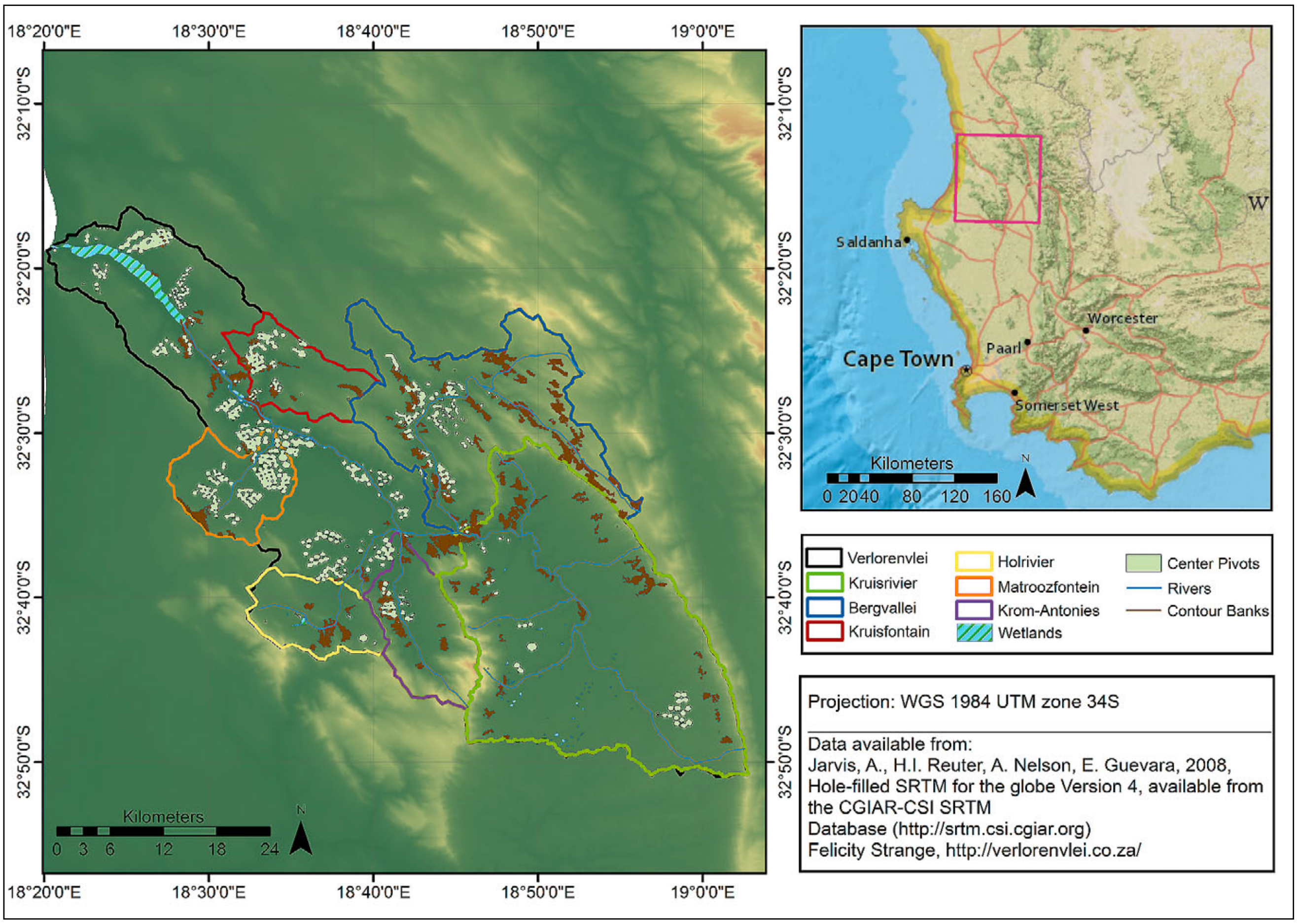


Figure 2: Sub-catchments of the Verlorenvlei and location of centre pivots and contour banks

quality and monitoring, are crucial for the sustainable use of water in this coastal area, where agricultural interests must be considered as well (Nel, 2004).

Two agricultural implementations that will be further discussed in this paper, centre pivot irrigation and contour bank farming (Fig. 2), are apparent in the catchment. Contour farming is a common practice for water and soil conservation in the Western Cape Province (Wakindiki et al., 2007). Contour banks are constructed perpendicular to cultivated slopes, as well as at specific intervals downslope. Their main purpose is to reduce slope lengths and water flow velocity and to store and prolong surface runoff. The impact of contour bank farming on flood reduction and sediment dynamics has been studied in various semi-arid basins (Kingumbi et al., 2004; Nasri, 2007; Baccari et al., 2008; Lesschen et al., 2009; Ouessar et al., 2009; Steudel et al., 2015). In centre pivots, sprinklers are attached below lateral pipes, which are used as a water supply. They represent a typical pattern of sprinkler irrigation (Omary et al., 1997; Foley, 2008). In the Sandveld area, the volume of water applied through irrigation exceeds the natural rainfall by a factor of between 3 in winter and 5 in summer months (Knight et al., 2007).

As no measured runoff series was available for the whole Verlorenvlei catchment, results presented within this study are for the sub-catchment of Kruisriver at station Tweekuilen (G3H001). This station provided a sufficient time series from 1970–2009 with only 3.2% missing data. Both mentioned agricultural implementations are apparent in this sub-catchment.

Gaborone Dam

The Gaborone Dam catchment (4 500 km²), which is part of the Notwane River Basin (FAO, 2004), is located in the southeastern part of Botswana and shares a border with South Africa. The dam itself functions as the main water source for Gaborone City and the surrounding settlements (Meigh, 1995; DWA, 2014a). The Notwane River has its source in the Kalahari sandveldt flowing to the northeast until reaching the Limpopo River. About one-third of Botswana's population lives in the Notwane Basin, which includes large developed cities such as Gaborone, Molepolole, Mochudi, Kanye, Lobatse, and Jwaneng. According to Köppen-Geiger classification, the catchment matches the requirements of BSh (hot, arid steppe) (Peel et al., 2007) with a mean annual temperature of 20.3°C and a precipitation of 450–500 mm/a (Meigh, 1995; Peel et al., 2007). The climate is characterised by a rainy season from November to March and a dry season from April to October. Due to low humidity conditions, a mean PET of about 1 500 mm was estimated by Adams et al. (1999), and PET amounts can be up to four times higher than rainfall (FAO, 2004). All the rivers in the Gaborone Dam catchment are ephemeral. The Gaborone Dam was established in 1963 and was subsequently raised by 25 metres from 1984–1986. This increased its potential capacity from

