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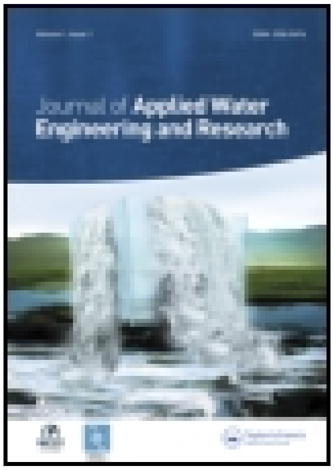

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Hydraulic-hydrologic model for water resources management of the Zambezi basin

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Hydraulic–hydrologic model for water resources management of the Zambezi basin

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The paper focuses on the development of the hydraulic–hydrological model used to simulate water resources management scenarios in the Zambezi River basin. The main challenges of the implementation of the model are the scarcity of continuous reliable discharge data and the significant influence of large floodplains. The Soil and Water Assessment Tool, a semi-distributed physically based continuous time model, was chosen as simulation tool. Given the complexity and the size of the basin under study, an automated calibration procedure was applied to optimize the relative error and the volume ratio at multiple stations. Using data derived from satellite observations, the model is first stabilized during two years, then calibrated over six years and finally validated over three years. The study evidences the importance of evaluating the model at different points of the basin and the complementarities between performance indicators.

Keywords: hydraulic–hydrologic modeling; indicators; calibration

Introduction

The development of water resources models in Southern Africa is greatly challenging. Firstly, the importance of the hydrological processes observed on catchments below the Sahara Desert such as evapotranspiration does not necessarily match what can be extensively observed in temperate catchments (Pilgrim et al. 1988). Secondly, there is a constraining and prevalent lack of hydrological data within most countries in the area.

Within this framework, the African DAms ProjecT (ADAPT) is focusing on the planning and operation of large dams in a complex river basin in order to meet social needs and environmental constraints. Holding multiple hydropower schemes, lakes and large floodplains, the Zambezi River Basin was chosen as a case study because of its complexity and because of the constraining lack of hydrological data, which prompts for innovation on the applied hydrological and hydraulic models.

Modeling the hydrology of the Zambezi River Basin has been attempted in global studies with arguably poor results, namely regarding the timing and amplitude of peak flows (e.g. Yates 1997). Schuol et al. (2008b) calibrated the Soil and Water Assessment Tool (SWAT) model over the whole African Continent with monthly river discharges. Over the Zambezi catchment, the Nash–Sutcliffe (NS) efficiency coefficient was below zero for both calibration and validation periods.

Specific studies over the entire Zambezi catchment showed better results but also illustrated difficulties related to model calibration. A water balance coupled with a water transport model was implemented operating at 0.5° spatial scale and at a monthly time step (Vörösmarty & Moore III 1991; Vorosmarty et al. 1991). The result of the global calibration was a systematic and substantial overestimation of the mean annual runoff.

A lumped rainfall-runoff model was calibrated for long-term mean annual flow over the period 1900–2002 using re-aggregated monthly precipitation data (Beck & Bernauer 2011). The results of the calibration were characterized by Pearson correlation coefficients varying from 0.6 to 0.98. Nevertheless, validation over an independent period was not carried out.

In order to study the hydrology of a sub-basin uninfluenced by large artificial reservoirs, the Upper Zambezi Basin was modeled at a monthly time step for the period 1961–1990 as a single storage bucket with three parameters (Harrison & Whittington 2002) and calibrated and validated using 15 years for each phase with a resulting Pearson correlation coefficient of 0.8. However, due to the poor high flow performance, a manual adjustment of the parameters was necessary, leading to correlation coefficients of 0.6 and 0.5, respectively, for calibration and validation periods.

In another modeling attempt, the Spatial Tools for River basin Environmental Analysis and Management

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(Aerts et al. 1999) and a Lumped Elementary Watershed model were calibrated on the same sub-basin over the period 1960–1972 at a monthly time step (Winsemius et al. 2006a). The NS coefficient was about 0.8. Again, no validation was undertaken.

More recently, a forecasting framework for the discharge prediction at three different sub-basins of the Zambezi River (Upper Zambezi, Luangwa and Kafue) was developed by Meier et al. (2011) for the period from July 1995 to January 2002 at a 10-daily time step. The NS efficiency coefficients were around 0.8 but, again, no validation was implemented as the six years of data were used for calibration.

A rainfall-runoff model was calibrated over two distinct watersheds in the Western Zambezi region to allow short terms reservoir inflow prediction based on radar altimetry (Michailovsky & Bauer-Gottwein 2014). The model was calibrated over the period from 2001 to 2004 and validated over the period from 2005 to 2008. Poor results were obtained during the validation period due to large errors in the precipitation estimates and uncertainties in the floodplain sub-model.

In all cases, calibration has proven difficult and raises practical concerns regarding future model uses. Reasons leading to this state of things go beyond data scarcity and include the uneven distribution of the existing gauging stations and the hydrological particularities of the wetlands. Several studies partly addressed the problem of lack of data by using novel satellite-derived data sources in addition to rainfall measurements, such as terrestrial water storage change (Winsemius et al. 2006b), radar altimetry (Michailovsky et al. 2012) and soil moisture (Meier et al. 2011).

Regarding the generally poor results reported in past studies, the necessity to develop a model able to simulate the floodplain processes as well to take into account the influence of artificial reservoirs is evident. Moreover, almost no modeling effort has been undertaken below the monthly time step, which would be important for modeling hydropower production. Also of importance, up to now, water resources management studies have been conducted without the use of validated basin-scale rainfall-runoff models (Gandolfi et al. 1997; Matondo & Mortensen 1998; Beilfuss & Brown 2010; The World Bank 2010; Tilmant et al. 2010).

The present study discusses the development of a semi-distributed hydraulic–hydrological model at daily time step, which will be used to simulate future mid-term hydropower development scenarios in the Zambezi basin. Below, the section “Study area and data” describes the study area, the model set-up and the data used. The methodology is presented in the section “Calibration methodology” and the results obtained in the section “Results and discussion”. Conclusions are summarized in the section “Conclusions”.

