BASEFLOW SEPARATION BASED ON STORAGE-OUTFLOW MODELLING OF STREAMFLOW RECESSIONS, WITH APPLICATION TO SEMI-ARID CATCHMENTS IN TANZANIA

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Abstract

Discharge in many rivers is often fed by baseflow provided by drainage of the saturated zone in the shallow permeable soils. It is becoming clear that the outflow from this saturated zone is not linear proportional to storage as is commonly assumed in many algorithms. The objectives of this study therefore, are first to explore the extent to which the assumption of linearity in storage-outflow relationships is valid and secondly to introduce an alternative approach to baseflow separation algorithms for estimating direct runoff time series. Numerical analysis of streamflow recessions from the semi-arid catchments of the Great Ruaha basin in Tanzania reveals a non-linear relationship between baseflow and storage. This relationship is used to derive an alternative approach to estimate direct runoff. The method involves fitting an exponential reservoir model using an iteration algorithm. The study goes further to evaluate the parameter sensitivity using the methodology of Generalized Likelihood Uncertainty Estimation (GLUE). Finally this study has found that a major difficulty in storage-outflow modelling of streamflow recessions, irrespective of the linearity of the model is the variation of model parameters from one event to the next event.

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1. INTRODUCTION

Baseflow separation from streamflow hydrographs has long been a topic of interest in hydrology (Hall, 1968; Tallaksen, 1995) since the baseflow recession curve itself contains valuable information about the aquifer properties. Baseflow recession analyses are routinely used in low flow forecasting, water supply allocation, hydroelectric powerplant designs and waste dilution schemes (Tallaksen, 1995). Also baseflow separation from quick storm response is required for numerous widely used hydrological models and other water resource applications (Vogel and Kroll, 1996).

During periods when catchment inputs, evapotranspiration and groundwater extractions are negligible, the streamflow recession curve will be an expression of the storage-outflow relation for the catchment. Knowledge of this relation can be useful for applications including forecasting and prediction of baseflow (Bako and Owoade, 1988; Vogel and Kroll, 1992). Previous recession analyses for baseflow separation have focused mainly on catchments fed by substantial aquifers (Clausen, 1992). However, in many catchments, baseflow may be provided by drainage of a saturated zone rather than by deeper groundwater (Anderson and Burt, 1980). Beven and

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Kirkby (1979) developed a conceptual model (TOPMODEL) for drainage of the saturated zone in a shallow soil. Ambroise et al. (1996) extended this model and tested the predicted recession behaviour against the master recession curve for a 36 ha catchment with mixed grassland and forest cover. Apart from these studies, little empirical attention appears to have been paid to the form of the storage-outflow relation for a saturated throughflow system in field catchments.

Storage-outflow modelling of streamflow recessions allows the determination of characteristics for the groundwater reservoir, a prerequisite for the separation of baseflow from total flow and the estimation of groundwater storage and recharge. Following tradition, and because of the easier mathematical formulation, conceptual models for storage-outflow relationships are still predominantly linear. For storage-outflow modelling of streamflow recessions the algorithm of the single linear reservoir is commonly used in engineering practice and research studies for baseflow separation (Nathan and McMahon, 1990; Wood *et al.*, 1992; Schwarze *et al.*, 1997). However, it is unlikely that natural storage effects could be truly linear (Prasad, 1967; Wittenberg, 1994; Moore, 1997; Wittenberg, 1999). The large number of existing techniques and the high level of subjectivity in separating baseflow contribution from total streamflow (Tallaksen, 1995) indicates that the problem is not fully understood. This study therefore, has two main objectives. The first is to explore the extent to which the assumption of linearity is valid with application to semi-arid catchments. The second objective was to introduce an alternative method to the baseflow separation algorithms for estimating direct runoff time series.

2. METHOLOGY

2.1. Catchments and Data

The data used in this study were rainfall and streamflow records available on a daily basis for 4 catchments of the Usangu plains of the Great Ruaha basin in Tanzania. The details of the selected catchments are given in Table 1. Figure 1, shows the map of the location of the catchment area within Tanzania.

