Journal of Agriculture, Science and Technology

REGIONALISATION OF PARAMETERS OF A CONCEPTUAL RAINFALL-RUNOFF MODEL FOR STREAM FLOW ESTIMATION IN UNGAUGED CATCHMENTS: AN APPLICATION TO THE UPPER TANA BASIN, KENYA

J. K. Mwangi
Department of Civil Engineering, Jomo Kenyatta University of Agriculture and Technology, Nairobi
E-mail: joymwa86@yahoo.com

ABSTRACT

Design of hydraulic structures for the storage and conveyance of water in river basins poses major problems in ungauged catchments due to lack of sufficient stream flow data. Improvement of stream flow data can be achieved through rainfall-runoff modelling, where rainfall-runoff models are used to simulate stream flow. For a model to be used for stream flow simulation in ungauged catchments, its conceptual parameters need to be correlated to its physical catchment characteristics, a process known as regionalisation. IHACRES, a lumped conceptual rainfall-runoff model was calibrated to six catchments ranging in size from 49 km^2 to 600 km^2 within the upper Tana basin to obtain a set of model parameters that characterise the hydrological behaviour of these catchments. Physical catchment characteristics representing topography, soil and land cover were derived from spatial data using GIS. By correlating these two sets of parameters, equations were developed which related the conceptual parameters to catchment characteristics and which enabled the estimation of model parameters from catchment characteristics. The estimated parameters were used to simulate stream flows in two validation catchments within the same geographic region and the goodness of fit evaluated. The stream flows simulated using the derived regional parameter sets agreed well with the observed stream flow series. The R^2 values were 0.21 and 0.67 while the Nash-Sutcliffe efficiency values were 0.21and 0.68 respectively. Although some R^2 values were low, considering limitations of data availability and quality, the results showed that the methodology can be used to generate stream flow data in ungauged catchments for water resources planning and other management interventions.

Key words: GIS, IHACRES, rainfall-runoff model, ungauged catchments, simulation

1.0 INTRODUCTION

The planning, design and operation of water resources systems are important components of river basin management. The development of sound river basin management strategies requires long term stream flow data for estimating water balances at different points in a stream network. These data can be obtained from catchments gauged with automatic flow recorders. However, such instruments are expensive to acquire and maintain, hence many catchments in developing countries are ungauged and even the gauged ones have inconsistent records. This is because gauging stations may be insufficient, irregularly distributed or poorly maintained. Stream flow data is therefore inadequate and need to be improved. This is achieved through rainfall-runoff modelling using distributed, semi-distributed or lumped models. Distributed models are complex and hence limited in application due to huge data requirements. The less complex lumped models are widely used because they require less input data and pose little computational burden.

Rainfall-runoff models used for generating stream flow data have either conceptual parameters only or both conceptual and physical parameters that need to be determined before they can be used for data generation. Conceptual parameters are determined through model calibration, which is achieved through optimisation algorithms, (Sorooshian and Gupta, 1995) and requires rainfall and stream flow data. Physical parameters are determined using spatial data from topographic, soil and land use maps in a GIS environment. Most studies on rainfall-runoff modelling have concentrated on gauged catchments because of availability of data for model calibration and validation. However, major problems occur in ungauged catchments where water resources management interventions have to be carried out using limited data. Direct adoption of models from gauged catchments is not feasible due to variability of hydrological processes from one place to another (Pilgrim, 1983). Rainfall-runoff models can be used to generate data in ungauged catchments after regionalisation, which involves relating flow characteristics at gauging stations to catchment physical and climatic characteristics. The resulting quantitative relationships are then used to derive model parameters for the ungauged catchments, allowing simulation of stream flows given rainfall data. Better simulation results are obtained if the selected catchments are in the same region where there is minimal variability in hydrological processes (Onyando *et al.*, 2005). Models for use in regionalisation should be those with few parameters in order to avoid over-parameterisation (Pilgrim, 1983; Jakeman and Hornberger, 1993).

Various regionalisation methods have attempted to apply models to ungauged catchments using models of variable complexity (Post and Jakeman, 1996, 1999; Kokkonen *et al.*, 2003; Sefton and Howarth, 1998). However, such studies have been limited in Kenya due to lack of consistent data for model calibration and validation. Past studies on rainfall-runoff modelling have been reported by Onyando (1994), Onyando and Sharma (1995) and Onyando and Chemelil (2004) and

Onyando *et al.,* (2005) who, using event based rainfall and runoff data from humid areas of Kenya, simulated stream flows using lumped models. The main limitation of regionalisation as a method of estimating stream flows in ungauged catchments is the need for data from many catchments in the same region (Kokkonen, 2002). Although use of many catchments gives better relationships between model parameters and catchment attributes (Schaake *et al.,* 1997), it increases the variation of climate and physiography hence introducing more variables in the regression analysis (Seibert, 1999). Generally, catchments with similar characteristics show similar hydrological behaviour and hence it is possible to provide a regional parameter set where parameter values vary with measurable catchment characteristics (Seibert, 1999).