Study area and data

The Zambezi River basin

The Zambezi River basin lies fully within the tropics between 10°S and 20°S encompassing humid, semi-arid and arid regions dominated by seasonal rainfall patterns associated with the Inter-Tropical Convergence Zone. Rainfall varies considerably from year to year and occurs almost entirely between October and March. The resulting mean annual discharge at the delta was estimated at 3800 m^3/s (Tilmant et al. 2010). The river is characterized by large natural floodplains attenuating the runoff and large artificial impoundments regulating the flow. The long-term flow series as well as the climate observations reveal inter-annual cycles of high, medium and low runoff with a duration varying from 10 to 80 years (Tyson et al. 2002; Jury 2003; Mazvimavi & Wolski 2006). Since the runoff cycles have been reported to be primarily explained by rainfall cycles (Farquharson & Sutcliffe 1998; Beilfuss & Dos Santos 2001), the hypothesis adopted in this study is that a calibrated rainfall-runoff model will be able to reproduce the observed cycles even if not tested over the entire climate cycle.

The hydrological model: SWAT 2009

Two criteria were defined to select the hydrological modeling tool: the application of a source code available in the public domain able to be transferred to the stakeholders and the choice of a model already applied in Southern Africa with promising results which would contribute to an appropriate definition of the region’s hydrological processes (Milzow et al. 2011). Resulting from these criteria, the SWAT, 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 was chosen.

SWAT 2009 is a semi-distributed physically based continuous time model constituted in multiple components, including a hydrological module. The broad principle of the model is to simulate the water balance in each of the geographical sub-units in four storage volumes – snow, soil profile, shallow aquifer and deep aquifer – by considering precipitation, interception, evapotranspiration, surface runoff, infiltration, percolation and subsurface runoff (Arnold et al. 1998; Neitsch et al. 2005). The runoff’s estimation is based on the Soil Conservation Service (SCS) curve number (CN) procedure (USDA Soil Conservation Service 1972). A very significant retention parameter in the SCS method is defined by the CN, which is a function sensitive to the soil’s permeability, land uses and antecedent soil moisture conditions. Three options for estimating potential evapotranspiration are proposed: Hargreaves (Hargreaves & Samani 1985), Priestley–Taylor (Priestley & Taylor 1972) and Penman–Monteith (Monteith 1965).

In order to adapt the model to the large floodplains commonly found on Southern African basins, the source code for the reservoir elements was completed based on existing models (Cohen Liechti et al. 2014). The floodplains attenuate the runoff, reducing and delaying flood peaks downstream (Beilfuss & Dos Santos 2001). They are characterized by significant evaporation losses and seasonal fluctuations. During high flow periods, water spreads over the banks and inundates the floodplains whereas, during low flows, the water runs mostly along the main channels. To simulate either the base flow constantly flowing out of the floodplain towards the main channel or the upper flow, occurring when the floodplains are inundated, a double equation relying on a reservoir model has been introduced for outflow computation. The base flow (Q_{base}) is dependent on the water depth in the reservoir and on a release coefficient k (Equation (2)). The upper flow (Q_{up}) is computed using a free crest weir formula conditioned by an overflow constant (a) and an overflow exponent (b). This only occurs when water level inside the reservoir is above $H_{\min}$ (Equation (3)).

$$Q_{\text{outflow}} = Q_{\text{base}} + Q_{\text{up}}, \tag{1}$$

$$Q_{\text{base}} = k \cdot H, \tag{2}$$

$$Q_{\text{up}} = \begin{cases} 0 & \text{if } H \leq H_{\min}, \\ a \cdot (H - H_{\min})^{b} & \text{if } H > H_{\min}, \end{cases} \tag{3}$$

where k, a and b are model parameters.

Input data

Topographic and land cover information

Based on prior modeling experiences of the Zambezi and usage of the SWAT model, the following data sets, available for Africa and a large part of the World, were chosen in order to derive the river network and sub-catchments, as well as to characterize soils and land uses:

1. the Digital Elevation Model (DEM) from the US Geological Survey's public domain geographic database HYDRO1 k which is derived from the 30 arc-second DEM of the world GTOPO30 at a resolution of 1 km;
2. the soil map produced by the Food and Agriculture Organization of the United Nations at a resolution of 10 km (FAO 1995). A new version of the soil map is now available from the Harmonized World Soil Database of the FAO (FAO/IIASA/ISRIC/ISSCAS/JRC 2012). After a first comparison the differences on the Zambezi basin do not appear to be very substantial. However, it would be useful to include the refined data in a further version of the model, given that the new soil types can be documented in the SWAT database;
3. the land-use grid from the Global Land Cover Characterization at a 1 km resolution (GLCC, Version 2, http://edcsns17.cr.usgs.gov/glcc/).

The soil and land-use associated characteristics were obtained from literature (Schuol et al. 2008a, 2008b).

Precipitation

TRMM 3B42, NASA's standard sub-daily precipitation product, was chosen as precipitation source based on a detailed study of the different satellite products (Cohen Liechti et al. 2012). It is produced since 1998 in four steps (Huffman et al. 2007): (1) passive microwave (PM) estimates are calibrated and combined, (2) infrared (IR) estimates are computed using PM estimates for calibration, (3) PM and IR estimates are combined and (4) data are rescaled to monthly total using Global Precipitation Climatology Centre data. The estimates are released on a 0.25° by 0.25° grid at three-hourly temporal resolution (00:00, 03:00, . . . , 21:00 UTC) in a global belt extending from 50°N to 50°S. Version 7a of the TRMM 3B42 product was used in the calibration procedure as it constitutes an improvement compared to version 6.

Temperature

The temperature grids (daily minimum and maximum) were compiled from the NCEP/DOE 2 Reanalysis data (Kanamitsu et al. 2002) provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their website at http://www.esrl.noaa.gov/psd/. The spatial coverage varies from 88.542°N to 88.542°S and from 0°E to 358.125°E, stored on a Gaussian grid of 192 longitude bands of 1.875°.

