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Regionalising a meso-catchment scale conceptual model for river basin management in the semi-arid environment

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ABSTRACT

Meso-scale catchments are often of great interest for water resources development and for development interventions aimed at uplifting rural livelihoods. However, in Sub-Saharan Africa IWRM planning in such catchments, and the basins they form part of, are often ungauged or constrained by poor data availability. Regionalisation of a hydrological model presents opportunities for prediction in ungauged basins and catchments. This study regionalises HBVx, derived from the conceptual hydrological model HBV, in the semi-arid Mzingwane Catchment, Limpopo Basin, Zimbabwe. Fifteen meso-catchments were studied, including three that were instrumented during the study. Discriminant analysis showed that the characteristics of catchments in the arid agro-ecological Region V were significantly different from those in semi-arid Region IV. Analysis of flow duration curves statistically separated sub-perennial catchments from (sub-)ephemeral catchments. Regionalised parameter sets for HBVx were derived from means of parameters from the sub-perennial catchments, the (sub-)ephemeral catchments and all catchments. The parameter sets that performed best in the regionalisation are characterised by slow infiltration with moderate/fast "overland flow". These processes appear more extreme in more degraded catchments. This is points to benefits to be derived from conservation techniques that increase infiltration rate and from runoff farming. Faster, and possibly greater, sub-surface contribution to streamflow is expected from catchments underlain by granitic rocks. Calibration and regionalisation were more successful at the dekad (10 days) time step than when using daily or monthly data, and for the sub-perennial catchments than the (sub-)ephemeral catchments. However, none of the regionalised parameter sets yielded $C_{NS} \geqslant 0.3$ for half of the catchments. The HBVx model thus does offer some assistance to river basin planning in semi-arid basins, particularly for predicting flows in ungauged catchments at longer time steps, such as for water allocation purposes. However, the model is unreliable for more ephemeral and drier catchments. Without more reliable and longer rainfall and runoff data, regionalisation in semi-arid ephemeral catchments will remain highly challenging.

1. Introduction

Small to meso-scale catchments are often of great interest for water resources development (e.g. Mazvimavi, 2003; Niadas, 2005; Nyabeze, 2005), for environmental planning (Walker et al., 2006) and for development interventions aimed at uplifting rural livelihoods (Ncube et al., 2010). In semi-arid areas of Sub-Saharan Africa, rising water demand and the challenge of frequent droughts creates a desire for water resources development and a requirement for integrated water resources management planning in order to balance food security, other economic needs and the needs of the environment in the allocation and development of surface water flows (Peugeot et al., 2003; Love et al., 2006). These challenges will grow worse with rising populations in most river basins, and the anticipated impacts of global warming leading to increased water scarcity (Fung et al., 2011) and making the need for IWRM planning more pressing.

However, many river basins suffer from limited data availability and more limited process knowledge (Bormann and Diekkrüger, 2003; Ndomba et al., 2008). In developing countries, many basins are ungauged (Mazvimavi et al., 2005). This lack of data constrains planning and can be a stumbling block to conflict resolution among users competing for scarce water resources (Nyabeze, 2000). Prediction of discharge and other hydrological characteristics of ungauged basins is therefore an important priority for water resources management – as well as for hydrological science – and

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was adopted by the International Association of Hydrological Sciences in 2002 as the Prediction of Ungauged Basins (PUB) research agenda (Sivapalan et al., 2003).

One approach to address these challenges is regionalisation, which provides methods to upscale small-scale (or meso-scale: scale of approximately 10^1–10^3 km^2; Blöschl and Sivapalan, 1995) measurements to a large scale (or basin or regional scale: scale of >10^4 km^2) model, or to outscale measurements from gauged catchments to ungauged catchments. For the purposes of hydrological modelling, key parameters to regionalise are those that represent processes, such as flow response decay time, and contribution of faster and slower flow to total discharge (Littlewood et al., 2002; Troch et al., 2007). These parameters are essential for process-oriented simulation, which is important in order to better understand the possible effects of different environmental influences (Ott and Uhlenbrook, 2004; Johst et al., 2008). Additionally, there is tension between adequate model parameterisation, in order to address heterogeneities within and between catchments, and rising model complexity and uncertainty (Beven, 1993; Lin and Radcliffe, 2006; Marcé et al., 2008) – and the challenges that limited data availability pose to the latter issues (Bormann and Diekkrüger, 2003).

Model parameter sets are calibrated through a series of models runs on catchments which have a long time series of data (Heuvelmans et al., 2004). Calibration can be against a single critical parameter (e.g. Nyabeze, 2005) or multi-criteria calibration of a parameter set (e.g. Seibert, 2000; Uhlenbrook and Leibundgut, 2002). Alternatively, a multivariate statistical approach can be used to determine the relationships between biophysical catchment descriptors and hydrological catchment parameters (e.g. Chiang et al., 2002; Mwakalila et al., 2002). No single regionalisation procedure has been developed that yields universally acceptable results (Ramachandra Rao and Srinivas, 2003) and all regionalisation methods require reliable and long-term data series. This can be problematic in semi-arid regions of Africa (Nyabeze, 2002; Mazvimavi, 2003), such as the Mzingwane Catchment, the portion of the northern Limpopo Basin that lies within Zimbabwe, in which 11 of the 30 secondary catchments are completely ungauged, there is high inter-annual and intra-annual variability in runoff and many ephemeral tributary catchments (Nyabeze, 2002, 2005; Love et al., 2010a).

For river basins with many ungauged catchments, or with limited data availability, regionalisation represents one of the possible approaches to addressing the lack of data required for planning purposes. An alternative approach is to estimate model parameters from catchment characteristics (Koren et al., 2004; Kapangaziwiri and Hughes, 2008), although this also requires sufficient available data.

The Mzingwane Catchment Council, the stakeholder-based statutory authority for water resources planning in the catchment, needs to balance different sectoral water requirements and issue new water permits as demand changes and new areas are developed. For these purposes, an understanding of annual runoff is needed (Mzingwane Catchment Council and Zimbabwe National Water Authority, 2009). Given the data constraints of the Mzingwane Catchment, it is helpful to be able to regionalise model parameters from better-understood catchments to poorly gauged and ungauged tributaries.

This study explores the challenges of regionalisation of widely-used box models in semi-arid catchments. The main objective is to regionalise one or more model parameter sets for the Mzingwane Catchment using HBVx, a model developed from HBV (Bergström, 1992; Seibert, 2002) in a gauged field study catchment (Love et al., 2010b). The regionalisation exercise will use field study data and historic data from those gauged tributary catchments within the national hydrological data network for which there is reasonable data availability. The second objective is to determine whether or not distinct groups of tributary catchments can be identified and separate parameter sets regionalised for each group. The third objective is to improve the understanding of catchment behaviour and relate it to catchment characteristics.

2. Methods

2.1. Study area

The northern Limpopo Basin in Zimbabwe is a semi-arid area, with rainfall varying from 360 mm a^{-1} in the south to 630 mm a^{-1} in the north (Love et al., 2010a). Rainfall is seasonal, controlled by the Inter Tropical Convergence Zone and falling between October/November and March/April (Makarau and Jury, 1997). Rainfall occurs over a limited period of time, and often a large portion of the annual rainfall can fall in a small number of events (Twomlow and Bruneau, 2000).

Geologically, most of the catchment is underlain by the Zimbabwe Craton: mafic greenstone, Shamvaian clastics and Archaean granitoid terrain. The south is underlain by Limpopo Belt Archaean gneisses, and the south-west and far south-east by Karoo basalts, intrusives and sediments. Alluvial deposits are present in the lower reaches of most of the larger rivers (Bubye, Mwenezi, Mzingwane, Shashe, Thuli and their larger tributaries (Chinoda et al., 2009). The soils are mainly solonetz, cambisols, leptosols, luvisols, arenosols and lixisols (Bangira and Manyevere, 2009). The Mzingwane Catchment is covered mainly by a mixture of croplands, pastureland and woodland.