According to DANIDA (1995), most of the Usangu plains are semi-arid dominated by erratic and unreliable rainfall varying between 400-600 mm per year. The annual potential evaporation varies from approximately 1400 mm to 1850 mm. Most of the plains are flat and the average elevation only varies from 1000 m to about 1150 m.

Table 1: Data for the selected catchments in the Usangu plains (DANIDA, 1995)

Station code	Catchment name	Hydrometric station	Location		Area (km^2)
			Latitude	Longitude	
IKA7A	Chimala	Chitekelo (MBEYA)	8° 55'S	33° 58'E	167
IKA8A	Great Ruaha	Salimwani (MBEYA)	8° 54'S	37° 07'E	795
IKA9	Kimani	Gt. N. Road (MBEYA)	8° 51'S	34° 11'E	448
IKA11A	Mbarali	Igawa (MBEYA)	8° 47'S	34° 22'E	1600

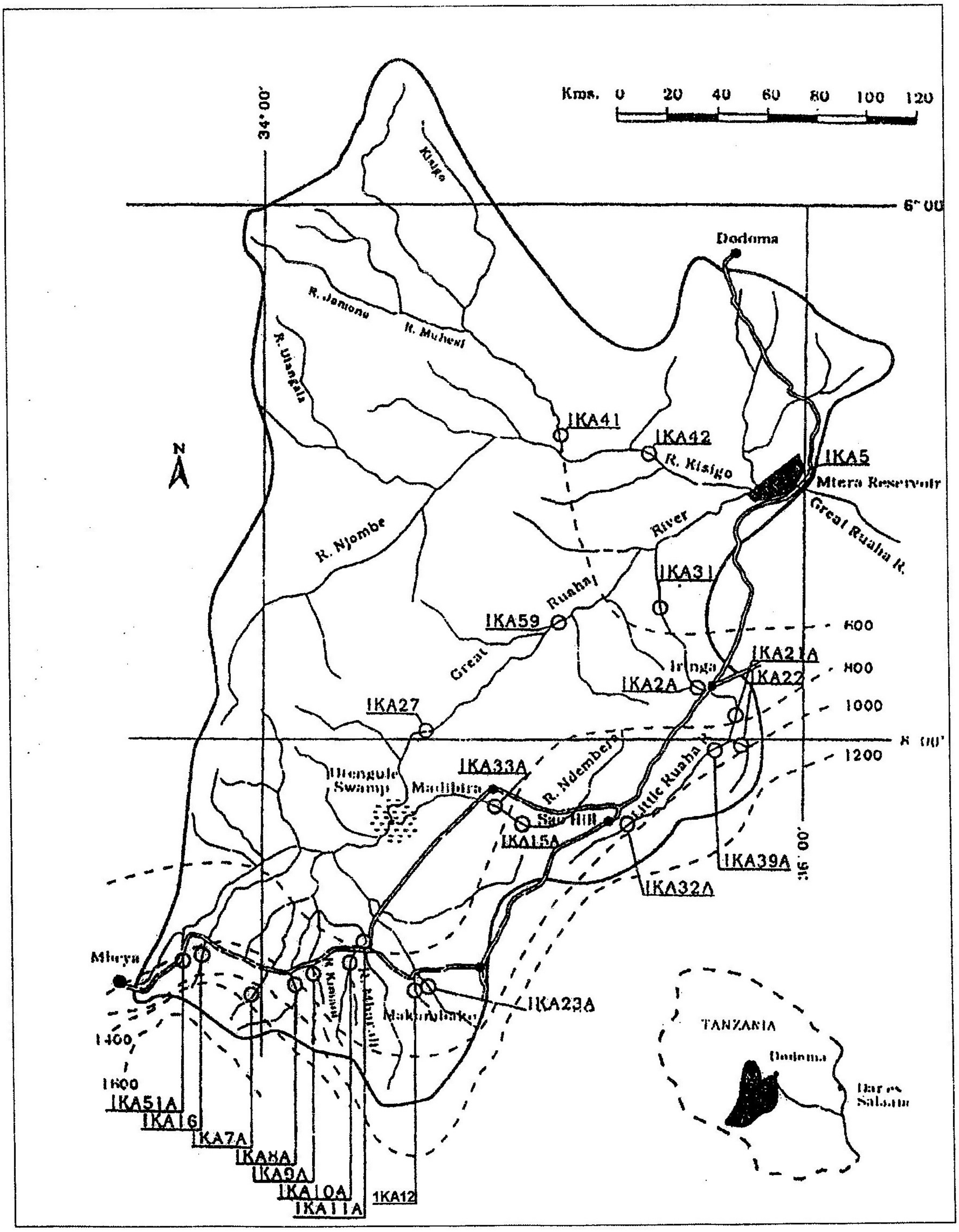

Figure 1. Location of hydrometric stations and mean annual rainfall (dotted lines)

Since the baseflow in this study is assumed to be provided by drainage of the saturated zone in the shallow permeable soil, all catchments with ephemeral streams were excluded in the analysis, also to limit the uncertainty introduced by lumped handling of rainfall, the catchment size was restricted to 1600 km². For this reason, four samples of catchment were selected as representative of the statistical population of catchments in the region. The selected catchment consists of main rivers upstream the irrigation schemes in Usangu plains. The vast majority of the consumption water uses (both natural and due to human activities) is taking place in this area. The main water demand in the Usangu plains is due to abstraction of water for irrigation purposes. With the continuous in-migration to the area and the extension of the paddy irrigation schemes further increase in the water demand may be expected in the future.

2.2 Data Analysis

2.2.1 Storage-Outflow Modelling of Streamflow Recession

Two conceptual storage-outflow models with single reservoirs were considered. These were the linear reservoir and the non-linear (exponential) reservoir models.

2.2.1.1 Linear Reservoir Model

The continuity equation for a reservoir was given by Singh (1988) as:

$$I - Q = \frac{ds}{dt} \qquad (1)$$

where I is the rate of inflow, Q is the rate of outflow, and S is the storage. These quantities are all functions of time.

Using a simple linear relationship between discharge and storage:

$$S = kQ \qquad (2)$$

where k is the storage parameter.

