Regional calibration of the Pitman model for the Okavango River

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Abstract

This paper reports on the application of a monthly rainfall-runoff model for the Okavango River Basin. Streamflow is mainly generated in Angola where the Cuito and Cubango rivers arise. They then join and cross the Namibia/Angola border, flowing into the Okavango wetland in Botswana. The model is a modified version of the Pitman model, including more explicit ground and surface water interactions. Significant limitations in access to climatological data, and lack of sufficiently long records of observed flow for the eastern sub-basins represent great challenges to model calibration. The majority of the runoff is generated in the wetter headwater tributaries, while the lower sub-basins are dominated by channel loss processes with very little incremental flow contributions, even during wet years. The western tributaries show significantly higher seasonal variation in flow, compared to the baseflow dominated eastern tributaries: observations that are consistent with their geological differences. The basin was sub-divided into 24 sub-basins, of which 18 have gauging stations at their outlet. Satisfactory simulations were achieved with sub-basin parameter value differences that correspond to the spatial variability in basin physiographic characteristics. The limited length of historical rainfall and river discharge data over Angola precluded the use of a split sample calibration/validation test. However, satellite generated rainfall data, revised to reflect the same frequency characteristics as the historical rainfall data, were used to validate the model against the available downstream flow data during the 1990s. The overall conclusion is that the model, in spite of the limited data access, adequately represents the hydrological response of the basin and that it can be used to assess the impact of future development scenarios.

Introduction

To enable estimates of the impact of climatic change and water resource development scenarios on river flow, there is a need to understand the natural system, especially the spatial variability of the hydrological response to climatological inputs. A catchment hydrological model provides a tool for such estimates, provided that it includes relevant descriptions of dominant processes and that sufficient geographical and climatological information is available. It is necessary that limitations in availability and quality of data, or the model's capability to reflect basin behaviour, do not affect the quality of the model outputs to such a degree that the simulated streamflow has to be rejected as an acceptable description of observed conditions. If the reliability of the model output is low, the use of models linked to scenarios will not be a feasible way to predict changes in streamflow due to water abstractions or climatic change. If we cannot model the present, we cannot model the future. Consequently, ensuring that simulated streamflow accounts for spatial differences in physical and climate characteristics, and reflects patterns of monitored flow represents a great challenge and a prerequisite for future model-based hydrological scenario assessments.

This paper is an assessment of the application of the monthly modified Pitman rainfall-runoff model to the data-poor Okavango River basin in Southern Africa (Fig. 1), as a basis for assessment of the impacts of climatic variability and change, as well as various development scenarios. The Okavango River rises in the Angolan highlands as the Cubango River, and has one major tributary, the Cuito River. At the Namibian border, the two rivers merge to become the Okavango River that then drains into the Okavango delta after reaching Botswana (Kgathi et al., this issue). The vast majority of the streamflow is generated in the Angolan headwater catchments (Wilk et al., this issue) and the inter-annual and multi-annual variability is pronounced (Kgathi et al., Wolski et al., both this issue). The aim of this paper is to assess whether a model set up, calibrated and validated against the available data is adequately representative of the hydrological characteristics of the basin and whether it can be recommended for use in scenario assessments. The implications are that the model, in order to serve this purpose, should truly reflect the runoff response to climate forcing and satisfactorily reproduce the runoff magnitude, frequency and variability characteristics. The study is part of the EU funded project WERRD (Water and Ecosystem Resources in Regional Development) and builds on earlier work, presented by Andersson et al. (2003). The details of the use of the model to assess development and climate change scenarios are reported in a companion paper (Andersson et al., this issue).

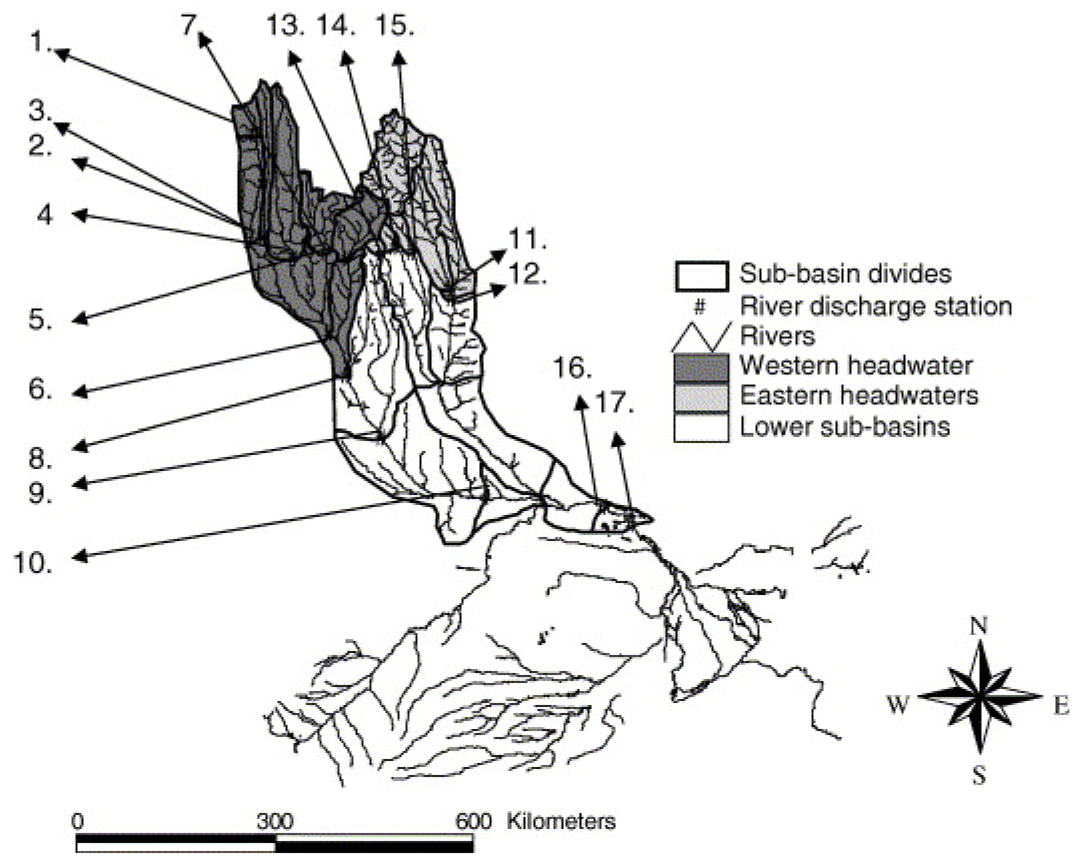

Figure 1. Defined sub-basins for the Okavango basin that contribute flow to the Okavango Delta. Information about the 17 gauged sub-basins is given in **Table 2**.

The Pitman model

A modified version of the Pitman monthly rainfall-runoff model has been established and calibrated for the Okavango basin. The Pitman model has become one of the most widely used monthly time step rainfall-runoff models within Southern Africa. The original model was developed in the 1970s (Pitman, 1973), while the basic form of the model has been preserved through all the subsequent versions that have been re-coded by the original author and others, including the version used in this study. The calibration process has focussed on several key problem areas, which are frequently encountered when trying to establish a model in an area where hydrometeorological data are relatively scarce and where estimations are required for ungauged sites within the basin. One problem concerns the fact that in situ measurements of climatological variables over the entire basin were only available for the calibration period (1960–1972), while remote-sensing derived rainfall estimates had to be relied upon for the validation period (1991–1997).