Seventeen meso-catchments within the northern Limpopo Basin were selected on the basis of the following criteria: (i) Availability of discharge data. (ii) Development: the selected catchments were upstream of all major dams. (iii) Proximity to rainfall station(s): less than 50 km distance. (iv) Catchment scale: area $\leqslant$1500 km^2. (v) Catchment shape: the long axes of the selected catchments were less than 50 km in length, measured from catchment outlet to the most distant point on the watershed (Engeland et al., 2006), in order to exclude long, narrow catchments liable to be highly diverse. The selected catchments are shown in Fig. 1 and their data sources in Tables 1 and 2. Characteristics of the catchments are set out in Table 3. Fifteen catchments were used for calibration and regionalisation of model parameters and the other two for blind regionalisation: evaluating the performance of the regionalised parameter sets against catchments whose data had not been previously used in calibration.

2.2. Data quality control

The quality of input data is of high importance since this influences both model performance and the parameter sets to be regionalised. There is a minimum quantity of input data required for model parameterisation and where input data is limited by missing values, problems can be created as it has been shown that where measurements are only available for some days, results may differ significantly depending upon which days measurements are available for (Seibert and Beven, 2009). The study areas have high spatial and temporal variability in rainfall, and runoff (Love et al., 2010a,b) which is likely to exacerbate this problem.

The time series were visually inspected, along with supporting materials such as the station files. The following exclusions were made for each station, in order to remove unreliable data: (i) Where rainfall or discharge data was missing for 2 months or more, the year was excluded. (ii) Where rainfall or discharge data was missing for 2 weeks or more during the months of November to April (rainy season), the year was excluded. (iii) Where a note

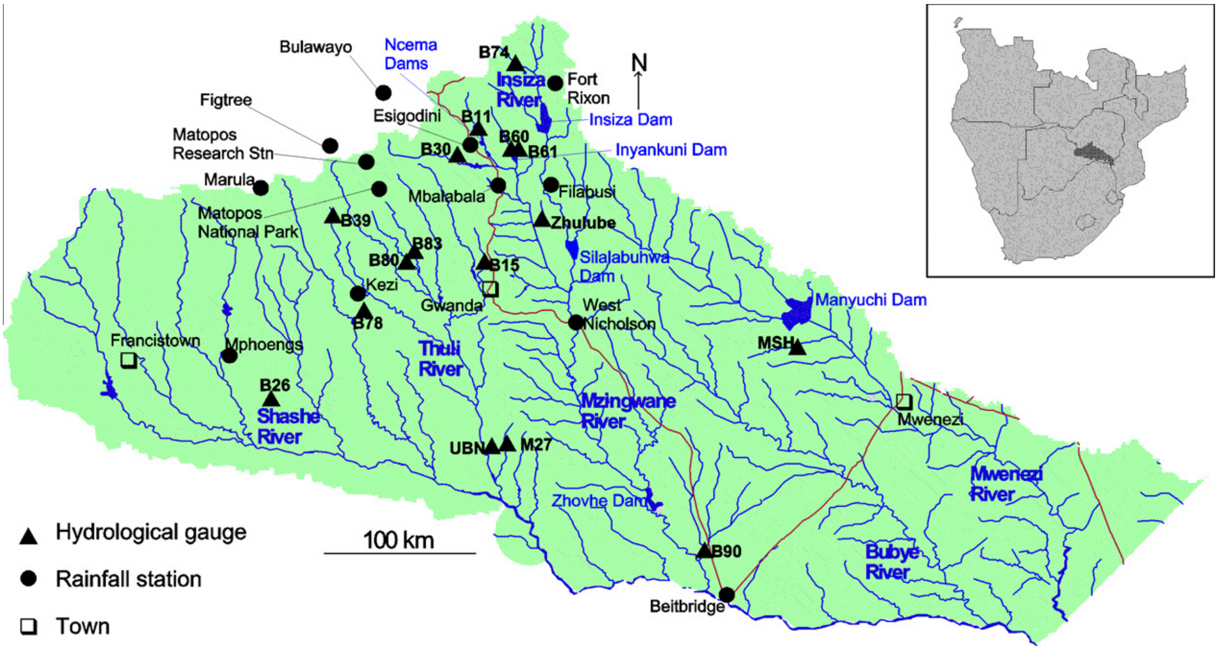

Fig. 1. Location of selected catchments and of the Zhulube Catchment, for which the HBVx model was developed from HBV (Love et al., 2010b). Inset: Location in southern Africa.

has been made in the station file that readings were unreliable (e.g. due to siltation, security), the year was excluded. (iv) For dekad time series (10 days), dekads containing one or more days with missing rainfall or discharge data were excluded. (v) For monthly time series, months containing six or more days with missing rainfall or discharge data were excluded.

2.3. Catchment classification

The catchments were classified into groups, for separate calibration of the HBVx model parameters.

The first classification method was based upon a provisional classification, made using the standard Zimbabwean agro-ecological zones (Vincent and Thomas, 1960). The agro-ecological zonation takes into account climatic factors and soil types. This provisional classification was then refined by discriminant analysis. This is a multivariate analysis procedure for testing the statistical significance of a pre-existing (user-determined, not statistically-derived) classification. The canonical discriminant functions that separate classes from each other are derived, using a linear combination of the variables and the Mahalanobis distance (Chiang et al., 2002; Gordon et al., 2004). The technique which has proven effective in the classification of river basins, using catchment characteristics as the variables and proposed groups of catchments as the classes (Wiltshire, 1986; Chiang et al., 2002). For this study, eight catchment characteristics were selected to describe the main properties of the catchments, see Table 3 excluding the designation of agro-ecological region, which is the subject of the classification.

The second classification method used was comparison on monthly flow duration curves of the catchments using the Kolmogorov–Smirnov test. This is a non-parametric test used to fit the cumulative distribution function of a sample to a distribution function (Loucks and van Beek, 2005). A two sample Kolmogorov–Smirnov test determines whether or not two sample groups come from statistically different populations (Panik, 2005). It has been used extensively in hydrology (Tate and Freeman, 2000; Niadas, 2005), including for the comparison of flow duration curves (Kileshye-Onema et al., 2006).

2.4. HBVx model application

The HBV (Hydrologiska Byråns Vattenbalansmodell) family of models, whilst developed and applied initially in Sweden, have also been used in semi-arid and arid countries such as Australia, Iran and Zimbabwe (Lidén, 2000; Lidén and Harlin, 2000; Oudin et al., 2005; Masih et al., 2008). The HBVx model comprises HBV light (Seibert, 2002) with an interception storage pre-processor (Love et al., 2010b).

The interception pre-processor calculates daily reference evaporation using the Hargreaves formula (Allen et al., 1998), and potential evaporation at catchment level derived using mapped land use and crop coefficients (Table 4). Daily interception was then calculated following De Groen and Savenije (2006) with a threshold interception storage of 5 mm. However, if the amount of rainfall intercepted was more than could be evaporated on that day, some moisture will remain in interception storage until the next day, thus decreasing the available volume of interception storage for that day (Love et al., 2010b).

The interception pre-processor operates as the first routine in HBVx, and is followed by the standard set up of HBV light: a soil moisture routine and a runoff generation routine with two reservoirs (Fig. 2). The soil moisture routine is governed by the non-linear function β, which computes the amount of infiltration water that goes into runoff generation, and the maximum soil moisture storage FC (mm), which is similar to field capacity. The runoff generation routine comprises an upper, fast-reacting reservoir, and a lower, slow-reacting reservoir. Flow of water from these reservoirs into runoff is governed by the linear storage coefficient (K_0, K_1, K_2) and overflow from the upper storage (Q_0) based upon exceedance of the threshold storage volume UZL (mm). The parameters used in the model are explained in Table 5.

Given the limited rainfall data available, it was not worthwhile to subdivide the catchments into subcatchments – the greater the extent to which a model is distributed, the finer the resolution required on input data series such as rainfall (Lin and Radcliffe, 2006).

The parameter ranges are shown in Table S1 (Supplementary material), and were selected based on experience in application of HBV in other catchments and on field observations (e.g. Uhlen-

Table 1
Selected catchments and data availability.

