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CORRELATION ANALYSIS BETWEEN THE PHYSICAL CATCHMENT DESCRIPTORS (PCD'S) AND THE IHACRES RAINFALL-RUNOFF MODEL PARAMETERS -*A CASE STUDY OF KASESE DISTRICT CATCHMENTS*

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Abstract

This study examined the utility of the physical catchment descriptors (PCD's) to predict model parameters so as to explore transferability of IHACRES model parameters based upon the physical catchment characteristics. The model was calibrated for four catchments to obtain a set of dynamic response characteristics (DRCs) describing the hydrological behaviour within the region. For the four catchments namely Mubuku, Rwimi, Nyamugasani and Chambura, IHACRES model was calibrated with an R^2 of 0.12, 0.25, 0.38 and 0.51 respectively. There were poor measures of fit between observed and modeled stream flow (R^2). This could have been due to lack of good-quality time series of rainfall data representative of the whole basin and influence of snow melt for Mubuku, Rwimi and Nyamugasani catchments. Physical catchment descriptors (PCDs) indexing topography, soil type, land cover, length of main channel, drainage density, and basin area were correlated to the hydrological model parameters. A set of DRC–PCD relationship results indicate that strongest correlations were found with the quick flow proportion (Vq), catchment storage index (1/c), catchment drying constant (TauW) and the temperature modulation factor (f) with the PCD's. These relationships can be used to predict the model parameters in ungauged catchments to model flows. However, further work is necessary in analyzing the relationship between PCDs and model parameters using longer records of stream flows and climatic data to improve the reliability of the results.

Key words: Correlation, Physical Catchment Descriptors (PCD), Dynamic Response Characteristics (DRC), Ungauged Catchments

1. Introduction

Accurate estimation of stream flow is essential for engineering design, water resources management and planning, pollution control, conservation and even recreational use. However, although there are several gauging stations in most of the catchments, data are not always available where a need exists. Given that rainfall data are usually available, rainfall-runoff models provide a technique for the simulation of flows given a set of model parameters. In the case of ungauged basins such direct measurements of stream flow are never available and prediction in those basins requires alternative approaches. A major difficulty in predicting hydrology of ungauged basins is the fact that watershed response is uniquely governed by interactions of climate, topography, geology, and vegetation. One approach is to use information from models derived at gauged locations as a basis for such modeling based upon watershed attributes. Statistical relations between calibrated model parameters and watershed characteristics may capture information about the governing hydrologic processes and serve to develop a classification system useful for reducing predictive uncertainty at ungauged locations.

In this study IHACRES model which has been used to model the pluvial watersheds in mountainous regions is better for the Kasese district that is mountainous. IHACRES is a relatively simple form of model based upon excess precipitation (Jakeman et al., 1990, Littlewood and Jakeman, 1994; Littlewood et al., 1997). Despite the simple formulation IHACRES has been shown to be suitable in a wide range of rainfall-runoff catchments. Regionalization approaches to daily streamflow predictions using the IHACRES model have been previously reported (Kokkonen et al., 2003) for the Coweeta watershed and Sefton and Howarth (1998) for the United Kingdom. Kokkonen et al. (2003) considered 13 catchments within a 16 km^2 watershed.

In order to predict flows at ungauged sites using calibrated rainfall-runoff models, a method of estimating a parameter set is needed. A number of techniques have been employed including determining regression relationships between model parameter values and catchment's attributes, adopting a parameter set from a nearby catchment that is expected to have sufficiently similar response characteristics and interpolation schemes (e.g. kriging) of parameter values from nearby catchments.

Methods based on estimating parameter sets rather than individual parameter values have a considerable advantage due to the highly nonlinear nature of catchment responses and the correlations that typically exist in rainfall-runoff models (Croke and Norton, 2004). Application of regression relationships between catchment attributes and individual parameters requires parsimonious models that have strong relationships between parameters and catchment attributes as well as little correlation between different parameters. While IHACRES (Jakeman, *et al.*, 1990) has been used in previous regionalisation studies (e.g. Post and Jakeman 1996 and 1999, Post et al. 1998, Sefton and Howarth 1998, and Kokkonen et al. 2003), the CMD version of the non-linear loss module has a potentially better structure for regionalization. Regionalisation by describing these hydrological characteristics in terms of physical descriptors then allows estimation of the unit hydrograph for any catchment in the region. Application of this methodology allows flow series to be constructed and the sensitivity of flow to the hydrological characteristics and to physical descriptors to be investigated**.**

The objective of this paper is to explore transferability of model parameters between catchments, based upon catchment characteristics. The ultimate goal is to provide guidance to water resource practitioners to reduce predictive uncertainty at ungauged locations (Whitfield et al., 2006).

