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Theodora Cohen Liechti[a], José Pedro Matos[bc], David Ferràs Segura[de], Jean-Louis Boillat[f] & Anton J. Schleiss[g]

[a] Research Assistant, Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015 Lausanne, Switzerland

[b] Research Assistant, Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015, Lausanne, Switzerland

[c] SHRHA, Instituto Superior Técnico (IST), Technical University of Lisbon (UTL), Av. Rovisco Pais, Lisboa 1049-001, Portugal. Email:

[d] Research Assistant, Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015, Lausanne, Switzerland

[e] SHRHA, Instituto Superior Técnico (IST), Technical University of Lisbon (UTL), Av. Rovisco Pais, Lisboa 1049-001, Portugal. Email:

[f] Senior Researcher, Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015 Lausanne, Switzerland. Email:

[g] Professor, Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015 Lausanne, Switzerland. Email:
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Research paper

Hydrological modelling of the Zambezi River Basin taking into account floodplain behaviour by a modified reservoir approach

THEODORA COHEN LIECHTI, *Research Assistant, Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015 Lausanne, Switzerland. Email:* theocohen@gmail.com *(Author for correspondence)*

JOSÉ PEDRO MATOS, *Research Assistant, Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015, Lausanne, Switzerland, SHRHA, Instituto Superior Técnico (IST), Technical University of Lisbon (UTL), Av. Rovisco Pais, Lisboa 1049-001, Portugal. Email:* jose.matos@epfl.ch

DAVID FERRÀS SEGURA, *Research Assistant, Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015, Lausanne, Switzerland, SHRHA, Instituto Superior Técnico (IST), Technical University of Lisbon (UTL), Av. Rovisco Pais, Lisboa 1049-001, Portugal. Email:* david.ferrassegura@epfl.ch

JEAN-LOUIS BOILLAT, *Senior Researcher, Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015 Lausanne, Switzerland. Email:* jean-louis.boillat@epfl.ch

ANTON J. SCHLEISS, *Professor, Laboratory of Hydraulic Constructions (LCH), Ecole Polytechnique Fédérale de Lausanne (EPFL), Station 18, CH-1015 Lausanne, Switzerland. Email:* anton.schleiss@epfl.ch

ABSTRACT
Floodplains are regions of great interest for environmental assessment as they constitute important ecological reserves and contribute efficiently to natural flood attenuation. However, the implementation of a model describing the basic hydrological behaviour of floodplains is not an easy task due to the complexity of the processes included. Although several attempts have been made to simulate floodplain effects in global rainfall-runoff models, no satisfactory routines have been developed yet. In this study, an adapted version of the Soil and Water Assessment Tool (2009) reservoir model is proposed and applied to the Zambezi Basin at daily time step with the intention of adequately modelling floodplain behaviour. The model separates the outflow of the reservoir simulating the floodplain into main channel flow and flow over the floodplain area. The improved solution was compared with the original model regarding its potential to simulate observed discharges in terms of volume ratio, the Nash–Sutcliffe coefficient and hydrograph plots. These evaluation criteria attest, for both calibration and validation periods, that the modified model is superior to the original one for simulating the discharge downstream of large floodplains. A sensitivity analysis is carried out at two geographical levels: at the outlet of a floodplain and at the outlet of the entire basin. The results show that upper flow parameters are more sensitive than base flow parameters.

Keywords: hydrological modelling; floodplain; sensitivity; calibration

1 Introduction

The development of water resource models in southern Africa is a great challenge. Within the framework of the interdisciplinary research project African DAms ProjecT, the planning and operation of large dams in a complex river basin are investigated to meet social needs and environmental constraints. The hydrological processes in this region are significantly different from what has been extensively observed in temperate catchments (Pilgrim *et al*. 1988). A key component of the hydrological cycle in this region, namely the floodplains, has been identified as problematic areas for the hydrological modelling of watersheds in Africa (Schuol *et al*. 2008b, Tshimanga *et al*. 2011, Pedinotti *et al*. 2012).

Floodplains are defined as ‘areas of low lying land that are subject to inundation by lateral overflow water from rivers or lakes with which they are associated’ (Junk and Welcomme 1990). These regions are of great interest for environmental

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assessment because they constitute an important ecological reserve and contribute to natural flood attenuation (Tockner and Stanford 2002, Mitsch and Gosselink 2007).

In previous studies, different models were developed to include floodplain hydrology. In the Niger basin (Pedinotti *et al*. 2012), the ability of the Interactions between Soil, Biosphere, and Atmosphere–Total Runoff Integrating Pathways continental hydrologic system (Decharme *et al*. 2012) to represent key processes related to the hydrological cycle was assessed in four different configurations to evaluate the impact of the flooding scheme on discharge simulation. In this model, the floodplain reservoir fills when the river water depth exceeds the critical bank-full level and interacts with the other components through infiltration, precipitation and evaporation. Considering the inner delta of the Niger as a floodplain instead of a single river channel resulted in improved model performance, confirming the importance of the flooded area.

The eco-hydrological soil and water integrated model was extended to reproduce the relevant water and nutrient flows, including retention processes, in European riparian zones and floodplains (Hattermann *et al*. 2006). Daily groundwater table dynamics were implemented at the hydrotope level (a set of elementary units in the sub-basin that have the same geographical features, such as land use and soil type). The results show that riparian zones and floodplains are important buffer systems influencing the water balance.

In the large-scale hydrodynamic model developed by Paiva *et al*. (2011, 2013), the catchments are divided into floodplain units in which the inundation is simulated using a simple storage model. The floodplains are characterized by a function which relates flooded area to water level and by an equivalent width over which exchange with the main channel occurs, both defined based on the digital elevation model.

Neal *et al.* (2012) presented a sub-grid channel model within a 2D hydrodynamic model which allows the simulation of channels much smaller than the digital elevation model (DEM) resolution. On the floodplain, the model simulates flows across the DEM by applying a 1-D approximation of the shallow water equations (ignoring only the advection term) across two-dimensional grids. Additionally, evaporation from open water (mm/day) can be accounted for in the model as a simple loss term.

In Southern Africa, multiple tools have been developed to simulate the hydrology of the Okavango delta, which is characterized by a large floodplain (mean inundated area of around 5000 km^2 and intermittently inundated area exceeding 12,000 km^2) (Milzow *et al*. 2009). A successful model was established by Gieske (1997) based on the work of Dincer *et al.* (1987). This model represents the floodplain as a set of inter-linked reservoirs (cells) and fixes the outflow from each cell as the overflow starting at a certain volume threshold mitigated by a time-specific constant for each reservoir. The same equations were used in a hybrid reservoir-geographic information system (GIS) model implemented by Wolski *et al.* (2006).

