Assessing the human impact on hydrology in the Gaborone Dam catchment, Botswana

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Abstract

One of the major challenges of hydrological modelling in semiarid areas of Southern Africa is the balance between data availability and adequate assessment of impacts of land use/ land cover and human activities on hydrological conditions at small to medium catchment scales. The Gaborone Dam catchment in Botswana is an example, in which human activities have influenced flow dynamics leading to reduced dam inflows due to the construction of more than 200 small farm dams spread across the catchment. However, due to insufficient rainfall recording instruments or adequate flow gauging stations in the catchment, the effects of human activities and rainfall variability on runoff generation processes in the catchment and its associated impact on the dam inflow were not quantitatively assessed. In this study, some neighbouring flow stations with sufficient runoff data, available land cover information, and data about small dams have been used to study relevant hydrological processes. Information from these catchments were then transferred to the Gaborone Dam catchment to feed a distributed, process-oriented hydrological modelling system (JAMS/J2000) in order to describe and assess the hydrologic conditions under different scenarios. Initially, the model was built and validated to accurately represent the undisturbed hydrological conditions in the basin (baseline model). The validated baseline model was applied to study different anthropogenic interventions such as withholding predetermined water amounts in order to address the impact of farm dams. Here we present first modelling results indicating a notable impact of human activities on runoff and storage dynamics in the basin.

Introduction

The adequate water management in semi-arid areas presents a challenge in different ways. The natural processes are complex in space and time and at the same time highly variable. Moreover, due to population growth and infrastructure developments, increased demand for water is inevitable. This leads to increased problems in water supply in these areas. Coupled with these is the spread and intensification of agricultural land and meadows. These challenges are predominant in one of the fastest growing cities of Africa, Botswana's capital city of Gaborone, and have adversely affected water supply in and around the city. The Gaborone Dam catchment, located in the southeastern Botswana, is the main water source to the city, and the surrounding settlements (Meigh, 1995, DWA, 2014). Since 2002, there has been a steady decrease in the volume of the Gaborone Dam, reaching the lowest record of 1% in history at the end of 2015 (Water Utilities Cooperation, 2015), leading to failures of water supply by the 141 million cubic meter (MCM) dam (Plessis and Rowntree, 2003). Some studies indicate that the decline of the volume of water are caused by the construction of several small farm dams in the upstream of Gaborone Dam. The farm dams are used for watering livestock and irrigation. 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 and Rowntree, 2003).

A number of case studies has shown smaller farm dams can affect the flow pattern of a basin. For example, Habets et al. (2014) showed 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 and Mantel, 2010; Mantel et al., 2010), in particular the effects on the base flow. Meigh (1995) discussed the impact of smaller farm dams on the flow patterns and its relevance for the 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 water supply for Gaborone. The study showed that the farm dams reveal a complete capacity of 10% of mean annual runoff. He 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 since an increased impact in downstream areas was shown by increased inflow volumes to these dams (Meigh, 1995). Also he 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. A study carried out in a small sub catchment of the Limpopo river basin by Meijer et al. (2013), highlighted that the influence of farm dams on the water balance is the depending on the local physiogeographic characteristics of the individual basin. Important factors are size of the catchment area of the dams, soil properties as well as land use characteristics. Also Nathan and Lowe (2016) reached similar conclusions as Meigh (1995) & Meijer et al. (2013) in their study on the impact of farm dams on the hydrological regime in Australia.

These problems occur more frequently in regions where inadequate management practices led to problems such as desertification and drought already (Hughes, 2007; Meigh, 1995; Wheater, 2008). In order to consider these processes in addition to physical processes in hydrological modeling, special tools and methods are needed (Parida et al., 2006; Wheater, 2008). Integrated distributed models provide a way to describe spatio-temporally variable hydrological processes including influences of human activities.