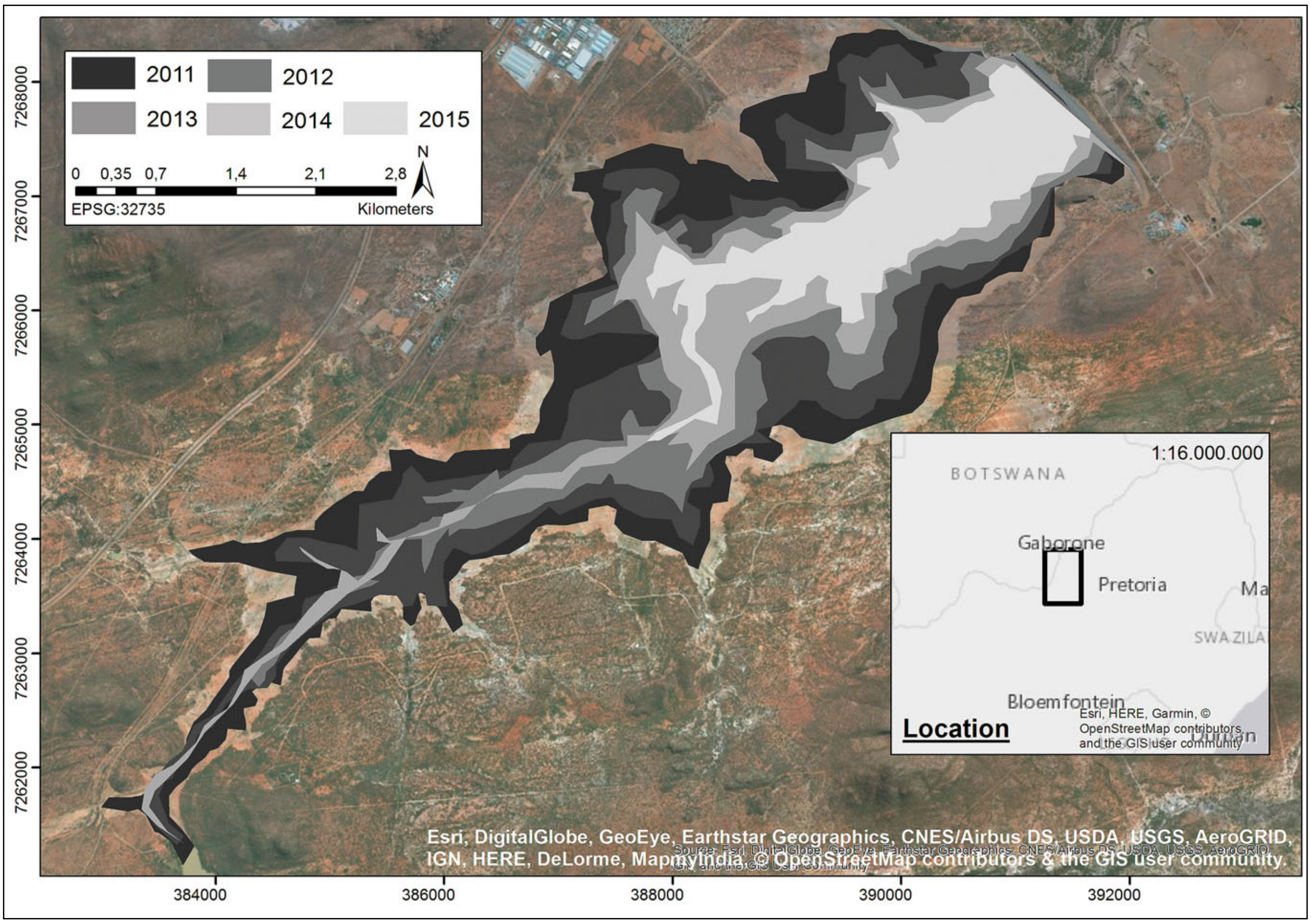


Figure 3: Visualisation of the shrinking size of the Gaborone Dam, Gaborone, Botswana (2011–2015), perimeters derived by digitisation using Landsat 7 and 8 cloud-free scenes at the end of the rainy season (March–May); lines from outside to inside show 2011 to 2015.

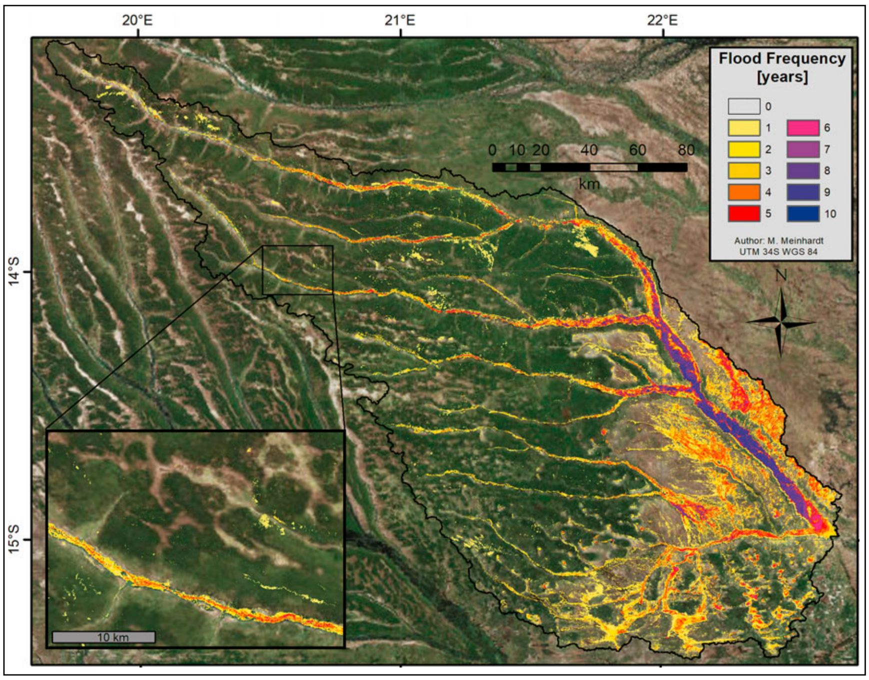


Figure 4: Flood frequency in the Luanginga catchment derived from Landsat/DFI peak flood images based on a time series of 10 years.

23 to 141.1 million cubic meters (Knight, 1990; WUC, 2014). Since 2002, there has been a steady decrease in the volume of the Gaborone Dam (Fig. 3), reaching the lowest record in history of 1% at the end of 2015 (WUC, 2014), leading to failures of water supply (Plessis & Rowntree, 2003).

Luanginga

Wetlands like the Verlorenvlei are especially sensitive to hydrological regime changes (Mitsch & Gosselink, 2000). The third catchment studied here was the Luaginga. It is a tributary of the Upper Zambezi River and covers an area of ~33 000 km², ranging from the Angolan highlands to the Barotse floodplain of the Zambezi River. The catchment is characterised by an annual flow regime and extensive wetland areas upstream of the gauge outlet at Kalabo, the central business district of the area. Due to the annual flood (Fig. 4), which peaks in April, the floodplain consists of exceptionally fertile soils with high agricultural productivity and is also known for its rich cultural heritage. These factors combine to make the area within the watershed particularly sensitive to changes in hydrological conditions because humans, flora, and fauna are adapted to life in this special ecosystem.

To model future changes caused by climate change until the end of this century, two different climate models and two sce-

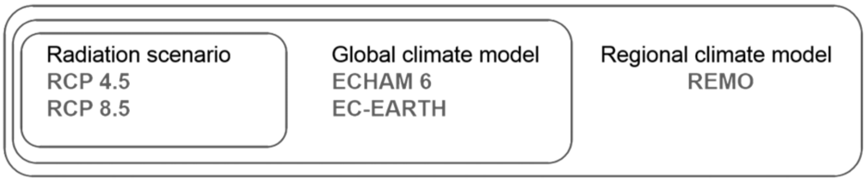


Figure 5: Structure of the applied climate scenarios.

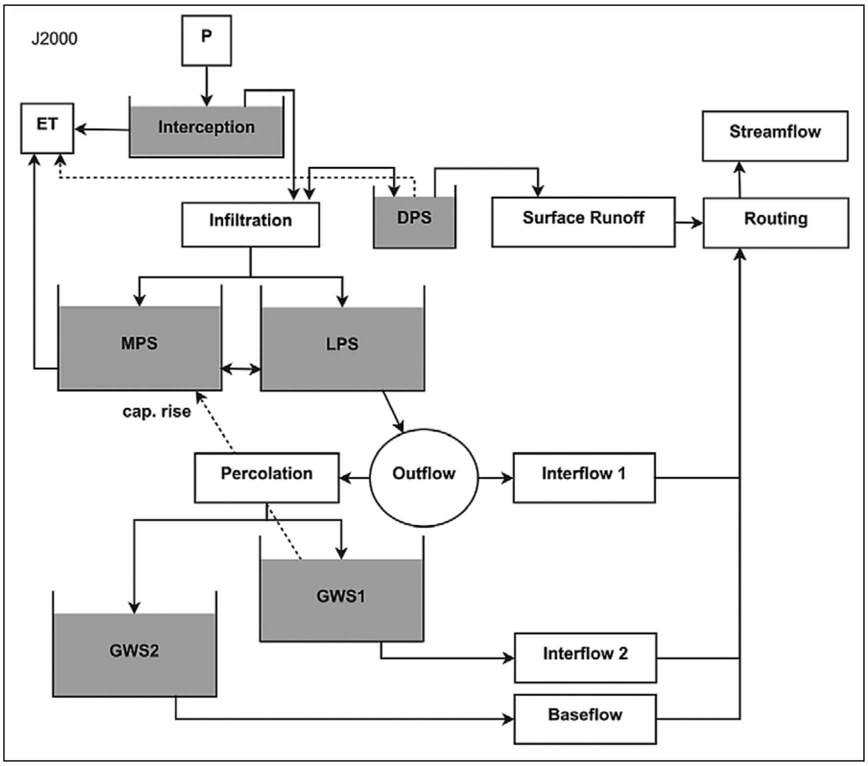


Figure 6: Graphical representation of the J2000 model structure (Knoche et al., 2014). *Abbreviations: DPS – depression storage; MPS – mid-size pore storage; LPS – large pore storage; GWS – groundwater storage.*