In Tanzania, a simple model for the Usangu wetlands provided a useful basis for contemplating water management options (McCartney *et al*. 2008). Here floodplains are represented as a reservoir and the outflow computed by a rating equation that depends on the water level measured at the outlet.

Few large-scale hydrological models have been applied in Africa. The coupled routing and excess storage (CREST) is a distributed hydrological model including a rainfall-runoff generation and cell-to-cell routing, feedback mechanisms and representing a sub-grid cell variability (Wang *et al*. 2011). It was successfully implemented for the Nzoia basin, a sub-basin of Lake Victoria in Africa (Khan *et al*. 2011). The variable infiltration capacity model, a semi-distributed hydrology model calculating evapotranspiration, soil moisture storage, baseflow and runoff for each simulation grid cell at each simulation time step, was applied over an ungauged African basin (Minihane 2012).

The Soil and Water Assessment Tool (SWAT, version 2009) was introduced as a semi-distributed physically based continuous time model that is able to handle very large watersheds due to its high computational efficiency. SWAT simulates four types of water bodies: wetlands, ponds, depressions/potholes and reservoirs. Despite this, only the reservoir module receives water from all upstream sub-basins, whereas the other water bodies collect the water flowing from their sub-basin alone (Neitsch *et al*. 2009). Moreover, the surface area (SA) variation of the water body is not taken into account in the sub-basin water balance calculation. As a consequence of these remarks, modifications are needed to apply the model to regions with significantly large floodplains.

An integrated modeling system for riparian floodplains was developed in SWAT and successfully applied to a watershed in Canada (Liu *et al*. 2008). This system includes a function to delineate a sub-watershed into three types of drainage areas: (1) isolated floodplains, (2) riparian floodplains and (3) direct streams. The riparian floodplains receive water from upland fields, including surface runoff, interflow and groundwater flow, and possibly from the river reach if the river water level is higher than the floodplain's. The floodplain water is lost by evapotranspiration, seepage and outflow into the river reach. While this modelling approach is detailed, it also requires numerous parameters and intensive geographical knowledge of the catchment.

The purpose of this study is to develop a simplified model for floodplain hydrology to be incorporated in SWAT, enabling it to better reproduce the observed discharge in African basins characterized by large seasonally flooded floodplains. The model will be evaluated over multiple yearly cycles focusing on its ability to simulate the measured flow in terms of annual volume and hydrograph shape, especially during the flood season. The original SWAT reservoir model was used to represent the floodplains and a new outflow computation method was implemented. The case study comprises large floodplains which perform in a similar way as reservoirs, buffering and attenuating the flood waves during rainy periods. In the Zambezi basin, four floodplains have been taken into account with a total extension of about 25,000 km^2 when inundated, pointing out the importance but also the complexity of the processes to be modelled.

The numerical model and its new developments are described in Section 2. The study area and the methodology are presented in Section 3. Three model configurations are compared in Section 4, namely: (1) the modified reservoir model, (2) the original reservoir model and (3) a model without reservoirs. A sensitivity analysis on the modified reservoir parameters is also discussed. Conclusions are summarized in the last section.

2 Numerical model (SWAT 2009)

2.1 *General description*

The SWAT is a river basin scale model available in the public domain and actively supported by the USDA Agricultural Research Service at the Grassland, Soil and Water Research is used in the present study. Two criteria led to the choice of this tool for hydrological modelling: (1) selecting a model already applied in Africa with promising results which would contribute to an appropriate definition of the hydrological processes (Schuol *et al*. 2008b, Mango *et al*. 2011, Dessu and Melesse 2012) and (2) working with a source code available in the public domain in order to allow for an easy model transfer to stakeholders.

SWAT 2009 is a semi-distributed physically based continuous time model. The model uses hydrologic response units (HRUs) to describe the spatial heterogeneity in land cover, soil types and terrain slopes within a watershed. The model estimates the water balance in each HRU for four storage volumes, snow, soil profile, shallow aquifer and deep aquifer by considering processes of precipitation, interception, evapotranspiration, surface runoff, infiltration, percolation and subsurface runoff (Arnold *et al*. 1998, Neitsch *et al*. 2009). Two methods for estimating surface runoff are available: the Green & Ampt infiltration method, which requires precipitation input at sub-daily scales (Green and Ampt 1911) and the Soil Conservation Service (SCS) curve number procedure (U.S. Department of Agriculture (USDA) Soil Conservation Service 1972), which makes use of daily precipitation. The latter was selected as the simulation time step is daily. A retention parameter, which assumes a very important role in the SCS method is defined by the curve number (CN) and is a sensitive function of the soil's permeability, land use and antecedent soil water conditions. The SWAT model offers three options for estimating potential evapotranspiration (PET): Hargreaves (Hargreaves and Samani 1985), Priestley–Taylor (Priestley and Taylor 1972) and Penman–Monteith (Monteith 1965). The inputs required for the Priestley–Taylor and Penman–Monteith methods are quite substantial: solar radiation, surface air temperature, relative humidity and wind (only for Penman–Monteith method), whereas the Hargreaves method estimates PET based only on maximum and minimum surface air temperature. Due to limitations in the available meteorological data, the Hargreaves method was applied in this study.

2.2 *Original reservoir model*

In the original SWAT 2009 code (revision number 477) (Neitsch *et al*. 2009), two types of reservoir models exist: (1) a reservoir placed out of the main channel, receiving water only through runoff from the sub- basin in which it is located and not from the upstream parts of the basin through main channel flows and (2) a reservoir located on the main channel, receiving water from the upstream parts of the basin as well as from its own sub-basin. In numerous earlier works (Schuol *et al*. 2008a, 2008b, Ndomba and Van Griensven 2011, van Griensven *et al*. 2012), the floodplains located on the main channel were simulated using the latter alternative, which is described below.

The reservoir model includes in the daily water balance inflow (V_{flowin}), outflow (V_{flowout}), seepage from the reservoir bottom (V_{seep}), rainfall (V_{pcp}) and evaporation (V_{evap}) in the following equation:

$$V = V_{\mathrm{stored}} + V_{\mathrm{flowin}} - V_{\mathrm{flowout}} + V_{\mathrm{pcp}} - V_{\mathrm{evap}} - V_{\mathrm{seep}}, \qquad (1)$$

where V is the volume of water in the impoundment at the end of the day and V_{stored} is the volume of water stored in the water body at the beginning of the day.