Precipitation events in semi-arid regions are of relatively short duration, limited areal extent, and often associated with different intensities (Hughes, 2007). Summer heavy rainfall events have a significant share of the total annual precipitation (Günther, 2002). According to

Alexander (1985) low latitudes and high radiation amounts lead to high annual mean temperatures and therefore to a high potential evapotranspiration. Caused by the described spatio-temporally variable precipitation events, a strong variability is also reflected in the discharge behavior of semi-arid areas. For a realistic representation of prevailing human activities combined with natural hydrologic dynamics, the used model should be process based, i.e. able to reproduce lateral and vertical processes (Arnold and Fohrer, 2005; Hughes, 2004).

Based on the above described environmental issues, our study aims to explore the impact of human activities on water resources within the Gaborone Dam catchment and discusses the need for assessment of these impacts for sustainable water management. This is achieved first, by reproducing the rainfall-runoff dynamics of the data-poor Gaborone Dam catchment by utilizing the integrated, process-based, distributive model framework JAMS/J2000 (Kralisch and Krause, 2006) in order to assess water availability within the catchment under different scenarios. The first phase has involved configuring the model to represent the undisturbed natural conditions of the hydrological system. The second step included the representation of anthropogenic influences that are apparent within the Gaborone Dam catchment. In this context, the model was adapted by implementing simulation routines that reflect the local conditions of the region and show a notable impact on the hydrological conditions (e.g. advanced routing techniques and modules simulating the influence of small farm dams).

Study Area

The Gaborone Dam catchment (4500 km²) is located in the south-eastern part of Botswana, sharing a border with South Africa. According to Köppen-Geiger classification, the catchment matches the requirements of BSh (hot, arid steppe) (Peel et al., 2007) with a mean annual