Discharge and water level

The critical data set for reliable hydraulic–hydrological modeling is the time series of measured discharges which allows the calibration and validation of the model. The most extensive available database containing historical discharge records in the Zambezi Basin is managed by the Global Runoff Data Centre D – 56002 Koblenz, Germany (GRDC), which operates under the World Meteorological Organization (WMO) (Fekete et al. 1999). In the global database, 67 daily and 30 monthly stations located within the Zambezi basin have been identified. In addition, the Department of Water Affairs of Zambia (personal communication) provided a list of 34 stations with the associated discharge data over the Zambian part of the basin. The Zambezi River Authority (ZRA), managing the Kariba dam, the Zambia Electricity Supply Corporation Limited (ZESCO), managing Itezhi-Tezhi and Kafue Gorge dams and the Hidroeléctrica de Cahora Bassa (HCB), managing the Cahora Bassa dam, shared some of the information recorded at the dams. They also provided outflow series at the main reservoirs.

Despite these valuable contributions, most of the data series are not continuous and some stations were not used due to reliability concerns. As can be seen in Figure 1, most of the available discharge data for the period of interest are distributed in the upper and middle parts of the basin, being none available downstream of Cahora Bassa.

ZRA, ZESCO and HCB also transmitted the water levels measured at Itezhi-Tezhi, Kafue Gorge, Kariba and Cahora Bassa reservoirs. These levels were converted to water volumes using a linear relation as the level varies only by small amplitude compared to the reservoir height and the reservoir surface.

The years 1998–2006 were chosen as the period to be modeled. To assess the temporal pattern of the modeled years, the variability of the observed discharge at Victoria Falls between 1958 and 2007 was compared to the variability of the observed discharge between 2000 and 2006. From this analysis, the modeled period was considered representative of the multi-years cycles.

After a compilation of the observed data from upstream to downstream and an assessment of the percentage of missing data at each place, only nine stations were kept as calibration/validation points (Figure 1). The three major reservoirs (Itezhi-Tezhi, Kariba and Cahora Bassa) were also selected as calibration/validation points for reservoir volume variation.

Model set-up

For evapotranspiration, as the inputs required by Priestley–Taylor and Penman–Monteith methods are demanding and the meteorological data available are limited, the Hargreaves method (Hargreaves & Samani 1985), based solely on maximum and minimum surface air temperature, was chosen.

Model inputs were processed within the ESRI ArcGIS 9.3.1 software using the ArcSWAT interface version 2009.93.7a (Winchell et al. 2010). Based on the topography, a minimum drainage area of 5000 km^2 was defined to discretize the watershed in about 200 sub-basins. This threshold was chosen as a balance between the precision of the input data (soil and land use), the limitations of the applied conceptual models, and the complexity of the model, considering the limited number of calibration points available. The sub-basins directly draining to reservoirs, lakes and wetlands were then refined by superposing to the previous discretization a Geographic Information System (GIS) layer of African lakes and flats, resulting in a total of 405 sub-basins (Figure 1).

The geomorphology, stream parameterization and overlay of soil and land cover were automatically accomplished within the interface. SWAT calculates the hydrological cycle over Hydrological Response Units (HRU) which consist of “lumped land areas within the sub-basin that are comprised of unique land cover, soil and management combinations” (Neitsch et al. 2009). In the present case, the HRUs were delimitated using thresholds of 35% of the sub-basin’s surface for land use, soil type and slope classes, resulting in a total of 778 units. The thresholds were chosen in order to take into account a large part of the information available on the soil and land-use maps while keeping the complexity of the model low, reducing

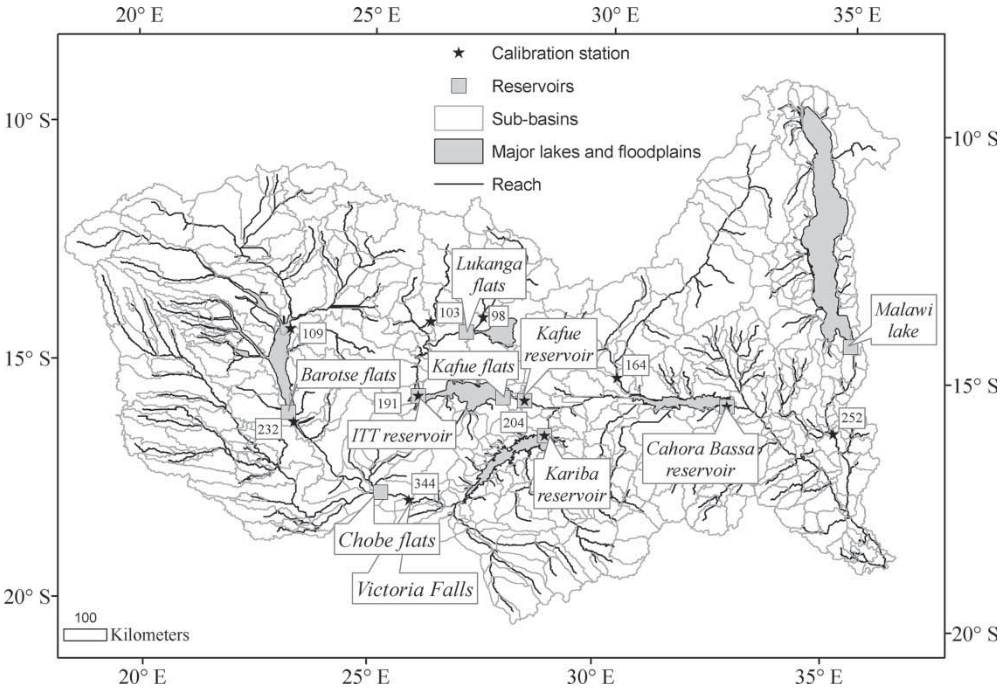

Figure 1. Sub-basins delineation with the corresponding reaches, the reservoirs and the calibration/validation stations.

both the calculation time and the number of parameters to calibrate.