Catchment, abbreviation used in Fig 1	Area (km^2)	Mean annual unit runoff (mm a^{-1})	Days of flow (d a^{-1})	Discharge time series	Rainfall station	Temperature station	Radiation station
B11 Ncema	218	94	186	1951–2003	Bulawayo Esigodini	Bulawayo	Bulawayo
B15 Lumeni	267	74	201	1952–2005	Mbalabala	Bulawayo	Bulawayo
B26 Sansukwe	189	7	44	1955–1997 1984–2005	Mphoengs	West Nicholson	West Nicholson
B30 Mzingwane-Mzinyathini	448	138	146	1959–1980 1998–2000	Bulawayo Esigodini MRS	Bulawayo	Bulawayo
B39 Mpopoma	91	29	112	1959–1980 1988–2000	MRS MNP	Bulawayo	Bulawayo
B56 Thuli	645	64	250	1965–1998	Kezi Mbalabala MNP	West Nicholson	West Nicholson
B60 Inyankuni	194	49	99	1965–2004	Esigodini Mbalabala	Bulawayo	Bulawayo
B61 Inyali	49	32	88	1965–1999	Esigodini Mbalabala	Bulawayo	Bulawayo
B64 Ingwizi	712	50	23	1988–1997	Marula Mphoengs	West Nicholson	West Nicholson
B74 Jama	75	25	87	1968–2005	Esigodini, Fort Rixon	Bulawayo	Bulawayo
B78 Zgalangamante	49	36	68	1969–2005	Kezi	Kezi	West Nicholson
B80 Maleme	523	33	126	1970–2004	MNP	Kezi	Bulawayo
B83 Mtsheleli	363	83	197	1970–2004	MNP	Kezi	Bulawayo
B90 Mtetengwe	1500	14	45	1975–1976 1983 1987–1990 2003–2005	Beitbridge	West Nicholson	West Nicholson
M27 Mnyabezi 27	22	2.3	7	2006–2008	a	West Nicholson	West Nicholson
MSH Mushawe	220	50	205	2006–2008	a	West Nicholson	West Nicholson
UBN Upper Bengu	7	0.9	5	2006–2008	a	West Nicholson	West Nicholson
Zhulube	30	77	57	2006–2008	a	West Nicholson	West Nicholson

MRS = Matopos Research Station; MNP = Matopos National Park; a = catchments instrumented during this study – see Table 2.

Table 2
Instrumentation installed in field study site catchments.

Catchment	Discharge stations	Climate stations
M27 Mnyabezi 27	Dam and limnigraph	7 catch gauges Class A evaporation pan
MSH Mushawe	Bridge and limnigraph	17 catch gauges Class A evaporation pan
UBN Upper Bengu	Dam and limnigraph	8 catch gauges Class A evaporation pan
Zhulube	Composite gauge (V-notch and broad crest)	14 catch raingauges Class A evaporation pan

brook et al. 1999; Uhlenbrook and Leibundgut, 2002; Love et al., 2010b). This is considered preferable to unguided automatic calibration which can give preposterous parameter values in semi-arid catchments (Lidén, 2000).

The time series for the selected catchments were each calibrated at three time steps: daily, dekad (10 days) and monthly. Prior to each run, the model was initialised in order to better represent initial conditions (Noto et al., 2008). Initialisation was for 1 year (daily time step), 1.5 years (dekad) or 2 years (monthly). Calibration was carried out using 20,000 runs of the genetic algorithm method (Seibert, 2000). The genetic algorithm calibrations were repeated several times to confirm that similar parameter sets were derived from each calibration. The selected objective functions were the Nash–Sutcliffe Coefficient (C_{NS}) and mean volume error (dV_d)

$$C_{NS} = 1 - \frac{\sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^{n}(Q_{obs,i} - \overline{Q_{obs}})^2} \tag{1}$$

$$dV_d = \frac{365 \times \sum_{i=1}^{n}(Q_{obs,i} - Q_{sim,i})}{n} \tag{2}$$

where Q_{obs} (mm d^{-1}) is the observed discharge, Q_{sim} (mm d^{-1}) the simulated discharge and n the number of time steps i (days – or dekads or months) in the simulation.

2.5. Regionalisation

The parameters sets which were developed during the calibration processes were used to develop regionalised parameter sets

Table 3
Selected catchment characteristics used in discriminant analysis.

Catchment	B11	B15	B26	B30	B39	B60	B61	B74	B78	B80	B83	B90	M27	MSH	UBN	Source
Rainfall: long term mean (mm a^{-1})	621	627	484	605	592	627	627	627	455	586	586	360	417	552	320	Mean annual rainfall for full time series of that station. Data from Department of Meteorological Services, except for M27, MSH, UBN, instrumented during study
Rainfall: standard deviation (mm a^{-1})	198	211	269	210	216	196	211	196	229	208	208	219	82	–	14	Standard deviation of annual rainfall for full time series of that station. Data from Department of Meteorological Services, except for M27, MSH, UBN, which were instrumented during study
Geology: fraction granitoid (–)	0.50	0.50	0.80	0.50	1.00	0.20	0.50	0.95	0.60	1.00	1.00	0.00	1.00	1.00	1.00	1:250 000 Limpopo Basin GIS in Chinoda et al. (2009)
Soil: fraction lixisols (–)	0.30	0.30	0.00	0.50	0.00	0.40	0.15	0.05	0.10	0.00	0.00	0.00	0.00	0.00	0.00	1: 250 000 Limpopo Basin GIS in Bangira and Manyevere (2009)
Land cover: fraction forest (–)	0.05	0.05	0.00	0.20	0.25	0.05	0.00	0.00	0.00	0.40	0.30	0.80	0.60	0.13	0.00	Mapped from false colour composite (bands 3, 4 and 5) of Landsat scenes: path170row074 dated 23 04 2000, path170row075 dated 03 12 2000, path171row074 dated 01 09 2001, path171row075 dated 01 11 2001
Land degradation: fraction of land degraded (–)[b]	0.05	0.05	0.50	0.30	0.00	0.00	0.00	0.10	0.50	0.03	0.05	0.10	0.40	0.00	1.00	
Land tenure: fraction communal land (–)[a]	0.00	0.50	1.00	0.40	0.00	0.00	0.00	0.00	0.50	0.05	0.10	0.30	1.00	1.00	1.00	Mapped from 1:250 000 series, Surveyor General of Zimbabwe (1996)
Topography: mean slope (%)	9	9	12	9	5	11	11	12	12	9	9	11	12	23	12	FAO Terrasat media of terrain slopes, derived from GTOPO30 (CPWF, 2006)
Agro-ecological region (–)	IV	IV	V	IV	IV	IV	IV	IV	V	IV	IV	V	V	V	V	Vincent and Thomas (1960): V is the drier areas, less suitable for dryland cropping than IV

[a] Excludes unsettled areas.
[b] Land is considered degraded where vegetation cover appears absent on Landsat image (excludes fields).

Table 4
Crop coefficients used for different land cover types, varying by season. For cultivated land, values for maize in East Africa (FAO, 2008) were used.

Land cover, this study	South African equivalent	January	February	March	April	May	June	July	August	September	October	November	December
Woodland: highveld	Woodland (indigenous tree/bush savanna)[a]	1.14	1.14	1.14	1.14	1.00	1.00	1.00	1.00	1.07	1.14	1.14	1.14
Woodland: mopane	Mopani veld[b]	0.74	0.74	0.71	0.57	0.54	0.47	0.43	0.50	0.57	0.64	0.69	0.71
Mixed grassland and woodland	Mixed bushveld[b]	1.00	1.00	0.93	0.86	0.71	0.64	0.57	0.64	0.79	0.93	0.93	1.00
Mixed grassland and woodland (degraded)	Veld in poor condition[c]	0.79	0.79	0.79	0.64	0.29	0.29	0.29	0.29	0.43	0.57	0.71	0.79
Wetland	Wetland grasses[c]	1.14	1.14	1.14	1.00	0.86	0.71	0.57	0.57	0.57	0.71	0.86	1.00
Rocky hills	Veld/rock 50–100% rock[c]	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43	0.43

Source: [a]Jewitt, 1992; [b]Schulze and Hohls, 1993; [c]Schulze et al., 1995. The original crop coefficients were derived for use with pan evaporation data (Schulze et al., 1995). These were converted for use with reference evaporation data by dividing the original crop coefficient with the pan coefficient (taken as 0.7).

for HBVx: the means for each parameter of the values generated from calibration of the ephemeral catchments (Group A), sub-ephemeral catchments (Group B) and sub-perennial catchments (Group C), at daily, dekad and monthly time steps (see Table 7 for definitions).