The continuity equation for a linear groundwater reservoir without inflow, yields:

$$\frac{ds}{dt} = -Q \qquad (3)$$

since S = KQ, equation (3) becomes,

$$K\frac{dQ}{dt} = -Q \qquad (4)$$

Integration of equation (4) in the limits t = 0 and t, with Q_o and Q_t, respectively yields:

$$\int_{Q_o}^{Q_t} \frac{dQ}{Q} = -\frac{1}{K}\int_0^t dt \qquad (5)$$

which in turn yields:

$$\log(Q_t) = -(1/k)\,t + \log(Q_o) \qquad (6)$$

From Equation (6) a plot of $\log(Q_t)$ against time (t) yields a straight line with a slope of 1/k

Ever since Maillet (1905), this linear function has been widely used to describe the baseflow recession, where Q_t is the discharge at time t, Q_o the initial discharge, and k the recession constant which can be considered to represent average response time in storage. This linear function implies that the groundwater aquifer behaves like a single linear reservoir with storage linearly proportional to outflow, namely S = kQ (Wittenberg and Sivapalan, 1999).

It is, however, evident that the parameter k fitted to different discharge ranges of the recession curves in actual rivers does not remain constant but increases systematically with decrease of streamflow (Wittenberg, 1994; Moore, 1997), which is a strong indication of nonlinearity. The convenient assumption that the baseflow may be the outflow from two or more, parallel linear reservoirs, representing components of different response times is often made (Moore, 1997), and does result in better fits to the observed recession curves. However, this is perhaps only because there are more parameters to be calibrated, giving more degrees of freedom for curve fitting. In most catchments it is unlikely that the dynamic groundwater aquifer can be divided so neatly into such independent storage zones. It is more likely that it consists of a spatially variable system of hydraulically communicating pore or fissure systems. Thus, the use of single but non-linear reservoir is considered to be more physically realistic. Non-linear reservoir algorithms using power law model have been proposed and implemented in a large number of catchments around the world (Wittenberg, 1994; Wittenberg, 1999; Chapman, 1997; Brutsaert and Lopez, 1998). In the present study, to allow for non-linearity the linear storage-outflow relationship is generalised by an exponential reservoir model (Beven *et al.*, 1995).