The artificial and natural lakes, as well as the major wetlands along the main channel, were modeled as unregulated reservoirs. For the regulated reservoirs, the simulated outflows were constrained to the observed ones during the calibration in order to reproduce exactly the operations. The initial volumes were set according to the observations at the beginning of the calibration period. To analyze the results without constraints regarding the outflow from the dams, the present state was simulated with operation rules derived from observed data and literature review (The World Bank 2010).

SWAT developers recommend at least one year of stabilization period to allow the model to properly reproduce the water cycle processes and diminish the influence of the inaccurate initial conditions (e.g. initial soil water content, initial depth of water in the shallow aquifer and initial depth of water in the deep aquifer). Due to the size of the basin, two years of stabilization were adopted (1998–1999). In order to make the most of the scarce discharge data available, in the final phase of the calibration the same years were reused for calibration (1998–2003), being after the two years of stabilization period the simulation's main parameters reset to observed conditions wherever possible (e.g. setting the initial volume in the artificial reservoirs to observed values). The remaining years (2004–2006) were kept for validation.

Calibration methodology

The calibration procedure was defined in three steps. At first, the model parameters to optimize were chosen. Secondly, the objective functions (OFs) were defined based on the future model use and, thirdly, an algorithm was implemented to find the "best" parameter sets. Depending on the calibration results, the parameters as well as their bounds were refined and the OF changed to improve the result in an iterative progression.

Choice of the parameters

The first step of the calibration procedure consists in parameter specification. As SWAT partitions the watershed into sub-basins and smaller HRUs, some parameters have a uniform value over the entire watershed and others depend on soil type, land use and/or topographic features. To select the most sensitive parameters and define their reasonable bounds, literature related to SWAT (Muleta & Nicklow 2005; Bekele & Nicklow 2007) and recent studies where it was applied to Africa (e.g. Schuol & Abbaspour 2006; Schuol et al. 2008a) were consulted. As a complement, the sensitivity analysis procedure of van Griensven et al. (2006) included in the ArcSWAT interface (Winchell et al. 2010) was used to assess the importance of different parameters on runoff generation process. The method combines the Latin Hypercube and One-factor-At-a-Time sampling, assuring that changes in the outputs after each model run can be unambiguously attributed to the parameter that was changed (van Griensven et al. 2006). The parameters were defined according to the acceptance of a catchment-wide parameterization. The groundwater parameters as well as the surface runoff lag time and the parameters related to the evaporation estimation were considered as uniform over the entire basin. The HRU parameters related to the soil or land cover were changed relatively to the global set, still translating the physical diversity defined by the GIS data and reducing the number of parameters to be calibrated. The floodplain parameters were calibrated as different for each floodplain. In total, 16 parameters were calibrated. They are listed in Table 1.

Definition of the OF

Given that the success of an automatic calibration process is highly dependent on the OF chosen (Gupta et al. 1998), in the second step of the procedure, an OF was defined. Before selecting the indicators the calibration objectives were defined as follows: (1) as the model is to be used to simulate different scenarios of water resource exploitation mainly focused on dam operations, the error in runoff volumes should be minimized and (2) the global shape of the simulated hydrograph should be similar to that of the observed hydrograph.

The general form of a multi-objective calibration problem can be stated as follows:

$$\hat{\mathbf{x}}_{\text{opt}} = \arg\min_{\mathbf{x}} \mathbf{F}(\mathbf{x}) = \arg\min_{\mathbf{x}} \left[F_1(\mathbf{x}), F_2(\mathbf{x}), \ldots, F_p(\mathbf{x})\right],$$
$$\mathbf{x} = (x_1, \ldots, x_i),\ \mathbf{x} \in X, \tag{4}$$

where X is the parameter space, $\mathbf{x}$ a set of parameters and $\mathbf{F}(\mathbf{x})$ the set of associated OFs.

As the set of functions $\mathbf{F}(\mathbf{x})$ will be minimized by the algorithm with respect to the whole catchment, the performance measures have to be reformulated to be applicable to several discharge stations/reservoir storage areas.

In the present study, two of the three performance indicators described below were selected for the multi-objective minimization, allowing the algorithm to converge faster. The objectives were not combined but treated independently in order to delineate a Pareto front.

More precisely, the following performance indicators along with the associated OF to be minimized were used in the calibration procedure: the relative error (RE) (Equation (5)), the NS efficiency coefficient (Equation (6)) and the volume ratio (VR) (Equation (7)):

$$\text{RE} = \frac{1}{n}\sum_{i=1}^{n}\frac{\left|Q_{\text{s},i} - Q_{\text{o},i}\right|}{Q_{\text{o},i}}, \quad \text{OF} = \frac{\sum_{j=1}^{N}\left(\text{RE}_j\right)}{N}, \tag{5}$$

Table 1. SWAT model parameters considered for calibration with their upper and lower bounds.

Parameter	Description	Unit	Lower bound	Upper bound
CANMX	Maximum canopy storage	mm	0	30
Infiltration				
CN_F	SCS curve number for moisture condition	%	– 0.25	0.15
SOL_AWC	Available water capacity of the soil layer	%	– 0.5	1
SOL_Z	Depth from soil surface to bottom of the layer	%	– 0.5	1
ESCO	Soil evaporation compensation factor	–	0.001	1
EPCO	Plant uptake compensation factor	–	0	1
SURLAG	Surface runoff lag time	day	0.5	1.5
Groundwater flow				
GW_REVA	Ground water 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
GW_DELA	Groundwater delay	day	20	300
ALPHA_B	Baseflow recession constant	day	0	0.5
CH_KII	Effective hydraulic conductivity in main channel alluvium	mm/h	0.1	50
Floodplain				
a	Reservoir overflow constant	$m^{3/2}/s$	900	55,000
b	Exponent of overflow equation for reservoir	–	1	3.5
k	Reservoir release coefficient	m^2/s	35	350