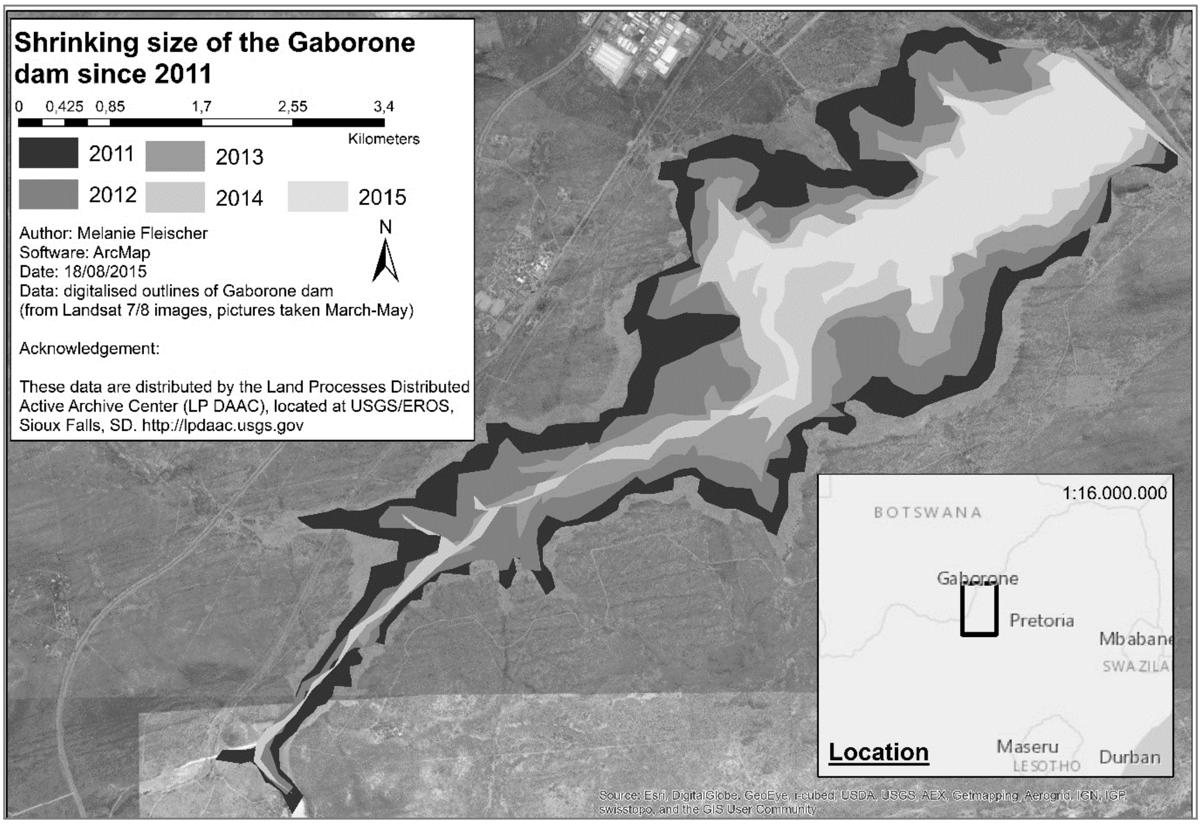

Fig. 1: Visualization of the shrinking size of the Gaborone Dam, Gaborone, Botswana (2011 - 2015), perimeters derived by digitization using Landsat 7 & 8 cloud free scenes at the end of the rainy season (March-May), lines from outside to inside show 2011 to 2015

temperature of 20.3°C and precipitation of 450 - 500 mm (Meigh, 1995; Peel et al., 2007). The climate is characterized by a rainy season from November to March and a dry season from April to October. Due to low humidity conditions, a mean evapotranspiration of about 1500 mm was estimated by Adams et al. (1999). The catchment runoff flows towards the Gaborone Dam, the main water supply source for the capital city of Botswana, Gaborone. The dam was established in 1963, from 1984-1986 it was raised by 25 meters, resulting in an increase of potential capacity from 23 to 141.1 million cubic meters (Knight, 1990; Water Utilities Cooperation, 2014). Since 2002, the dam experienced reductions in inflow leading to a decrease in volume, with a deterioration since 2011 (Fig.1). Spread around the catchment, small farm dams were built to store water primarily for stock watering, dams at the South African part are furthermore used for irrigation purposes (S. A. DWA, 2014; Meigh, 1995). The majority of dams in Botswana is located at the upstream part of the catchment.