Similar to many other conceptual models, the Pitman (1973) model consists of storages linked by functions designed to represent the main hydrological processes prevailing at the basin scale. The version applied includes modifications added during the application of the model for Phase 1 of the SA FRIEND programme (Hughes, 1997), as well the addition of a more explicit ground water recharge and discharge function (Hughes, 2004). In addition, Hughes et al. (2002) defined several components of the model where modifications could enhance the model's ability to address the requirements of regional water resource assessments in the SADC Region. A number of such components are considered and discussed in this paper including:

• The need to consider the distribution of rainfall within the primary modelling period of one month. The fact that daily rainfall data for the determination of such distributions are not always available is addressed and it is suggested that acceptable estimates can be based on data from other basins in the same region with similar rainfall totals and seasonal distributions.

• The need for a more explicit approach to ground water recharge and discharge that will permit improved links to ground water resource management. A recently developed routine for this purpose was tested (Hughes, 2004).

• Channel transmission losses need to be considered in semi-arid basins, especially for large rivers with substantial alluvial beds and floodplains. Such losses were accounted for in an implicit way.

• In large basins, it may be necessary to consider channel routing even when using a model with a monthly time step. This was considered by testing a channel routing function.

• The original interception routine in the Pitman model was compared with estimates based on a Markov model of the probability of a rain day, as well as a daily interception model.

• Frequently, only mean monthly values of potential evaporation at different locations are available. The use of monthly time series of evaporation was assessed, in spite of being based only on the limited availability of temperature data.

This version has been incorporated, together with a reservoir water balance model, into the SPATSIM (SPatial and Time Series Information Modelling) water resources database and modelling package developed at the Institute for Water Research (IWR), Rhodes University (Hughes et al., 2002). It represents a semi-distributed implementation of the model, whereby all identified sub-basins are modelled with independent compulsory parameter sets and input time series. However, not all sub-basins need the optional input requirements specified and if missing, they are assumed to be not relevant to that specific area.

Fig. 2 illustrates the main structure of the model, while Table 1 provides a list of the parameters of both the rainfall-runoff model and the reservoir water balance model and brief explanations of their purpose. Compulsory data requirements for the rainfall-runoff model include catchment area, a time series of catchment average rainfall, a time series of potential evaporation, or an annual value and monthly distributions. Separate values for January and July are provided for the interception storage parameters PI1, PI2 and the surface runoff parameter ZMIN. Seasonal distribution factors are then used to generate the values for the remaining months of the year. Optional requirements include seasonal distributions of irrigation water requirements and other water abstractions, as well as time series of upstream inflow, transfer inflow and downstream compensation flow requirements.

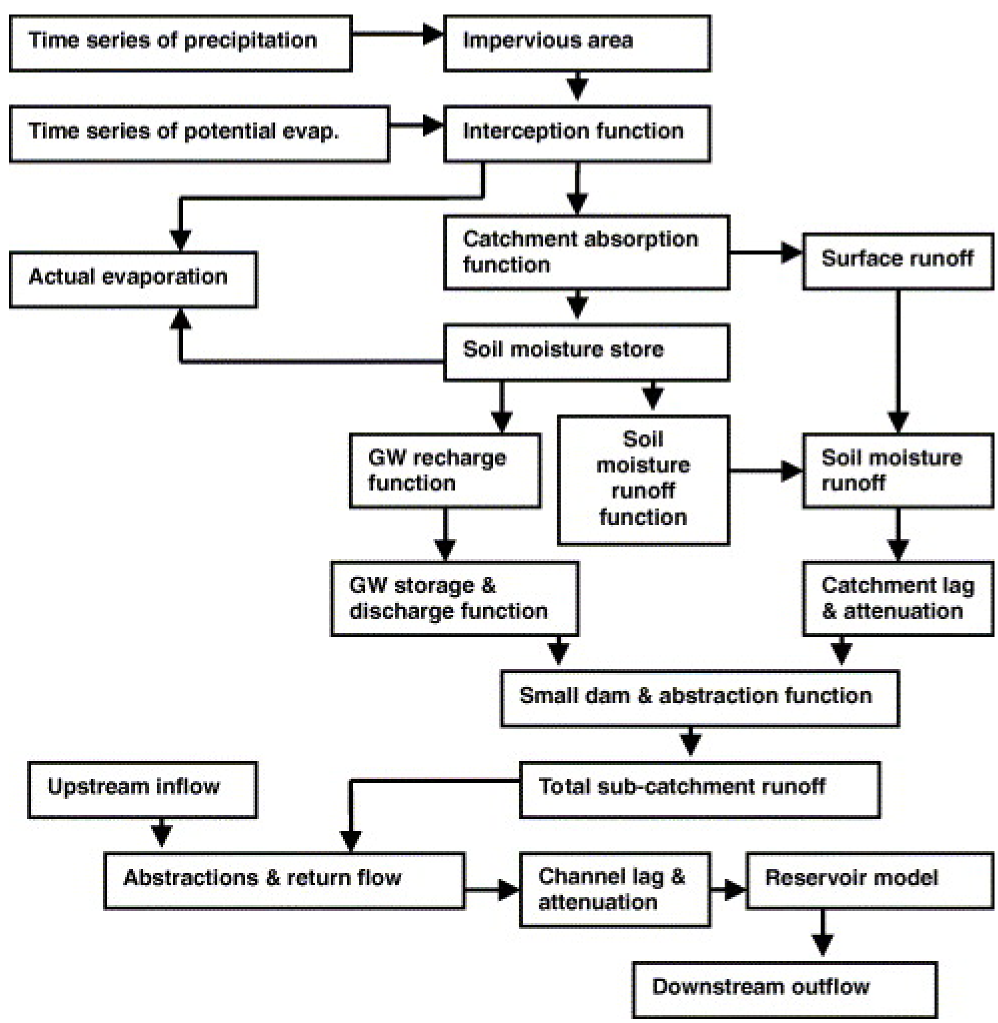

Figure 2. Flow diagram of the main components of the SPATSIM version of the Pitman model.

Table 1.

Pitman and reservoir model parameters

Parameter	Units	Pitman model parameter description
RDF		Rainfall distribution factor. Controls the distribution of total monthly rainfall over four model iterations
AI	Fract.	Impervious fraction of sub-basin
PI1 and PI2	mm	Interception storage for two vegetation types
AFOR	%	% area of sub-basin under vegetation type 2
FF		Ratio of potential evaporation rate for Veg2 relative to Veg1
PEVAP	mm	Annual sub-basin evaporation
ZMIN	mm $month^{-1}$	Minimum sub-basin absorption rate
ZAVE	mm $month^{-1}$	Mean sub-basin absorption rate
ZMAX	mm $month^{-1}$	Maximum sub-basin absorption rate
ST	mm	Maximum moisture storage capacity
SL	mm	Minimum moisture storage below which no GW recharge occurs
POW		Power of the moisture storage-runoff equation
FT	mm $month^{-1}$	Runoff from moisture storage at full capacity (ST)
GPOW		Power of the moisture storage-GW recharge equation
GW	mm $month^{-1}$	Maximum ground water recharge at full capacity (ST)
R		Evaporation-moisture storage relationship parameter
TL	months	Lag of surface and soil moisture runoff
CL	months	Channel routing coefficient
D.Dens		Drainage density
T	m^2 d^{-1}	Ground water transmissivity
S		Ground water storativity
Slope		Initial ground water gradient
AIRR	km^2	Irrigation area
IWR	Fract.	Irrigation water return flow fraction
EFFECT	Fract.	Effective rainfall fraction
RUSE	Ml yr^{-1}	Non-irrigation demand from the river
MDAM	Ml	Small dam storage capacity
DAREA	%	Percentage of sub-basin above dams
A, B		Parameters in non-linear dam area-volume relationship