$$\mathrm{NS} = 1 - \frac{\sum_{i=1}^{n} (Q_{\mathrm{s},i} - Q_{\mathrm{o},i})^2}{\sum_{i=1}^{n} (Q_{\mathrm{o},i} - \overline{Q_{\mathrm{o}}})^2}, \quad \mathrm{OF} = \frac{\sum_{j=1}^{N} (1 - \mathrm{NS}_j)}{N}, \tag{6}$$

$$\mathrm{VR} = \frac{\sum_{i=1}^{n} Q_{\mathrm{s},i}}{\sum_{i=1}^{n} Q_{\mathrm{o},i}}, \quad \mathrm{OF} = \frac{\sum_{j=1}^{N} |1 - \mathrm{VR}_j|}{N}, \tag{7}$$

where Q_s and Q_o are the simulated and observed discharges, n the number of discharge records available at each station and N the number of gauging stations.

RE and VR were also calculated at the reservoir stations where observed water levels were available with a difference in the RE calculation, as the error was computed relatively to the difference between the minimum and maximum operation volumes and not relatively to the observed values (Equation (8)):

$$\mathrm{RE}_{\mathrm{res}} = \frac{1}{n} \sum_{i=1}^{n} \frac{\left|\mathrm{Vol}_{\mathrm{s},i} - \mathrm{Vol}_{\mathrm{o},i}\right|}{\mathrm{Vol}_{\max} - \mathrm{Vol}_{\min}}, \tag{8}$$

where Vol_s and Vol_o are the simulated and observed volume, n the number of volume records available at each station ad $V_{\max}$ and $V_{\min}$ the minimum and maximum operation volumes.

In order to converge faster, the optimization algorithm was never set to optimize the three performance indicators but their values were calculated during the results' analysis and used to select to most appropriate parameter sets among the "best" solutions generated by the algorithm. The global RE and the global VR were set as the two OFs and NS kept for the results' analysis.

Automatic calibration algorithm

As several (potentially conflicting) objectives are being optimized, the solution of Equation (4) is not likely to be a unique set of parameters but rather a Pareto front of optimal non-dominated solutions. As the ensemble of possible solutions is quite large and the solution space is non-convex, the application of heuristic search algorithms is a sound option. To explicitly address the problematic of finding the front of non-dominated solutions the Multi-ALgorithm Genetically Adaptive Multi-objective method (AMALGAM), which has already been documented as a high performance solution compared to other evolutionary multi-objective algorithms for SWAT calibration (Zhang et al. 2010, 2011), was implemented (Vrugt & Robinson 2007; Vrugt et al. 2009).

AMALGAM can be classified as a meta-algorithm for multi-objective optimization as it uses several particular algorithms incorporating different concepts and combines their results. By doing so, it draws from the particular strengths of the best performing algorithms for each given problem, potentially reaching better results more efficiently. Particularly, solutions are adaptively changed based on the shape of the fitness landscape using four optimization methods: (i) non-dominated sorted genetic algorithm-II (Deb et al. 2002), (ii) particle swarm

Table 2. Indicators values at the discharge and water level stations.

	Calibration period (1998–2003)			Validation period (2004–2006)		
	NS	VR	RE	NS	VR	RE
Mean value	0.54–0.56	0.92–0.93	0.28–0.29	0.46–0.50	0.80–0.82	0.35–0.36
Station #109	0.72–0.74	0.74–0.77	0.37–0.38	0.81–0.84	0.86–0.90	0.25–0.25
Station #232	0.77–0.78	0.82–0.84	0.25–0.28	0.85–0.89	0.80–0.83	0.20–0.23
Station #344	0.61–0.65	0.98–1.01	0.34–0.35	0.81–0.83	0.81–0.84	0.24–0.25
Station #98	0.28–0.34	0.63–0.64	0.61–0.63	0.33–0.37	0.44–0.45	0.58–0.62
Station #191	0.60–0.64	0.87–0.88	0.43–0.47	0.54–0.58	0.64–0.66	0.30–0.31
Station #204	0.42–0.45	0.98–0.99	0.24–0.25	− 0.43 to − 0.25	0.76–0.80	0.22–0.25
Station #252	0.34–0.37	1.01–1.02	0.13–0.14	0.22–0.28	0.92–0.93	0.11–0.12
Itezhi-Tezhi	–	0.95–1.03	0.13–0.15	–	0.07–0.10	0.90–0.94
Kariba	–	1.19–1.21	0.20–0.22	–	1.29–1.35	0.30–0.35
Cahora Bassa	–	0.94–0.95	0.08–0.09	–	1.34–1.36	0.34–0.36

Note: NS, Nash–Sutcliffe coefficient; VR, volume ratio; and RE, relative error.

optimization (Kennedy & Eberhart 1995), (iii) adaptive Metropolis search (Haario et al. 2001) and (iv) differential evolution (Storn & Price 1997). The population of parameter sets evolves based on the results of the previous populations. The user defines the population size as well as the maximum number of iterations. Typically, the algorithm is stopped when it has reached a satisfying approximation of the Pareto front or when the convergence rate falls consistently below a certain threshold. In the present study, the population size was set to 40 and the algorithm was stopped when reaching a stable result, corresponding to a global RE of 0.31 and a global VR of 0.87. This was the result following about 150 generations.

Results analysis

Two concepts illustrate the importance of non-uniqueness of an optimal solution to the model calibration; the principle of equifinality (Beven & Freer 2001) and the concept of Pareto front (Gupta et al. 1998). In light of these concepts, no unique optimal solution is likely to be found mathematically without an appreciable degree of subjectivity. As such, human capacity to appreciate errors induced by data and model structure, as well as expert knowledge of the catchment's hydrology, recommend user judgment as a complement to the use of automatic algorithms. Using AMALGAM as the optimization tool with multiple objectives allowed the definition of a set of non-dominated solutions according to various trade-offs between objectives.