The amount of precipitation and evaporation is calculated based on the area of the reservoir's surface. In order to relate this SA to the volume stored in the reservoir (Eq. 2), two surface-volume pairs need to be defined: one corresponding to the volume of water permanently stored in the main channel during low flow (V_{min}) and one corresponding to the maximum capacity of the reservoir simulating the floodplain (V_{max}). Both values can be fixed based on a literature review or field survey.

$$\mathrm{SA} = \beta \cdot V^{\alpha}, \qquad (2)$$

where β and α are adjustment coefficients relating the volume and the surface of a reservoir by a power law.

The daily outflow volume may be determined using four different methods: (1) measured daily outflow, (2) measured monthly outflow, (3) average annual release rate (recommended for uncontrolled reservoirs) and (4) controlled outflow with targeted release (developed for artificial reservoirs). Among these, the average annual release rate is the best candidate to model floodplains.

The volume at the beginning of the time step is calculated by the following equation:

$$V' = V_{\mathrm{stored}} + V_{\mathrm{flowin}} + V_{\mathrm{pcp}} - V_{\mathrm{evap}} - V_{\mathrm{seep}}. \qquad (3)$$

When the average annual release rate method is chosen to calculate the reservoir outflow, the reservoir releases water whenever its volume exceeds the minimum. While the volume is between the minimum (V_{min}) and the maximum (V_{max}), the outflow depends on the average daily release rate (q_{rel}):

$$V_{flowout} = V' - V_{min} \quad \text{if } V' - V_{min} \leq q_{rel} \cdot \Delta t, \tag{4}$$

$$V_{flowout} = q_{rel} \cdot \Delta t \quad \text{if } V' - V_{min} > q_{rel} \cdot \Delta t. \tag{5}$$

If the volume exceeds the maximum, the outflow increases in order to maintain it within bounds:

$$V_{flowout} = (V' - V_{max}) + (V_{max} - V_{min}) \quad \text{if } V_{max} - V_{min} \leq q_{rel} \cdot \Delta t, \tag{6}$$

$$V_{flowout} = (V' - V_{max}) + q_{rel} \cdot \Delta t \quad \text{if } V_{max} - V_{min} > q_{rel} \cdot \Delta t. \tag{7}$$

The average daily release rate (q_{rel}) has to be defined by the user based on his knowledge of the reservoir.

The volume at the end of the time step is finally defined as follows:

$$V = V' - V_{flowout}. \tag{8}$$

The main disadvantages of this method when modelling floodplains are that the outflow does not always directly depend on the volume of stored water and that there will be no outflow if the volume decreases below the minimum.

Additionally, even if the SA of the reservoir is computed at each time step, it has no influence on the sub-basin SA where it is located. Therefore, the water balance of the sub-basin does not take into account the surface reduction/increase caused by the extension/reduction of the reservoir. In the case of floodplains, with highly variable surface and with large extents compared to the sub-basins where they are located, this may cause substantial deviations in the sub-basins' water balance.

2.3 *Modified reservoir model*

The original SWAT reservoir model was used to simulate the African floodplains (Schuol *et al*. 2008b). However, the results on the Zambezi Basin reached a Nash–Sutcliffe (NS) coefficient below zero, which was justified by the authors with difficulty in simulating outflow from the wetlands. The authors believe that there was, indeed, an inadequacy with the original SWAT reservoir model. Despite this, and overlooking the secondary effect of reservoir surface evaporation, a tendency to delay (or rush) flows in reservoirs will not contribute appreciably to a large bias (as over a sufficiently large number of years roughly what goes in the reservoir must come out). Large floodplains attenuate runoff, reducing and delaying flood peaks downstream (Beilfuss and Dos Santos 2001, The World Bank 2010), and are characterized by significant evaporation losses and seasonal fluctuations. During high-flow periods, water spreads over bank and inundates the floodplains whereas during low flows, it runs only along the main channel. It has been observed that such floodplains have a great impact on the water storage capacity of the sub-basins (Meier *et al*. 2011).

Modelling floodplains as natural reservoirs with specific storage and outlet characteristics proved to be a successful approach for hydrological simulation (The World Bank 2010). As such, a set of two equations to reproduce the outflow from the floodplains (Eq. 9) was developed and appended to the original SWAT reservoir model. The base flow (Q_{base}) is defined by a release coefficient and depends on the water depth (H) in the reservoir simulating the floodplain (Eq. 10). The additional inflow is stored in the reservoir and released as an upper flow (Q_{up}) if the water depth exceeds a fixed threshold (H_{min}), corresponding to the minimum water level in the main channel, as from a free-crest weir (Eq. 11).

$$Q_{outflow} = Q_{base} + Q_{up}, \tag{9}$$

$$Q_{base} = k \cdot H, \tag{10}$$

$$Q_{up} = \begin{cases} 0 & \text{if } H \leq H_{min} \\ a \cdot (H - H_{min})^b & \text{if } H > H_{min} \end{cases}, \tag{11}$$

where k is the release coefficient, a (overflow coefficient) and b (overflow exponent) are the model parameters used in the calibration process.

The overflow coefficient is an aggregate of the constants for weir flow rate definition and the weir width (Eq. 12). The weir width corresponds to the mean width of the floodplain; it is assumed to be different for each floodplain, but constant through time.

$$a = C_d \cdot \sqrt{2 \cdot g} \cdot w, \tag{12}$$

where C_d is the discharge constant for the weir, g is the gravitational constant and w is the weir width in metres. The bounds for the overflow coefficient depend on the geometrical characteristics of the floodplain. The calibration process could be aimed at the discharge constant (C_d) alternatively to the overflow coefficient *(a)* if enough data were available to define the weir width (w). However, in the present case study, in light of insufficient information on the geometry of the floodplains, the overflow coefficient *(a)* was used as a calibration parameter.

The standard value for the overflow exponent is 1.5, but in order to account for specificity of the floodplains, it was assumed that it can vary from 1 to 3.5. Accordingly, the units of the discharge constant (C_d) will vary to provide a discharge result in m^3/s.

The release coefficient controlling the base flow (k) varies within a wide range as it allows the simulation of the main channel flow and can be very different between floodplains.