The three best-performing regionalised parameter sets were then applied blindly to two catchments (B56 and B64) which had not been used in the classification and calibration exercises. This exercise could not be extended to more catchments, as the remaining catchments had been eliminated as having insufficient data quality.

2.6. Uncertainty of input data

The uncertainty in the model that may arise due to variability of rainfall data has been discussed. The sensitivity of catchment rainfall, the major input to the model, to spatial variability of rainfall within a catchment was evaluated using the 10% elasticity index (e_{10}) suggested by Cullmann and Wriedt (2008):

$$e_{10} = \frac{Out_1 - Out_0}{0.1 \times Out_0} \tag{3}$$

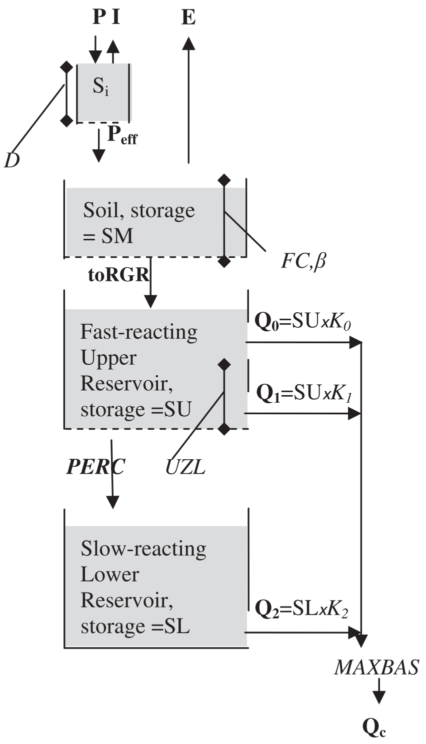

Fig. 2. Schematic diagram of the HBVx model structure, after Love et al. (2010b). Parameters and variables are explained in Table 5. PERCAll parameters mm d^{-1}, except *D* (mm), UZL (mm), FC (mm), *β* (–), and MAXBAS (–). Fluxes are shown in **bold** and other model parameters in *italics*.

Table 5
Parameters used in HBVx.

Parameter	Narrative	Unit	Comment
P	Precipitation	mm d^{-1}	Derived from rainfall stations using Thiessen polygons
S_i	Interception storage	Mm	Capacity = D = 5 mm
E	Soil evaporation and transpiration	mm d^{-1}	Daily total evaporation less interception flux
I	Interception flux	mm d^{-1}	
P_{eff}	Effective rainfall	mm d^{-1}	Rainfall less interception flux
FC	Maximum soil moisture storage	mm	
LP	Threshold below which actual evaporation does not reach potential evaporation due to moisture stress.. This is given as ratio (soil moisture divided by FC)	–	
β	Non-linear function partitioning the amount of infiltration water going to runoff generation and the amount going to soil moisture	–	
toRGR	Moisture transferred to runoff generation routine	mm d^{-1}	
UZL	Threshold for start of overland flow	mm	
Q_0	Overland flow	mm d^{-1}	Controlled by coefficient K_0 (–)
Q_1	Discharge from saturated soil or shallow groundwater	mm d^{-1}	Controlled by coefficient K_2 (–)
PERC	Percolation	mm d^{-1}	Flux from fast-reacting upper reservoir (saturated soil or shallow groundwater) to lower reservoir (deep groundwater)
Q_2	Discharge from deep groundwater	mm d^{-1}	Controlled by coefficient K_2 (–)
Q_c	Total discharge from catchment	mm d^{-1}	$Q_c = Q_0 + Q_1 + Q_2$
MAXBAS	Routing parameter	d	Set at 1.0

where Out_0 is the initial catchment rainfall being studied and Out_1 is the catchment rainfall after the value for one rainfall station has been increased or decreased by 10% (both were done).

3. Results

3.1. Observed flows

The high inter-annual variability in runoff can be seen in Fig. 3, especially in the more arid catchments B26, B78 and B90. A comparison of catchment area with runoff coefficient shows a clear negative relationship (Fig. 4).

3.2. Catchment classification

Discriminant analysis of the catchment classification by agro-ecological region shows a strong statistical basis for separating the catchments into those in Region IV and Region V (Table 6). The variables that form the strongest basis for the classification are the standard deviation of the annual rainfall and the land cover.

Two sets of flow duration curves were prepared for the selected catchments: monthly flow normalised against catchment area (unit flow, mm month^{-1}) (Fig. 5a) and monthly flow normalised against mean monthly flow (–) (Fig. 5b).

Visual inspection of the flow duration curves (Fig. 5) suggests three groups (Table 7). The three Group A catchments are all in the drier south of the study area (Fig. 1) – and correspond to Group 2 of the discriminant analysis (Table 5), that is, the catchments in Region V. The three Group C catchments are in the central northern area, but there are also Group B catchments in that area.

The significance of these groups was tested using the Kolmogorov–Smirnov test (Table 8). This confirmed the group of sub-perennial catchments (C) as a statistically different population from the ephemeral (A) and sub-ephemeral catchments (B) and the combined group AB (A + B). Groups A and B are not statistically different from each other, although this result may reflect the small sample size in Group A ($n = 3$).

3.3. Calibration

The results of the calibration exercise are shown in Table 9. Calibration at a daily time step produced results $C_{NS} > 0.3$ in only one catchment. The best results were obtained at a dekad time step, with six of the 13 catchments yielding $C_{NS} > 0.4$ and nine yielding $C_{NS} > 0.3$. This included all of the catchments in Groups B and C. Performance at a monthly time step was better than at a daily time step but not as good as at the dekad time step. There was no consistent difference in the values of parameters generated through the autocalibration (available in Supplementary material) between the different groups, except for generally low FC values for Groups B and C.

Model performance was compared with several catchment characteristics. Higher C_{NS} values were associated with the more perennial catchments ($R = 0.40$, negative correlation of performance to days of now flow), but the best correlation was with the proportion of degraded land in a catchment ($R = 0.59$, negative