The following methodology is proposed to select the adequate parameter set(s):

1. Multiple parameter sets are selected from the automatic calibration algorithm results according to the OF's values.
2. The OF values, as well as complementary indicators are computed at each station for the calibration and validation periods.
3. The best(s) solution(s) is(are) subjectively chosen based on the results obtained for the hydrographs and eventually manually adjusted to fit the specific needs of the user.

As the calibration method is developed for a basin equipped with hydraulic schemes, the measured water level is available at the main reservoirs and can be converted to reservoir volume. Therefore, performance measures are also computed for the reservoir volume variation.

Results and discussion

The location of the discharge and controlled reservoir stations used for the calibration process is shown in Figure 1 along with the floodplains included in the model.

Calibration indicators

The indicator issued from the calibration (1998–2003) and validation (2004–2006) periods illustrate the difficulty in reaching an adequate calibration at all points in the basin (Table 2). On the Zambezi River (stations #109, 232 and 344), NS values are higher than 0.6 and better during the validation period than the calibration period. On the Kafue River (stations #98, 191 and 204), NS values are much lower and VR value drops during the validation period. At Itezhi-Tezhi, the volume is underestimated by 90% during the validation period due to low inflows over two of the three years. At Kariba, the volume is overestimated by 20% during the calibration period and by about 30% in the course of the validation period. At Cahora Bassa, the overestimation during validation period reaches 35%.

Hydrographs

In terms of hydrographs (Figure 2), as mentioned above, the hydrological processes are not as well represented in the Kafue Basin (stations #98, 191 and 204) as in the Upper Zambezi Basin (stations #109, 232 and 344). The reason may be that the hydrological processes in that region are different from those observed on the Upper Zambezi basin

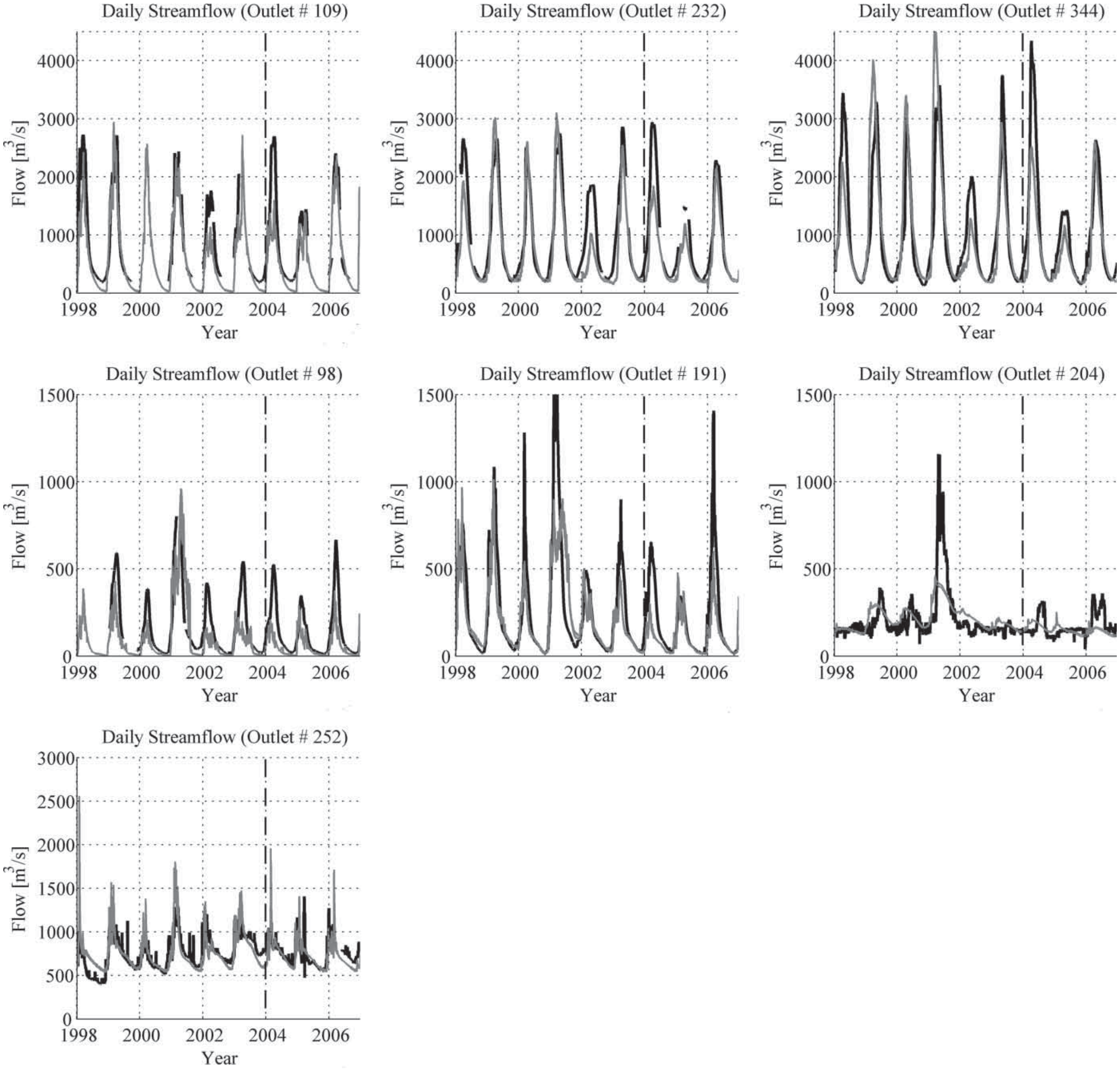

Figure 2. Hydrographs of observed (black line) and simulated data (grey line) after the final iteration of the calibration procedure at stations #109 (Lukulu), #232 (Senanga), #344 (Victoria Falls), #98 (Chilenga), #191 (inflow of Itezhi-Tezhi reservoir), #204 (outflow of Kafue reservoir) and #252 (Shire). The dashed vertical line separates the calibration period (1998–2003) from the validation period (2004–2006).

and that the global parameterization of the model does not allow the desirable differentiation between the two regions. At station #191 (inflow to the Itezhi-Tezhi reservoir), the base flow and the flood peaks are close to the observed data during the calibration period except for the year 2001 which is also problematic at station #204. The high flows during validation period are underestimated over the whole Kafue sub-basin, leading to a consequent reservoir volume underestimation at Itezhi-Tezhi (Figure 3(a)).