Methods

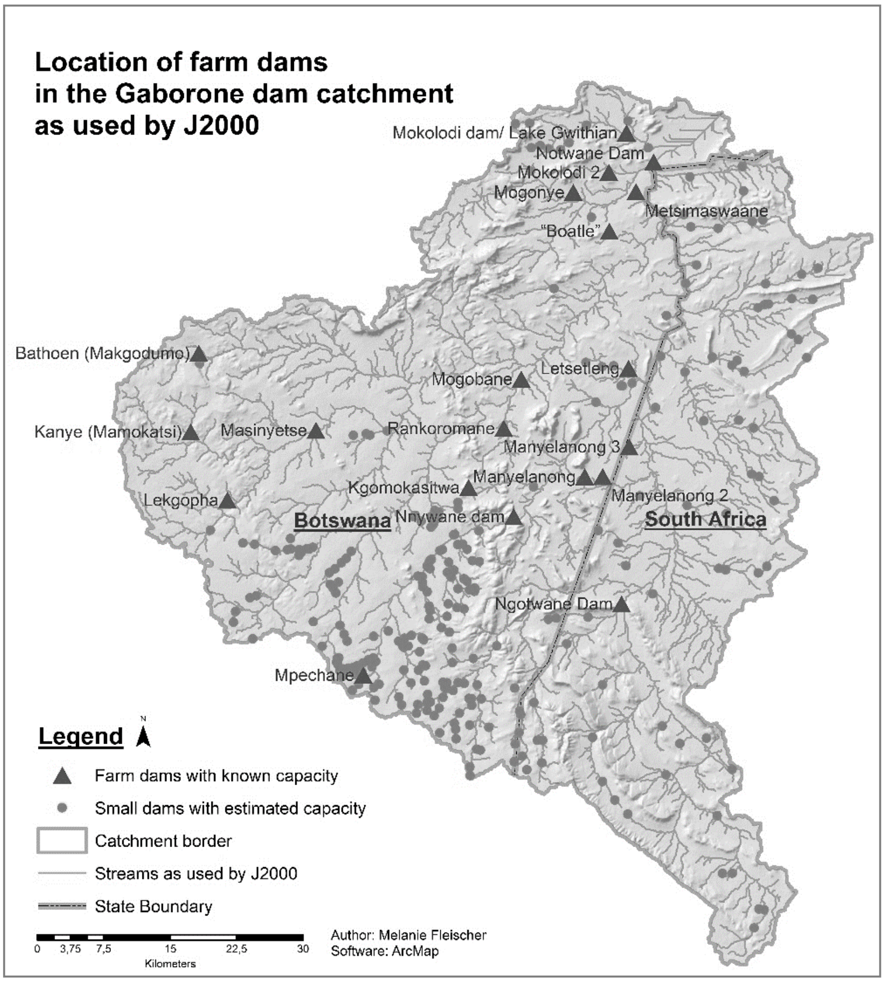

Fig. 2: Location of dams within the Gaborone Dam catchment (state: 2016, derived by digitization using Google Earth images), triangles showing dams with known capacity, dots showing dams with estimated capacity

Due to the small number of climate stations, only sketchy data was 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. Since daily data were required by the model for calibration purposes, the calculated monthly values were converted to daily values setting the monthly value respectively. Results and experiences from neighboring catchments showing a sufficient measured runoff time series were utilized in the model building for Gaborone Dam catchment. All data used for modelling within this study were freely available.

The process-oriented, spatially distributed modelling system JAMS/J2000 was used to address the hydrological dynamics within the Gaborone Dam catchment. The model consists of encapsulated modules, of which each represents a different hydrological process and runs for different temporal resolutions, of which daily values were used in this study (Kralisch and Krause, 2006; Krause, 2002, 2001). Following an distributive approach, the model utilizes the Hydrological Response Units approach (HRU) (Flügel, 1995; Krause, 2001) which were delineated according to (Wolf et al., 2009).

The model was adapted to local conditions apparent within the catchment. Adaptions were made for evapotranspiration, soil depth and contribution of different runoff components to overall runoff. Furthermore, the routing mechanism between spatial entities was switched from single- to multi-flow routines in order to more precisely catch the spatial variability within the flat terrain (Pfennig et al., 2009).

In order to capture the impact of the influence 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 shown in Fig. 2. Here, only those dams were chosen by digitizing their position in Google Earth 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. For these 20 dams, information about capacity and overall volume were made available through (B. DWA, 2014; DWA, 1992). Furthermore, about 217 small dams with minor relevance each were considered throughout the catchment (B. DWA, 2014). For each of these dams, the related river segment was identified and labeled to derive zonal statistics for capturing their location within the catchment.

Making use of these information, a new module for farm dam simulation was then implemented into JAMS/J2000 hydrological model. Accounting for the fact that precise information especially about smaller farm dams is often missing, this approach allows simulating the function of farm dams in a conceptual way. Here, it can be used to either