2.2.1.2. Exponential Reservoir Model

The exponential storage-outflow relation was originally proposed as part of the TOPMODEL concept by Beven and Kirkby (1979), and is based on assumptions of quasi-steady state saturated throughflow in a soil in which hydraulic conductivity decreases exponentially with depth. For the purpose of this study, the exponential reservoir model is generalized as:

$$Q_b = Q_o e^{-z/m} \qquad (7)$$

where Q_b is the outflow from the saturated zone considered as baseflow, Q_o is the initial discharge, z is the local water table depth and m is a model parameter. The derivation of Equation (7) can be found in Beven and Kirkby (1979); Beven *et al,*. (1995) and Beven (2000).

A revised formulation of the TOPMODEL stores has been presented by Beven *et al.* (1995) and it shows that if a linear relationship between local storage deficit s and depth to water table z holds, Equation (7) can be written as:

$$Q_b = Q_o e^{-s/m} \qquad (8)$$

Solution of Equation (8) for a pure recession in which inputs are assumed to be zero shows that discharge has an inverse or first order hyperbolic relationship to time as:

$$\frac{1}{Q_b} = \frac{1}{Q_o} + \frac{t}{m} \qquad (9)$$

2.2.2 Parameter Estimation and Baseflow Separation

If Equation (9) is an appropriate relationship to represent the subsurface drainage of a given catchment a plot of $1/Q_b$ against time should plot as straight line with slope 1/m. The catchment average storage deficit before each time step is updated by subtracting the unsaturated zone recharge and adding the baseflow calculated for previous time step, thus:

$$S_{t+1} = S_t + Q_o e^{-\left(\frac{S_t}{m}\right)} - CR_t \qquad (10)$$

Where R_t is the observed rainfall at time t and c is a parameter to be calibrated.

If an initial discharge, $Q_{t=0}$, is known and assumed to be only the result of drainage from the saturated zone, Equation (8) can be inverted to give a value for S at time t = 0 as:

$$S = -m\left[\ln\left(\frac{Q_{t=o}}{Q_o}\right)\right] \qquad (11)$$

The Equation (10) to (11) therefore, form the basis for separating the baseflow from the total streamflow during storm events. Then given the time series of streamflow and rainfall, the time series of direct runoff (storm runoff) Q_d can be calculated as:

$$Q_d = Q_t - Q_o e^{-\left(\frac{S_t}{m}\right)} \qquad (12)$$

where Q_t is the total observed streamflow at time t.

Therefore in this approach, three parameters were considered (m, Q_o and c) for estimating baseflow using an iterative algorithm method. These parameters may be considered to be bulk "physical" characteristics at the catchment scale. Parameter c represent the proportion of rainfall which percolates as recharge to the groundwater; parameter m has been suggested by Beven *et al.*, (1995) as a scaling depth of the effective catchment soil profile; parameter Q_o is a discharge when recession of streamflow commences. The model performances were evaluated from the graphical comparison between the recession curves of observed Q_t and the estimated Q_b. And Nash-Sutcliffe efficiency which is statistically known as coefficient of determination indicating proportion of the variance in the data explained by the model was used to assess the goodness of fit and is defined by Nash and Sutcliffe (1970) as:

$$R^2 = 1 - \frac{\sigma_e^2}{\sigma_o^2} \qquad \sigma_e^2 = \Sigma(Q_o - Q_s)^2; \qquad \sigma_o^2 = \Sigma(Q_o - Q_m)^2 \qquad (13)$$

where Q_o is the observed recession flow; Q_s is the simulated recession flow; Q_m is the mean observed recession flow; σ_o^2 is the variance of the observed recession flow data calculated over all time steps used in fitting the model and σ_e^2 is the variance of the differences between observed and simulated recession flow at each time step. As the model fit improves the value of R^2 will approach 1. If the model is no better than fitting the mean of the observed recession flow ($\sigma_e^2=\sigma_o^2$), the value of R^2 will be zero or less.