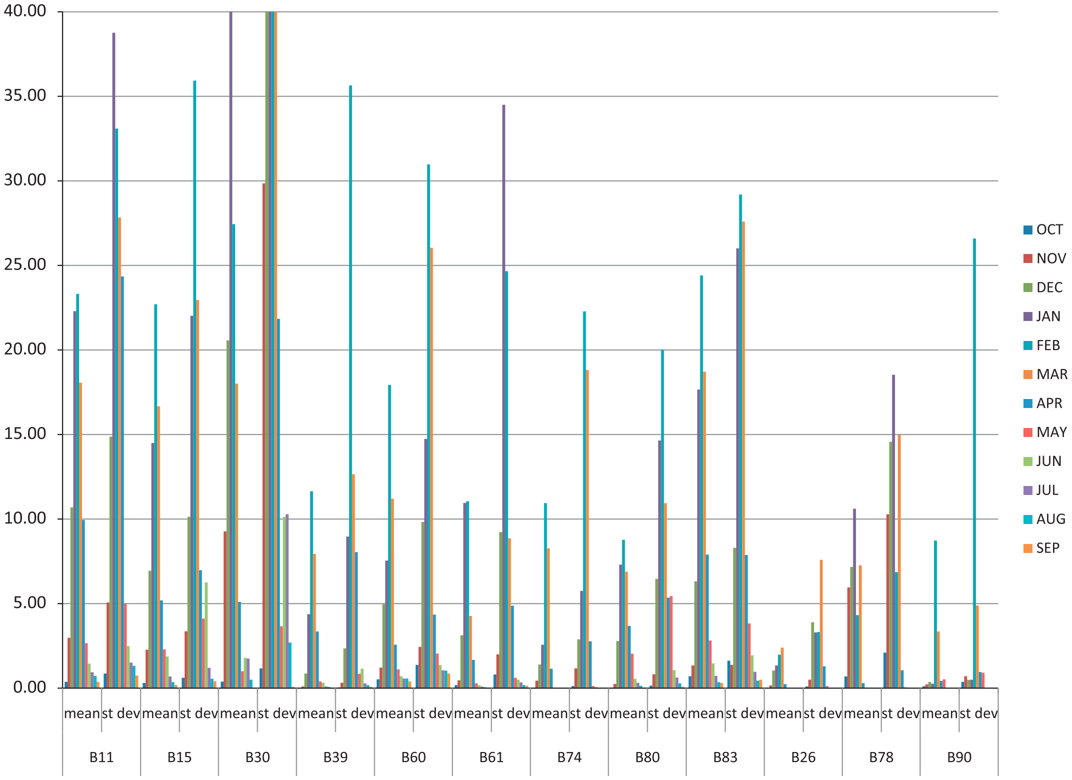

Fig. 3. Mean and standard deviations of unit flows (mm a^{-1}) for the selected catchments, full time series available.

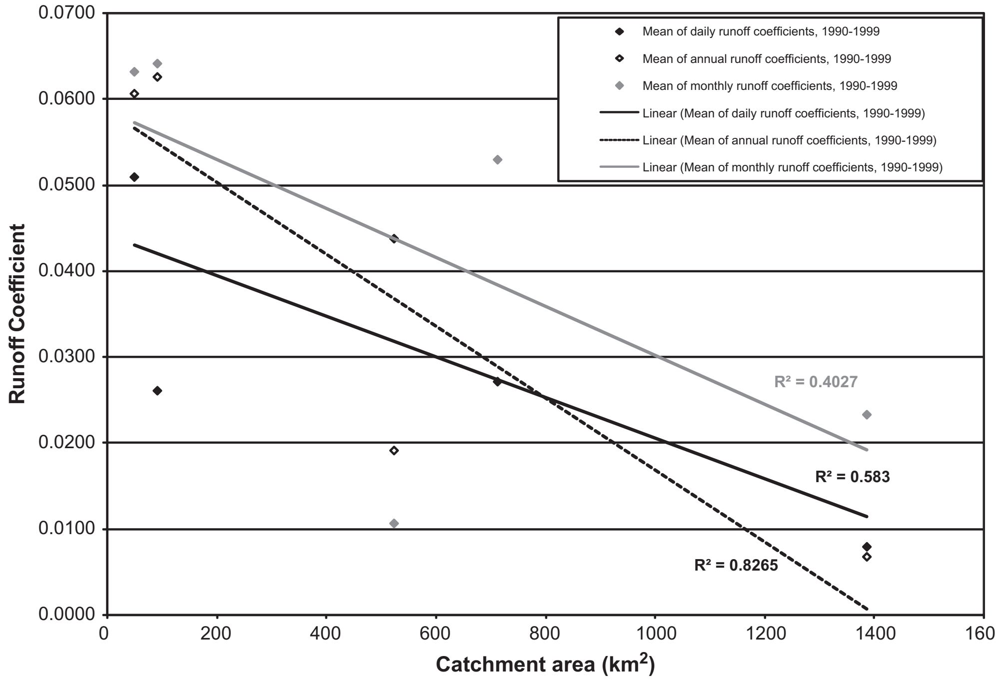

Fig. 4. Comparison of runoff coefficients with catchment size.

correlation). Other catchment descriptors compared to model performance did not show correlation.

The proportion of degraded land was found to be positively correlated to the fast runoff coefficient, often interpreted as overland flow K_0 (from the parameter sets developed during calibration; see Supplementary material) at a daily time step ($R = 0.45$) but not correlated with the intermediate runoff coefficient, K_1, and the slow runoff coefficient, K_2 ($R = -0.18$, $R = -0.23$, respectively). These are often interpreted as discharge from shallow groundwater and deep groundwater, respectively.

The proportion of the catchment underlain by granitoid was found to be positively correlated to the coefficients for flow from the two sub-soil reservoirs K_1 and K_2 (from the parameter sets developed during calibration; see Supplementary material) at a daily time step ($R = 0.49$ for K_1; $R = 0.43$ for K_2) but not to the coefficient for "overland" flow from the soil box ($R = 0.21$ for K_0).

Table 6
Results of discriminant analysis of catchment characteristics.

Main results	
Groups	2
Variables	8
Cases	15
Group 1 (Region IV)	B11, B15, B30, B39, B60, B61, B74, B80, B83
Group 2 (Region V)	B26, B78, B90, M27, MSH, UBN
Wilk's Lambda	0.03267 (0 = perfect discrimination)
Tolerance of variables	
Variable	*Tolerance (0 = completely redundant)*
Geology	0.151
Soil	0.223
Land cover	0.356
Degradation	0.253
Rainfall mean	0.264
Rainfall standard deviation	0.452
Tenure	0.283
Slope	0.281

3.4. Regionalisation

The parameter sets used in regionalisation are shown in Table 10. The performance of each of these sets is shown in Table 11. The three field study catchments gave very poor results throughout, probably due to the short time series (1 or 2 years).

The parameter set which performed best was "*dekadBC*", with 43% of the series giving $C_{NS} > 0.3$. The second best was "*monthlyBC*", with 36% of the series giving $C_{NS} > 0.3$. The third set was "*monthlyABC*", with 29% of the series giving $C_{NS} > 0.3$. All of these parameter sets have low values for β, PERC 1 and moderate values for K_1 and FC. This is indicative of relatively slow infiltration and percolation with moderate to fast "overland flow".

Blind regionalisation gave mixed results (Table 12), with each parameter set giving $C_{NS} > 0.3$ for only one of the two catchments at a given time step. Performance is better for B56, the less arid catchment.

The sensitivity of catchment rainfall to spatial variability is clearly shown in Table 13: a 10% change in rainfall of one rainfall station has a substantial effect on catchment rainfall. On a daily