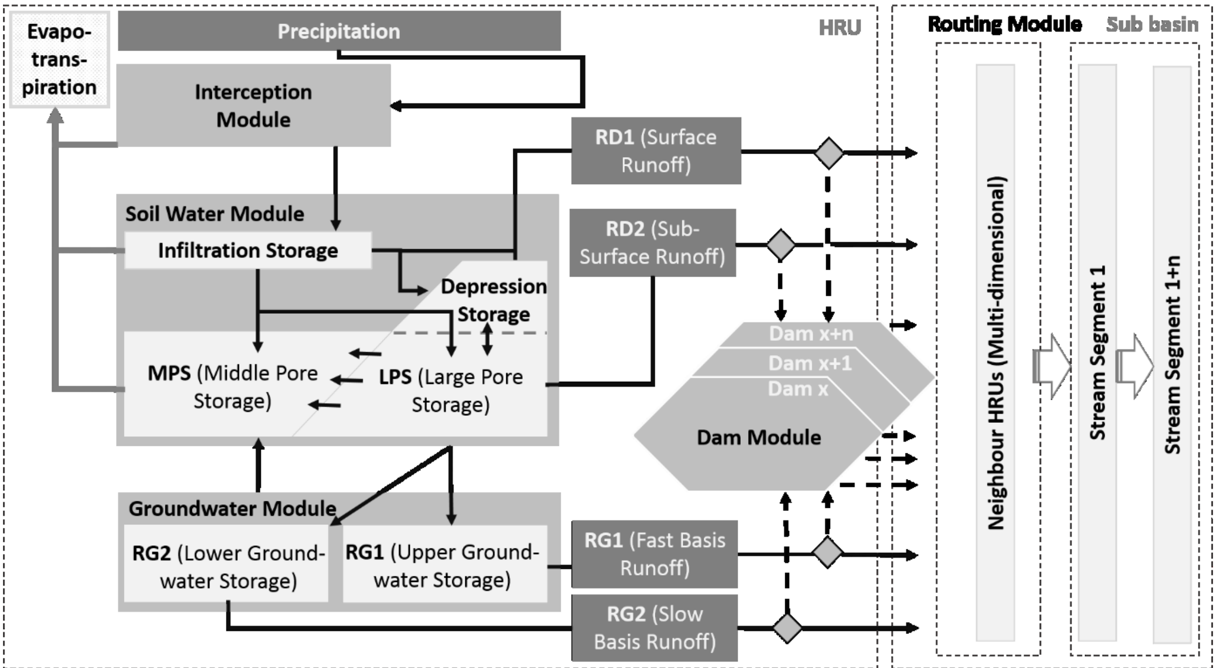

Fig. 3: Concept of J2000 as used in the presented study, modified after Krause 2001, Krause 2002 & Steudel et al. 2015

represent single, large dams or a larger number of small dams belonging to a certain sub-watershed as a lumped unit. The impact of the dam is simulated at the belonging 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 (e.g. amount of water used, dam volume) of the dam simulation module can be adapted for calibration based on observations.

Using this new simulation module, the number of dams, their capacity and thus their impact on the runoff generation can be easily increased or decreased in order to adapt the model to any conceivable scenario. Fig. 3 shows the concept of the JAMS/J2000 hydrological model used for the presented study.

Results & Discussion

After adapting the model to the local conditions of the study area, results without the implementation of the new farm dam module showed reliable results regarding the representation of all hydrologically relevant processes, such as evapotranspiration, which is classified as process having a high influence on runoff processes (Hughes, 2007). Figure 4 shows the modelled evapotranspiration values as calculated by J2000 using Penman-Monteith equations, compared to measured values from an A-pan at the climate station "Molatedi Dam" (B. DWA, 2014) for the years 1991 – 2001. Modelled evapotranspiration values showed a mean yearly evapotranspiration of 1800 millimeters compared to 2200 millimeters at Molatedi dam station. Modelled values showed lower values also during the course of the years. According to Adams et al. (1999), the modelled values are within range- considering the interpolation of climate input values over the catchment area compared to measured values at one specific climate station.