narios each were used to run the JAMS/J2000 model in the Luanginga catchment. As shown in Figure 5, they are all based on the regional climate model REMO, which has a high spatial resolution of 0.22 degree (25 km) and is forced either by EHAM or EC-Earth (0.44 degree) using the RCP 4.5 and 8.5 scenarios. The added value of this downscaling performed by the REMO model in comparison to the original ECHAM and EC-Earth data is discussed in Fotso-Nguemo (2017a, 2017b) and mainly based on its higher spatial resolution, which plays a significant role when considering the topography of the catchment, stretching from the Angolan Bié Plateau towards the Zambezi floodplains. Hänsler et al. (2011) showed that in southern Africa, the data (scaled down dynamically with REMO) corresponds to the spatial and temporal patterns of observation, and the seasonal precipitation characteristics are better reproduced by this downscaling compared to the original ECHAM and EC-Earth data with the coarse 0.44 degree resolution. Further, a so-called "scaling" or "simple multiplicative" bias correction (Fowler & Kilsby, 2007; Gudmundsson et al., 2012) based on measured long-term monthly precipitation means was applied to the REMO data as a spatially distributed correction factor in the JAMS/J2000 model, where it is interpolated between the stations and multiplied with the interpolated precipitation for each spatial model entity (Meinhardt, 2017).

The adaptive hydrological modelling system JAMS/J2000

In this section, the main concept of the hydrological model will be described. A detailed explanation of the developed model extensions will be given in the following section.

The process-oriented modelling system JAMS/J2000 was used to address the hydrological dynamics within the pilot catchments. The model consists of encapsulated modules, each of which represents a different hydrological process and runs for different temporal resolutions (Krause, 2001, 2002; Kralisch & Krause, 2006). Following a spatially distributed approach, the model utilises the Hydrological Response Units concept (HRU) (Flügel, 1995; Krause, 2001; Nepal, 2002; Watson et al., 2018) to represent spatial input data. The HRUs were delineated by overlaying information about soil, geology, and relief parameters according to Wolf et al. (2009). Accordingly, J2000 is a spatially fully distributed hydrological model (Krause, 2002) using a routing topology to distribute lateral and surface water budgets between spatial model units (HRUs) along the topographical gradient. Its process-based soil water balance module functions as the central 'regulation and distribution system' (Krause et al., 2006; Knoche et al., 2014) and mutually interacts with nearly all other J2000 process modules (Fig. 6; Knoche et al., 2014). Spatial model units contain two soil storages: the mid-size pore storage (MPS) represents the effective field capacity water budget that is reduced by the AET only. The large pore storage (LPS) cannot hold water against gravity and therefore 'is considered as the source of all subsurface flow processes in the J2000 model' (Krause et al., 2006; Knoche et al., 2014). Infiltration water is distributed to the MPS and the LPS based on a distribution coefficient until these storages are filled or the maximal infiltration rate is reached. Infiltration excess water is stored as depression storage (DPS) at the surface. When DPS is exceeded, surface runoff is generated and routed to the adjacent downslope spatial unit. The LPS outflow is distributed into lateral runoff and percolation depending on the slope and a calibration parameter. There are two groundwater storages for each spatial model unit, one having a quick hydrological reaction and one having longer residence times. The percolation water is distributed between the two groundwater storages depending on a calibration parameter and the slope (Krause et al., 2006; Knoche et al., 2014). The J2000 runoff concentration and flood routing is calculated for the spatial model units and a network of river reaches. Lateral flows calculated for each grid cell are passed to downslope grid cells until a river reach is connected, where the lateral runoff is transmitted to the streamflow budget. 'Flood routing in the river network is calculated by a simplified kinematic wave approach, using Manning's formula to calculate flow velocity' (Krause et al., 2006; Knoche et al., 2014). For the Verlorenvlei and Gaborone Dam catchments, the routing mechanism between spatial entities was switched from single- to multi-flow routines in order to more precisely capture the spatial variability within the flat terrain (Pfennig et al., 2009).

Further individual adaptations implemented to represent the specific conditions in the study areas (contour farming, irrigation agriculture, farm dams, and flood plains) are described in the following subsections.

In order to provide an easy and user-friendly way to set up such a model, software toolsets like the RBIS (River Basin Information System; Zander & Kralisch, 2016) and the GRASS-HRU (Schwartze, 2008; Schwartze et al., 2012), service- and web-based tools for geo(-data) processing, were used to provide a data basis and generate input data for the JAMS/J2000 modelling system.

Contour farming

To incorporate the effect of the locally applied land use management practice of contour bank farming, a contour bank module according to Steudel et al. (2015) was integrated. This involves the addition of contour bank storages to each HRU. The volume of this storage depends on the contour length per HRU and a predefined catchment-specific mean height of the contour bank wall. The total length per HRU is calculated during the pre-processing HRU delineation (Pfennig et al., 2009) and depends on site-specific conditions, such as slope and land use. The main inflows into the contour bank storage are surface runoff and sub-surface runoff (interflow) (Steudel et al., 2015). The proportion of surface runoff which exceeds the maximum storage capacity of the contour bank is routed as surface runoff into the next neighbouring HRU. The proportion of interflow flowing into the storage is a function of the actual interflow and a gradient (difference between water level of the saturated soil zone with the ditch and the actual total water level of this zone). Water in the ditches infiltrates and/or percolates into the underlying soil or groundwater zone. For channel drainage, each HRU with assigned contour banks is routed to the stream network according to the calculated flow accumulation. To build contour banks, guidelines for the Western Cape region (Mathee, 1984) recommend to farmers that the distance between contour banks should be planned according to:

$$\boldsymbol{V = 0.25 \times S + 0.5}$$

with

V = Vertical distance of contour banks [m]

S = Slope [%]

A detailed description of the contour bank extension can be found in Steudel et al. (2015). Within this study, adaptions were made in the delineation of the contour banks, which were then used by the model. Contrary to the parameters used by Steudel et al. (2015), the values were adapted according to the equation above. In order to fit the special circumstances in the Verlorenvlei area, the total contour bank length per HRU from different delineations using various parameter combinations was compared to the real length from digitised contour banks utilising Google Earth. The parameters described in the following equation show the best fit between modelled and real contour lengths:

$$\boldsymbol{V = 0.6 \times S + 0.5}$$

Irrigation

In order to represent water abstractions for irrigation in the model, a simulation approach that is applicable in situations where only limited information is available about the exact location and irrigation water amounts was needed. As a test case, the Verlorenvlei catchment with its large proportion of irrigated agricultural land use was chosen. In the model, the principle method of representing irrigation followed a three-step approach (Branger et al., 2016):