Parameter	Units	Pitman model parameter description
IRRIG	km^2	Irrigation area from small dams
Parameter	Units	Reservoir model parameter description
CAP	Mm^3	Reservoir capacity
DEAD	%	Dead storage
INIT	%	Initial storage
A, B		Parameters in non-linear dam area-volume relationship
RES1–5	%	Reserve supply levels (percentage of full capacity)
ABS	Mm^3	Annual abstraction volume
COMP	Mm^3	Annual compensation flow volume

The model operates over four iterations and the distribution of the total monthly rainfall is controlled by an *S*-curve function that depends on total rainfall and the rainfall distribution (RDF) parameter. Lower values of RDF result in a more even distribution of rainfall, the effect being more pronounced for higher total rainfalls (Fig. 3). The interception function is based on the interception capacity parameter (PI), which, in addition to being seasonally variable, can be given values for two different vegetation types. The depth of rainfall intercepted in any month is based on an empirical relationship between the relevant PI parameter and rainfall depth, while interception storage satisfies the evaporation demand at the potential rate. To allow for attenuation of the seasonal hydrograph in the lower sub-basins of the system, where incremental flow contributions are negligible, riparian areas that were hypothesised to be fed by seepage from the river, and from which water was assumed to evaporate, were modelled as open water surfaces ("dummy" reservoirs).

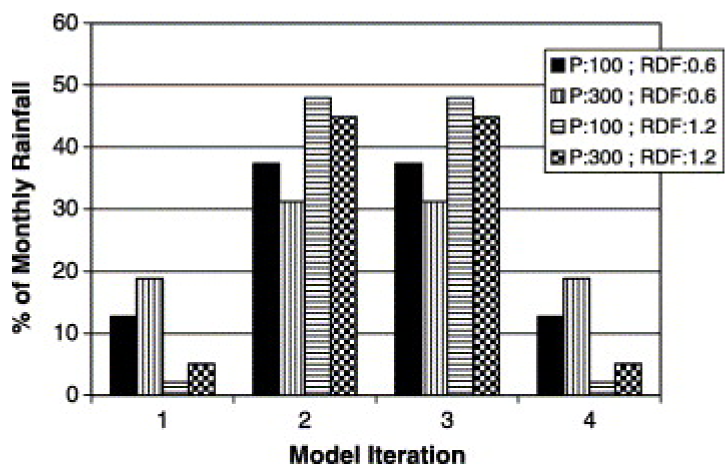

Figure 3. Illustration of the effects of different total monthly rainfall (P) and RDF parameter values on the distribution of rainfall over the 4 model iterations in a month.

The compulsory requirements for the reservoir water balance model are monthly distributions of normal drafts (fraction of annual abstraction requirement, ABS in Table 1) and compensation flow requirements (fractions of annual requirement, determined by the parameter COMP), as well as monthly distributions of drafts and compensation flow for up to five reserve supply levels (defined by parameters RES1–RES5).

Available data

Records of river discharge are lacking from Angola since the beginning of the civil war, but have been continuously available from the two downstream stations in Namibia and Botswana (Table 2). A database of monthly rainfall (no daily rainfall data were available for the Angolan part of the basin) for each sub-basin was used as input to the model for the 24 sub-basins. The availability of records from rain gauges was drastically reduced after the onset of the Angolan civil war (Wilk et al., this issue). Consequently, gauged rainfall data could only be used from 1960 to 1972. Sub-basin rainfall time series were derived from an inverse distance weighting procedure, described by Wilk et al. (this issue). Satellite based rainfall estimates for the basin were used for the period 1991–1997, using data from the Tropical Rainfall Measuring Mission (TRMM), Special Sensor Microwawe Imager (SSM/I) (Wilk et al., this issue).

Table 2 Gauged sub-basins in the parts of the Okavango Basin that contribute to inflow to the Delta (No. refers to Table 2 and Fig. 1)

No.	Basin name	Upstream catchment area (km^2)	Data record (used)				Mean annual runoff	
			Start date	End date	Length (months)	Missing data (months)	$m^3 \times 10^6$	mm
1	Chinhama	1822	10/1963	09/1974	132	2	608.0	334
2	Kubango[a]	7133	10/1963	09/1974	132	0	1530.3	214
3	Cutato	3621	10/1963	09/1974	132	6	739.6	204
4	Cuchi	10594	10/1963	09/1974	132	6	1345.3	127
5	Cuelei	5466	06/1966	09/1973	100	3	644.3	118
6	Caiundo	38420	10/1957	09/1974	204	52	4758.5	124
7	Menongue[a]	5623	03/1962	09/1974	151	0	640.8	114
8	Mucundi	50701	05/1962	09/1974	149	7	5197.7	103
9	Catambué[a]	71260	10/1965	09/1971	72	0	6343.5	89
10	Rundu	95642	10/1945	09/1999	648	0	5204.8	54
11	Cuito	15857	10/1965	09/1974	72	26	3435.6	217
12	Cuanavale	23347	10/1966	09/1967	12	0	3344.6	143
13	Luassinga	540	02/1965	09/1967	32	0	69.4	128
14	Cuiriri	742	10/1964	09/1967	36	0	125.2	169
15	Upper Cuiriri	1395	02/1965	09/1974	116	26	245.1	176
16	Mukwe	226236	10/1949	09/1998	588	0	9584.3	42
17	Mohembo	228778	01/1975	09/2000	312	58	8465.1	37

[a] These basin names have been changed from the original names in flow records to current Angolan names.

In order to extend the use of the model from the 1960–1972 period to the 1991–1997 period, it was necessary to ensure that the satellite rainfall data had the same basic characteristics as the gauged rainfall data. As discussed by Wilk et al. (this issue) the satellite derived rainfall data had a positive bias relative to gauge data and a correction equation was developed (Eq. (1)). Annual precipitation variations and amounts of this corrected satellite data were found to be similar to data from a Zambian gauge 5° east at a similar latitude in the Kafue basin and the data from 1960 to 1972.

$$\begin{aligned} &\text{For SATP} \leqslant 150\text{ mm} \quad \text{RSATP} = \text{SATP} \\ &\text{For SATP} > 150\text{ mm} \quad \text{RSATP} = 8.8 \times \text{SATP}^{0.56} \end{aligned} \qquad (1)$$

where SATP is the original satellite rainfall and RSATP is the revised estimate.

Data for monthly average potential evaporation were based on available measurements of pan evaporation from a few locations, and averages calculated for each sub-basin (Wilk et al., this issue). In addition, monthly deviations from average evaporation were calculated with the Hargreaves equation (Hargreaves and Allen, 2003 – Eq. (2)) to construct time series of monthly evaporation (Wilk et al., this issue).

$$Et=0.0023S_0(T+17.8)\sqrt{\delta T} \qquad (2)$$

where S_0 is the water equivalent of extraterrestrial radiation (mm d^{-1}) for the given location, T is temperature (°C), and δT difference between mean monthly maximum temperature and mean monthly minimum temperature. Monthly air temperatures were taken from databases provided by the Tyndal Centre (Mitchell et al., 2004).

Soil distributions and geology, topography and forest cover are shown in Fig. 4. Soils information was obtained from FAO, while the geological information and topography map are from the USGS (Persits et al., 2002). The GLC2000 land cover map, from which forest cover was derived, was made available by the Global Vegetation Modelling Unit (http://www.gvm.jrc.it/glc2000). It is based on a dataset of 14 months of pre-processed daily global data acquired by the VEGA2000 dataset from the vegetation sensor onboard the SPOT 4 satellite.