The approach of Generalised Likelihood Uncertainty Estimation (GLUE) methodology as proposed by Beven (2000) was used to assess the parameter sensitivity. The evaluation procedure was based on the following major steps:

1 Determining a feasible parameter ranges from initial analysis of recession curves and calibration of exponential reservoir model;
2 Using a Monte Carlo Simulation method to choose random parameter values from uniform distributions spanning specified ranges of each parameter;
3 Using a likelihood value (Nash-Sutcliffe efficiency) to divide acceptable simulations (value>0.5) from unacceptable simulations (value <0.5);
4 Normalizing likelihood values for the parameter sets that yield acceptable simulations such that the sum of the normalized likelihood values equals 1; and
5 Using the same generated parameter sets and associated likelihood value and model outputs to assess parameter sensitivity.

In the GLUE procedure a prior likelihood estimate was updated with a new (posterior) likelihood measure calculated for the prediction of a new set of observation. The *Bayes equation* was used to find a reasonable combined likelihood measure. The type of combination using *Bayes equation* may be expressed in the form:

$$L_p(\underline{\Theta}_i|\underline{\mathrm{Y}}) = \frac{L_o(\underline{\Theta}_i)L(\underline{\Theta}_i|\underline{\mathrm{Y}})}{C} \qquad (14)$$

Where $L_o(\underline{\Theta}_i)$ is the prior likelihood of the i^th^ parameter set; $L(\underline{\Theta}_i|\underline{\mathrm{Y}})$ is the likelihood calculated for the current evaluation given the set of observations $\underline{\mathrm{Y}}$; $L_p(\underline{\Theta}_i|\underline{\mathrm{Y}})$ is the posterior likelihood and C is a scaling constant to ensure that the cumulative posterior likelihood is unity.

3. RESULTS AND DISCUSSIONS

Two inferences can be drawn from the graphical interpretation of streamflow recession curves. First, if the recessions were consistent with a linear reservoir model, they would plot as straight lines on a semi-log graph. As seen in Fig. 2, the plot of log(Q) against time shows that, the recessions are clearly non-linear. The linear reservoir model is generally recognised in this study as being valid over only a limited range of recession period, this indicates that, response (retention) time will not be a constant over longer ranges and computed baseflow will not reflect reality. Secondly, if the recessions were consistent with the exponential reservoir model, they would plot as straight lines on a plot of 1/Q against time. Figure. 3, shows that the recessions are roughly consistent with the exponential (non-linear) reservoir model. However, the variation in shapes of some recession segments indicates either that the catchment behaves like a multi-reservoir system, or that variations in recharge exert a major influence on streamflow recessions.

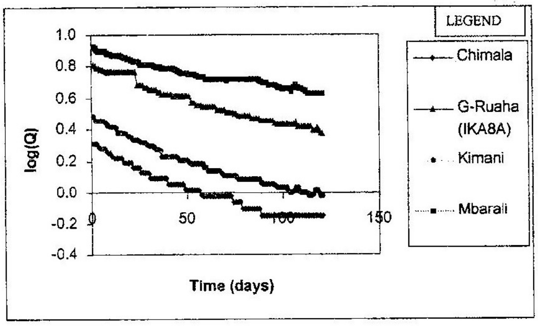

Figure 2. Recession flow segments for the linear resevoir model

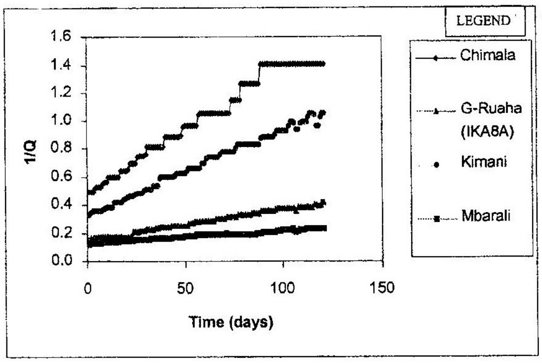

Figure 3. Recession flow segments for the non-linear (exponential) resevoir model