2. Description of the Study Area

Kasese District is located in the western region of Uganda. It lies between latitudes 0°12**'**S and 0°26**'**N longitudes 29°42**'**E and 30°18**'**E. The district is bordered to the north by the district of Bundibugyo, the north east by Kabarole, to the south by Bushenyi and to the west by the Republic of Zaire (Kasese District profile, 1998).

The total land area of the district is 2724 Km^2 while the area covered by water bodies is 461 Km^2. Of the total area of the district, Queen Elizabeth National Park covers 885 $Km^2$and Rwenzori National Park covers an area of 652 Km^2. This leaves only 1647 Km^2 for human settlement. Presently the population of the district is estimated at 360,000 (assuming an annual growth rate of about 2.1% for 1991-1995 period) this gives an average land density of about 220 people per square kilometre for the settled areas.

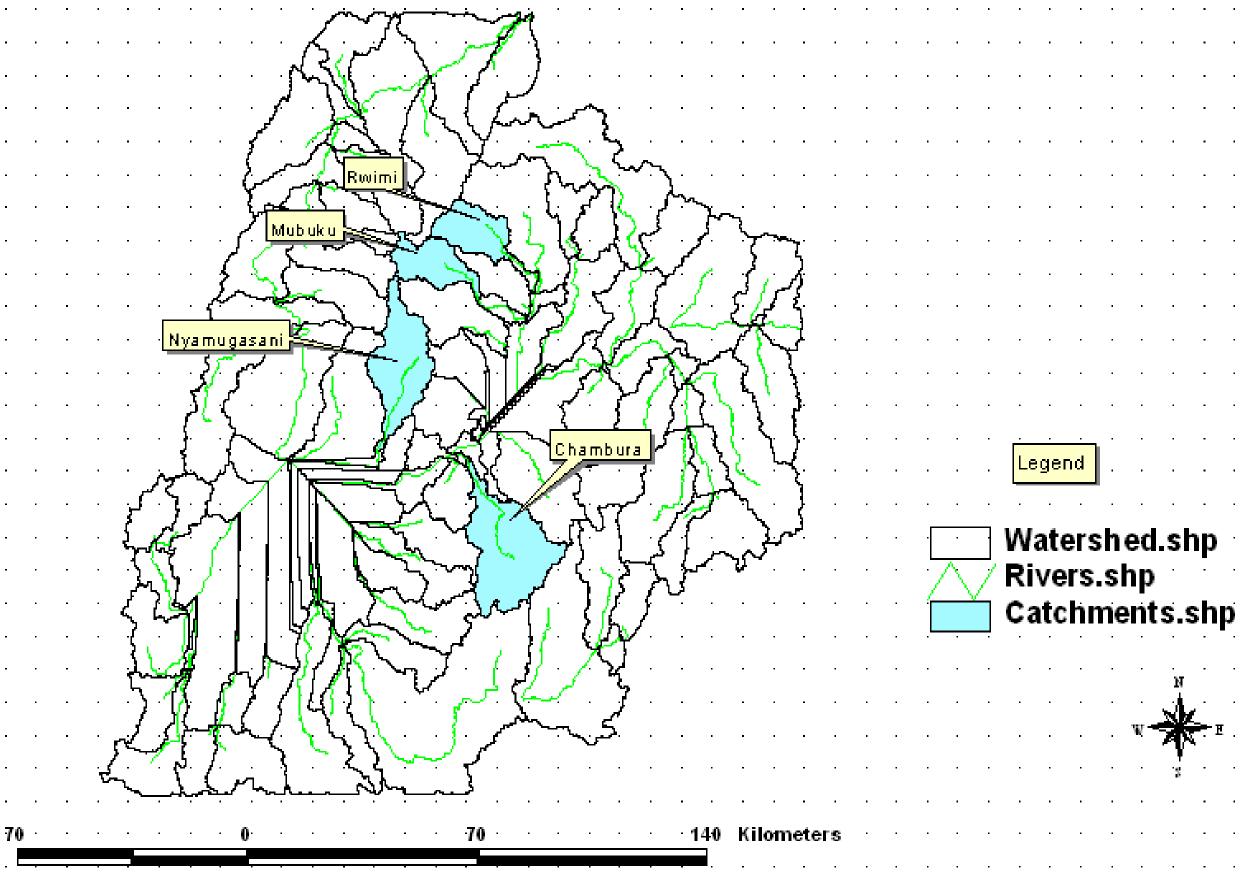

Figure 1: Kasese district sub-catchments

Major rivers in Kasese District include Nyamugasani which tranverses Kyondo, kyarumba, Kisinga and Katwe sub-counties. Lhubiriha River forms the boarder between Uganda and Zaire. Nyamwamba River flows through Kilembe and Rukooki subcounties, and Kasese Town council and into lake George swamp system. Sebwe (Isebo) River supplies water for Mubuku Irrigation Scheme, and also traverses Bugoye and Rukooki sub-counties. Mubuku River passes through Bugoye, Maliba and Karusandara sub-counties, and then drains into the Lake George swamp system.

3. Methodology

3.1 Data and Data Processing

The temporal and spatial databases for Kasese district catchments were sourced from different ministries and organizations as shown in Table 3.1. The meteorological stations used for this study were all climate stations located within the Kasese district catchments. A Digital Elevation Model of 90-m resolution together with ancillary spatial data layers, were used in the study to generate summary statistics of catchment attributes. Table 3.2 shows the rainfall stations within the catchment and the summary of the data.