The objective of this study was to simulate daily stream flows in sub-catchments of the Upper Tana basin using regionalised parameters of IHACRES (Identification of Hydrographs and Components from Rainfall, Evaporation and stream flow) model.

2.0 DESCRIPTION OF STUDY AREA

The study area lies in central Kenya between longitudes 36.58°E and 37.54°E and latitudes 0.16°S and1.20°S, at an altitude of between 1,000 m and 4,000 m (Figure 1). It experiences a bimodal rainfall pattern with rainfall increasing with altitude. Stream flows are influenced by climate with topography and relief affecting seasonal and annual rainfall distributions. The upper parts of the basin receive an annual rainfall of about 1,200-2,400 mm, while the lower parts receive about 800-1,200 mm annually (Jaetzold and Schmidt, 1983). These rainfall variations have an effect on stream flows such that seasonal distribution of rainfall is reflected in stream flow variations. Estimated potential evaporation exceeds rainfall in most parts of the basin except for the high altitude areas, with the deficit being most pronounced in the lower catchments. The annual average is 1,500 mm.

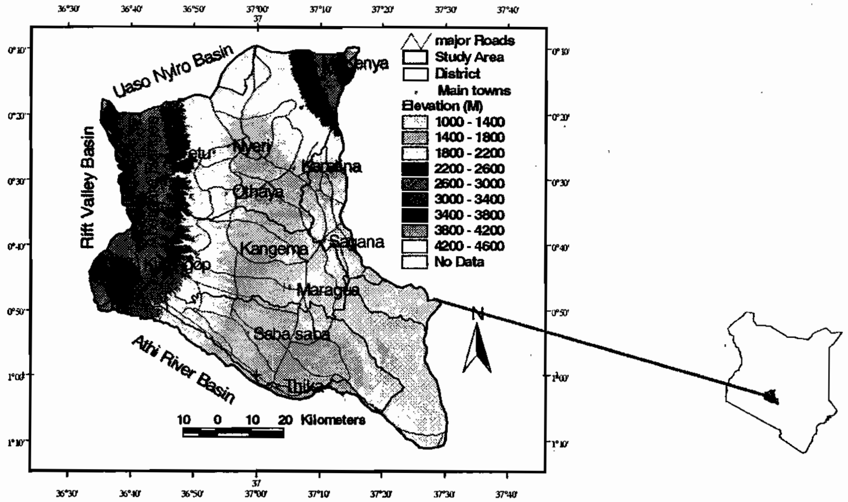


Figure 1: Location and relief of study area

The area is drained by several perennial streams that include Chania, Thika, Maragua, Rwamuthambi, Sagana and Gura, that originate from the western slopes of Mt Kenya and the eastern slopes of the Aberdare Ranges. Flows in these streams show marked variations in seasonal and annual volumes that pose a major challenge to the management of water resources in the basin. The area is divided into various agro-ecological zones with different soil types that influence land use are predominantly clay-loams of volcanic origin that have high infiltration rates, are resistant to erosion and are highly permeable. They are suited for coffee and tea growing. The area is densely populated with intensive irrigated agriculture that reduces the dry season's low flow in streams.

3.0 METHODOLOGY

3.1 The Rainfall-runoff Model

The IHACRES is a lumped parameter rainfall-runoff model based on the unit hydrograph principles that uses temperature and rainfall data to estimate stream flow. The parameters are calibrated prior to simulation by comparison with observed stream flow data (Jakeman and Hornberger, 1993). During calibration, four of the model's parameters c (increase in catchment wetness index per unit rainfall in the absence of any decrease due to evapotranspiration. It is usually set such that the volume of rainfall excess is equal to the total stream flow volume over the estimation period), t_q (the recession time constants for quick flow), t_s (the recession time constant for slow flow) and v_s (the proportional volumetric contribution of slow flow to total stream flow) are determined directly from the raw rainfall, stream flow and temperature data, while the other two parameters t_w (the rate at which catchment wetness declines in the absence of rainfall) and f (temperature modulation factor which determines how t_w changes with temperature for a constant catchment wetness index (S_k) are calibrated using a trial and error procedure, optimising the model fit to the observed data.