The daily water depth in the reservoir is calculated based on its volume. As for the surface-volume relation (Eq. 2), two depth-volume couples need to be defined, one corresponding to the volume of water permanently stored into the main channel during low flow ($V_{\min}$) and one corresponding to the maximum capacity of the reservoir simulating the floodplain ($V_{\max}$) (Eq. 13).

$$H_t = \delta \cdot V_t^{\lambda}, \tag{13}$$

where δ and λ are adjustment coefficients linking the volume and the water depth of a reservoir assumed by a power law.

Such parameters can be derived from a DEM analysis if the data are available at a scale corresponding to the floodplain characteristics or defined based on the literature review or field survey. The parameters can also be adapted by the user depending on the simulation results. For example, if $V_{\min}$ is too low, the downstream base flow will be too high and if $V_{\min}$ is too high the downstream base flow will be too low. $V_{\max}$ will not affect the simulation results.

Finally, an improvement has been made to the original model concerning the relation between the sub-basin and reservoir surface. Because the reservoir surface can be relatively important to the sub-basin surface and can be subject to substantial fluctuations in time, it is subtracted at every time step from the sub-basin surface to compute an accurate water balance.

The initial volume of water inside the floodplain should be defined by the user. If no data are available, it is recommended to run the model starting from a period with minimum flow so that the floodplain would be as empty as possible and that the initial conditions would have a limited influence on the simulation results.

3 Methodology and application

In order to evaluate the adequacy of the modified reservoir model, it was applied on the Zambezi River Basin, considered as representative for large floodplains regions. In spite of this, the proposed methodological approach was conceived to be suitable for wider applications. Its particularities are to rely on global data sets for a model set up, to proceed with a general purpose automatic calibration process and to include a sensitivity analysis of the floodplain simulation parameters.

3.1 *Study area*

The Zambezi River Basin, located in the southern part of the African Continent, is the fourth largest drainage basin in Africa. From its headwaters in Angola to the delta in Mozambique, the

Figure 1 Basin map with countries, gauging stations, major reservoirs and floodplains.

Zambezi River runs over 2600 km and connects eight nations that share different portions of its 1.4 M km^2 drainage basin (Figure 1): Angola (18.3%), Namibia (1.2%), Botswana (2.8%), Zambia (40.7%), Zimbabwe (15.9%), Malawi (7.7%), Tanzania (2.0%) and Mozambique (11.4%) (Vörösmarty and Moore III 1991). The basin lies fully within the tropics between 10°S and 20°S, an area that encompasses humid, semi-arid and arid regions and is dominated by seasonal rainfall patterns associated with the inter-tropical convergence zone.

The river includes three distinct stretches: the Upper Zambezi, the Middle Zambezi and the Lower Zambezi (Beilfuss and Dos Santos 2001, Moore *et al*. 2007). The Upper Zambezi is characterized by the Northern Highlands, where the river is born, and the Central Plains, which are constituted by two major floodplains attenuating the runoff: the Barotse and the Chobe flats. Between Victoria Falls and the Cahora Bassa reservoir, limiting the Middle Zambezi, the river connects with the Kafue River, a major tributary characterized by two large floodplains (the Lukanga and the Kafue flats) and two large dams (Itezhi-Tezhi and Kafue Gorge). In total, four major floodplains are located in the upper and middle parts of the basin (Barotse, Chobe, Lukanga and Kafue) from which the two majors are the Barotse flats (permanently inundated area of around 1000 km^2 and intermittently inundated area of about 11,000 km^2) and the Kafue flats (permanently inundated area of around 2000 km^2 and intermittently inundated area of about 7000 km^2).

To illustrate the influence of the floodplains, two gauging stations were chosen as a reference for the analysis: the first one was located at the outlet of the Kafue flats and the second one located at the outlet of the Barotse flats (Figure 1). The discharge data at the station downstream of the Kafue flats consist of a reconstructed inflow hydrograph of the Kafue Gorge reservoir based on the observed outflow and water level.

3.2 *Model set up*

The DEM from the United States Geological Survey's public domain geographical database HYDRO1 k, at a spatial resolution of 1 km (http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info), was used to delineate the sub-basins. A minimum drainage area unit of 5000 km^2 was first set to delineate these. Subsequently, sub- basins around the lakes and floodplains were refined by overlapping a GIS layer of lakes and flats of Africa, increasing the number of sub-basins to a total of 405.

To define the HRUs, the soil map produced by the Food and Agriculture Organization of the United Nations (FAO 1995) and the land-use grid from the Global Land Cover Characterization (Version 2, http://edcsns17.cr.usgs.gov/glcc/) were included. The minimum percentage in land use, slope or soil class must cover within a sub-basin in order to generate a particular HRU was set to 35%, resulting in a total of 778 HRUs. This criterion results from a compromise aiming to limit the number of HRUs while keeping a substantial level of information.

The artificial and natural lakes, as well as the important floodplains located on the main channel, were modelled as reservoirs. For the artificial reservoirs, namely the hydropower plant reservoirs, the simulated outflow was constrained to the observed outflow records to reproduce the operations in conformity. For the floodplains, the initial volume was adjusted to match observed initial conditions at the downstream gauging station when available or adjusted, depending on the season at the start of the calibration period.

According to a previous reliability analysis (Cohen Liechti *et al*. 2012), TRMM 3B42 version 7a, National Aeronautics and Space Administration (NASA) standard precipitation product was selected as the precipitation source. The estimates for this product are published on a 0.25° by 0.25° grid with a 3-hourly temporal resolution (00:00, 03:00, . . . , 21:00 UTC). The temperature grids (daily minimum and maximum) are compiled from the National Centers for Environmental Prediction / Department Of Energy (NCEP/DOE) reanalysis data (Kanamitsu *et al*. 2002) provided by the National Oceanic and Atmospheric Administration / office of Oceanic and Atmospheric Researc / Earth System Research laboratory Physical Sciences Division (NOAA/OAR/ESRL PSD), Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/. All input data were aggregated to daily in order to match the simulation time step. Discharge data were provided by the Global Runoff Data Centre (Fekete *et al*. 1999) and the Department of Water Affairs of Zambia (personal communication).

3.3 *Model calibration and validation*

The years of 1998 and 1999 were used as a stabilization period to allow the model to converge towards the 'true' water cycle and, thus, rule out influence of imperfect initial conditions. In order to increase the number of available calibration data, the final conditions of the stabilization period were used as initial values to calibrate the model on the period 1998–2003. The years of 2004–2006 were kept for validation.