Filling of the missing values were done by inverse distance square method. Areal rainfall for the catchments was obtained by using arithmetic mean method. The climatic data used in this study are Maximum and Minimum Temperature for one representative station. The summary of the flow data is given in Table 3.3.

Table 3.1: Data used in this study and the source

No.	Data	Type	Office/ Institute
1	Digital Elevation Model(DEM) of 90X90m resolution	Map and Numerical	Online global data source, ftp://e0srp01u.ecs.nasa.gov/srtm/version1/africa/
2	Land cover and vegetation map(1992)	Map and Numerical	National Forest Authority, GIS and RS Section (1992)
3	Gauge stations and data (Stream flow)	Numerical	Ministry of water and environment, Directorate of water resources management, Entebbe.
4	Gauge stations and data (rainfall and temperature)	Numerical	Ministry of water and environment, department of meteorology.

Table Error! No text of specified style in document.**.2: Rainfall stations and the data summary catchment**

Stations	From	To	Years	No. of data Points	% Missing data
Kasese	1/1/1964	31/12/1974	11	4018	1.79
Mweya	1/1/1964	31/12/1974	11	4018	2.22
Kilembe	1/1/1964	31/12/1974	11	4018	0.05
Kiburara	1/1/1964	31/12/1974	11	4018	0.80
Rwimi	1/1/1964	31/12/1974	11	4018	0.00
Isunga	1/1/1964	31/12/1974	11	4018	0.00

Table Error! No text of specified style in document.**.3: Summary of flow data for Kasese catchments**

Station	From	To	Years	No. Points	% age Missing data
Mubuku	1/1/1964	31/12/1971	8	2922	0.99
Chambura	1/1/1964	31/12/1974	11	4018	0.77
Rwimi	1/1/1964	31/12/1974	11	4018	0.75
Nyamugasani	1/1/1964	31/12/1974	11	4018	27.6

3.2 Catchment delineation and extraction of PCDs

In order to delineate subcatchments and to identify the stream flow network, DEM with 90-m resolution and drainage points that define the catchments of interest were used. The DEM processing involved digital terrain analysis using the DEM to obtain the river network. This included the determination of cell grid dimension, computation of the slope of each cell, flow direction, and delineation of catchment boundaries. Catchment boundaries and other physical characteristics like flow direction, stream density, basin area, basin slope, hill slope length, longest drainage path were generated using step by step procedure under ArcView GIS and HEC-GeoHMS extension.