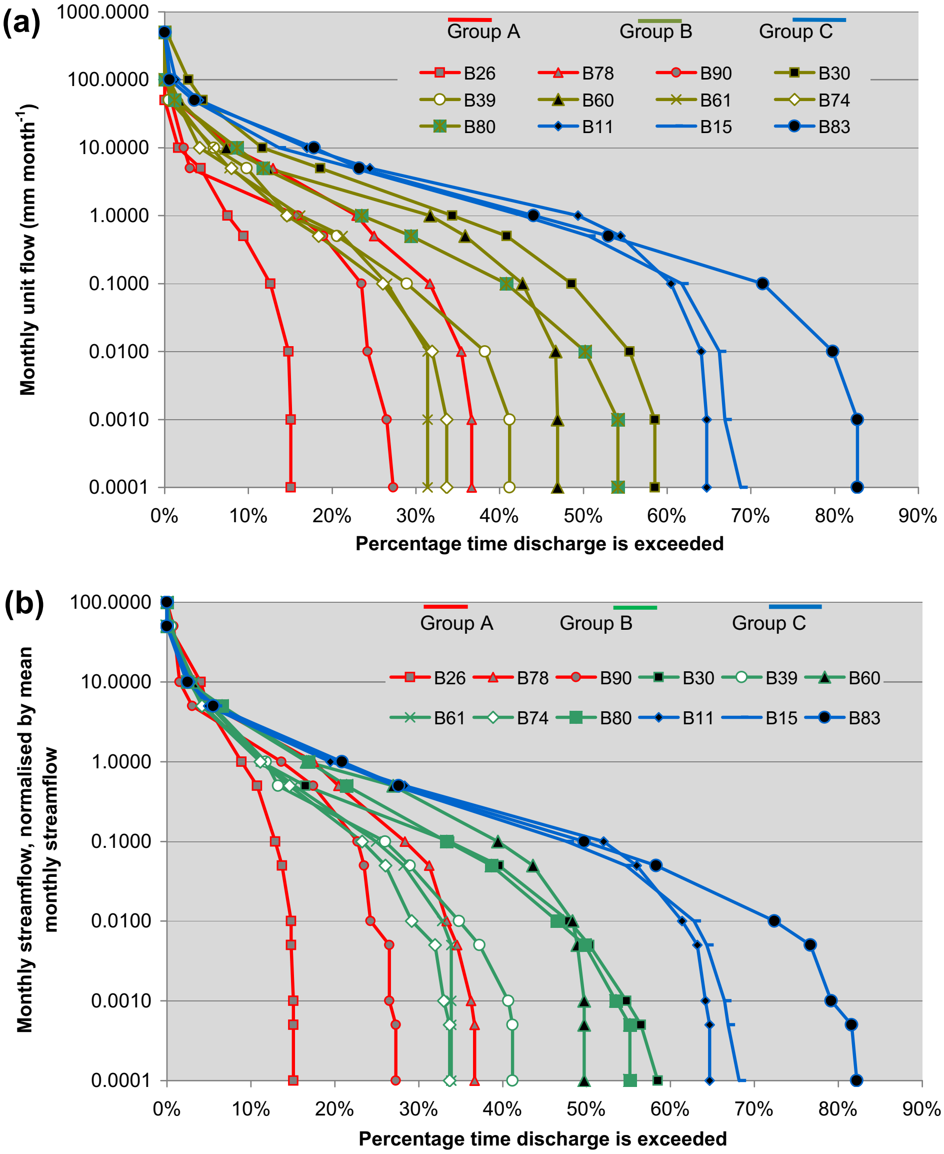

Fig. 5. Monthly flow duration curves for the selected catchments, using (a) unit flow (monthly discharge values normalised by catchment area) and (b) monthly discharge values normalised to the mean for that catchment.

Table 7
Catchment classification based on monthly flow duration curves.

Group	Characteristic flow duration curve	Catchments
A	Ephemeral catchments with few low flows, giving curves with no significant increase in percentage exceedance time for discharge below 0.1 mm month^{-1} or below 10% of the mean – suggestive of flash floods	B26, B78, B90
B	Sub-ephemeral catchments with some discharge occurring between 30% and 60% of the time	B30, B39, B60, B61, B74, B80
C	Sub-perennial catchments, with some discharge occurring for more than two-thirds of the time	B11, B15, B83

time step, the effect can be extreme if rainfall is only reported from one station. This can also be seen in Fig. 6: the gauge at *E Nyathi* recorded heavy rainfall on 8 January, but the other gauges in the catchment recorded heavy rainfall the following day. Had only three or less gauges been used to represent rainfall in the catchment (as is the case for the catchments not instrumented in this study), the catchment rainfall could easily have been incorrectly estimated on either day.

4. Discussion

4.1. Catchment classification

Comparison of the results of the discriminant analysis of catchment characteristics (Table 6) and the Kolmogorov–Smirnov test on the flow duration curves (Table 8) suggests that the agro-ecological region classification (Vincent and Thomas, 1960) can be related to catchment flow characteristics. The lack of statistical support for the separation between sub-ephemeral and ephemeral catchments (Groups A and B; Table 8) could be due to the small sample size of Group A or could be suggest a limitation to agro-ecological region classification as a predictor of catchment

Table 8
Results of the Kolmogorov–Smirnov test on monthly flow distribution, using C_α from Stephens (1974).

Case	Test statistic (monthly flow)	Test statistic (unit flow)	K_α at 0.10 significance level	Result
A vs. B	0.278	0.278	0.369	No difference
A vs. C	0.559	0.504	0.509	Different populations (for monthly flow normalised to mean only)
B vs. C	0.428	0.443	0.353	Different populations (for both monthly flow normalised to mean and unit flow)
AB vs. C	0.562	0.547	0.326	Different populations (for both monthly flow normalised to mean and unit flow)

Table 9
Calibration of the HBVx model using the genetic algorithm of Seibert (2000); reasonable model results ($C_{NS} \geqslant 0.4$) are given in **bold** and marginal model results ($0.3 \geqslant C_{NS} > 0.4$) are given in *italics*.

Catchment	Group	Daily		Dekad		Monthly	
		C_{NS} (−)	dV_d (mm a^{-1})	C_{NS} (−)	dV_d (mm a^{-1})	C_{NS} (−)	dV_d (mm a^{-1})
B26 Sansukwe	A	0.14	4	0.29	4	**0.60**	−12
B90 Mtetengwe	A	−0.01	4	0.12	0	0.12	0
UBN Upper Bengu	A	−7.77	−9	*0.38*	0	×	×
MSH Mushawe	A	*0.32*	505	0.20	348	×	×
M27 Mnyabezi 27	A	−64.41	−48	**0.80**	0	×	×
B78 Zgalangamante	A	−0.28	−35	0.21	−16	0.15	−7
B30 Mzingwane-Mzinyathini	B	×	×	×	×	0.13	19
B39 Mpopoma	B	*0.30*	65	*0.35*	−3	0.16	56
B60 Inyankuni	B	−0.10	−42	*0.30*	2	0.28	2
B61 Inyali	B	0.15	−20	**0.44**	−6	**0.41**	1
B74 Jama	B	0.23	13	**0.58**	−2	*0.31*	5
B80 Maleme	B	0.12	−24	**0.42**	2	**0.47**	−3
B11 Ncema	C	×	×	×	×	**0.52**	−1
B15 Lumeni	C	0.24	−54	**0.66**	2	**0.61**	10
B83 Mtsheleli	C	0.13	−19	**0.42**	3	0.36	1
Group C	C	×	×	×	×	**0.50**	4

Table 10
Parameter sets used in regionalisation. See Fig. 2 for the meaning of the parameters.

Parameter set	Origin	FC (mm)	LP (−)	β (−)	PERC (mm d^{-1})	UZL (mm)	K_0 (d^{-1})	K_1 (d^{-1})	K_2 (d^{-1})
dailyA	Mean of catchments' sets[a], excludes B78	150.0	0.7	5.00	2.50	83.1	0.7711	0.0589	0.0003
dailyBC	Mean of catchments' sets, excludes B39, B74	150.0	0.7	1.55	2.50	99.9	0.5000	0.0550	0.0001
dekadA	Mean of B78, B90 catchments' sets	118.4	0.7	1.89	0.46	93.6	0.6575	0.1992	0.0019
dekadBC	Mean of B60, B80 catchments' sets	125.0	0.7	1.50	0.50	95.0	0.6000	0.3000	0.0001
dekadBC2	Mean of catchments' sets: rest of group BC	10.0	0.7	1.25	0.40	15.0	0.7500	0.3000	0.0010
dekABC	Mean of catchments' sets	78.3	0.7	2.02	0.66	66.7	0.7184	0.2313	0.0013
monthlyBC	Excludes B60, B80	10.0	0.7	1.00	0.37	64.6	0.6422	0.3000	0.0020
monthlyABC	Mean of catchments' sets	53.3	0.7	1.04	0.41	79.5	0.6465	0.2963	0.0012

[a] Catchment set: The parameter set for a given catchment associated with the best objective functions during calibration (Table 8 and Supplementary material).

Table 11

Results of regionalisation of the HBVx model; reasonable model results ($C_{NS} \geqslant 0.4$) are given in **bold** and marginal model results ($0.3 \geqslant C_{NS} > 0.4$) are given in *italics*. The use of "×" denotes that a catchment was not regionalised against a particular parameter set, either due to insufficient data at that time step of the parameter set being inapplicable, e.g. parameter sets derived exclusively from Group A catchments were not regionalised to Group C catchments.