At first, the original SWAT calibration parameters were chosen based on the sensitivity analysis tool included in the ArcSWAT interface (Winchell *et al*. 2010). The incorporated method combines the Latin hypercube (LH) and one-factor-at-a-time sampling, assuring that the changes in the output of each model run can be unambiguously attributed to the parameter that was changed (van Griensven *et al*. 2006). More precisely, during the analysis, the SWAT runs $(p + 1)^{*}m$ times, where p is the number of parameters being evaluated and m is the number of LH loops. Then, the list of selected parameters was compared to the one used in previous studies (Schuol *et al*. 2008b, Zhang *et al*. 2009) and the associated boundaries for calibration were defined (Table 1). Finally, the new reservoir model parameters (a, b and k) were added to the list. Regarding the Zambezi basin, given that floodplains can cover

Table 1 SWAT model parameters included in the final calibration procedure with their upper and lower bounds

Parameter	Description	Unit	Lower bound	Upper bound
SURLAG	Surface runoff lag time	day	0.5	1.5
ALPHA_B	Base flow recession constant	day	0	0.5
GW_DELA	Groundwater delay	day	20	300
GW_REVA	Ground water 'revap' coefficient for flow to move into the overlying unsaturated zone	–	0.1	0.4
REVAPMN	Threshold depth of water in the shallow aquifer for ground water to move into the overlying unsaturated layers	mm	1	400
GWQMN	Threshold depth of water in shallow aquifer for return flow (to the reach) to occur	mm	5	100
ESCO	Soil evaporation compensation factor	–	0.001	1
CN_F	SCS curve number for moisture condition	%	−0.25	0.15
CH_KII	Effective hydraulic conductivity in main channel alluvium	mm/hr	0.1	50
SOL_AWC	Available water capacity of the soil layer	%	−0.3	1
SOL_Z	Depth from soil surface to bottom of the layer	%	−0.5	1
EPCO	Plant uptake compensation factor	–	0	1
CANMX	Maximum canopy storage	mm	0	30
Floodplain parameters				
a	Reservoir overflow parameter	$m^{3/2}/s$	1100	55,000
b	Exponent of overflow equation for reservoir	–	1	3
k	Reservoir release coefficient	m^2/s	35	350

vast areas, over thousands of kilometers, and that the water head over the 'weir' at the outlet will typically not be superior to 1 m, the overflow coefficient (a) will have large values varying from 1100 to 55,000 $m^{3/2}/s$ for an overflow exponent (b) equal to 1.5. Concerning the release coefficient (k), its bounds were set from 35 to 350 m^2/s to account for the large base flow produced by the floodplain located in the downstream part of the basin.

The multi-algorithm genetically adaptive multi-objective method was chosen as the heuristic search algorithm for generating optimized parameter sets (Vrugt and Robinson 2007, Vrugt *et al.* 2009) based on two evaluation criteria, the NS coefficient and (Eq. 14) the volume ratio (VR) (Eq 15). The averaged value for both criteria over all the discharge stations available was optimized.

$$\mathrm{NS} = 1 - \frac{\sum (Q_{\mathrm{obs}} - Q_{\mathrm{sim}})^2}{\sum (Q_{\mathrm{obs}} - \overline{Q_{\mathrm{obs}}})^2}, \tag{14}$$

$$\mathrm{VR} = \frac{\sum Q_{\mathrm{sim}}}{\sum Q_{\mathrm{obs}}}. \tag{15}$$

Three different configurations for floodplain modelling were calibrated and tested: (1) simple channel routing (no reservoir for the floodplains), (2) the original SWAT reservoir model defined by an average release rate and (3) the modified SWAT reservoir model. Each configuration was calibrated separately, and the set of parameters displaying the best value for both indicators was selected for plotting the simulated hydrographs.

3.4 *Sensitivity analysis*

A sensitivity analysis was carried out with the goals of determining the importance of the new reservoir parameters over the whole hydrological model outcome and qualitatively assessing their implications on the model's uncertainty.

The results of the sensitivity analysis are given in terms of the sensitivity index: the fraction of the variance in the model due to a certain parameter in respect to the total variance of the model due to the whole parameter space. Resulting from this definition, the sensitivity indices vary in the range between 0 and 1. A sensitivity index equal to 0 indicates that the system is insensitive to the corresponding parameter. Vice versa, values close to 1 mean a high sensitivity to the parameter being assessed.

The analysed hydrological model is a spatially and temporally extended nonlinear dynamic system. Due to the nature of such a system, the global sensitivity analysis method selected is the Fourier amplitude sensitivity test (FAST). The FAST method is used to estimate the expected value and the contribution of individual inputs to the variance of the output (Cukier *et al.* 1973). The main advantage of a global method is that multiple locations in the physically plausible parameter space are evaluated.

The FAST method was first applied based on temporal dynamics of parameter sensitivity (TEDPAS), which allows the quantification of the model components that dominate the simulation response (Reusser and Zehe 2011). In a second step, a non-time dependent FAST was carried out for a year of simulation (2000 for the Barotse plains and 2001 for the whole Zambezi) based on the NS coefficient (Eq. 14) and the VR (Eq. 15). These indicators express how good the model fits the observed data.

The implementation has been done using the FAST R package which is reported by Reusser and Zehe (2011). The methodology can be summarized in the following steps:

1 Select the parameters to be assessed.
2 Generate sets of parameter values and launch SWAT simulations for each set.
3 Carry out a FAST applied to direct model outputs (discharge, water level and volumes in the reservoirs) at each time step (TEPDAS).
4 Carry out a FAST applied to performance criteria for a selected simulation period.

The effect of the new floodplain parameters was determined at two geographical levels: (1) at the outlet of the Barotse floodplains for the parameters of this floodplain and (2) at the outlet of the entire basin for the parameters of the two major floodplains (the Barotse and the Kafue).

The local assessment at the outlet of the floodplain gives qualitative understanding of the order of importance of each parameter according to the floodplain characteristics and discharge; it allows the identification of the principal components of the system. This sensitivity analysis was conducted dynamically (TEDPAS) and averaged over time using NS and VR as objective functions. The assessment of the two sets of floodplain parameters on the discharge at the outlet of the basin allows evaluating the importance of the floodplain effect on the global hydrograph.