3.3 IHACRES Model Description

The rainfall-runoff model (IHACRES) used in this research is based on the catchment moisture deficit (CMD) model of Croke and Jakeman (2004). The IHACRES (Identification of unit hydrographs And Component flows from Rainfall, Evaporation and Stream flow data) model is a simple lumped (integrated) catchment scale rainfall-stream flow model. In the first part is a non-linear loss model: an evaporation loss module to calculate effective rainfall: this computes the amount of rainfall that does not contribute to direct runoff (i.e., lost due to evapotranspiration or held in soil storage) through continuous update of an index representing catchment soil moisture. Rainfall excess is computed as a direct function of the soil moisture index and is routed to the catchment outlet via two parallel linear reservoirs representing quick and slow stream flow response (Kokkonen *et al*., 2003).

The second part is the linear module (a unit hydrograph module) defined as a recursive relation at a given time step (daily for this study) for modelled flow, calculated as a linear combination of antecedent flow values and effective rainfall (Jakeman and Hornberger, 1993). The effective rainfall output from the first step generates the necessary input to the unit hydrograph module. The linear module, representing the transformation of excess rainfall to flow discharge, allows very flexible configuration of linear stores connected in parallel and or series (Kokkonen *et al*., 2003).

A conceptual diagram of the structure of the IHACRES model is shown in Figure 3.1 as given by Evans and Jakeman (1998).

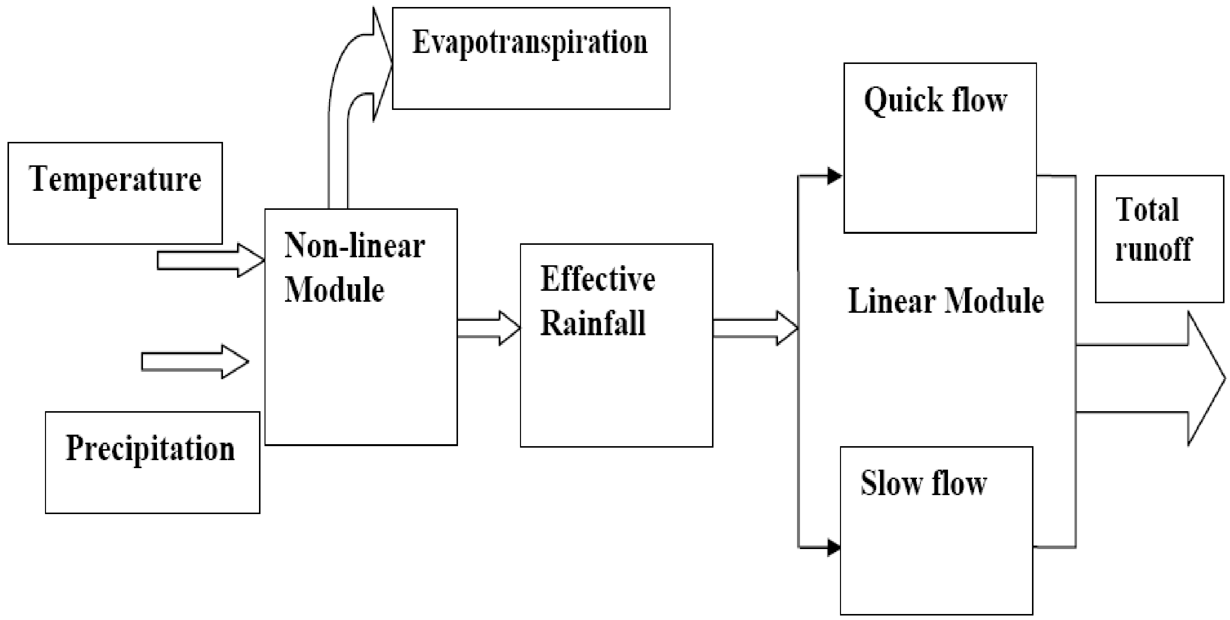

Figure 3.1: Structure of CMD-IHACRES (Evans and Jake man, 1998)

Model Parameter Optimization

The general procedures in calibrating the model are as summarized in the steps below:

Step 1- Setting the calibration periods. For this study, the calibration period found to give a good output of hydrograph for stream flow and rainfall was 1971 to 1974 for three catchments except for Mubuku catchment.