1. Calculate irrigation demand for all HRUs that feature irrigated agricultural land use at the current time *t*. This is done in two steps:
   a. Calculate the evapotranspiration deficit ($etDef_s$) between actual ($actET_s$) and potential ($potET_s$) evapotranspiration at each HRU *s* as
   $$etDef_s = actET_s / potET_s$$
   and compare it to a defined irrigation threshold (*iT*), which controls whether irrigation is used at all. For this purpose, which proportion of the actual evaporation is actually used (actET/potET) is calculated. If this proportion is below the threshold, irrigation is used. For example, a value of 0.9 for the threshold means that irrigation will be active if less than 90% of the potential evaporation is currently occurring. If $etDef_s$ is smaller than *iT*, continue with step b.
   b. Calculate the actual demand ($iDemand_s$) based on the actual ($actSW_s$) and maximum ($maxSW_s$) soil water storage at HRU *s* according to
   $$iDemand_s = cf\,(maxSW_s - actSW_s)$$
   with *cf* as a correction factor, which is a simple multiplier and calibration parameter that can be used to adapt the identified irrigation needs. The basis for this is initially the difference between current and maximum soil water storage. This difference is then multiplied by *cf* to determine the demand.
2. For each sub-basin *B*, sum up the irrigation demand ($iDemand_B$) for all HRUs
   $$iDemand_B = \Sigma_{s \in B}\, iDemand_s$$
   Then calculate the amount of irrigation water ($iVolume_B$) based on the available water in the stream segment ($streamVolume_B$) during the current model time step
   $$iVolume_B = \min\,(iDemand_B, streamVolume_B)$$
   and distribute the irrigation water to all demanding HRUs *s* proportional to their demand ($iDemand_s$).
3. At the next time step $t+1$, apply the irrigation water $iDemand_s$ at each HRU *s* according to a defined application procedure.

In order to allow for different types of irrigation in the test region, three optional application procedures were implemented in the model:

1. Sprinkler irrigation: precipitation is increased by the amount of irrigation water
2. Flood irrigation: net precipitation is increased by irrigation water amount (i.e., interception is not considered)
3. Dripper irrigation: the middle pore storage is increased by irrigation water amount (i.e., interception and infiltration are not considered)

As a general means to control where irrigation is possible, HRUs with irrigated land use were individually flagged. This included all areas which were designated as cultivated areas in the HRU parameter data set. For our study basin, sprinkler irrigation was used.

Farm dams

Due to the small number of climate stations, only sketchy data were available as input for hydrological modelling. Additionally, these time series are affected by numerous large gaps. As there was no measured runoff data available for calibration purposes, calculated monthly inflow values to the Gaborone Dam as stated by DWA (2006) were used in order to simulate seasonality and magnitudes of runoff. In order to capture the impact of small farm dams on runoff and storage patterns within the model, a concise analysis of existing dams in terms of location and capacity was carried out. This resulted in the assessment of 20 dams in total. Here, only those dams that are assumed to have the potential to create a noticeable impact on the overall runoff regime (i.e., dams with an area of more than one hectare) were chosen by digitising their position in Google Earth. For these 20 dams, information about capacity and overall volume was made available through DWA (1992, 2014). Furthermore, around 217 small dams with minor relevance were each considered throughout the catchment (DWA, 2014b). For each of these dams, the related river segment was identified and labelled to derive zonal statistics for capturing their location within the catchment.

Making use of this information, a new module for farm dam simulation was then implemented into the JAMS/J2000 hydrological model. Accounting for the fact that precise information is often missing, especially with regard to smaller farm dams, this approach allows simulation of the function of farm dams in a conceptual way. Here, it can be used to either represent single, large dams or a larger number of small dams belonging to a certain subwatershed as a lumped unit. The impact of the dam is simulated at the associated river reach in the following way:

1. If dam storage volume is available: extract a defined proportion of the overall reach runoff in the current time step and store the water in the dam, taking the maximum dam storage volume into account
2. At the beginning of the rainy season, empty a certain amount of the dam storage volume, thereby representing the water use over the year.

Using this simplified representation of dam operation, a dam can extract water amounting to its full volume only once a year. The water is then completely removed from the hydrological system, not taking into account its possible use for irrigation agriculture which, in theory, could mean that the stored water enters the hydrological cycle again. However, both assumptions are in line with investigations of dam operation and use of stored water. In order to account for the various unknown und uncertain parameters (e.g., individual dam volumes, operation details, water use), various parameters of the dam simulation module (e.g., amount of water used, dam volume) can be adapted for calibration based on observations. Using this new simulation module, the number of dams, their capacity, and thus their impact on runoff generation can be easily increased or decreased in order to adapt the model to any conceivable scenario.

Flood Plains

A floodplain simulation extension (J2000-Flood), characterised as a conceptual and easily transferable approach that is less data hungry and easy parameterisable, is used to simulate wetland inundation within the model. Due to the data-scarce situation in remote catchments, the extension's parameters (HRU elevation and river width) were obtained from remote sensing data only. On an iterative basis, the water height in each river segment is compared to the elevation of its neighboring HRUs. When the river segment's water level is higher (i.e., flooding occurs), the water is transferred to the HRUs and their topologically connected neighbours until the simulated flood level is too low to spread any further (Fig. 7).

Within the model, the distributed water volume is stored in the excess depression storage, interacting with soil and atmosphere, which allows evapotranspiration and infiltration to be modelled. Hence, the model is able to represent the annual flow and flood regime of the system and thus to address the effect of climate change and upstream land use changes on the flow regimes in the downstream watershed. In order to provide a spatial basis for model validation and calibration (in addition to gauge data), the inundated area was determined using the Desert Flood Index (DFI; Baig et al., 2013), which was generated from a time series of 14 Landsat image mosaics and is defined as:

$$\mathrm{DFI} = \frac{\mathrm{pGreen} - \mathrm{pSWIR} + 0.1}{(\mathrm{pGreen} + \mathrm{pSWIR})(\mathrm{NDVI} + 0.5)}$$

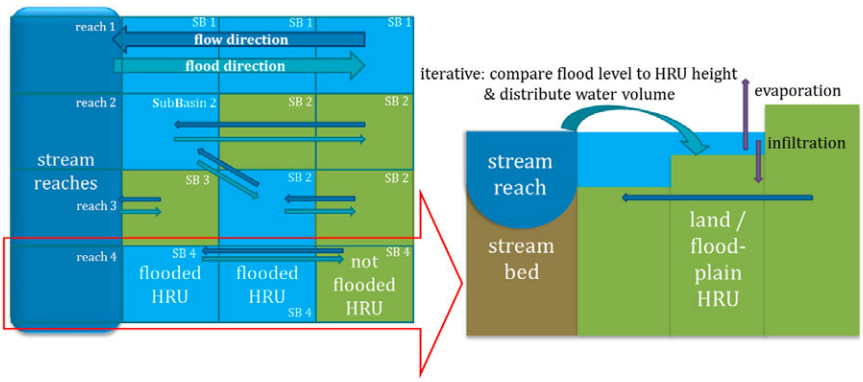


Figure 7: Schematic concept of the extension J2000-Flood in top (left) and profile view (right).

where NDVI is the Normalized Difference Vegetation Index and ρNIR, ρRed, ρGreen, and ρSWIR are the values of reflectance for the respective bands. As underflooded vegetation occurs frequently in the inundated areas, the DFI was chosen because it is better in the distinction of water and vegetation as well as bare soils compared to other indices (Baig et al., 2013; Wang et al., 2013). Moreover, it was successfully applied in the neighbouring Barotse floodplain (Zimba et al., 2018).

	e1	e2	Runoff [mm]
Without adaptions	0.48	0.42	22.413
Irrigation active	0.53	0.51	20.749
Contour farming active	0.55	0.56	18.238
All active	0.56	0.59	16.984

Table 1: Quality measures (Nash-Sutcliffe efficiency: e2, modified Nash-Sutcliffe efficiency: e1; Krause et al, 2005) and runoff produced by every implementation for the example period 01/01/1992 – 31/12/1992

Results

Verlorenvlei

A detailed description of the J2000 model applied to the Verlorenvlei catchment as well as its calibration and validation is shown in Watson et al. (2018) and Miller et al. (2018). Results of modelled runoff for the year 1992 (Fig. 8) is shown separately for the basic J2000 implementation ('natural hydrology'), implemented contour farming, and irrigation. The influence of irrigation and contour farming practices could be identified, particularly during the period from June to August, which experiences high rainfall and discharge events. During the peak period in July 1992, when the new implementations were active, the model showed less overestimation of runoff. This was also observed for low discharge periods. Regarding the quality measures (Tab. 1), it is obvious that the new implementations increase the model performance for high (Nash-Sutcliffe efficiency: e2; Krause et al., 2005) and low flow periods (modified Nash-Sutcliffe efficiency: e1; Krause et al., 2005) because runoff and, therefore, its overestimation is reduced.