The analysis of streamflow recession curves obtained from time series of daily discharges achieved close fit to exponential reservoir model. However, there is high variation in values of parameters from one event to the next, as evidenced by average deviation from the recession curves, expressed in terms of the coefficient of variation (standard deviation divided by the mean, corresponding to the least squares criterion) for each parameter (see Table 2). It can be hypothesized that this is due to spatial variations in groundwater storage, occurring as a result of spatial variations in rainfall and subsequent recharge.

Table 2. The mean estimated parameters of the exponential reservoir model

	Chimala catchment				G-Ruaha catchment			
Year	m	Qo	c	R²	m	Qo	c	R²
1962	71.86	10.00	0.30	0.95	271.70	10.00	0.80	0.55
1963	50.72	10.00	0.45	0.97	362.26	9.00	0.80	0.97
1964	84.81	10.00	0.50	0.99	543.40	11.00	0.75	0.99
1965	60.87	6.00	0.30	0.93	1086.79	11.00	0.20	0.96
1966	69.91	11.00	0.40	0.93	987.99	11.00	0.30	0.96
1967	77.22	11.00	0.30	0.89	67.92	6.00	0.30	0.73
1968	67.19	8.00	0.30	0.98	60.38	7.50	0.28	0.98
1969	41.72	3.50	0.35	0.98	43.47	6.00	0.30	0.99
1970	82.12	10.00	0.30	0.97	54.34	10.00	0.28	0.97
1971	53.34	4.50	0.60	0.97	51.75	6.00	0.40	0.97
1972	68.07	2.00	0.40	0.92	57.20	6.00	0.40	0.98
1973	58.79	6.50	0.50	0.97	54.34	6.00	0.40	0.98
1974	50.72	6.50	0.50	0.97	50.72	6.50	0.50	0.99
1975	59.47	6.50	0.40	0.95	59.47	6.50	0.40	0.99
1976	58.13	6.50	0.40	0.96	58.13	6.50	0.40	0.96
1977	40.74	6.50	0.30	0.98	40.74	6.50	0.30	0.99
1978	71.86	6.50	0.30	0.95	47.25	7.50	0.30	0.98
1979	72.87	10.00	0.40	0.98	35.06	7.50	0.35	0.86
1980	52.79	4.50	0.40	0.96	43.47	5.00	0.35	0.95
mean	62.80	7.34	0.39	0.96	209.28	7.66	0.41	0.93
std dev.	12.68	2.67	0.09	0.03	321.79	2.01	0.18	0.11
CV	0.20	0.36	0.23	0.03	1.54	0.26	0.43	0.12

	Kimani catchment				Mbarali catchment			
Year	m	Qo	c	R²	m	Qo	c	R²
1962	31.62	5.00	0.35	0.99	180.00	6.00	0.60	0.96
1963	35.71	5.00	0.35	1.00	135.00	6.00	0.32	1.00
1964	35.06	3.00	0.18	0.99	135.00	6.00	0.36	0.99
1965	25.71	3.00	0.18	1.00	60.00	3.00	0.30	0.95
1966	29.22	3.00	0.18	1.00	45.00	2.50	0.30	0.98
1967	32.14	3.00	0.18	1.00	60.00	2.50	0.28	0.99
1968	45.92	6.00	0.25	0.99	54.00	3.00	0.30	0.75
1969	37.09	1.50	0.20	0.79	41.54	2.50	0.30	0.97
1970	26.42	5.50	0.20	0.99	60.00	3.00	0.30	0.98
1971	33.25	3.00	0.40	0.97	54.00	3.00	0.25	0.98
1972	26.42	3.00	0.20	0.98	54.00	3.00	0.30	0.98
1973	34.44	3.00	0.30	0.99	67.50	3.00	0.25	0.97
1974	32.14	3.50	0.20	0.99	54.00	1.50	0.35	0.98
1975	30.13	3.00	0.20	0.99	60.00	1.50	0.18	0.97
1976	31.11	4.00	0.20	0.99	54.00	2.50	0.30	0.98
1977	30.13	2.50	0.18	0.99	25.71	2.50	0.30	0.92
1978	35.06	4.00	0.20	0.99	41.54	3.00	0.25	0.93
1979	33.83	4.00	0.30	0.99	41.54	2.50	0.30	0.91
1980	27.55	2.00	0.25	0.99	41.54	2.50	0.30	0.91