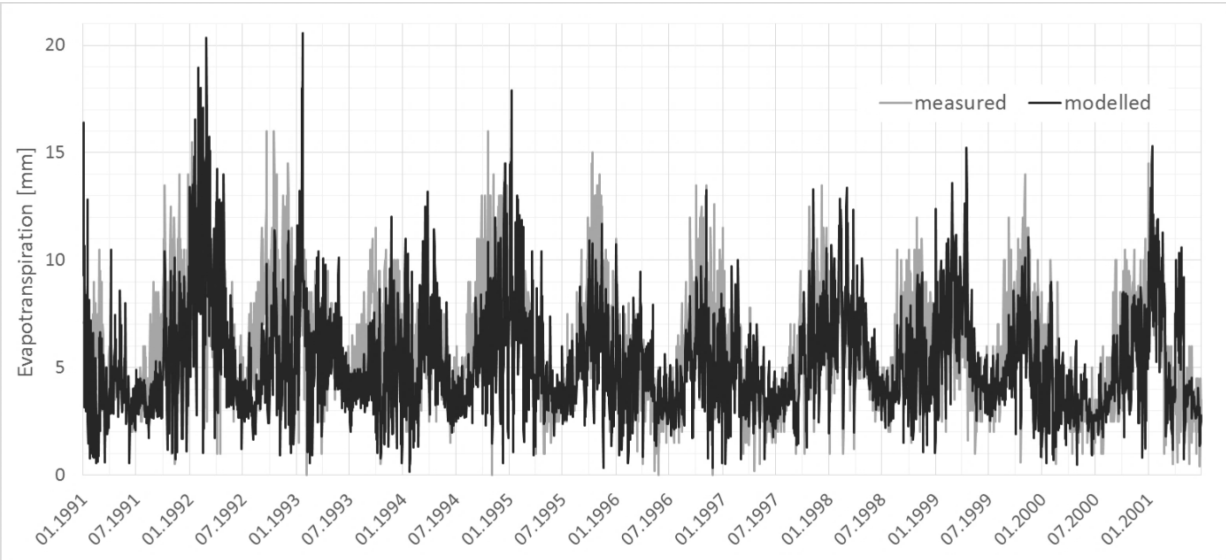

Fig. 4: Comparison between measured and modelled daily evapotranspiration values 1991-2001, measured values (light grey) refer to Moladeti dam climate station, dark line shows modelled Evapotranspiration as calculated by J2000 using Penman-Monteith

Simulated runoff (Fig. 5) reveals a reliable performance regarding seasonality and magnitude for months June to December, compared to calculated values as stated by DWA (2006).

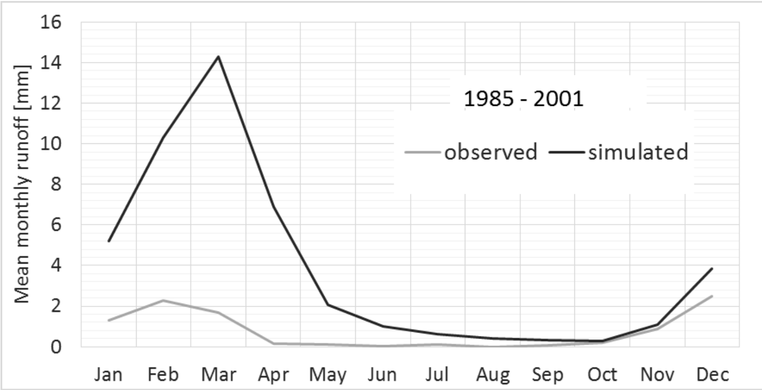

Fig. 5: Comparison of mean monthly runoff, dark line is showing modelled values by J2000, light grey line shows calculated values as stated by DWA, 2006

Values regarding peak runoff during the rainy seasons in January to April are overestimated by the model, with a highest overestimation for March. This is due to the strong response of J2000 to high and sufficient rainfalls which occurred in years 1988, 1991 & 2000. For these years, the model showed a strong overestimation, initiated mainly through long and strong retention periods followed after the peak runoff, triggered by intensive rainfalls. In addition, potential evapotranspiration showed comparatively low values during these years. Surface runoff within semi-arid areas is primarily from Horton's type (Smith and Goodrich, 2005). This arises as a result of convective precipitation events whose intensities exceed the infiltration capacity of the soils (Pilgrim et al., 1988). Excess water, which cannot infiltrate into the ground, is accumulated on the surface and may subsequently lead to fast runoff (Gupta, 2011). 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 (Beven, 2002; Hughes, 1995; Wheater, 2008). Accordingly, it can be assumed that surface runoff from Horton's type, particularly due to convective rainfall events during the rainfall season, often does not reach the receiving water or the outlet. The precipitation events are localized and, thus, cause a reduction of water which reaches 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 get lost through infiltration losses in the porous and dry riverbed on their way to the catchment outlet. Following Hughes (1995) often only runoff reaches the outlet, which was generated by large-scale rainfall events or by directly successive rainfall events. Another limiting factor regarding peak runoffs is reasoned in the relatively flat terrain characteristics within the catchment. Flat terrain often leads to wider areas being available for runoff processes leading to a temporal retention of runoff, thus leading to pronounced retention periods (Pan et al., 2012), also shown within this study. The impact of more than 200 farm dams for two representative years for notable dry (left) and wet (right) conditions within the catchment (Fig. 6) have shown that using the farm dam extension (simRO_D), simulated runoff was decreased in a distinctive way. For dry conditions, runoff compared to the initial