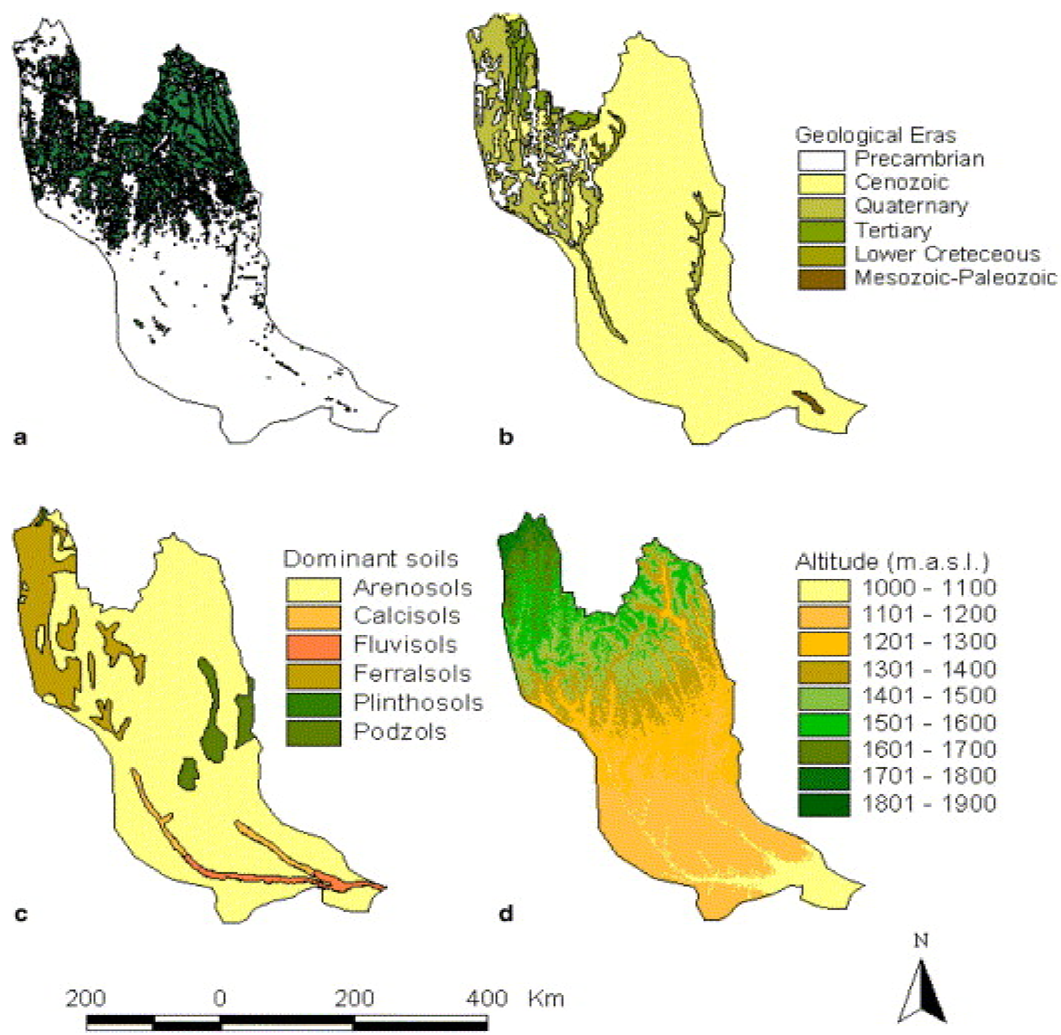

Figure 4. (a) Forest cover (VEG 1) (b) geology (c) soil and (d) altitude of the Okavango river basin.

Water abstractions were assumed to be relatively small for domestic use, plus limited use for irrigation. These were based on estimated populations in each sub-basin using population densities from aerial and ground surveys and national census counts (Andersson et al., this issue). The estimated population in the Angolan part of the basin in 1970 (337000) is very similar to today's estimate of 350000 (Mendelsohn and el Obeid, 2004) so these figures were used for the calibration period. Domestic water use in Namibia was assumed to be 25 l $head^{-1}$ d^{-1} in rural areas and 100 l $head^{-1}$ d^{-1} in Rundu. In Angola, domestic water use was estimated at 17 l $head^{-1}$ d^{-1} in rural areas and four times that amount in the cities of Menongue and Cuito-Cuanavale. The estimates were based on an average of the DFID and HR Wallingford, 2003 and Gleick, 1996 estimated values.

Water for irrigation was estimated on the assumption of 10000 and 500 farmers, informally irrigating 0.5 and 0.2 ha, in Angola and Namibia respectively. The irrigated amount was calculated as the difference between the monthly demand for each crop and the effective rainfall. Existing irrigation schemes in Namibia were also added to the abstraction amounts. This is further discussed by Andersson et al. (this issue).

Model setup and calibration

The Okavango basin above Mohembo was divided into 24 sub-basins (Fig. 1) of which 18 had gauging stations at their outlets (Table 2). Of these, 10 are located on the Cubango River (Chinhama to Rundu in Table 2). A further five are situated in relatively small headwater tributaries of the upper Cuito River (Cuito to Quiriri in Table 2) and have short records with a significant amount of missing data. There are two stations situated close to the inflow to the delta panhandle (Mukwe and Mohembo in Table 2). The former has the longest and most complete record. The Omatako River is the largest Namibian tributary (2 sub-basins not shown on Fig. 1), but there is no record of this ephemeral river system ever having contributed flow to the Okavango River (Crerar, 1997).

The complete period (1960–1972) for which historical rainfall data are available was used for calibration and was dominated by moderate to wet years, although 1972 was a dry year. The period 1991–1997 for which satellite derived rainfall data were used, and for which streamflow records are only available for the downstream stations of Rundu and Mohembo, represents a drier period (Fig. 7). This period was used to ensure that the calibrated parameter values were appropriate for use in future water resource estimations when the model is driven by satellite derived rainfall data, which will probably be the only available source of rainfall information in the foreseeable future.

The manual calibration guidelines provided by Pitman (1973) indicate which aspects of the simulation results are dominantly affected by changes to different parameter values. Several model parameters were determined a priori and remained fixed during the calibration period. Drainage density (D.Dens), ground water transmissivity (T) and ground water storativity (S) should not be calibrated, but estimated from available information about catchment characteristics. However, due to a lack of information on aquifer properties, some calibration was necessary.

Parameter calibration started in the headwater sub-basins and progressed downstream. Sub-basins with similar known (or assumed) characteristics were given similar parameter values and only modified where necessary to achieve satisfactory correspondence between observed and simulated sub-basin outflows. Calibrated parameters (Table 1) included surface runoff (ZMIN, ZAVE, ZMAX), the soil moisture storage and runoff function (ST, POW, FT), the ground water recharge (GPOW, GW), and the soil-moisture evaporation (*R*) parameters.

The correspondence between observed and simulated flow was evaluated using three main objective functions, each calculated on the basis of both un-transformed and natural log-transformed data:

• Coefficient of determination (R^2).

• Coefficient of efficiency (CE) (Nash and Sutcliffe, 1970).

• Mean monthly percentage error of the simulated flows (relative to observed).