Reservoir volume variations

At the artificial reservoirs, the outflow is constrained to the observed flow as data were made available by the dam operators. Therefore, the comparison of observed and simulated volumes leads to an error accumulation. If the outflow during one year is overestimated or underestimated, the resulting volume curve will be shifted up or down even if the simulated values for the following years become again similar to the observed data. Figure 3 should so be interpreted with this in mind. At Kariba (Figure 3(c)), the overestimation of discharge during years 1999 and 2001 leads to a volume overestimation of about 25% during the calibration period, which propagates into the validation period. The other variations have been well simulated by the model. The volume variations during the calibration period at Cahora Bassa are nearly perfectly reproduced by the model (Figure 3(d)). During the validation period, the volume is overestimated by 35%.

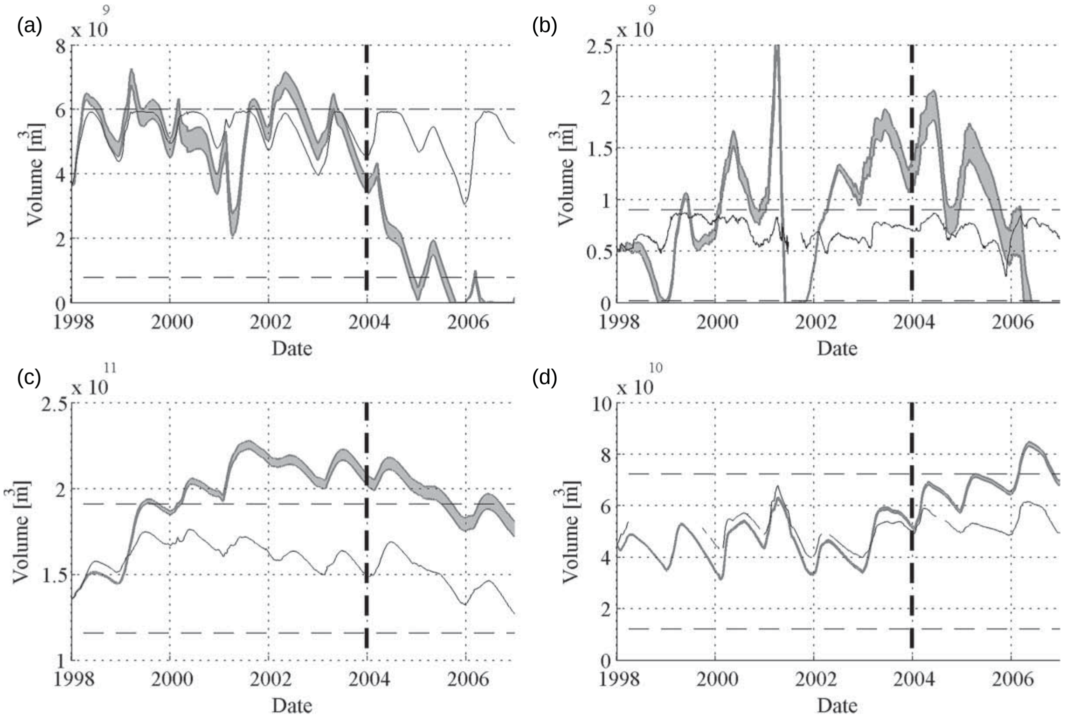

Figure 3. Simulated (grey band) and observed (black line) volume variation after the final iteration of the calibration procedure at Itezhi-Tezhi (a), Kafue Gorge (b), Kariba (c) and Cahora Bassa (d) dams with the full reservoir and the minimum operating volumes (dashed lines) for the calibration and validation periods (separated by a black vertical line).

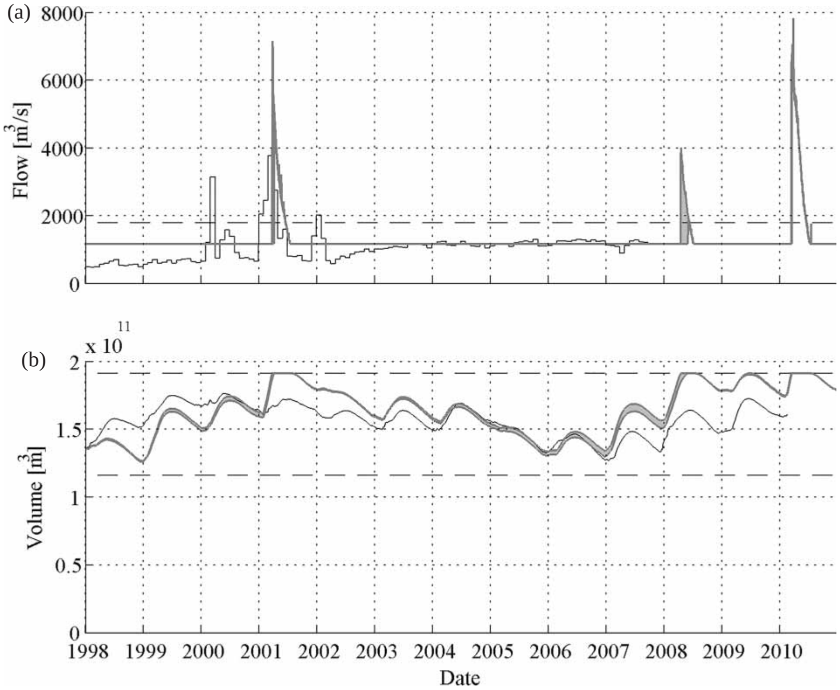

Figure 4. Observed (black line) and simulated (grey area) outflow (a) and volume (b) at Kariba reservoir for the present state scenario with the maximum turbine capacity and the minimum and maximum operation volumes (dashed lines).