The influence of the two components becomes much clearer when examining Figure 9. Overestimations of runoff in low flow months could be minimised by using the new implementations as evidenced by the peak discharges in August and September, which were less overestimated when the model used the implementations. Minimal differences between the original model and the model with active irrigation from June to July occur because irrigation only takes place if there is demand for irrigation. Reduction of runoff is due to the decrease in overland flow, with a higher influence when contour farming is active.

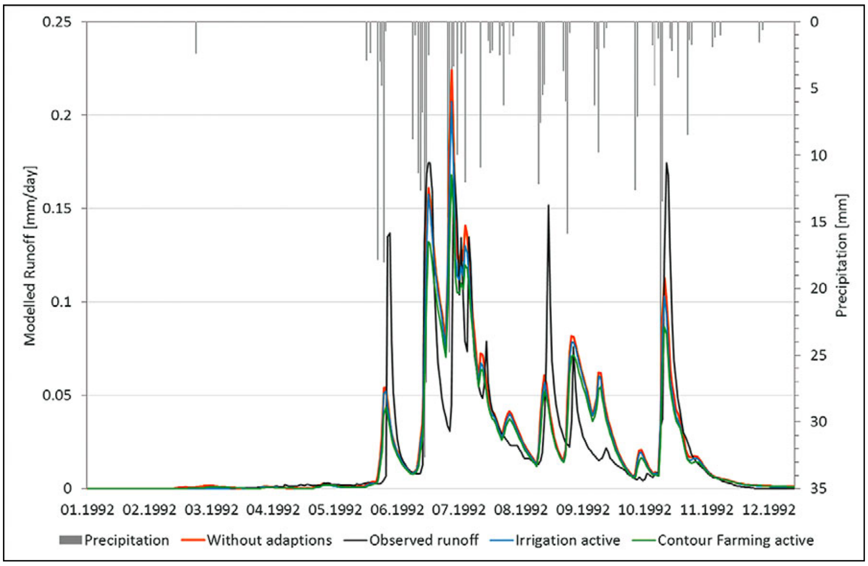


Figure 8: Rainfall, observed (grey) and simulated runoff (no adaptions made in orange, with contour farming active in green, with irrigation active in blue) for example period 01/01/1992 – 31/12/1992.

Gaborone Dam

When the model was adapted to the local study area conditions and operating without the implementations of the new farm dam module, reliable results regarding the representation of all hydrologically

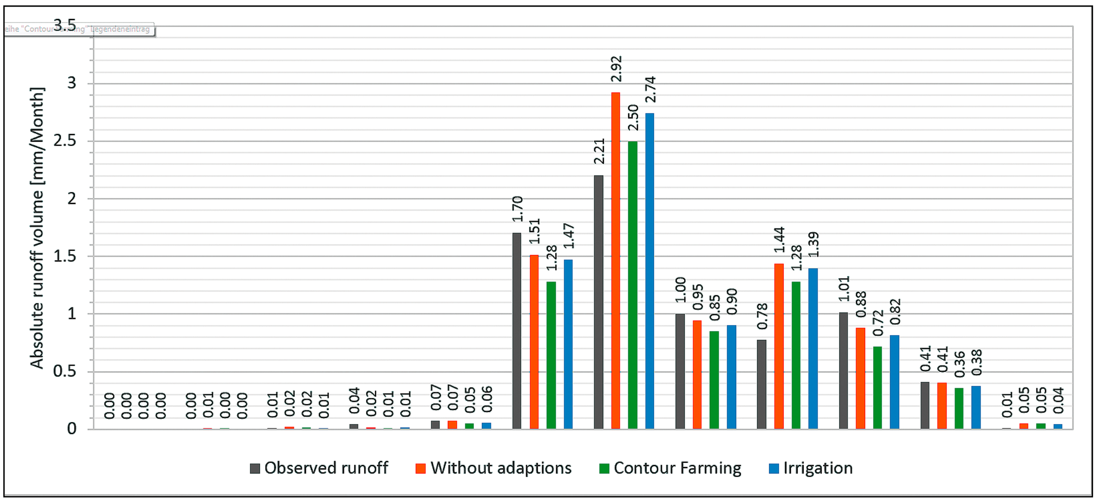


Figure 9: Monthly observed (grey) and simulated runoff (no adaptions made in orange, with contour farming active in green; irrigation active in blue) for example period 01/01/1992 – 31/12/1992.

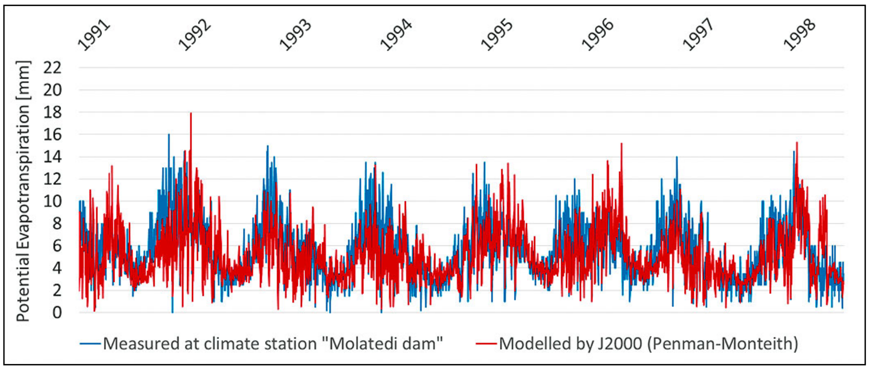


Figure 10: Comparison between measured and modelled daily potential evapotranspiration values from 1991-1998; measured values (blue) refer to Moladeti dam climate station, red line shows modelled evapotranspiration as calculated by J2000 using Penman-Monteith.

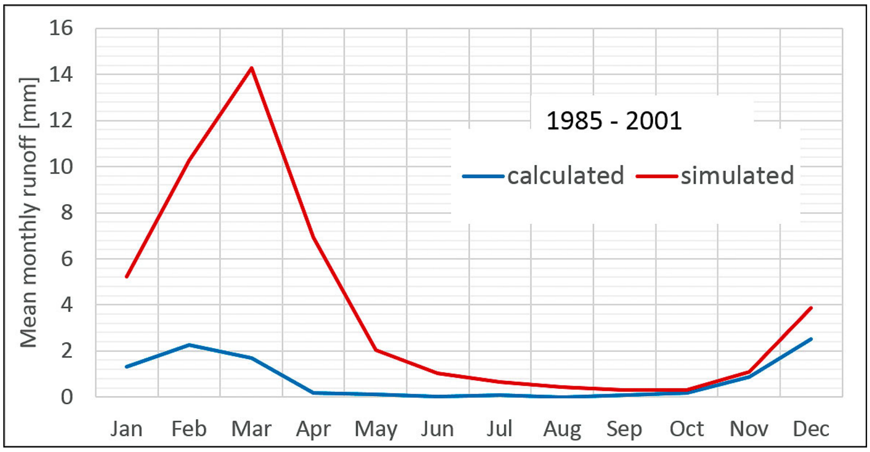


Figure 11: Comparison of mean monthly runoff; red line shows modelled values by J2000, blue line shows calculated values as stated by DWA (2006).

relevant processes such as evapotranspiration were obtained. Evapotranspiration is classified as a process having a high influence on runoff processes (Hughes, 2007). For instance, Figure 10 shows the modelled potential evapotranspiration (potET) values as calculated by J2000 using the Penman-Monteith method, compared to measured values from an A-pan at the climate station Molatedi Dam (DWA, 2014a) for the years 1991–2001. Modelled potET values showed a mean annual evapotranspiration of 1 800 mm, compared to 2 200 mm at Molatedi Dam Station. The lower potET values can be explained by vegetation dynamics represented in the model. In the first half of the rainy season, the vegetation starts to grow and the leaf area is not fully established, resulting in a reduction of the calculated potET. This dynamic cannot be represented by the measurements with an A-pan.