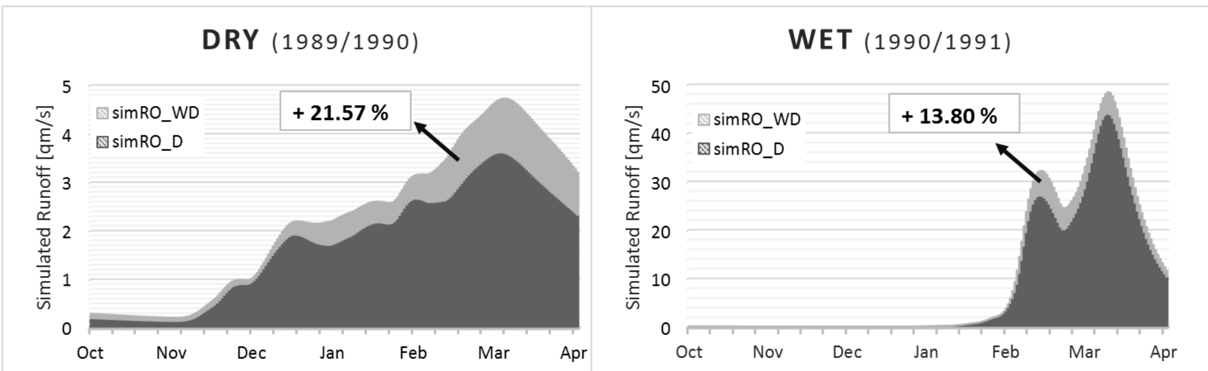

Fig. 6: Simulated Runoff comparison for the Gaborone Dam catchment between representative years of wet (1990/1991) and dry (1989/1990) conditions with simRO_WD = simulated runoff without the dam extension & simRO_D = simulated runoff with the dam extension

model was lowered by 21.6 percent, for wet conditions by 13.8 percent. Taking this into consideration, the modelling results of the present study support the assumption of Habets et al. (2014) & Meigh (1995) of a notable influence of farm dams in dry years. The difference in climatically normal years was at 12 percent in mean, which is close to the reduction of runoff by 10 percent, described by Meigh (1995). The use of a spatially distributed model showed advantages in accurately representing the localization of the farm dams and therefore their different influences on the runoff processes. The same is true for the reliable representation of climate circumstances, evapotranspiration as well lateral soil water processes. The overestimation of runoff during the wet season was reduced after the implementation of the farm dam module but was still present. Reasons 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.

Conclusions

In summary, the study presented here demonstrates the influence of the farm dams on runoff generating processes and storage dynamics in Gaborone Dam catchment. By implementing an extension to represent these dams, the discharge volume in normal years was reduced on average by 12 percent, while in very dry years, the influence of the dam's accounts for over 20 percent. Influence is notable in wet years but did not differ in a distinctive way compared to normal conditions. The applied hydrological model J2000 showed a good performance in terms of seasonality and simulation of processes having a high impact on runoff generation. During the low-rainfall periods, the model was able to represent the magnitude of runoff. However, during the heavy rainfall periods (especially January to March) an overestimation of total runoff was caused by the model. This circumstance was reduced after the implementation of the farm dam extension. The results supported the usability of an integrated distributed hydrological model to address the hydrological conditions within the Gaborone Dam catchment, including anthropogenic influences.
For the future work, the modelling of conditions driven by climate projection data, and the calculation of scenarios of an increased number of farm dams of different sizes are in progress. Through this, combined with a combination of both types of scenarios, future conditions and their impact on the hydrological regime in the Gaborone catchment area could be estimated. Furthermore, the usability of MODIS evapotranspiration products for modeling in semi-arid river basins with insufficient data situations is currently assessed with the Gaborone Dam catchment being an experimental site.

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