IHACRES consists of two modules in series. The first module is a non-linear loss module that converts rainfall to effective rainfall, defined as that part of rainfall that leaves the catchment as stream flow. It uses temperature and rainfall data to estimate relative catchment moisture index which determines the proportion of rainfall that becomes effective rainfall. The second module is a linear unit hydrograph module representing the transformation of effective rainfall to stream flow. It allows a flexible configuration of linear stores in parallel and/or series (Figure 2), which is identified from the time series of rainfall and stream flow data, but is either one store only, representing ephemeral streams, or two stores in parallel, allowing both slow and quick flows to be represented. The parsimony of the linear module ensures that the model is defined by just six parameters, making it relatively simple in structure compared to other conceptual rainfall-runoff models. Its parametric efficiency makes it suitable for regionalisation studies since it is easy to relate its parameters to catchment attributes. The six parameters may be considered as dynamic response characteristics (DRCs), as together they can be used to predict daily hydrologic response of a catchment. The model assumes a linear relationship between effective rainfall and stream flow. The non-linearity normally observed between rainfall and stream flow is accommodated in the non-linear module, which converts rainfall to effective rainfall, the underlying concept being that catchment wetness varies with antecedent rainfall and evapotranspiration. A catchment wetness index, S_k which indicates the potential of the catchment to produce stream flow from rainfall is therefore computed at each time step. It varies from zero to unity, depending on the antecedent rainfall and the rates of water loss to evapotranspiration and stream flow.

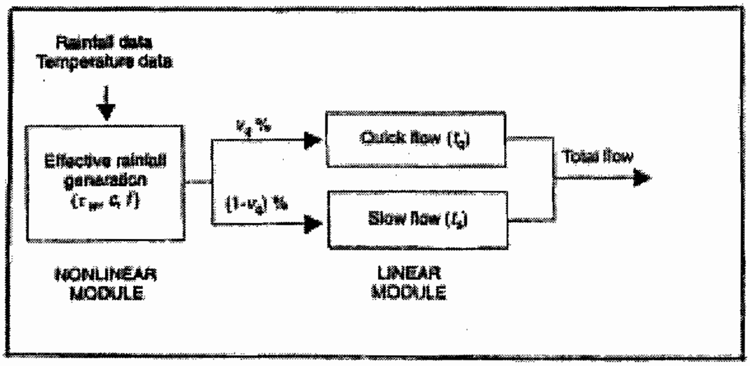


Figure 2: Schematic representation of the IHACRES model

Source: Kokkonen *et al.,* (2003)

A zero value of S_k indicates a relatively dry catchment, with rainfall falling at this time producing no effective rainfall, while a value of unity indicates that the catchment is relatively saturated and all rainfall falling at this time will become effective rainfall. The index S_k is given by:

$$S_k \quad \frac{r_k}{c} \quad 1 \quad \frac{1}{{}_w\, t_k} \quad S_{k\ 1} \quad \text{.......................................}(1)$$

where c is the parameter that determines the impact that a unit input of rainfall has on the catchment storage, r_k is rainfall and $t_w(t_k)$ is the time constant (days) of catchment losses at daily mean temperature t_k (C) according to:

$${}_w\, t_k \quad {}_w \exp 20 f \quad t_k f \quad \text{.......................................}(2)$$

where t_w is the time constant (days) of catchment losses at 20°C. The constant 20°C is a reference temperature chosen depending on conditions in the study area and may therefore vary while ¦ is a factor describing the effect of a unit change in temperature on the loss rate. Effective rainfall u_k is then calculated according to:

$$u_k \quad \frac{1}{2} \; s_k \quad s_{k\ 1}\, r_k \quad \text{.......................................}(3)$$

The percentage of rainfall, that becomes effective rainfall in any time step, varies linearly (between 0 and 100 %) as the catchment wetness index varies (between 0 and unity). For calibration, the model requires time series of rainfall, stream flow and a surrogate variable representing evaporation.

3.2 The Catchments

The area was delineated into sub-catchments using a 90 m by 90 m shuttle radar topographic mission (SRTM) DEM and the established river gauging stations as outlet points. The DEM was also used to derive topography based physical catchment descriptors (PCDs) required in the development of PCD-DRC relationships. Basing on availability of continuous rainfall and stream flow data for model calibration and validation, six catchments were selected for the study. The selected catchments covered a wide range of locations and morphological types with each catchment being limited to 600 km^2 in order to reduce uncertainties that may result from lumping of rainfall. The catchments were selected such that they were representative of the statistical population of catchments in the area both geographically and in parameters space.

3.3 Hydrological Data

Stream flow data was obtained from the Ministry of Water Resources and Irrigation for eight gauging stations covering the period 1970-1990. After evaluation, the period 1970-1975 was selected for further analysis because of good quality data that was available. The criteria adopted for the selection of stations was quality of data, length of available records, spatial distribution and minimum percentage of missing data (less than 10% WMO, 1994). Rainfall data for 16 stations for the concurrent period were obtained from the Kenya Meteorological Department.