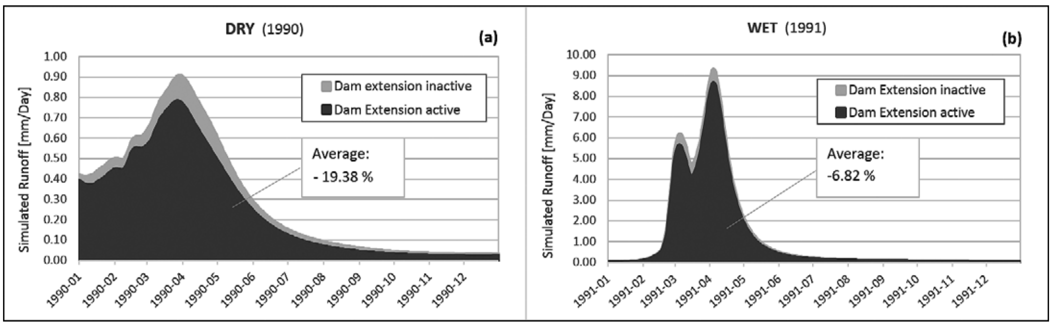
Simulated runoff (1985–2001; Fig. 11) fails in part to demonstrate reliable performance, but regarding the months June to December, the performance is acceptable compared to calculated values as stated by DWA (2006). These values are long-term monthly means, about which we have no detailed or quality information. Considering this data availability, reliability, and model performance, it was neither useful nor even possible to calculate any quality measures as was done for the other catchments in this study. Peak runoff values (i.e., during the rainy season from January to April) are overestimated by the model, with the highest overestimation observed for the month of March. This is due to the strong response of J2000 to high and sufficient rainfalls which occurred in the years 1988, 1991, and 2000. For these years, the model showed a strong overestimation, initiated mainly through long and strong retention periods following the peak runoff, triggered by intensive rainfalls. In addition, potential evapotranspiration showed comparatively low values during these years.

The impact of more than 200 farm dams for two representative years for notable dry (a) and wet (b) conditions within the catchment (Fig. 12) showed that using the farm dam extension, simulated runoff decreased in a distinctive way. When the runoff was compared with the initial model, the results showed that runoff had decreased by 19.4% and 6.8% for the dry and wet conditions, respectively. Regarding the modelling for the whole period, values for wet years achieved 14.7% and 17.1% for dry years. Taking a closer look to the water balance for the sub-catchment where the farm dam module was used (1985–2001), the runoff from this area decreases by 29% if farm dams are taken into account. This corresponds to 10% of the precipitation, whereas without farm dams, 14% of the precipitation were modelled as runoff.

Luanginga

After calibration using gauge data for the period of 1959–1968, relatively good results were achieved (Nash-Sutcliffe

Figure 12. Simulated runoff comparison for the Gaborone Dam catchment between representative years of (a) dry (1990) and (b) wet (1991) conditions, simulated runoff without the dam extension (grey), and simulated runoff with the dam extension (light grey).



efficiency: e2 0.81; relative percentage volume error: PBIAS -4.29). Model results for the validation period, from 1981–2003, were also acceptable, with an e2 of 0.75 and a very good PBIAS of -1.29. Similar values were obtained using the modified e2, which is more sensitive to low flows: e1 0.69 for the calibration period, and e1 0.6 for the validation period. However, Figure 13 shows some shortcomings regarding the simulation of peak discharge, which is either under- or oversimulated for many years. Regarding the water balance of the validation phase (1981–2003), 93% of the precipitation evapotranspirates and only about 5.4% drains to the catchment outlet. In this context, it is interesting to note that 20% of the precipitation percolates first, but due to capillary rise and the implemented inundation, it is able to evapotranspirate later.

The validation of the spatial flood extent in total also resulted in a good correlation ($R^2 = 0.71$) between the inundated area derived from the DFI and the modelled flood area. The accuracy of the spatial distribution of the inundated area was obtained by calculating the area under the curve (Fig. 14). For example, 10% of the highest DFI values correspond to 80% of the modelled inundation in 1992. In total, the results range from an outlying value of 0.59 up to a promising 0.88. In addition, the more detailed spatial pattern also appears acceptable, resulting in an accurate simulation of the inundation in the main floodplain in most years. Considering the elevation uncertainty inherent to the digital elevation model, as well as data sparsity in terms of both time series length and station presence and location, the results are deemed satisfactory. More details about the used data sets, model calibration, and validation, as well as further results, are shown in Meinhardt (2017).

Overall, the model is able to accurately represent the annual flood regime of the system, and thus to address the potential effect of various climate change scenarios on the hydrological processes in the watershed. Under the RCP 8.5 scenario, using input data from the EC-Earth and ECHAM models and following a process of downscaling using the REMO model and bias correction, the model results revealed a substantial decrease in both runoff generation (39%) and and percolation (32%), providing an indicator for groundwater recharge being very likely (Fig. 15). The model also allows a spatially distributed output of all hydrological components like percolation as represented in Figure 16, showing areas of higher decreases particularly

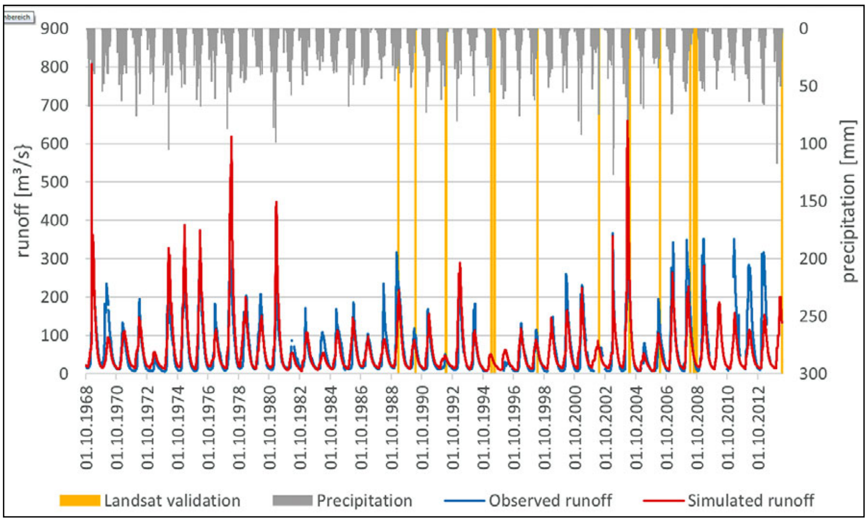


Figure 13: Observed vs. simulated runoff at the gauge in Kalabo (validation period 1981-2003) with DFI years marked).

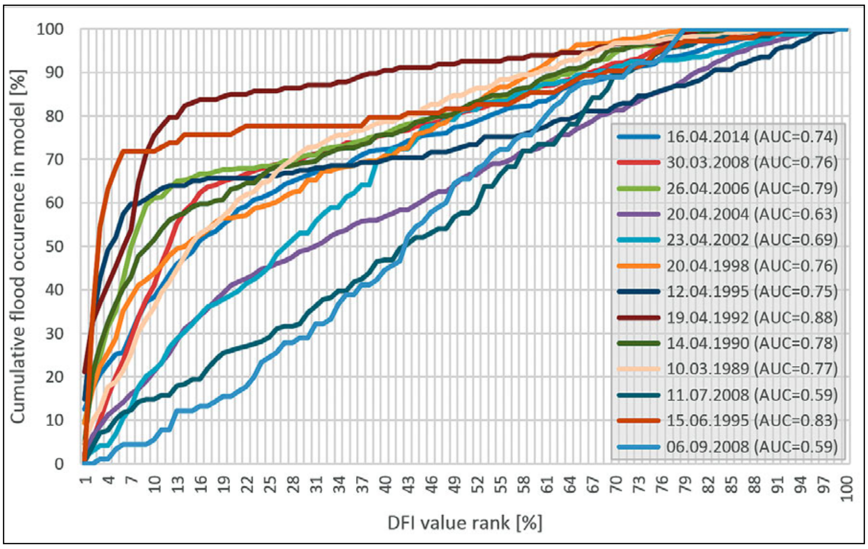


Figure 14: Area under the curve of the simulated flood extent (y-axis cumulated) compared to the derived DFI area (x-axis ranked) for the Luanginga catchment.