The objective of the manual calibration was to limit both untransformed and log-transformed mean monthly percentage errors to within ±5% and to maximise the R^2 and CE values, while visually ensuring a satisfactory correspondence between observed and simulated flow patterns. This approach ensures that the calibration process does not favour any component (e.g., high or low flow) of the hydrograph.

The following set of principles was considered, in order to establish a regional calibration procedure for large, data-poor, river basins.

(A) Artificial influences should be catered for using the relevant parameters for these components, or input time series of transfer inflow. Water abstractions in all the sub-basins were less than 1.5% of annual volumes and in most close to zero .

(B) Establish an understanding of the physical meaning of the parameters to be used as a basis for the regionalisation of their values, based on known physiographic characteristics. Sub-basin distributions of surface runoff parameters (ZMAX, ZMIN, ZAVE), soil moisture storage (ST) the runoff function parameter (POW), the runoff rate (FT), and the recharge parameters (GPOW, GW) were determined in a way that reflected available information about soil distributions (Fig. 4c) and topography (Fig. 4d). Ground water parameters were set to reflect differences in geology (Fig. 4b). The initial value of ST was achieved by focusing on high rainfall months, but recognising that dubious data quality at high flows can affect calibrations. Due to the non-linear runoff equation, ST also has an impact on runoff during low rainfall months. Therefore, after initial calibration, ST, POW and FT were adjusted to achieve reasonable simulations across the entire time series. GPOW and GW were the focus of the calibration exercise for dry season flows and recession. For the lower sub-basins, the volumes and surface areas of the “dummy” reservoirs (representing channel transmission losses) were quantified on the basis of channel lengths and widths of floodplains and swamps, with some consideration given to remote sensing based assessments (Wilk et al., this issue).

(C) Analyse daily distributions of typical monthly rainfall inputs. A comparison revealed that monthly totals and seasonal distributions of rainfall were similar for the upper, streamflow generating, parts of the Okavango basin and the Kafue basin in Zambia. Given the assumption that daily rainfall distributions were similar, experience from the Kafue basin (Hughes et al., 2003) were used to pre-set the rainfall distribution function parameter (RDF) to a value of 0.7.

(D) Identify the distribution of the two dominant vegetation types and evaluate suitable parameter values. Proportions of the sub-basins covered by non-forested and forested vegetation types were calculated from the land-use map (Fig. 4a). For interception storage, standard parameter values (Hughes, 1997) of 1.5 mm in June and 1 mm in January were applied for non-forested areas, while values of 4 and 3 mm were used for forested areas. The forest/non-forest potential evapotranspiration ratio (FF) was set to 1.3.

(E) Use time series of potential evaporation, instead of monthly distributions, to represent temporal variations in the water balance. An evaluation was made of the use of time series of potential evaporation, compared with using standard monthly values. Due to the limited availability of the temperature data needed to compile evaporation time series, the same corrections to mean monthly values were applied for the entire basin (Wilk et al., this issue).

(F) Recognise the limitations of the available rainfall and flow data and try to avoid calibrating erroneous rainfall-runoff signals. The possibility of gauging problems at high flows was considered and extreme maximum monthly runoff values were only given moderate consideration in the calibration.

Results

Test of alternative evaporation and interception routines

Model outputs based on the use of fixed monthly distributions of potential evaporative demand were compared to those based on the use of time series calculated as described above. As simulations were moderately improved for some sub-basins, but made very little difference in other cases, it was decided to include the time series of potential evaporation in the selected final model setup.

The estimates of interception loss generated by the Pitman model were compared with estimates based on a Markov model of the probability of a rain day, as well as a daily interception model (De Groen, 2002). The parameters of the Markov model were taken from studies undertaken in Zimbabwe under similar climate conditions. The two estimates compared quite favourably, suggesting that no improvements could be made by modifying the Pitman model approach.

Regional calibration

The observed flow records reveal that most streamflow generation takes place in headwater tributaries where rainfall is more abundant (Wilk et al., this issue) and that there are considerable differences in runoff response from the western tributaries (the Cubango River) compared to the eastern (the Cuito River), despite similar rainfall characteristics (Wilk et al., this issue). The regional calibration approach accounted for these differences in physiographic and climatological characteristics.

Western headwaters

Sub-basins in the western upper part of the basin are underlain by rocks of volcanic and metamorphic origin, as well as some Karoo Group sandstone and mudstone, all with a thin mantle of Kalahari sand (see Fig. 4 and Mendelsohn and el Obeid, 2004). The western tributaries show substantial seasonal flow variation (Fig. 5) and required a parameterisation with higher drainage densities, and lower transmissivities and storativities, compared to the eastern area, for successful calibration. The Menongue sub-basin (No. 7 in Fig. 1 and Table 2) appeared to represent a transitional zone between the harder rock in the western parts (Precambrian) and the Kalahari sands of the eastern region (see Fig. 4). Parameters obtained after calibration are shown in Table 3. The maximum absorption rate (ZMAX) was highest for the eastern parts of the region, corresponding to higher absorption rates in areas with lower slopes and more permeable soils, i.e. with higher proportions of Kalahari sand. ZMIN shows a similar, but inverse pattern, where decreasing values in an easterly direction may reflect the influence of surface sealing in sub-basins with sandier soils. The soil moisture storage capacity (ST) parameter also increased in an easterly direction, reflecting the greater storage capacities in the Kalahari sand dominated areas. The power of the moisture storage-runoff equation (POW) was lowest in the west, possibly reflecting heterogeneous wetness conditions due to spatially variable soil distributions and significant topographic differences within a sub-basin.

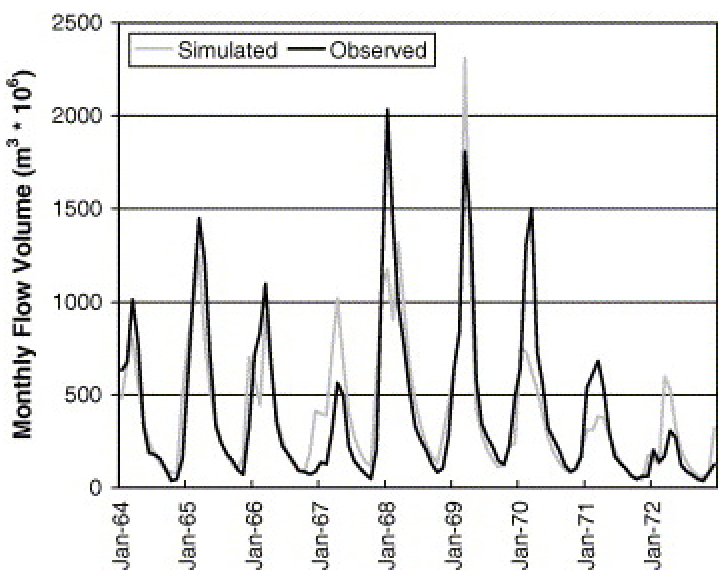

Figure 5. Observed and simulated monthly flows at the gauge at the outlet of the Caiundo sub-basin in the headwaters of the Cubango River (No. 6 in **Fig. 1** and **Table 2**).