4 Results and discussion

4.1 *Comparison of the reservoir models*

The NS and VR indicators have been calculated based on daily, monthly and yearly mean discharge to validate the modified model. At the monthly and yearly time step, the indicators are given for the whole period, whereas at the daily time step the calibration and validation periods are separated. Due to the discontinuity of the observed data series downstream of the Barotse floodplain, no pertinent indicators could be computed at a yearly time step.

Downstream of the Barotse floodplain, the modified reservoir model, the original reservoir model and the model with no reservoir are nearly equivalent in terms of VR (Table 2). The NS during the calibration period is improved by more than 15% by the modified model compared to the original model, which corresponds to a better reproduction of the hydrograph shape as shown in Figure 2. At the monthly time step, the difference between the models is lower, the modified model still reaching the highest NS. By looking at the hydrograph (Figure 2(a)), the modified reservoir model performed better in two aspects. The smoothing effect of the floodplain was reproduced both during low and high flows and the decrease in discharge followed the

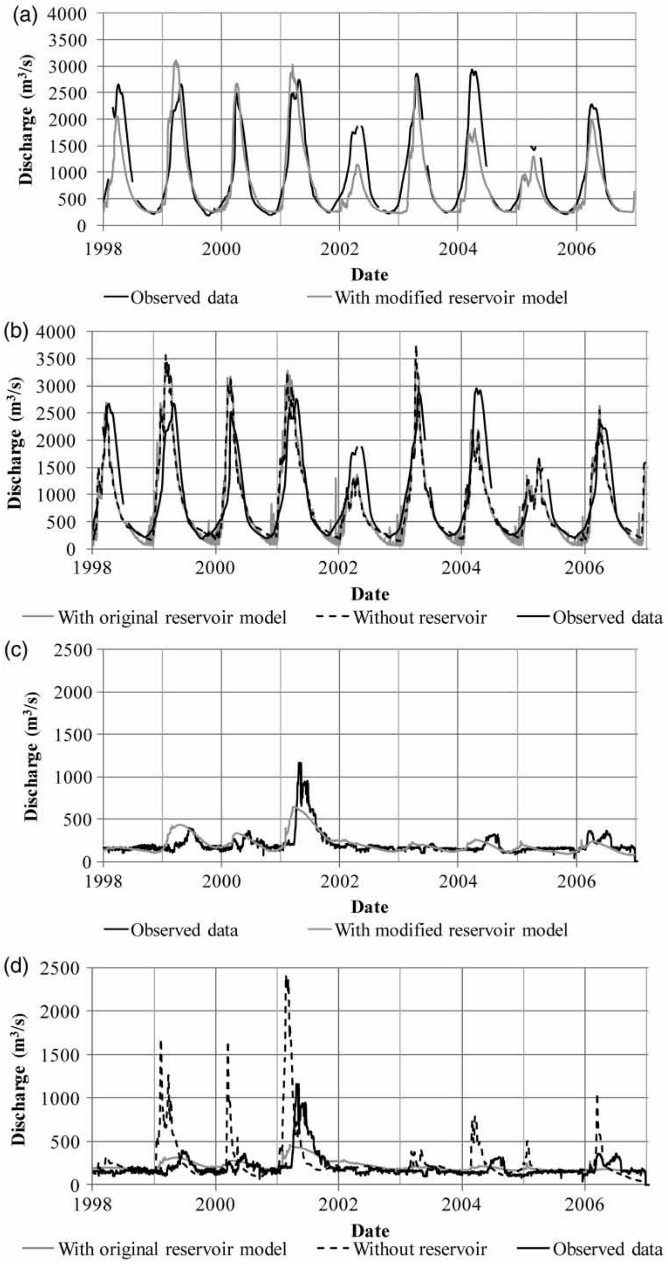

Figure 2 Discharge observed at the stations below Barotse flat (a and b) and below Kafue flats (c and d) compared with the discharge modelled with the new reservoir model (a and c), the original reservoir model and without a reservoir (b and d). Both calibration (1998–2003) and validation period (2004–2006) are presented.

observed pattern instead of showing a pronounced drop as in the case of the original reservoir model (Figure 2(b)).

Downstream of the Kafue floodplain, the improvements resulting from the modified model are not as important as downstream of the Barotse floodplain. Compared to the original model, the NS is slightly improved with the modified reservoir model (Table 2). During the validation period, the models do not display simulation skills since the NS is close to zero. This is due to the inadequacy between the observed and simulated small-amplitude peak flows. In terms of VR, the two reservoir models are equivalent, again pointing towards the adequacy of the annual water balance

Table 2 NS and VR values of the three configurations tested for daily, monthly and yearly time step

Configuration (calibration/validation)	NS Barotse	NS Kafue	VR Barotse	VR Kafue
Upstream floodplain	0.80/0.86	0.50/0.45	0.87/0.88	0.94/0.70
With modified reservoir				
Daily	0.77/0.81	0.51/0.05	0.86/0.78	1.08/0.81
Monthly	0.77	0.53	0.82	1.03
Yearly	–	0.79	–	1.03
With original reservoir				
Daily	0.65/0.78	0.44 / −0.10	0.90/0.84	1.09/0.94
Monthly	0.72	0.46	0.87	1.07
Yearly	–	0.67	–	1.07
Without reservoir				
Daily	0.66/0.76	−4.04/−2.27	0.93/0.87	1.34/0.99
Monthly	0.71	−3.79	0.90	1.29
Yearly	–	0.09	–	1.27

reproduction. The superiority of the modified representation is especially shown at monthly and yearly time steps over the entire period as the NS is higher than for the original model. The model without reservoir clearly overestimates the flow volume and is qualified by negative NS values.

The hydrograph observed below the Kafue floodplain is not very smooth as it is calculated based on the water balance equation at the Kafue Gorge reservoir. None of the models were able to fully reproduce the observed peaks. Nonetheless, the reconstructed series is uncertain as it relies on water level variations and on observed outflows both at the turbines and at the spillways, which may be subject to non-negligible deviations. With the modified reservoir model, the base flow of the hydrograph is reproduced and the peak flows are closer to what is observed than the original reservoir model's estimates, even if they are sometimes still too low or too early (Figure 2(c)). The original reservoir model does not delay the peaks, but attenuates excessively the flood (Figure 2(d)). Without the reservoir, the model cannot reproduce the effect of the large floodplain (Figure 2(d)).