mean	32.26	3.53	0.24	0.98	66.55	3.13	0.31	0.95
std dev.	4.71	1.17	0.07	0.05	39.32	1.35	0.08	0.06
CV	0.15	0.33	0.29	0.05	0.59	0.43	0.26	0.06

An impression of the parameter sensitivity can be gained from Figure 4, which depicts the cumulative distributions for each parameter. Lacking any prior information about the covariation of the individual parameters, each was sampled independently from uniform distributions across the feasible parameter range. A straight line on each plot would represent the prior distributions. The strongest departures from the prior distributions are shown by parameter c indicating that is more sensitive than other two parameters.

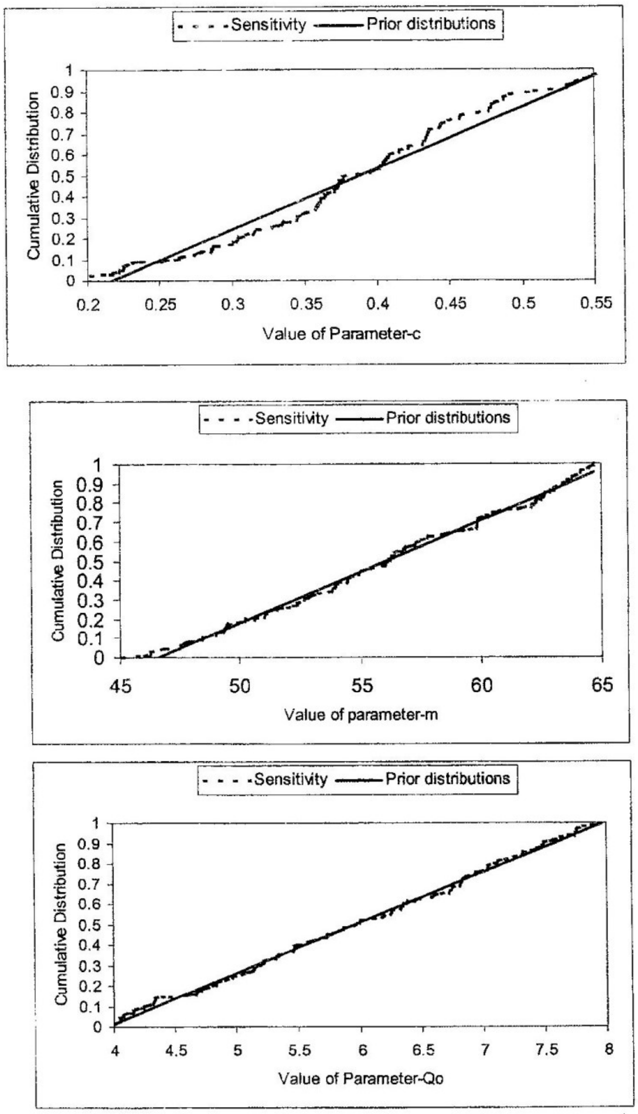

Figure 4. Parameter sensitivity analysis

Within the GLUE framework, the parameter sensitivity analysis approach used in this study is essentially a *nonparametric* method in that it makes no prior assumptions about the variation or covariation of different parameter values, but only evaluates sets of parameter values in terms of their performance. The special characteristic of *Bayes equation* within the GLUE framework, is its multiplicative operation, if any evaluation results in a zero likelihood, the posterior likelihood will be zero regardless of how well the model has performed previously. This may be considered as an important way of rejecting non-behavioural model parameters, it may cause a re-evaluation of the data for that period. As an example, the synthesized baseflow hydrographs using an exponential reservoir model are shown in Fig. 5. This figure depicts major components of hydrograph: Direct (storm) runoff and Baseflow (groundwater runoff).