Table 3 Catchment characteristics and calibrated Pitman model parameter values for the western upper sub-basins

Characteristics and parameter values	Sub-basin							
	Chinhama	Kubango	Cutato	Cuchi	Cuelei	Menongue	Caiundo	Mucundi
Area hard rock (%)	14	33	9	22	28	10	23	5.5
Mean slope (degrees)	1.3	1.3	1.4	1.4	1.4	1.4	1.3	1.4
Forested area (%) AFOR	18.3	40.0	44.0	60.0	66.1	68.4	34.6	36.7
Annual Pan Evap. (mm) PEVAP	1897	1980	1980	1980	2021	2021	2501	2900
Summer minimum absorption rate (mm month^{-1}) ZMINs	80	100	100	100	50	10	50	80
Winter minimum absorption rate (mm month^{-1}) ZMINw	80	100	100	100	50	10	50	80
Mean absorption rate (mm month^{-1}) ZAVE	400	500	500	400	400	700	600	600
Maximum absorption rate (mm month^{-1}) ZMAX	600	700	700	700	700	1000	1000	1000
Maximum storage capacity ST	400	500	500	620	550	900	1000	1000
Power: storage-runoff curve POW	2.5	2.7	2.6	2.7	3.0	3.0	3.4	3.4
Runoff rate at ST (mm month^{-1}) FT	38	18	35	25	22	15	5	2
Power: storage-recharge curve GPOW	2.0	2.5	2.2	2.5	2.4	2.1	2.5	2.5
Maximum GW recharge (mm month^{-1}) GW	20	16	16	16	18	20	6	4
Evaporation-storage coefficient *R*	0.2	0.2	0.2	0.1	0.0	0.3	0.1	0.0
Surface runoff time lag (months) TL	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Channel routing coefficient (months) CL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.02
Drainage density	0.8	0.7	0.7	0.7	0.6	0.3	0.7	0.7
Transmissivity	10	10	10	15	20	20	15	12
Storativity	0.005	0.007	0.006	0.008	0.008	0.010	0.010	0.010
Initial groundwater slope	0.030	0.030	0.030	0.030	0.030	0.012	0.005	0.005

Parameters not referred to were equal for all sub basins; RDF = 0.7, AI = 0, PI1s = 1.5, PI1w = 1.0, PI2s = 4.0, PI2w = 3, FF = 1.3, SL = 0. See Table 2 and Fig. 1 for location of sub-basins and Table 2 for descriptions of parameters.

The correspondence between monitored and modelled river flow was generally acceptable and results were relatively consistent across all sub-basins. It is possible that channel losses start to play a role in Mucundi, which is the lowest sub-basin of the western headwater sub-basins. For the gauging station at the outlet of Mucundi (No. 8 in Fig. 1 and Table 2), a coefficient of efficiency of 0.745 and a mean monthly error of +0.8% was achieved (Table 4).

Table 4.
Correspondence between modelled and simulated flow based on untransformed (normal) and natural log (ln) transformed flow

Sub-basin	**Location**	**Months included in calibration**	**Normal**		**Ln values**		**Mean monthly error (%)**	
			R^2	**CE**	R^2	**CE**	**Normal**	**Ln**
Chinhama	Western headwaters	109	0.843	0.841	0.880	0.879	−4.4	0.4
Kubango	Western headwaters	111	0.780	0.779	0.828	0.788	−2.2	3.5

Sub-basin	Location	Months included in calibration	Normal		Ln values		Mean monthly error (%)	
			R^2	CE	R^2	CE	Normal	Ln
Cutato	Western headwaters	105	0.814	0.813	0.775	0.752	−0.6	3.3
Cuchi	Western headwaters	105	0.612	0.610	0.697	0.649	−0.7	4.6
Cuelei	Western headwaters	76	0.494	0.494	0.715	0.676	1.5	2.3
Caiundo	Western headwaters	120	0.755	0.751	0.803	0.767	−0.1	2.9
Menongue	Western headwaters	130	0.633	0.608	0.709	0.691	−2.2	−0.4
Mucundi	Western headwaters	121	0.749	0.745	0.809	0.790	0.8	1.9
Catambué	Lower basins	72	0.737	0.736	0.795	0.781	0.2	1.6
Rundu	Lower basin	156	0.775	0.770	0.839	0.823	0.4	1.8
Cuito	Eastern headwaters	67	0.745	0.726	0.758	0.757	−1.1	0.1
Cuanavale	Eastern headwaters	12	0.714	0.693	0.689	0.676	−0.4	0.1
Luassinga	Eastern headwaters	32	0.295	−1.155	0.294	−1.334	−2.4	−1.8
Cuiriri River	Eastern headwaters	36	0.544	0.518	0.579	0.563	−3.4	−1.1
Upper Cuiriri	Eastern headwaters	69	0.557	0.526	0.554	0.495	2.1	0.8
Mukwe	Lower basin	156	0.852	0.851	0.905	0.901	1.7	0.5
Mohembo	Lower basin	0	–	–	–	–	–	–

R^2 = Coefficient of determination, CE = Coefficient of efficiency (**Nash and Sutcliffe, 1970**).

Eastern headwaters

Thick deposits of Kalahari sands (Fig. 4c) underlie the eastern upper sub-basins (Nos. 11–15 in Fig. 1 and Table 2), which are characterised by high baseflow and relatively small seasonal variability, indicating considerable groundwater recharge and discharge.

From most gauging stations in the eastern headwaters, records were too short for adequate calibrations (Table 2). Satisfactory calibration against monitored flow records was only obtained for the station at the outlet of the Cuito sub-basin (No. 11 in Fig. 1 and Table 2), where a coefficient of efficiency of 0.726 and a mean monthly error of −1.1% was achieved (Table 4). Calibrated parameter values for the Cuito sub-basin (Table 5) were similar to those for Menongue in the eastern part of the Cubango headwaters (Table 3).

Table 5.

Catchment characteristics and calibrated Pitman model parameter values for the eastern upper sub-basins

Array parameter	**Sub-basin**				
	Luassinga	**Longa**	**Upper Cuiriri**	**Cuito and North East**	**Cuanavale**
Area with hard rocks (%)	0	0	0	0	0
Mean slope	1.2	1.3	1.5	1.4/1.2	1.4
Forested area (%) AFOR	69.9	77.5	70.0	75.2	71.8
Annual Pan evaporation (mm) PEVAP	2046	2046	2046	2137	2137
Summer minimum absorption rate (mm month^{-1}) ZMINs	100	30	50	30	20
Winter minimum absorption rate (mm month^{-1}) ZMINw	100	30	50	30	20
Mean absorption rate (mm month^{-1}) ZAVE	800	500	600	600	600
Maximum absorption rate (mm month^{-1}) ZMAX	1200	1000	1000	1200	1200
Maximum storage capacity ST	900	900	900	1000	1000
Power: storage-runoff curve POW	3.4	4.0	4.0	3.2	3.1
Runoff rate at ST (mm month^{-1}) FT	12	12	20	12	10
Power: storage-recharge curve GPOW	1.6	1.6	1.6	1.6	1.6
Max. GW recharge (mm month^{-1}) GW	25	30	30	35	16
Evaporation-storage coefficient *R*	0.5	0.6	0.6	0.6	0.6
Surface runoff time lag (months) TL	0.25	0.25	0.25	0.25	0.25
Channel routing coefficient (months) CL	0.0	0.0	0.0	0.0	0.0
Drainage density	0.3	0.4	0.3	0.4	0.4
Transmissivity	20	20	20	20	20
Storativity	0.01	0.01	0.01	0.01	0.01
Initial groundwater slope	0.025	0.025	0.025	0.025	0.025

See **Table 3** for the values of parameters not referred to.

The eastern sub-basins are characterised by lower drainage densities, and higher storativities, compared to the west. The optimised parameters reflect the slow hydrological response, with sustained ground water discharge (Fig. 6). Compared to the western-sub-basins, the maximum absorption rate (ZMAX), the soil moisture storage (ST), and the power of the moisture storage-runoff equation (POW) were set to higher values, whereas the maximum runoff from moisture storage (FT) was set to a lower value.