Globally, the most inadequate model configuration is, as expected, the configuration without a reservoir (Figure 2(b) and 2(d)), which emphasizes the necessity to include the floodplains in the hydrological model. The modified reservoir model allows for a more accurate simulation of the discharge pattern, especially for the very large floodplains. Moreover, the model can be calibrated for each floodplain with the parameters *a*, *b* and *k*, which ensures the best possible fit.

4.2 *Sensitivity analysis*

4.2.1 *Sensitivity analysis at the Barotse floodplain*

Table 3 presents the information of the FAST sensitivity indices of the floodplain parameters in regard to NS and VR for the year 2000. For both indicators, the SWAT model appears to be most sensitive to the overflow coefficient (*a*) followed by the overflow exponent (*b*) and the release coefficient (*k*).

In the Barotse floodplain, according to the model set up and for the simulated year, the upper flow is predominant to base flow. In a calibration run, the overflow parameters (*a* and *b*) would take a more important role than the base flow parameter (*k*). One explanation is that the high flows have more influence on both VR and NS values than low flows. It is likely that, depending on the discharge and the floodplain features, the predominant processes can be governed mainly by either base or upper flows; if so, it would be expected that the relative importance of the three proposed parameters varies accordingly.

To evaluate how sensible the model is to each parameter depending on time, the TEDPAS was launched for the same location and period. Figure 3 represents the FAST sensitivity indices per each time step and parameter and in regard to volume in the reservoir and outflow from the reservoir. The fluctuation of the FAST Index regarding volume (Figure 3(a)) is smooth and shows the relatively constant value of the overflow parameter (*a*). On the other hand, the overflow exponent (*b*) index increases during the high-flow period (April–May) corresponding to a decrease of influence of the release coefficient (*k*). This means that the reservoir level is higher than the minimum throughout the year as there is constantly an upper flow and that the overflow exponent is sensible mainly when the water level is high. In terms of sensitivity to the outflow (Figure 3(b)), the fluctuations are more pronounced. The sensitivity of the overflow parameter (*a*) is high during the whole period except when the discharge is increasing (March) or decreasing

Table 3 Sensitivity indices of the Barotse floodplain parameters regarding NS and VR (*a*: overflow parameter, *b*: overflow exponent and *k*: release coefficient)

Parameter	NS FAST Index	VR FAST Index
a	.64	.54
b	.15	.26
k	.03	.11

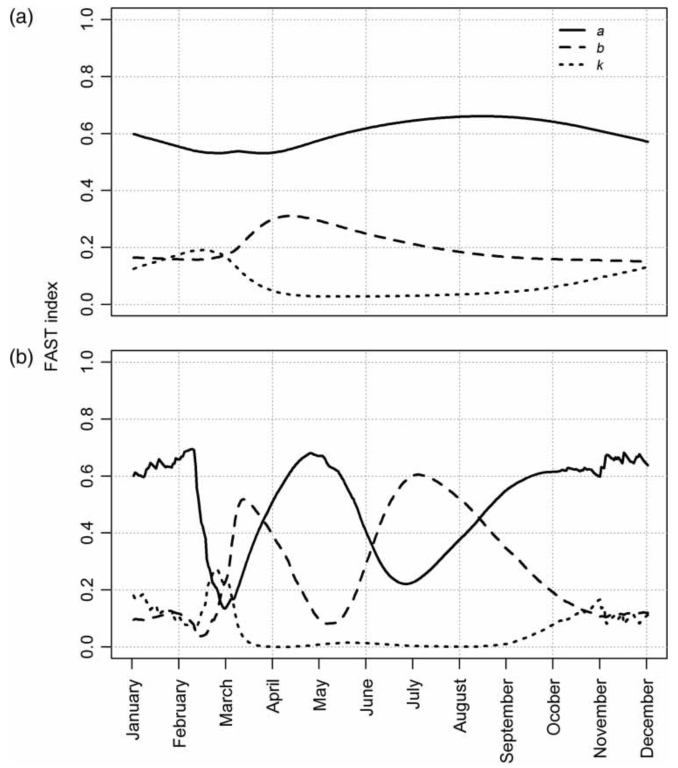

Figure 3 FAST Index of the Barotse floodplain parameters (*a*: overflow parameter, *b*: overflow exponent and *k*: release coefficient) for the year 2000 over the volume of the reservoir (a) and the outflow from the reservoir (b).

(July). During these months, the overflow exponent (*b*) gains importance. The index of the release coefficient (*k*) is, as expected, higher during the dry period (September–February) than during the wet periods.

The discharge output resulting from all the simulations in the parameter space is presented in Figure 4. As expected from the parameter index, a high variance on discharges can be observed during the wet season.

4.2.2 *Sensitivity analysis at the Zambezi basin outlet*

The aim of this approach was to assess the influence of the floodplain parameters over the whole Zambezi basin. For this purpose, the two major floodplains in the basin (Barotse and Kafue), belonging to different sub-basins, were selected.

In Figure 5, the discharges are displayed for the different set of parameters used in the FAST assessment (91 sets in total). A thicker line indicates higher discharge variance. It can be observed that for years with low peaks, e.g. 1998, the variation of the discharges is low, so in such years the model will be less sensitive to the floodplain parameters being assessed. During wet years, the variation of discharges occurs mainly during the recession period due to a delay on the response of the floodplains. For this reason, the year selected to evaluate FAST Indices was 2001, when the peak is clearly higher and presents a stronger variation of the discharges.

The comparison of the sensitivity of both floodplains is presented in Figure 6 for the year of 2001. For the overflow parameters (Figure 6(a) and (b)), the sensitivities to the parameters from both floodplains follow similar patterns with a clear delay for the Barotse floodplain, located more upstream than the Kafue floodplain. A different pattern is observed in comparison between the base flow parameter (Figure 6(c)), which appears to be more influent in the Kafue floodplain than in the Barotse floodplain. As its sensitivity depends on the floodplain geometry and on the flow regime and can, therefore, vary from one floodplain to the other, this fact indicates the importance on considering individual parameterizations for each floodplain. Despite the fact that the relative importance of each parameter depends on floodplain geometry, the sensitivity to overflow parameters has a natural tendency to be higher than to base flow parameters for indicators as NS and VR which are more influenced by high discharges than low discharges. Globally, it is during wet periods that the hydrological model is more sensitive to reservoir parameters.