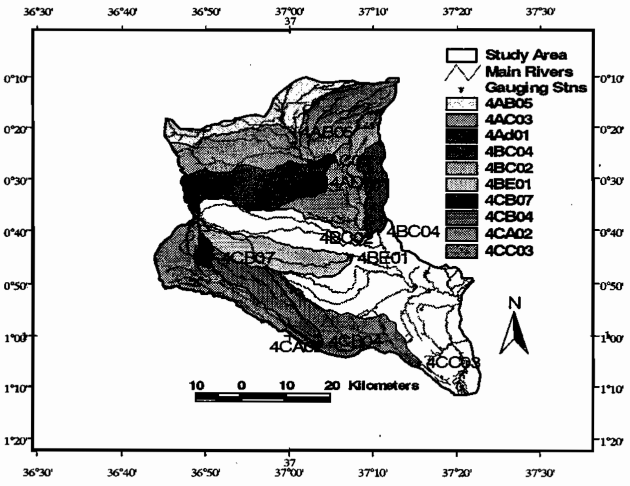


Figure 3: Delineated study catchments

The raw data were checked to identify and fill in missing values. To fill in missing stream flow data, an average of that particular day's flow over a twenty year period was taken, while missing rainfall values were filled using the inverse distance method, which involves computing the weights of the surrounding rain gauges on the basis of their distances from the rain gauge with the missing rainfall data (Muthusi, 2004). Monthly temperatures for the area and period of study for were obtained from Kalders (1988). Areal rainfalls were computed using the Thiessen polygon method, which attempts to make allowance for irregularities in gauge locations by weighting the record of each gauge in proportion to the area, which is closer to that gauge than to any other gauge.

3.4 Model Calibration and Validation

The model was calibrated with daily rainfall-stream flow time series during a common period of observation (1970-75) in order to account for climatic variability. For each catchment, a real rainfall, stream flow and monthly temperature data were used to calibrate and validate the model. Firstly, the period of record was divided into three non-overlapping two-year calibration periods (Jakeman *et al.*, 1993), which allowed each model to be exposed to some inter-annual variability. It also balanced the problems of variance and bias by ensuring that the hydrological response of the catchment does not change during the calibration period. Shorter calibration periods generally yield model parameters with very high variance while longer calibration periods are likely to encompass changes in the hydrologic system such as a shift in the stage discharge-rating curve (Jakeman *et al.*, 1993). The models were therefore calibrated for two years (1970-71, 1972-73 and 1974-75). Since IHACRES model assumes an initial catchment wetness index (S_k) of zero, each calibration period was made to start and end on a low flow (in this case the month of January). The parameters of the model that performed well with all catchments were adopted as the dynamic response characteristics (DRCs) of these catchments and related with their physical catchment characteristics. A model validity test was performed which involved keeping the parameter sets obtained during calibration constant and running the model in simulation. The resulting simulated flows were compared with the observed flows and the goodness of fit evaluated graphically and statistically. Sensitivity tests which involved assessing flow response to variations in model parameters were carried out in one of the calibration catchments,. Since IHACRES model package automatically determines the value of parameters t_q, $_s$, n_s and c, only parameters ¦ and t_w were varied during calibration.

3.5 Derivation of Physical Catchment Descriptors

Physical catchment indices were derived for all catchments, to represent topography soil and land cover using the DEM, soil and land cover maps. Based on spatial distribution and low correlation with other indices, 14 indices were selected for further analysis. IHACRES being a conceptual model, no field measurements of these attributes were carried out and this limited the information available to quantify some PCDs. The inclusion of time variant indices allowed the hydrological response of these catchments to be affected by changing land use/climate, an implicit assumption being that the DRCs-PCDs relationships were constant and that change in either of them did not affect the processes governing these responses. The PCDs were quantified as follows:

3.5.1 Topographical Indices

Drainage density (D_Dens) was obtained by dividing the total length of streams within each catchment by its area.

3.5.2 Mean Catchment Slope and Elevation (Elev.)

These were computed from the DEM using Arc View Gis. Slope indicates the kinetic energy available to move water towards the basin outlet and is related to total flow as well as to base flow.

3.5.3 Stream Gradient (S_Gradient)

This was determined by dividing the total length of the main stream with the elevation difference between its highest point and the outlet point.

3.5.4 Catchment Area

This is defined as the area draining to the catchment outlet and was determined using Arc View Gis.

3.5.5 Land Cover and Soil Indices

The coverage of various land use types was derived from land use data available on Africover maps. These areas were divided by the respective catchment areas to obtain a dimensionless index. The same applied to soils data obtained from the digital terrain database of East Africa map (FAO, 1997)

3.5.6 Geological and Climatic Indices

Due to lack of easily quantifiable geological data, geology was omitted as a PCD. Climate was also omitted as it was assumed that IHACRES model is capable of filtering out, to a sufficient extent any effects arising from different climatic descriptors (Kokkonen *et al.*, 2003).

3.6 Development of DRC-PCD Relationships

Using data from the calibration catchments DRC-PCD relationships were developed through inspection, correlation analysis, principal component analysis, stepwise and multiple regressions.