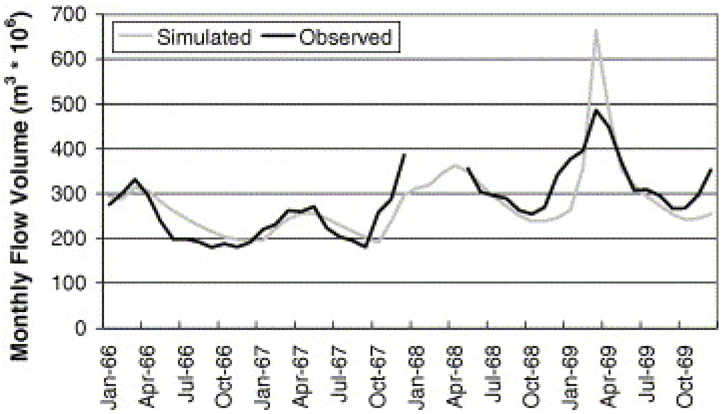

Figure 6. Observed and simulated monthly flows at the outlet of the Cuito sub-basin in the headwaters of the Cuito River (No. 11 in **Fig. 1** and **Table 2**).

Lower basin

The majority of the downstream sub-basins are also underlain by thick deposits of Kalahari sand (Fig. 4a) and contribute little flow, even during wet years. Downstream decreases in flow, except during wet season events, indicate that channel transmission loss is an important process. Simulation of the integrated flow from the whole basin to the downstream station Mukwe (16 in Fig. 1 and Table 2) is shown in Fig. 7. The calibrated parameters (Table 6) reflect this limited contribution and that attenuation of the flow (through the channel routing parameter CL) is an important process. The volumes and surface areas of the "dummy" reservoirs, which were used to simulate channel and riparian losses, were quantified on the basis of channel lengths and assumed widths of moist riparian zones. "Dummy" reservoir volumes of 90 and 26 $m^3 \times 10^6$ were used for Rundu (sub-basin above 10 in Fig. 1) and Mukwe (sub-basin above 16 in Fig. 1), respectively.

Calibrated model parameters reflect the fact that the Omatako River did not contribute to flow in the Okavango during the calibration period. When the model generates a limited amount of streamflow in the Omatako sub-basin during the wet season, the "dummy" reservoir representing channel losses reduced this to zero flow at the outlet. For the outlet of the Mukwe sub-basin, a coefficient of efficiency of 0.851 and a mean monthly error of +1.7% was achieved (Table 4 and Fig. 7).

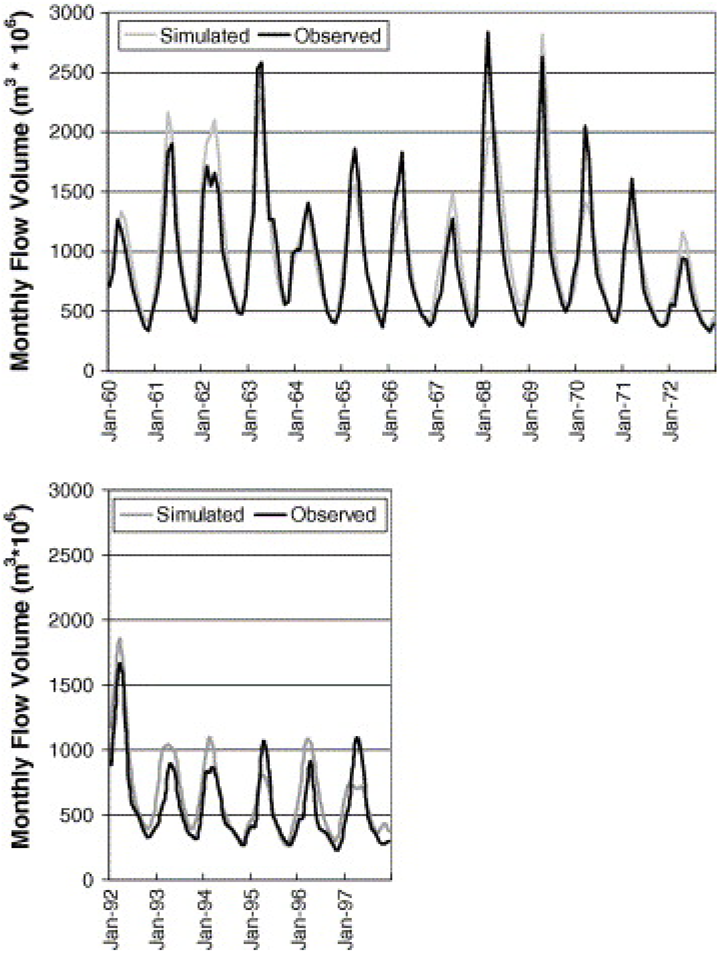

Figure 7. Observed and simulated monthly flow at the outlet of the Mukwe sub-basin in the lower part of the Okavango River, close to the panhandle of the Okavango delta (No. 16 in **Fig. 1** and **Table 2**).

Table 6 Catchment characteristics and calibrated Pitman model parameter values for the lower sub-basins

Array parameter	Sub-basin					
	Catambué	Rundu, Sambio	Dirico, Cuiriri River, P Passagem	Omatako	Mukwe	Mohembo
Area with hard rocks (%)	0	0	0	0	0	0
Mean slope	0.8	0.3/0.3	0.3/1.1/0.7	0.4	0.3	0.3
Forested area (%) AFOR	11.0	0.0	2.5	0.0	0.1	1.1
Annual pan evaporation (mm) PEVAP	2137	2500	2137	2137	2137	2137
Summer minimum absorption rate (mm month^{-1}) ZMINs	80	100	100	150	150	150
Winter minimum absorption rate (mm month^{-1}) ZMINw	80	100	100	150	150	150
Mean absorption rate (mm month^{-1}) ZAVE	600	600	600	1000	800	800
Maximum absorption rate (mm month^{-1}) ZMAX	1000	1000	1000	1400	1000	1000
Maximum storage capacity ST	1000	1000	1000	1100	1000	1000
Power: storage-runoff curve POW	3.4	3.4	3.4	3.4	3.4	3.4
Runoff rate at ST (mm month^{-1}) FT	1	1	1	0	1	1
Power: storage-recharge curve GPOW	2.5	2.5	2.5	2.5	2.5	2.5
Max. GW recharge (mm month^{-1}) GW	4	2	4	4	4	5
Evaporation-storage coefficient *R*	0.0	0.0	0.0	0.0	0.0	0.0
Surface runoff time lag (months) TL	0.25	0.25	0.25	0.25	0.25	0.25
Channel routing coefficient (months) CL	0.08	0.15	0.15	0.15	0.00	0.00
Drainage density	0.7	0.6	0.4	0.2	0.3	0.3
Transmissivity	15	15	15	20	15	15
Storativity	0.01	0.01	0.01	0.01	0.01	0.01
Initial groundwater slope	0.003	0.001	0.001	0.001	0.001	0.001

See Table 3 for the values of parameters not referred to.

Validation of the model calibration, using remote sensing rainfall data

In the absence of gauged rainfall data, the validation was based on the revised satellite rainfall data, discussed above. Comparisons of monitored and measured river discharge were only possible for the two downstream stations for which gauged flow data were available for both the 1960–1972 and 1991–1997 periods. The comparison (Figure 7 and Figure 8) showed that the results for the validation period were marginally poorer compared to the calibration period, for both Rundu and Mukwe, but still within acceptable ranges.