The results of the calibration optimization reach the intended objectives. The error in runoff volumes is minimized with a VR higher than 0.9 during calibration and around 0.8 during validation. Moreover, the global shape of the observed hydrograph is reproduced with a mean RE of 30% for the calibration period and 35% for the validation period. At the artificial reservoirs, the results for Kariba and Cahora Bassa show that the model is able to

Table 3. Average energy production for the present state scenario.

Hydropower plant	Mean annual energy (GWh)	25th quartile (GWh)	75th quartile (GWh)	Mean firm power (MW)	25th quartile (MW)	75th quartile (MW)	Mean annual spilled volume (10^9m^3)	25th quartile (10^9m^3)	75th quartile 10^9m^3)
Kafue Upper	4′930	4′586	5′474	372	125	625	1.71	0.00	2.39
Kariba	8′309	8′128	8′546	923	894	943	3.93	0.00	1.97
Cahora Bassa	12′928	12′923	12′972	1′449	1′442	1′458	20.61	9.26	28.37
Nkula Falls	893	892	893	102	102	102	15.96	15.10	16.10
Tedzani	644	644	645	73	73	73	15.36	14.44	15.41
Kapichira	484	571	572	55	65	65	15.51	16.49	18.20
Total	28′188	27′744	29′101	2′975	2′701	3′265	73.08	55.29	82.45

reproduce the volume variations even if the volume is overestimated for particular years. At Itezhi-Tezhi, the shape of the variations is followed by the model during calibration but not during validation.

Present state scenario

The simulation of the present state is done for 13 years, from 1998 to 2010, using the calibrated parameters to generate a reference scenario for the assessment of development scenarios. The outflow from the artificial reservoirs is computed by a simple hydropower production model based on the reservoir rule curve and limit operation levels.

The results obtained at Kariba dam – in terms of outflow and volume in the reservoir – are shown in Figure 4. Kariba's turbines were upgraded from 1200 to 1470 MW recently. Therefore, the observed base discharge increased during the analyzed period (Figure 4(a)). For the simulation, a mean outflow of 1200 m^3/s was set according to the registered outflow during 2004–2007 which allows the model to follow the observed fluctuation in volume. It overestimates the outflow observed from 1998 to 2004 avoiding nearly entirely the spillway releases from 2000 to 2002. The maximum turbine capacity is actually 1800 m^3/s, but the turbines are operated at about 65% of their maximum capacity. In terms of reservoir volume, the dam is operated below the flood rule curve and the volume is reduced before the flooding season (minimum in January) (Figure 4(b)).

In terms of energy production (Table 3), about 30,000 GWh/year are generated in the basin with a firm power of about 2200 MW which corroborates the results obtained by previous studies (Tilmant et al. 2010; The World Bank 2010). The hydropower plant with the highest production is Cahora Bassa, followed by Kariba and Kafue Gorge. The run-of-river power plants located on the Shire River generate only a limited amount of energy compared to the aforementioned ones.

Conclusions

In this study, a hydrological modeling framework for water resources management at a daily scale in a complex African river basin with large hydraulic structures is presented. An enhanced version of SWAT 2009 is proposed to include the floodplains and the artificial reservoirs. The calibration and validation process was separated in four steps: (1) choice of calibration parameters, (2) definition of OFs, (3) application of an AMALGAM and (4) analysis of the results in terms of statistics and hydrographs for the calibration and the validation periods. The methodology is applied on the Zambezi River basin. The discussion showed the importance of considering the hydrographs and volume variation plots for analyzing results as this allows the quality assessment of the model's estimates better than focusing on discharge's statistics and indicators alone. The methodology also emphasizes the need to define the future use of the model before calibration, as this influences substantially the OFs and, thus, the final solutions.

The differences between observed and simulated data stem from four error sources (Refsgaard & Storm 1996; Madsen 2000): (1) the meteorological input data, (2) the recorded observations, (3) the model structure and (4) the parameter values. In fact, although the calibration attempts to optimize performance indicators, it may also compensate for errors on input data and inadequacies in the model structure.

Input data uncertainty is relevant over the Zambezi basin as precipitation is estimated from satellite observations and other variables are based on broad global data sets. When compared to gauge data over the area, the satellite rainfall estimates' VR is close to 1, but the correlation at daily time step is quite low, near 0.25 (Cohen Liechti et al. 2012). Given this, the model should be able to reproduce the runoff volume, but discrepancies in the runoff shape could be explained by errors in rainfall data.

The second source of error concerns recorded discharge and reservoir level observations. Uncertainty of river discharge simulations comes probably from errors in the rating curve estimations (Di Baldassarre & Montanari 2009), individual measurements of discharge, which have uncertainties in the range of 2–19% using velocity–area methods (McMillan et al. 2012) and data reporting and handling. In the case of the Zambezi River, the large flow range and the variable channel geometry in the floodplains results in low reliability of the discharge measurements. Errors in observed outflows at the dams also come from various sources. First, the turbine flow is not directly measured, being estimated from the electricity production. Secondly, during floods, the outflow is estimated based on the reservoir level and the spillway's capacity, but not directly measured.

Compared with past attempts to model discharges in key locations of the Zambezi basin (Vorosmarty et al. 1991; Harrison & Whittington 2002; Winsemius et al. 2006a; Meier et al. 2011), the results can be considered as acceptable for applying the model to simulate development scenarios, taking into account the fact that the scenarios comparison will be based on relative values. The present work constitutes a significant contribution in terms of reliability and error assessment as it implemented a thorough validation procedure and used a hydrological model tailored to meet some of the specificities of the Zambezi River basin.

Further improvement of the calibration could be reached by using a longer simulation period allowing more discharge data to be taken into account. However, it is actually limited by the availability of rainfall estimates. For real-time or even forecasting use, the model could be adapted including a periodic update of the state variables like reservoirs levels but this is beyond the scope of the present study.

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