Principal component analysis was used to identify variables that explained a large proportion of the PCD variance. A stepwise regression was performed to identify PCDs with the strongest statistical relationship with DRCs. For each DRC, the variables suggested by correlation analysis and stepwise regression were combined in a multiple regression model such that each DRC was expressed in terms of PCDs (equation 4):

$y(k) = b_0 + b_1x_1(k) + b_2x_2(k) + \text{-------------} + b_p x_p(k) + e(k)$ ....(4)

With $k = 1, \text{---------}, N$ where:

$y(k)$ represents DRC; $x_1(k), x_2(k) \ldots x_p(k)$ denotes the PCDs in the k^{th} model simulation; N represents the total number of catchments; $b_{o,}\ b_{1,}\ b_{2\ldots}\ b_p$ denotes the ordinary regression coefficients obtained by minimising the regression residual e and p is the number of PCDs used in the regression model. The quality of the resultant regression model was judged by its ability to estimate the dependent variables for observations on independent variables not used in estimating the regression coefficients.

3.7 Validation of DRC-PCD Relationships

The developed estimation equations were validated by re-calculating the parameters of the calibration catchments as well as of two validation catchments. Since the purpose of regionalisation was to estimate stream flows at ungauged catchments of the basin and not to estimate model parameters, the usefulness of regionalisation was assessed by comparing the estimated and observed stream flows for the validation catchments.

3.8 Sensitivity Analysis

The parameters t_w and ¦ were varied over their calibration ranges in order to determine the effect of their changes on hydrologic response. One parameter was varied (increased/decreased by 50%) at a time while keeping the other constant at its calibrated value. At each variation, the new parameters were used to simulate stream flows, which were then compared with those before the variation in order to assess the effect of individual parameter change on stream flow simulation. The aim was to determine which parameter was most sensitive in terms of its effect on stream flow simulation.

4.0 RESULTS AND DISCUSSION

The models calibrated over the period (1974-75) were found to characterise well the hydrologic response of these catchments as they performed well over the calibration and validation periods and also fitted well to observed data (table1). The parameter set was therefore adopted as the dynamic response characteristics (DRCs) of these catchments and used to derive the DRC-PCD relationships.

Table 1: Calibration and simulation results

Catchment ID (1970-75)	*Calibration Results (1974-75)*		*Simulation Results*	
	R^2	E	R^2	E
4CB07	0.79	0.91	0.66	0.85
4CB04	0.85	0.91	0.67	0.79
4CA02	0.76	0.8	0.55	0.78
4BC04	0.57	0.78	0.55	0.77
4BE01	0.76	0.86	0.77	0.88
4BC02	0.58	0.85	0.64	0.86

Deviations of simulated flows from observed flows were assumed to have occurred principally due to recorded rainfall, being unrepresentative of basin rainfall while variations in R^2 values during calibration and validation was attributed to differences in catchment characteristics.

4.1 Relationship Between Model Parameters and Catchment Attributes

Parameter ¦ is strongly correlated with stream gradient (Table 3), meaning that stream gradient may have an indirect link with catchment relief and hence evapotranspiration, through the effect of temperature. The value of parameter **c** depends on the rate of catchment water loss as governed by parameter t_w and hence is related to the same catchment attributes (Table 3). In addition, like ¦, it is driven by vegetation present because of the effect of vegetation on the rate of evapotranspiration. Area has a strong relationship with c as large catchments have larger storage capacities than small ones. As expected only two components of flow recession were identified from rainfall and stream flow data, (Jakeman and Hornberger, 1993) and these were represented by time constants of quick and slow flow (t_q and t_s) as well as the relative volumetric throughput n_s Parameter t_q is related to drainage density and to elevation (Table 3). This is unexpected as in catchments with high drainage densities; water finds its way to the stream quickly and hence is expelled from the catchment meaning a low t_q value. The low recession of quick flow may therefore be due to the impact of attributes not considered in the analysis. Firstly, all the catchments are large and hence in-stream travel time is more influential than the time taken to reach the stream. In addition, since all catchments are long, it takes a long time for stream flow to reach the outlet point. Finally, parameter t_q is inversely related to most land cover attributes and the effect of vegetation on the movement of water is to delay its movement and increase the time it requires to reach the outlet point. The effect of this is to increase the quick flow recession constant even in the presence of dense stream network. The time constant governing slow flow t_s is correlated with t_q meaning that as t_q increases water gets time to infiltrate to the ground and become sub-surface flow which moves at almost the same pace as the quick flow. It was expected that t_s will show an inverse relationship with catchment slope (Post and Jakeman, 1996) since steeply sloping catchments tend to have a shorter t_s as subsurface water drains from them quickly. However, there was a small positive correlation probably because all the catchments have steep gradients. Vegetation cover delays surface flow enhances infiltration and hence increases base flow. The proportional volumetric contribution of slow flow to total flow n_s ranged from 0.33 to 0.85 probably due to the similarities of these catchments in terms of soil types and vegetation cover.