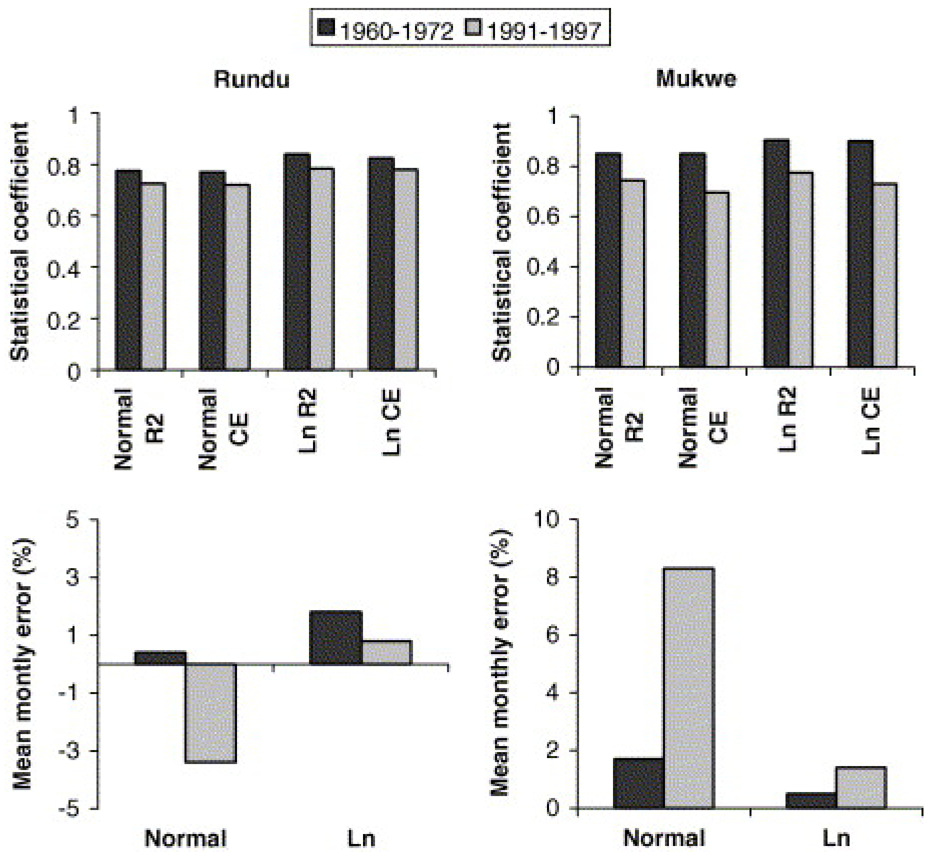

Figure 8. Comparison of correspondence statistics at the outlet of the Mukwe sub-basin between 1960–1972 (use of gauged rainfall), and 1991–1997 (use of adjusted remote sensing rainfall).

Discussion

Some years were consistently under-simulated for most of the gauged sub-basins (e.g. 1968 and 1970), while others tend to be consistently over-simulated (e.g. 1967). The spatial consistency suggests that this cannot be ascribed to streamflow gauging errors, nor to individual raingauge errors. Alternative reasons include over- or under-estimates of sub-basin areal rainfall, due to the sparse network of rainfall stations, or an inability of the model to satisfactorily represent the runoff response to rainfall in certain years. It is highly possible that the problem is associated with an inadequate representation of the sub-basin rainfall inputs, due to poor estimation of rainfall depths, or variations in rainfall intensity characteristics that cannot be represented in a monthly model. The lack of daily data from the Angolan part of the basin (i.e. from 95%

of the runoff generating area) precludes further assessment of the value of the rainfall distribution parameter (RDF) used in the simulations.

The introduction of the new ground water recharge routine improved the results for the Cuito basin (No. 11 in Fig. 1 and Table 2). From the perspective of the physical relevance of the parameters and the way in which the model represents real processes, the new approach is also considered an improvement. However, confirmation against more detailed hydroclimatological and physiographic data from the basin is still required.

While it is uncommon to have a channel flow routing component in a model with a long simulation time step, there seems to be little doubt that the monthly flow volumes are undergoing attenuation in the lower sub-basins. This small change, involving one additional parameter, therefore improved the simulation results quite substantially.

There are still uncertainties with regard to the extent of channel losses in the downstream sub-basins. The “dummy” reservoirs introduced to represent channel losses are able to produce the right effects, although establishing suitable parameter values has been based on inadequate information. A first approach to determine landscape characteristics in buffer zones along the Okavango River is presented by Wilk et al. (this issue). Combining the modelling approach and the remote sensing derived landscape information of the buffer zones is recommended for further work on the quantification of channel losses.

It was shown that the Pitman model estimates of interception loss were similar to those obtained with alternative models that more adequately consider daily rainfall distributions, and further development of the transpiration routines are not expected to offer improvements in the model results. The use of evaporation time-series, although based on rough climatic estimates, slightly improved the model estimates for some sub-basins, and therefore the use of remote sensing derived data for better spatial and temporal estimates of evaporation could be beneficial.

It should be noted that the calibrated parameter values of a hydrological model are not independent of the meteorological inputs. This is especially relevant in areas such as the Okavango basin, where the limited availability of gauged meteorological data constrains the determination of sub-basin spatial rainfall time series with a satisfactory degree of confidence. In addition, changes in water abstractions and land use between the calibration and validation period might have had an impact on the historical river flows, although this impact is expected to be quite small (Andersson et al., this issue).

While the differences between the model results for the calibration and validation period are not substantial, it remains difficult to interpret the validation results due to the uncertainties in the validity of the approach used to adjust the satellite rainfall data. That they require adjustment can hardly be in doubt, but the method of adjustment used was a pragmatic solution to a problem that is caused by the lack of recent ground-based rainfall measurements, and requires further investigation (Wilk et al., this issue).

Conclusions

With regard to the limited physiographic and climatological information about the Okavango River basin, and the limited access to gauged streamflow, the modelling results were satisfactory for the 1960–1972 calibration period. In general terms, the calibrated parameter values demonstrated regional consistency with the prevailing physiographic characteristics of the various sub-basins, in the context of the conceptual framework of the model. It seems unlikely that any other rainfall-runoff model would be able to generate results that are substantially better than those obtained by the Pitman model, given the limitations of the input data.

Given the uncertainties about the satellite rainfall for the 1990s, with the limited possibility of correlating these data against gauged rainfall, some uncertainty remains regarding the model's ability to be used outside the calibration period. However, given that the satellite data were adjusted to match the frequency characteristics of the historical rainfall data and not further adjusted during the validation model runs, the results for the 1990s period can also be considered satisfactory.

Thus, the calibrated model more than adequately represents the hydrological response of the basin as represented by the historical hydrometeorological data. Consequently, it can be used to assess the impact of future development scenarios (Andersson et al., this issue), given that likely water abstraction, land use change and reservoir construction scenarios can be adequately represented by the model. The fact that the model has performed satisfactorily across a range of historical climatic conditions (wet and dry periods), suggests that the calibrated model can also be used to assess flow regimes under various possible future climate scenarios. The problems experienced with the 1990s satellite rainfall data, and its apparent inconsistency with historical rainfall data, suggest that additional care would have to be taken in the preparation of future climate data. It has already been emphasised that the results of any rainfall-runoff model are very dependent upon the hydrometeorological inputs. To enable comparisons to be made between the historical flows and future possible flows, it is essential that the hydrometeorological input data for future climate scenarios are adequately referenced to the historical data used for model calibration purposes.

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