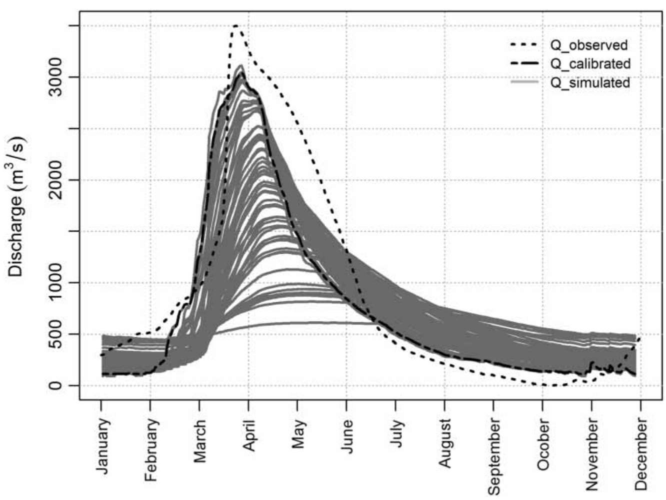

Figure 4 Discharge variation due to the floodplain parameters variation for the year 2000 at the outlet of the Barotse floodplain.

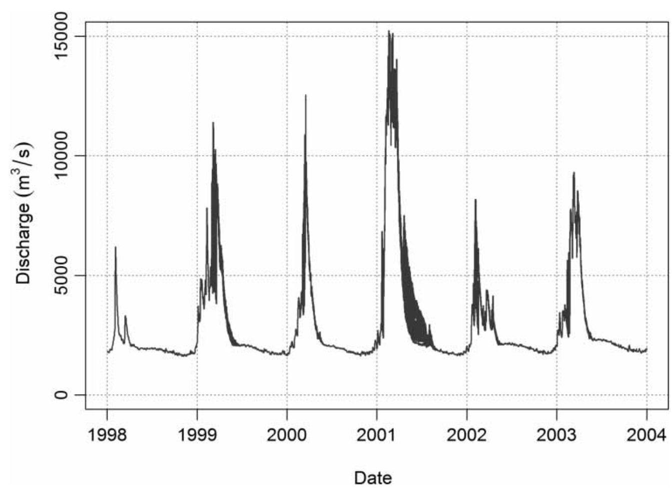

Figure 5 Discharge variation due to the floodplain parameters variation at the outlet of the basin.

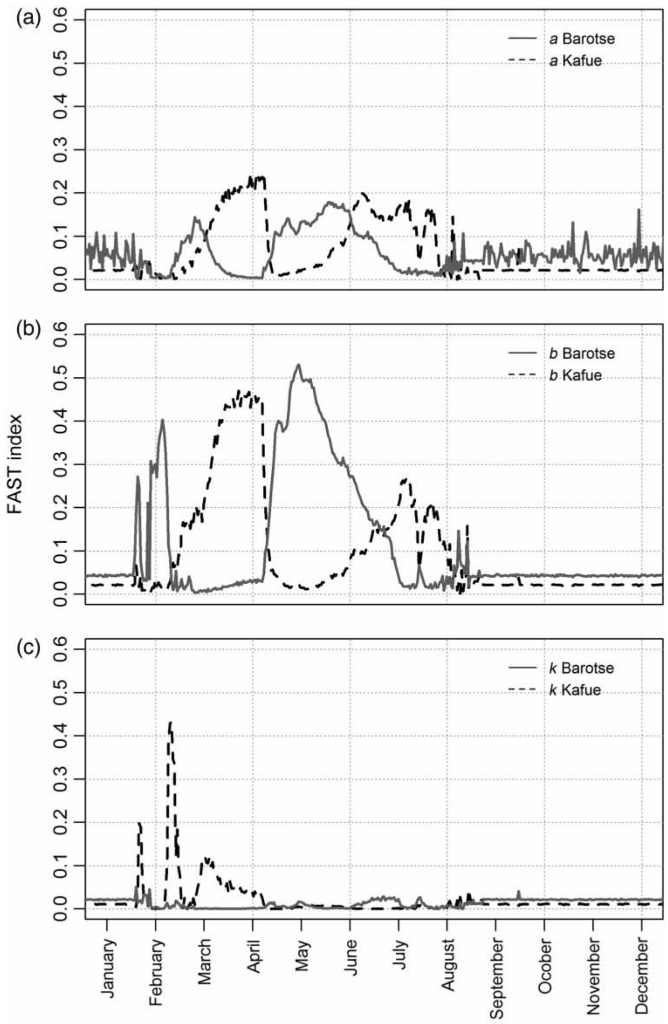

Figure 6 FAST Index on discharge for the year 2001 at the outlet of the basin for the floodplain parameters of the Barotse and Kafue reservoirs (*a*: overflow parameter, *b*: overflow exponent and *k*: release coefficient).

5 Conclusions

Important ecological reserves are created by floodplains and they act as natural flood attenuators by delaying and smoothing flow peaks. In the African Continent, these geographical features are characterized by large evaporation losses and seasonal fluctuations: during high-flow periods, water spreads over the bank and inundates the floodplain, whereas during low flows the stream propagates solely along the main channel. In this study, the reservoir model of SWAT 2009 was adapted to model large floodplains and applied to the Zambezi Basin as well. The outflow was computed using a double equation separating the overflow from the base flow. The modified and the original reservoir models were compared with the observed discharge in terms of VR, NS and hydrographs. The results confirmed that the modified model improves the simulation of the discharge below large floodplains both during high-flow and low-flow periods. With the modified reservoir model, NS values are higher than 0.5 for the calibration period and do not drop below zero during validation, evidencing the ability of the model to reproduce floodplain effects. The model developed in the present study follows a conceptual approach and does not represent in detail the process operating on the floodplains such as backward or multichannel flows.

The sensitivity analysis showed that the overflow parameters have more influence on the NS and VR criteria than the base flow parameters as they are effective during high-flow periods. As a consequence, at least overflow parameters should be considered in a calibration stage. The differences between the two floodplain behaviours were also highlighted, underlying the need of individual parameterization. Considering the particularities of floodplain regions, the modified model reveals its ability to simulate the behaviour of large inundated area, thanks to its spatial flexibility.

As further research, since the separation between base flow and upper flow can be a proxy allowing for different processes of degradation and/or transport of chemicals, sediments, etc. inside the floodplain, equations for water quality and sediment transport could be added to the outflow computation in the modified approach.

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