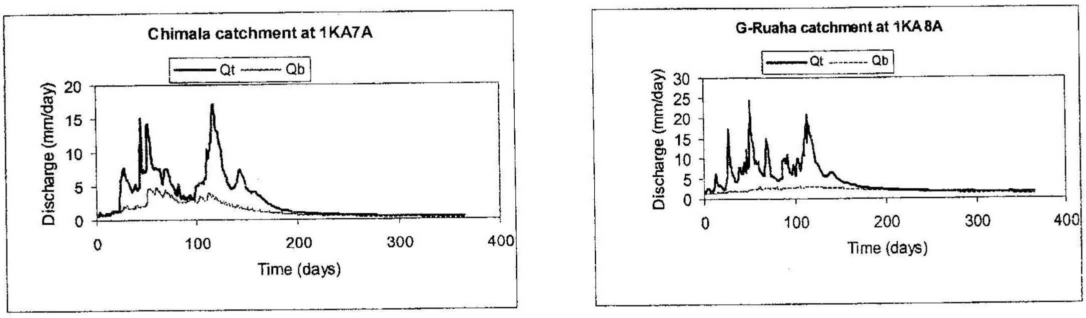

Figure 5(a). Total observed streamflow (Qt) and estimated baseflow (Qb) for 1980 period.

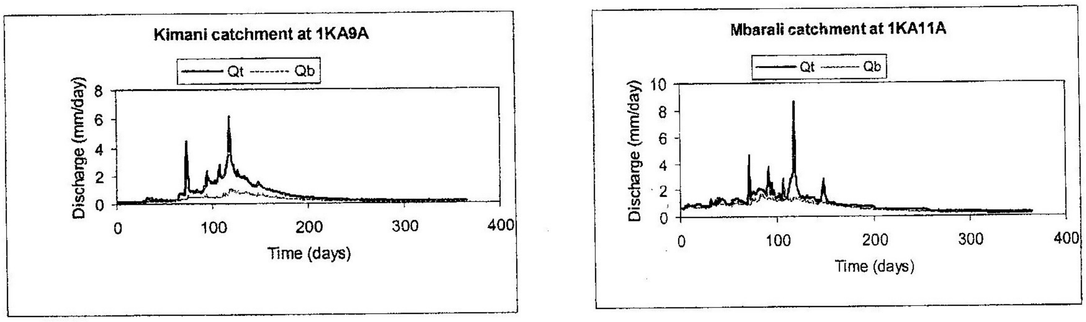

Figure 5(b). Total observed streamflow (Qt) and estimated baseflow (Qb) for 1980 period.

4. CONCLUSIONS

The main aim of this study was to explore the extent to which the assumption of linearity in storage-outflow relationships is valid and to introduce an alternative method to the baseflow separation algorithms for estimating direct runoff time series. Diagnostic plots revealed that the recessions were non-linear. Though the linear reservoir can be fitted satisfactorily to shorter recessions, the classical assumption of the linear reservoir is still an unquestioned component in otherwise highly developed models and should be reviewed. The non-linearity of the storage-outflow relationships found in this study is used to introduce an alternative approach to the baseflow separation algorithms. The study has gone further to examine parameter sensitivity for the non- linear (exponential) reservoir model. Finally the study has found that a major difficulty in storage-outflow modelling of streamflow recessions, irrespective of linearity of the model is the variation of model parameters from one event to the next.

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