Catchment[a]	Group	Daily time step				Dekad time step							
		dailyA		dailyBC		dekadA		dekadBC		dekadBC2		dekABC	
		C_{NS} (−)	dV_d (mm a^{-1})	C_{NS} (−)	dV_d (mm a^{-1})	C_{NS} (−)	dV_d (mm a^{-1})	C_{NS} (−)	dV_d (mm a^{-1})	C_{NS} (−)	dV_d (mm a^{-1})	C_{NS} (−)	dV_d (mm a^{-1})
B26 Sansukwe	A	0.03	−11	×	×	0.04	15	×	×	×	×	0.01	20
B90 Mtetengwe	A	−0.02	5	×	×	−0.00	2	×	×	×	×	−0.01	4
B78 Zgalangamante	A	−1.20	−21	×	×	0.02	−53	×	×	×	×	−0.05	−60
B30 Mzingwane-Mzinyathini	B	×	×	×	×	×	×	×	×	×	×	×	×
B39 Mpopoma	B	×	×	0.09	84	×	×	0.02	98	*0.30*	35	−0.01	93
B60 Inyankuni	B	×	×	−0.10	−41	×	×	0.26	18	−1.04	−108	0.21	10
B61 Inyali	B	×	×	0.14	−23	×	×	0.24	10	−0.23	−121	0.16	15
B74 Jama	B	×	×	0.12	40	×	×	0.21	88	**0.48**	−32	0.16	79
B80 Maleme	B	×	×	0.11	−25	×	×	**0.40**	15	−1.91	−97	0.28	11
B11 Ncema	C	×	×	×	×	×	×	×	×	×	×	×	×
B15 Lumeni	C	×	×	0.24	−56	×	×	**0.53**	27	−0.10	−121	**0.46**	1
B83 Mtsheleli	C	×	×	0.11	−27	×	×	*0.35*	22	−0.75	−100	0.29	1

Catchment	Group	Monthly time step									
		groupA		groupB		groupC		monthlyBC		monthlyABC	
		C_{NS} (−)	dV_d (mm a^{-1})	C_{NS} (−)	dV_d (mm a^{-1})	C_{NS} (−)	dV_d (mm a^{-1})	C_{NS} (−)	dV_d (mm a^{-1})	C_{NS} (−)	dV_d (mm a^{-1})
B26 Sansukwe	A	*0.35*	−34	×	×	×	×	×	×	**0.48**	−16
B90 Mtetengwe	A	−0.69	1	0.02	4	−0.08	5	0.08	0	−0.08	1
B78 Zgalangamante	A	0.15	−10	−0.18	−26	−0.12	−20	−0.19	−28	0.13	−11
B30 Mzingwane-Mzinyathini	B	×	×	0.12	75	0.11	82	0.12	51	0.05	89
B39 Mpopoma	B	×	×	0.10	93	0.07	99	0.11	80	0.01	96
B60 Inyankuni	B	×	×	0.11	−23	×	×	0.04	−48	0.28	−6
B61 Inyali	B	×	×	*0.33*	−31	×	×	*0.30*	45	0.28	−4
B74 Jama	B	×	×	*0.30*	50	×	×	*0.30*	24	0.19	66
B80 Maleme	B	×	×	0.03	−30	0.15	−16	−0.07	−47	**0.45**	−6
B11 Ncema	C	×	×	×	×	**0.51**	27	**0.51**	−20	*0.37*	26
B15 Lumeni	C	×	×	×	×	**0.61**	1	**0.53**	−49	**0.50**	−3
B83 Mtsheleli	C	×	×	**0.46**	13	0.09	12	−0.11	−49	*0.30*	−12

[a] Excludes field catchments UBN, MSH and M27 which had short time series.

Table 12
Results of blind regionalisation against catchments not used in deriving parameter sets.

Parameter set		dekadBC		monthlyBC		monthlyABC	
Catchment	Timestep	C_{NS} (–)	dV_d (mm a^{-1})	C_{NS} (–)	dV_d (mm a^{-1})	C_{NS} (–)	dV_d (mm a^{-1})
B56 Thuli	Daily	−0.85	−19	−9.9	−138	−2.82	−75
	Dekad	0.11	33	−0.15	−135	*0.30*	2
	Monthly	−0.15	35	*0.34*	10	0.17	23
B64 Ingwizi	Daily	−49	−85	−245	−248	−110	−160
	Dekad	−0.10	−1	−55	−100	−9.8	−45
	Monthly	*0.38*	−4	−13	−38	−0.78	−15

Table 13
Local sensitivity of catchment rainfall to spatial variability, demonstrated using station *E Nyathi* for catchment M27 and station *Esigodini* for catchment B30.

Catchment and measurement	10% Decrease in rainfall at selected station	10% Increase in rainfall at selected station	Selected station excluded from computation
M27			
Daily, 08/01/2008	−1.00	1.00	−10.00
Daily, 09/01/2008	0.00	0.00	−0.01
B30			
Mean annual rainfall	−0.36	0.36	−0.01

behaviour. The distinction between sub-perennial (Group C) and (sub-)ephemeral catchments (Groups A and B; Table 7), based upon the flow duration curves, was statistically supported (Table 8).

4.2. Model performance

During both calibration (Table 9) and regionalisation (Table 11), model performance was poor at a daily time step, with the exception of the catchments instrumented during this study. The poor performance at a daily time step can be explained by two factors: First, the measurement day for runoff is 00:00–23:59 of the same day while the measurement day for rainfall is 08:00–07:59 of the next day. However, most rainfall in Zimbabwe occurs in thunderstorms (Mazvimavi, 2003), which generally occur in the afternoon, which should minimise the impact of this error.

Second, rainfall in Zimbabwe shows high spatially variability (Mugabe et al., 2007; Unganai and Mason, 2002), which means that the available climate stations may under-represent or over-represent rainfall which occurs in a given catchment, especially the larger ones, and especially at a daily time step (Mazvimavi, 2003). For many of the catchments, the only available rainfall data comes from gauges outside, but adjacent to, the catchment. Spatial variability is not as great at a dekad time step, as can be seen from the totals in Fig. 6. Whilst a monthly time step will average out the spatial heterogeneity in rainfall data, it has the disadvantage that size and shape of discharge peaks are lost as discharge events lasting 1 or 2 days are averaged across the month. This variability is associated with uncertainty in catchment rainfall from a coarse network (Table 13).

Neither of these two factors applied to the catchments instrumented during this study as the measurement day was the same for rainfall and for runoff (08:00–07:59 of the next day) and the instrumented catchments had between 7 and 17 rainfall stations.

The sub-perennial catchments are easier to simulate with the selected box model than the (sub-)ephemeral catchments. This was also the case for the blind regionalisation, where the less arid and less ephemeral catchment was simulated better. This could be related to the fact that flow in ephemeral catchments is highly unequally distributed in space and time (Lange, 2005). Ephemeral catchments have more threshold processes and many more discrete flow events, with large, short-term variations in discharge, which are more difficult to simulate (Johst et al., 2008). Furthermore, the information content for a given length of time series is more limited for ephemeral catchments (Woolridge et al., 2003).