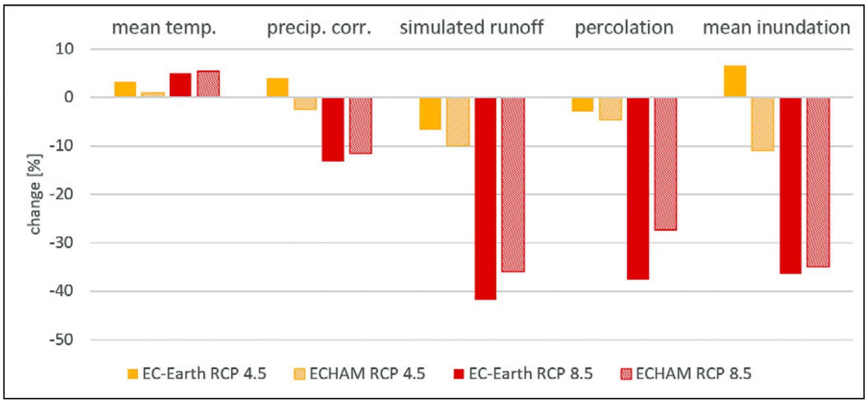


Figure 15: Percent change of precipitation, runoff, percolation, inundation extent, and temperature (change in °K) from 1986-2005 (historical) to 2081-2100 (RCP) for the Luanginga catchment.

in the floodplain. The changes presented by these models are mainly attributable to a substantial temperature rise of about 5°C, leading to a strong increase in evapotranspiration occurring until the end of the century. The decreases in water quantity as predicted by the models used would result in a reduction of flood extent (35%) and duration and, thus, alteration and damage to the highly productive and valuable wetland ecosystem. This, in turn, would signify increased risk to the people living in the region, many of whom depend upon the wetlands for their livelihoods.

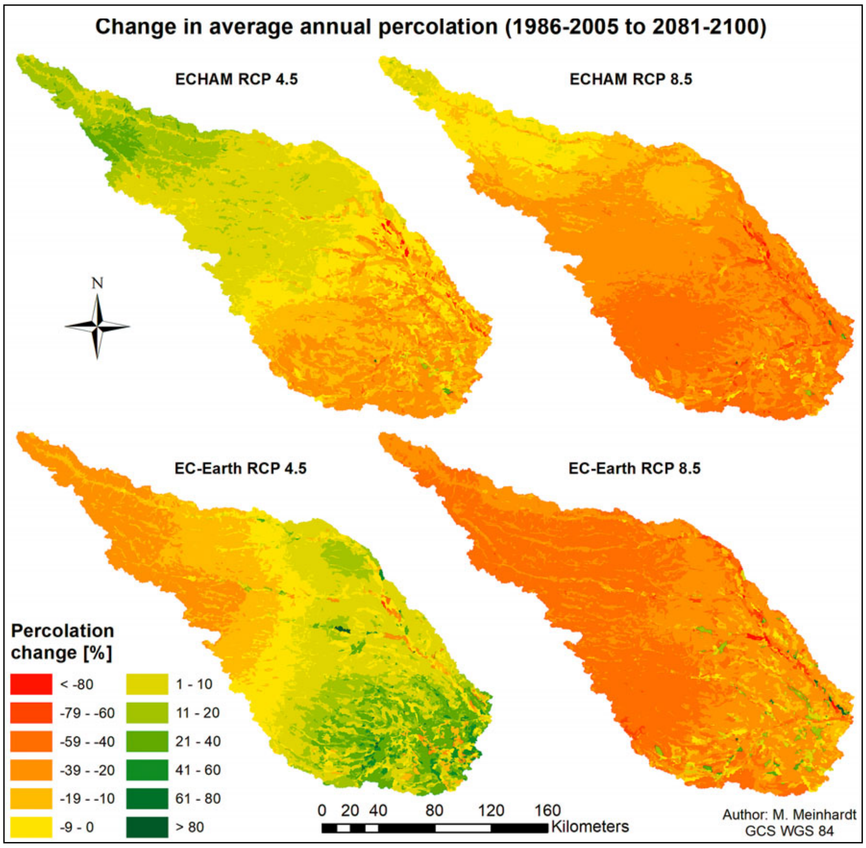


Figure 16: Average percolation (1986-2005 compared to 2081-2100) for the Luanginga catchment.

Discussion

The modelling results show a number of shortcomings, which are addressed in the following discussion. First of all, it must be appreciated that the locations of the climate stations used for the Luanginga and Verlorenvlei model are not ideal. Available stations which matched the calibration timeframe of the measured runoff and quality requirements are located far outside the catchment; for instance, the modelling of the Luanginga catchment relies mainly on the climate station in Mongu, which is situated about 60 km outside of the catchment. However, the distance to the headwaters is more than 400 km (Fig. 1). According to Wheather (2008), model performance decreases with increasing distance from climate stations to the designated catchment, which could explain why the Luanginga model failed to simulate peak discharge in many years. Additionally, nearly all climate series contained large gaps, so only a few stations could be used for modelling. Filling such gaps using other stations was not possible, as data gaps often occurred within the same time. Another limiting factor for model performance is the fairly uniform topography towards the outlet, which leads to very slow velocities, changes in flow directions, and bi-directional channels (VerWest, 2002; Druid, 2017). Furthermore, the water is not necessarily flowing in the direction of the steepest surface slope represented by the digital elevation model used, although this is assumed by the model and the HRU concept, as it was originally developed for areas with steeper gradients.

Focusing on the overestimation of runoff in the Gaborone Dam and Verlorenvlei catchments, it must be mentioned that surface runoff in semi-arid regions is primarily of Horton's type (Smith & Goodrich, 2005). This arises as a result of convective precipitation events whose intensities exceed the infiltration capacity of the soils (Pilgrim et al., 1988). Additionally, it is well known that the infiltration conditions of soil are highly variable in space and time due to processes like crusting. These are hard to represent in a hydrological model, especially on the meso and macro scales (Adornis et al., 2014). Excess water that cannot infiltrate into the ground accumulates on the surface and may subsequently lead to fast runoff (Gupta, 2010). The occurrence of this infiltration-excess overland flow is caused by the patchy vegetation cover on slope areas and shallow, poorly developed soils with low infiltration capacity, in conjunction with rigidities of the upper soil horizon (Hughes, 1995; Beven, 2002; Wheater, 2008). Accordingly, it can be assumed that surface runoff from Horton's type, particularly due to convective rainfall events during the rainy season, often does not reach the receiving water or the outlet. The precipitation events are localised and, thus, cause a reduction of water reaching the outlet as a result of infiltration excess at inclined surfaces (Hughes, 1995). Another limiting factor can be seen in so-called transmission losses (Graf, 1988), wherein large quantities of water are lost through infiltration losses in the porous and dry riverbed on their way to the catchment outlet. Following Hughes (1995), often only runoff which was generated by large-scale rainfall events or by directly successive rainfall events reaches the outlet. Another limiting factor regarding peak runoffs may result from the relatively flat terrain characteristics within the catchments. Flat terrain often leads to wider areas being available for runoff processes, leading to a temporal retention of runoff, in turn leading to pronounced retention periods (Pan et al., 2012), also shown within this study.

Looking at the numerous dams of the Gaborone catchment, it is of great importance to model the evapotranspiration correctly. According to Adams et al. (1999), the modelled evapotranspiration values are within range, considering the interpolation of climate input values over the catchment area compared to measured values at one specific climate station.