Table 2: Correlation matrix for calibrated DRCs and PCDs

	¦	t_w	1/C	t_q	t_s	n_s
Area	-0.60	0.08	-0.61	-0.45	-0.68	0.54
D_Dens	0.80	**0.88***	0.66	0.40	0.27	-0.74
Mean Elev.	-0.28	0.06	-0.48	0.78	0.64	-0.51
Mean Slop.	0.77	0.40	0.89	0.18	0.25	-0.48
S_Gradient	**0.86***	**0.87***	0.72	0.29	0.11	-0.57
AG_1	-0.64	-0.66	-0.58	-0.56	-0.47	0.77
AG_3	-0.70	-0.17	-0.89	0.21	0.03	0.14
AG3B	-0.30	0.47	-0.50	0.13	-0.22	-0.02
FR_2	-0.04	0.11	0.03	-0.33	-0.49	0.37
RL_2	0.20	0.24	0.1	0.01	-0.17	0.07
R_1	-0.50	-0.52	-0.56	0.38	0.38	0.05
R_2	-0.56	0.06	-0.77	-0.27	-0.48	0.41
R_3	-0.65	-0.82	-0.61	-0.03	0.13	0.37
M_2	**0.94****	0.52	**0.94****	0.36	0.42	-0.68

*Correlation significant at 0.05 level **Correlation significant at **0.01** level

After inspection, correlation analysis, stepwise and multiple regressions the following DRC-PCD relationships were obtained (Table 3), which were then used to estimate model parameters.

Table: 3 Developed optimized regression equations

DRCs	*Optimised Multiple Regression Equations of DRCs in Terms of PCDs*
f	$0.013+5.233RL_2+3.895M_2$
τ_w	$-76.702+0.505D\_Dens+40.946R_2+50.884RL_2$
$1/c$	$162.052+1373.537M_2$
τ_q	$-8.181+178.720S\_Gradient+9.810M_2+14.201AG_1$
τ_s	$65.647-0.056Area+596.878S\_Gradient-20.363R_2$
v_s	$0.426+1.680AG_1$

4.2 Evaluation of Model Performance

The quality of modelled data was judged by visual inspection of simulation hydrographs and by two quantitative parameters R^2 a measure of goodness of fit and the Nash-Sutcliffe (1970) efficiency E, which measures the deviation of observed flow from modeled flow. It is defined as:

$$E = 1 - \frac{\sum (q_i - \hat{q}_i)^2}{\sum (q_i - \bar{q})^2} \quad \text{..........} (5)$$

where: $\bar{q}$ is the mean of the Observed stream flow.

q_i is the Observed stream flow.

$\hat{q}_i$ is the simulated stream flow.

4.3 Simulation of Daily Stream Flows

The estimated parameters were used to simulate stream flows in two validation catchments and a comparison made with observed flows. The R^2 values obtained (0.67 and 0.19) compared well with the calibrated values of 0.68 and 0.20, showing that the relationships were valid. Graphical plots of observed and estimated flows (Figure 5) show good fits, except for the simulated peak flows of catchment 4AC03, which were underestimated. The observed high peak flows were not reflected in concurrent high rainfalls, indicating a possible error in the recorded data. The low R^2 value may be attributed to poor quality data and to differences in catchment characteristics. In addition, this catchment is very large (1,035 km^2) and errors may arise due to lumping of rainfall.

4.4 Estimation of Regional Parameters

Since a functional relationship was established and validated, the DRC-PCD relationships may be considered as a regional parameter set and used to estimate stream flows in ungauged catchments within the geographic region given rainfall and temperature data. The model was found to be sensitive to changes in parameter τ_w

which is the inverse rate of water loss to evapotranspiration and to stream flow. Land use/cover can be said to be a major driver of catchment hydrologic response.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Regionalisation has been successfully demonstrated for the Upper Tana basin using the IHACRES model. However, the results must be viewed in the context of the amount and quality of data that was available to quantify the DRCs, as well as the limited information that was available to quantify the appropriate PCDs. Regional relationships developed between hydrologic response characteristics and physical catchment descriptors can be used to make estimations of daily stream flows of ungauged catchments from an appropriate rainfall and temperature time series. The results of the study show that, with a suitable number of gauged catchments for model calibration and validation, IHACRES model can be regionalised and used to simulate rainfall-runoff processes in ungauged catchments of the Upper Tana basin. The methodology can be used to generate stream flow data for planned water resources projects in the basin. However, to improve the established DRC-PCD relationships and enable the application of results with greater confidence, a larger data set that explores a wider geographical space should be used.