The arid zone environment thus imposes constraints to the utility of the HBVx model. The more continuous the discharge, i.e. fewer events and lower variation of (sub-)perennial catchments, the more suitable for simulation with HBVx. A large part of the chal-

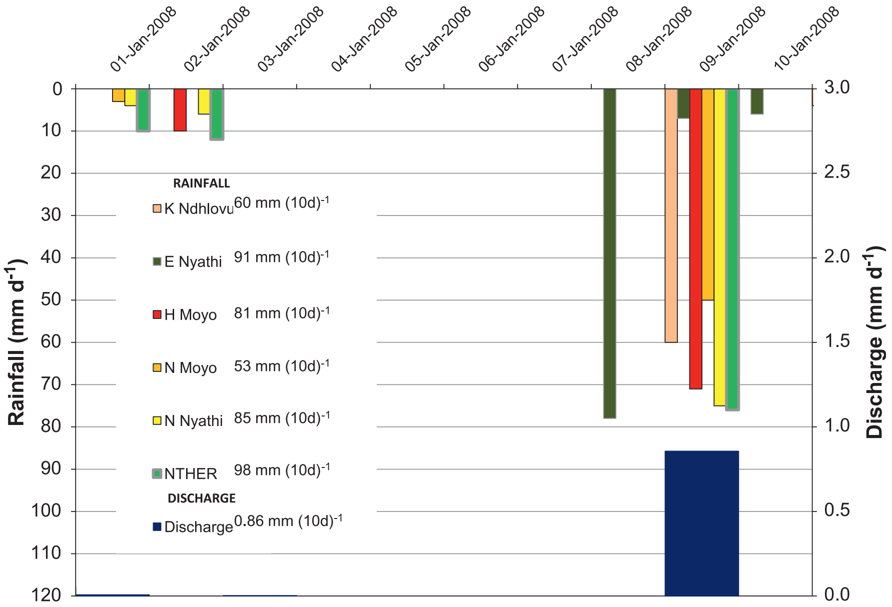

Fig. 6. Daily rainfall recorded from the six rainfall gauges in the Mnyabezi 27 research catchment (M27) and daily discharge recorded from the catchment outlet for the first dekad (10 day period) of 2008. Total fluxes for the dekad are given in the key.

lenge is being able to make satisfactory quantification of catchment rainfall (Hughes, 1995). This is likely similar with other conceptual box models.

4.3. Implications for semi-arid zone hydrology

The strong negative correlation between model performance and proportion of the catchment which is degraded suggests a strong influence of land degradation on flow processes. The fact that the proportion of degraded land is positively correlated to the fast runoff "overland flow" coefficient K_0 but not to the other flow coefficients suggests that land degradation can be linked to more rapid flow, especially overland flow. This is likely to largely be through the effect of loss of vegetation facilitating a fast response. Similar findings were made, for instance, by Lange and Leinbundgut (2003) in the Sahel, where land degradation was associated with decreased infiltration and increased overland flow. Rapid and more episodic flow events tend to be more discrete and thus more difficult to simulate with a box model.

The correlation between the fraction of a catchment underlain by granite and the "groundwater" flow coefficients K_1 and K_2 compares well to the findings by Longobardi and Villani (2008) that geology is the major factor affecting baseflow and by Mwakalila et al. (2002) that granitic catchments generate greater baseflow than other catchments.

Further research should test these findings against detailed soil moisture and water table levels. Woolridge et al. (2003) recommend use of soil moisture data as a more information-rich time series than discharge for the calibration of hydrological models in ephemeral catchments. However, in southern Zimbabwe such data is far scarcer than the limited rainfall and discharge data sets. Given the high variability in soil moisture content that is typical of semi-arid catchments (Gómez-Plaza et al., 2001) the utility of this measure for calibration is likely to be limited to experimental catchments.

The clear negative relationship between catchment size and runoff coefficient (Fig. 4), indicates that smaller catchments are more efficient in converting rainfall into runoff. This is not related to rainfall, as the smaller catchments (Table 1) are evenly-distributed between higher rainfall and lower rainfall areas (Table 3). Such a scale effect was also observed in studies of micro-catchments (below 1.5 km^2) in both humid to sub-humid environments (Cerdan et al., 2004; Castro et al., 1999; van de Giesen et al., 2000; Didszun and Uhlenbrook, 2008) and arid to semi-arid environments (Cantón et al., 2001; Joel et al., 2002). At the micro-catchment scale, factors such as spatially variable infiltration and the length of the slope (distance of overland flow before entry of runoff into a stream) control what proportion of site runoff is discharged from that scale as runoff and what proportion is redistributed to become soil moisture (van de Giesen et al., 2000). At the meso-catchment scale of this study, processes after runoff generation must operate upon the streams in order to result in the scale relationship observed, for example the re-infiltration of water from streams into groundwater or infiltration or evaporation losses in wetlands. Because of this scale relationship, upscaling parameters from smaller to large catchments, even nested catchments¸ is complex and can lead to over-estimation of the effects of a given phenomenon (such as erosion) that is measured at a smaller scale when upscaled to a larger catchment or basin.

4.4. Implications for river basin management

The HBVx model could be used to predict flows in some ungauged basins, although application outside the study area would require calibration to the new basin. As both the regionalisation and blind regionalisation have shown, it cannot be used reliably to predict flows in ephemeral or more arid basins.

The finding that the more degraded catchments are associated with faster flows (likely overland flow) has important implications for flood response management. From this perspective, catchment restoration could potentially play an important role in flood management, by decreasing faster flows and decreasing overland flow.

There are also important implications for setting up hydroclimatic networks in the semi-arid environment. Establishing a network of rainfall stations that has a sufficient density to ensure that aggregated rainfall at catchment level is representative is likely to be costly – especially considering that such a network would only record a few events per year in the more arid catchments. In cases where budgetary constraints prevent a sufficiently dense rainfall measurement network being established it is also essential to fully exploit remote sensing. Observations from an insufficient number of measuring stations will give uncertain results, leading to unrealistic management decisions – unless the level of uncertainty is clearly understood. In such cases the PUB approach represents a better scientific basis for hydrological study and for river basin management. However, the best results are likely to be obtained from remote sensing combined with a fe ground stations.

The parameter sets that performed best in the regionalisation exercise are suggestive of slow infiltration and percolation with moderate to fast overland flow, which is in line with the general process understanding of such catchments (e.g. Mugabe et al., 2007). These processes appear more extreme in the more degraded catchments. This suggests that rainwater utilisation could be improve through (i) in-field soil water conservation techniques that increase the rate of infiltration and percolation, such as mulching (Mupangwa et al., 2007), and (ii) micro-catchment or runoff farming and supplementary irrigation (Ncube et al., 2009) to capture overland flow from areas adjacent to fields. This is particularly important in the degraded catchments that have faster overland flow. Faster, and possibly greater, sub-surface contribution to streamflow is expected from catchments underlain by granitic rocks.

5. Conclusions

Analysis of flow duration curves allowed separation of the sub-perennial catchments (Group C) from the (sub-)ephemeral catchments (Groups A and B). This distinction could not be demonstrated statistically. However, this could be due to the small sample size of Group A or could suggest a limitation to agro-ecological region classification as a predictor of catchment behaviour.

Modelling at a daily time step using data from the national hydrological and meteorological networks is not practical for hydrological modelling, due to sparse coverage and the errors discussed above. The two causes are inter-linked and have implications for hydroclimatic network design. Even at a coarser time scale (dekad or monthly), none of the parameter sets regionalised could produce model performance better than $C_{NS} = 0.3$ for half of the catchments studied. The best-performing parameter sets produced mainly negative volume errors (dV_d), which are conservative for water resource modelling and water allocation but problematic for flood prediction. The regionalisation of the HBVx model carried out in this study of the Mzingwane Catchment is thus only partially successful. This could perhaps be improved by incorporating the possibility for negative volume into the lower storage box SL in order to simulate groundwater levels falling below the riverbed (Lidén, 2000). This would be an alternative to the approach followed in this study of restricting the flow coefficient from that box (K_2) to very low values.

The best performance was obtained at the dekad and monthly time steps, although evaluation by blind regionalisation was limited by data availability. The longer time steps (rather than daily) suggest that the model offers more to longer term water resources (and water allocation) planning than to process hydrology. This also presents an opportunity for coupling HBVx with the spreadsheet-based water balance model WAFLEX, for which an alluvial groundwater module has been developed that performs best at the dekad time step (Love et al., 2010c). The HBVx model thus does offer some limited assistance to river basin planning in semi-arid basins, particularly for predicting flows in ungauged catchments at longer time steps. However, the model is unreliable for more ephemeral and drier catchments.

Ultimately, without more reliable rainfall and runoff data with longer time series, regionalisation in semi-arid ephemeral catchments will remain highly challenging. Data availability, at the appropriate scale and the appropriate density, remains a major challenge in the semi-arid zone, both to river basin management and to accurate regionalisation between catchments. For rainfall data, combining remotely-sensed data with ground stations may be the way forward.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.pce.2011.07.005.

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