Some studies indicate that the decline of the volume of water is supported by the construction of several small farm dams upstream of the Gaborone Dam; these are used for watering livestock and for irrigation (Meigh, 1995; DWA, 2014b). Combined with the spread of arable land and meadows, the influence of the farm dams on the water balance increases (DWA, 1992; Meigh, 1995; Plessis & Rowntree, 2003). A number of case studies have shown that smaller farm dams can affect the flow pattern of a basin. Habets et al. (2014) revealed that accumulated water for irrigation is not available for runoff processes and reported a decrease in the outflow in presence of farm dams. Studies in South Africa confirmed the influence of farm dams on flow patterns (Hughes & Mantel, 2010; Mantel et al., 2010), particularly affecting the base flow. Meigh (1995) discussed the impact of smaller farm dams on the flow patterns and its relevance for inflow into the Gaborone Dam. He came to the conclusion that the construction of additional farm dams may cause a severe threat to the functioning of the dam as a viable water supply for Gaborone. The study showed that the farm dams had a complete capacity of 10% of mean annual runoff. Meigh (1995) stated that the total runoff volume of a catchment is also reduced by approximately the same amount. Additional factors such as location of the dams were identified as controls, as an increased impact on downstream areas was shown by increased inflow volumes to these dams (Meigh, 1995). Meigh also confirmed a greater impact of dams in drought years. Furthermore, the study indicated that a small number of large farm dams has less impact on the runoff than a higher number of small dams. This is due to the smaller surface area of larger dams in relation to their capacity, resulting in reduced evapotranspiration values.

The modelling results of the present study support the assumption of Habets et al. (2014) and Meigh (1995) of a notable influence of farm dams in dry years. Overestimation of runoff during the wet season was reduced after the implementation of the farm dam module, but was still present. Reasons for this observation can be seen in the lack of representation of runoff in very shallow areas with low slope and a partial under-representation of evapotranspiration. Furthermore, only calculated monthly values were available for direct model calibration, as well as short runoff time series of adjacent areas. Errors may arise here from comparing values from the calculation and from adjacent basins, as these sides partly exhibited steeper slopes and showed some notable differences in catchment size compared to the Gaborone Dam catchment.

Comparing the contour bank model extension of Verlorenvlei catchment with other studies, it is obvious that very few examined the implementation of contour banks in distributed hydrological models. For instance, Quessar et al. (2009) investigated the impact of earthen dikes on hydrological conditions in a Tunisian catchment by utilising the SWAT hydrological model (Arnold et al., 1998). The LAPSUS model was successfully applied by Lesschen et al. (2009) in the semi-arid Carcavo catchment in southeast Spain, showing that the spatial distribution of agricultural terraces determined hydrological connectivity at the catchment scale. Steudel et al. (2015) investigated the use of the hydrological model J2000 and the influence of contour banks on the hydrology and sediment transport in the Sandspruit catchment in South Africa. All three studies clearly indicated that contour farming has an influence on hydrological process dynamics and should be integrated into distributed hydrological models whenever such practices are apparent in a semi-arid catchment.

Different model types are available to integrate irrigation into hydrological modelling. Hagi-Bishow and Bonnell (2000) assessed the usability of the numerical LEACHM-C Model for semi-arid saline irrigation, resulting in the usability in poor-quality water catchments. The lumped, conceptual catchment model GR4J tested the reliability of low-flow simulations in a semi-arid Andean catchment facing climate variability and water-use changes (Hublart et al., 2015). This study resulted in confirming the model's applicability to assess the capacity of the system to meet increasing crop water needs. However, few studies used irrigation mechanisms as input to distributed hydrological models. As one example, Ahmed et al. (2011) applied the SWAT model (Arnold et al., 1998) in a Mediterranean catchment to a sprinkler irrigated watershed. They indicated the usability of distributed models for a simulation of irrigation demands.

Focusing on the Luanginga catchment, other studies show a very similar behaviour for the Upper Zambezi regarding the hydrological process dynamics (Bastiaansen, 1995; Gerrits, 2005; Winsemius et al., 2006; McCartney et al., 2013). Compared to other studies, none of these presents a model which maps the hydrological processes spatially distributed in a high degree of detail as well as for larger catchments of more than 10 000 km². These studies typically rely on in-situ measurements (Hunter et al., 2007; Pramanik et al., 2010) or model only smaller (27 km²; Adams et al., 2016) isolated wetlands or flooded areas (Thompson et al., 2004; Zhang & Mitsch, 2005; Fernández et al., 2016). This clearly shows the need and the importance of the developed flood extension, which creates a hydrological model system meeting the requirements mentioned above. Furthermore, this extension is parameterisable with remote sensing data, such as the SRTM-DGM, in order to simulate the flooded area and its depth and duration even in data-poor areas.

At the same time, input data like precipitation from the distant station in Mongu and especially the height accuracy from the elevation model account for major uncertainties of the presented modelling results. The SRTM-DGM employed is supposed to have an average height accuracy of approximately 3.1–4.4 m (RMSE 12.4–16.5 m) for areas with a slope less than 10° and grass and scrubland, which is typical for the catchment (Tighe & Chamberlain, 2009). To keep the impact of this height accuracy in the inundation modelling small, a spatial mean of the elevation was calculated for each HRU, which reduces the inaccuracy (Jung & Jasinski, 2015).

For the climate change analysis, a slight decrease in the precipitation is expected, but a more important effect from the rising temperatures will be increased evaporation and thus a reduction of the average annual runoff by 42 (EC-Earth RCP 8.5) and 36% (ECHAM RCP 8.5). Other studies also project declining flows in the region (Wolski et al., 2012; Kling et al., 2014; Zhao & Dai, 2015), which have already been confirmed by past hydrological measurements (Gaughan & Waylen, 2012). For example, values between 17–26% are given for the reduction of the mean discharge in the neighbouring Okavango (gauge Mukwe) up to the end of the century (Andersson et al., 2006; Todd et al., 2008). Kling et al. (2014) used EU WATCH data to model a decrease of up to 18% for the same period across the entire Zambezi. These values are lower in comparison with the study area of this work. The reason for this is probably the comparatively higher evaporation in the Luanginga. This is due to the larger proportion of the flood area to the respective catchment area size. In addition to the different catchment areas, the studies also used different climate models, scenarios, and hydrological models, which makes it difficult to compare them with each other. Together, however, they all result in strongly decreasing discharges until the end of the century. In addition, climate projection data include some uncertainties, especially under the unstable conditions of the tropical and subtropical atmosphere.

Moreover, the pilot catchment and its adapted models show the benefits of integrated distributed models because they provide a way to describe spatio-temporally variable hydrological processes including the influences of human activities as well as effects of climate change. For a realistic representation of prevailing human activities combined with natural hydrologic dynamics, the model employed should be process-based, i.e. able to reproduce lateral and vertical processes (Hughes, 2004; Arnold & Fohrer, 2005;). The use of a spatially distributed model in this study showed advantages in accurately representing the localisation of the farm dams and therefore their different influences on the runoff processes. The same is true for the reliable representation of climatic conditions, evapotranspiration, and groundwater recharge, as well lateral soil water processes.

Overall, transferability is ensured due to the fact that the implementations of inundation, farm dams, and irrigation simulation are developed in a conceptual way so they can be applied in other catchments, especially if data availability represents a constraint for the correct simulation of rainfall runoff mechanisms when human influences are present. The possibility of transfer is also given for the contour banks module. However, while delineating the location and number of contour banks, specific conditions in the respective catchments must be carefully considered (for example, land use forms, slope).

Conclusions

For all three pilot catchments in southern Africa, it has been shown that the selected approach of an adapted hydrological model is suitable to address the formulated problems. Additionally, the conceptual adaption approach used shows two advantages. First, the models can be applied in data-scarce regions; second, this allows transferability under similar conditions without work-intensive adaptions being necessary. For example, the flood implementation is currently applied in the upper Okavango River Basin. Moreover, it became obvious that it is necessary to adapt hydrological models to specific hydrological conditions on the catchment scale to model the hydrological processes and therefore the water balance correctly. Hence, the adapted models presented here make a valuable contribution to properly quantifying the impacts of changing climate and land management on hydrological process dynamics.

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