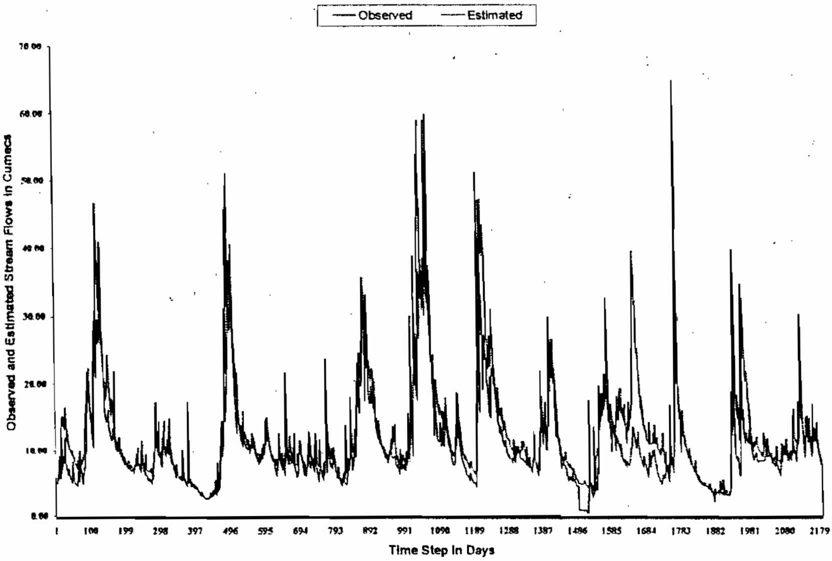


Figure 4: Observed and estimated flows for Gura River at Station 4AD01 (1970-75)

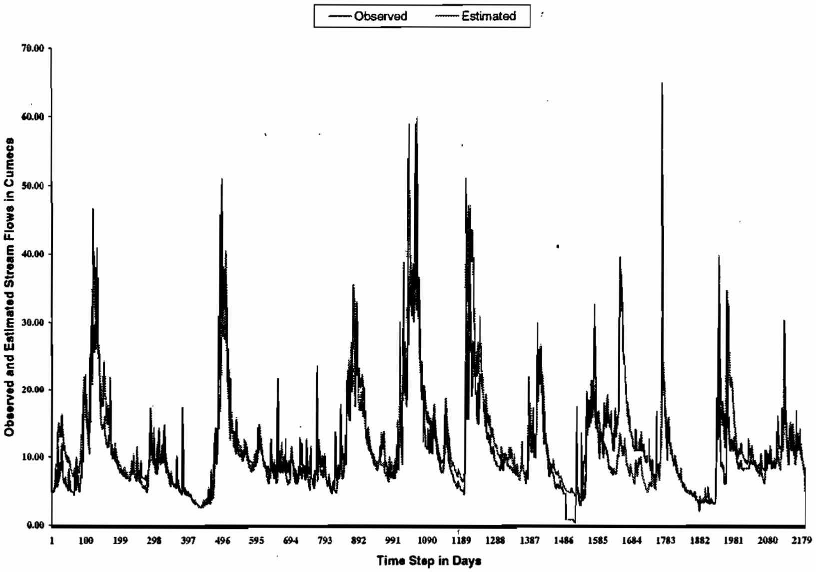
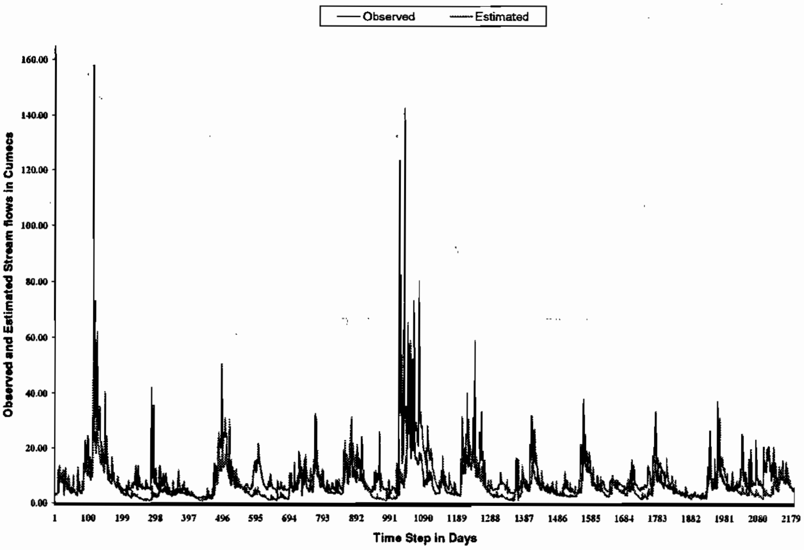


Figure 4: Observed and estimated flows for Gura River at Station 4AD01 (1970-75)



REFERENCES

Food and Agriculture Organisation (FAO) of the United Nations (1997). Digital Soil Map of the World. CDROM. Rome Italy.

Jaetzold R. and Schmidt H. (1983). Farm Management handbook of Kenya, Vol. II Part **C,** East Kenya- Ministry of Agriculture/GTZ, Nairobi, Kenya.

Jakeman A. J. and Hornberger G. M. (1993). How Much Complexity is Warranted in a Rainfall Runoff Model? *Water Resources Research,* **29**(8), pp 2637 - 2649.

Kalders J. (1988). Evapotranspiration in Kenya, Irrigation Section, Ministry of Water Development, Government of Kenya, Nairobi, Kenya.

Kokkonen T. S., Jakeman A. J., Young P. C. and Koivusalo H. J. (2003). Predicting Daily Flows in Ungauged Catchments; Model Regionalisation from Catchment Descriptors at The Coweta Hydrologic Laboratory, North Carolina. *Journal of Hydrological Processes,* **17**, pp 2219-2238.

Kokkonen T. S. (2002). Rainfall-Runoff modelling – Comparison of modelling strategies with focus on ungauged predictions and model integration. *PhD. Thesis Helsinki University of Technology*, Finland.

Muthusi F.M. (2004). Evaluation of the USGS Stream Flow Model for Flood Simulation (Case study of the Nyando Basin) Msc. Thesis, Jomo Kenyatta University of Agriculture and Technology, Nairobi, Kenya.

Forecasting through Conceptual Models Part 1 - A Discussion of Principles. *Journal of Hydrology,* **10**, pp 282-290.

Onyando J.O. (1994). Estimation of Runoff Volumes and Peak Rates in Rural Catchments of Kenya. *M.Sc Thesis, University of Nairobi*, Kenya.

Onyando J. O. and Sharma T. C. (1995). Simulation of Direct Runoff Volumes and Peak rates for Rural Catchments in Kenya, *East Africa. Hydrological Sciences Journal,* **40**(3), pp 367-380.

Onyando J. O. and Chemelil M. C. (2004). Flood Hydrograph Generation from Small Catchments in Kenya. *East African Journal of Physical Sciences,* **5**(1), pp 331- 42.

Onyando J. O., Olang, L. O. and Chemelil, M. C. (2005). Regional Analysis of Conceptual Rainfall-runoff Models for Runoff Simulation in Ungauged catchments: The case of Upper Ewaso Ngiro drainage basin in Kenya. *Journal of Civil Engineering Research and Practice*, **2** (1), pp 23 -37.

Pilgrim D. H. (1983). Some Problems in Transferring Hydrological Relationships Between Small and Large Drainage Basins and between Regions. *Journal of Hydrology,* **65**, pp 49-72.

Post D. A. and Jakeman A. J. (1996). Relationships between Catchment Attributes and Hydrological Response Characteristics in Small Australian Catchments. *Journal of Hydrological Processes,* **10,** pp 877-892.

Post D.A. and Jakeman A. J. (1999). Predicting theDaily Stream Flow of Ungauged Catchments in S.E Australia by Regionalizing the Parameters of a Lumped Conceptual Rainfall- runoff Model. *Journal of Ecological Modeling,* **123**, pp 91-104.

Schaake J. V., Duan Q., Koren V. I. and Cong S. (1997). Regional Parameter Estimation of Land Surface Parameterisation for GCIP large-scale area Southwest, Paper presented at the 13th conference on Hydrology, American Meteorological Society, Long Beach, California, 1997.

Sefton C. E. and Howarth S. M. (1998). Relationships between Dynamic Response Characteristics and Physical Catchment Descriptors of Catchments in England and Wales. *Journal of Hydrology,* **211**, pp 1-16.

Seibert J. (1999). Regionalisation of Parameters for a Conceptual Rainfall-runoff model. *Journal of Agriculture and Forest Meteorology*, **98-99**, pp 279-293.

Sorooshian S. and Gupta V. K. (1995). Model Calibration **In**: Computer Models in Watershed Hydrology. Singh V. P. (Ed.), pp 23-68. Water resources publication, New York.

World Meteorological Organisation (1994). Guide to Hydrological Practices No. **168**, pp 421- 429. Geneva, Switzerland.

APPENDICES

Appendix 1 Description of soil types used in the study

R_1- Well drained, extremely deep, dark reddish brown to dark brown, friable and slightly smeary clay

R_2- Well drained, extremely deep, dusky red to dark reddish brown, friable clay.

R_3- Well drained, extremely deep; dusty red to dark reddish brown, friable clay, with inclusions of well drained, moderately deep, dark red to dark reddish brown, friable clay over rock.

M_{2-} well-drained, very deep, dark reddish brown to dark brown, very friable and smeary, clay loam to clay.

Source: Exploratory soil map and Agro-Climatic zone map of Kenya, 1980
By W.G Sombroek, H.M.H. Braun and B.J.A. Van Der Pouw
Kenya Soil Survey

Appendix 2. Description of land cover attributes used in the study.

AG_{1-} Rain fed herbaceous crop

AG3- Rain fed shrub crop

AG3B-Scattered rain fed shrub crop (Field density 20-40% of polygon area.)

FR_{2-} Closed trees

RL_2-Shrub savannah

Source: (FAO, 1997 Africover Coverages)