Step 2- Setting the linear module calibration. This was set by performing a cross correlation to calculate the delay between rainfall and stream flow data.

Step 3- Setting the Non linear Module calibration. This was set by selecting the classic Module. Several grid searches were performed to search through parameter space to find so as to obtain a good parameter set.

The coefficient of determination (R^2) and a percentage 'average relative parameter error' (%ARPE) for the parameters in the linear module are program outputs. The criteria that a good model is one that has a high value for R^2 and a low value for %ARPE, was used. The transfer function parameters are optimized using an instrumental variable procedure.

The total number of parameters for IHACRES model are six and they include (1/c, TauW, f, Vs, Tq and Ts) as represented in (Table 3.4).

Table 3.4 The parameters describing the IHACRES model include

Parameters	Description
f	Temperature modulation factor (f) in 1/ °C
TauW	Catchment drying time constant (TauW) in days
Tq	Quick flow reservoir time constant (Tq) in days
Ts	Slow flow reservoir time constant (Ts) in days
1/c	Catchment storage index/Volume-forcing constant (1/c) in 1/mm
Vq	Proportion of effective rainfall which becomes quick flow Vq

4. Results and Discussions

4.1 Model Calibration

A 'best' model fit between simulated and observed flow obtained by repeatedly calibrating the unit hydrograph module using different values of the loss module parameters (τw and f), searching for a good model-fit and good precision on the unit hydrograph parameters. Details of the 'best' model fits for these four catchments are listed in (Table 4.1).

Table 4.1 Derived "best" model fit parameters for each catchment

IHACRES model Parameters	Watersheds(Catchments)			
	Mubuku	Rwimi	Nyamugasani	Chambura
Temperature modulation factor (f)	0.0	0.0	0.0	6.0
Proportion of effective rainfall which becomes quick flow (Vq)	0.215	0.12	0.264	0.663
Quick flow reservoir time constant (Ts)	115.050	17.097	78.832	430.256
Slow flow reservoir time constant(Tq)	2.626	3.101	3.408	11.821
Catchment storage index/volume forcing constant (1/c)	1.0	1.0	1.0	1.0
Catchment drying time constant (Tw)	5.0	997	572.0	305

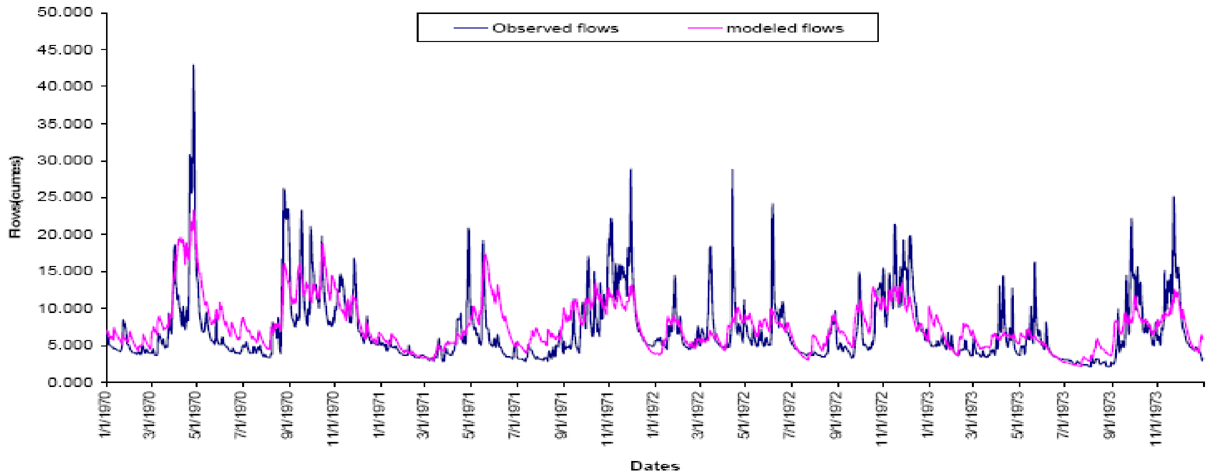

Figure 4.2: Comparison between observed and modelled flows for Chambura sub-catchment

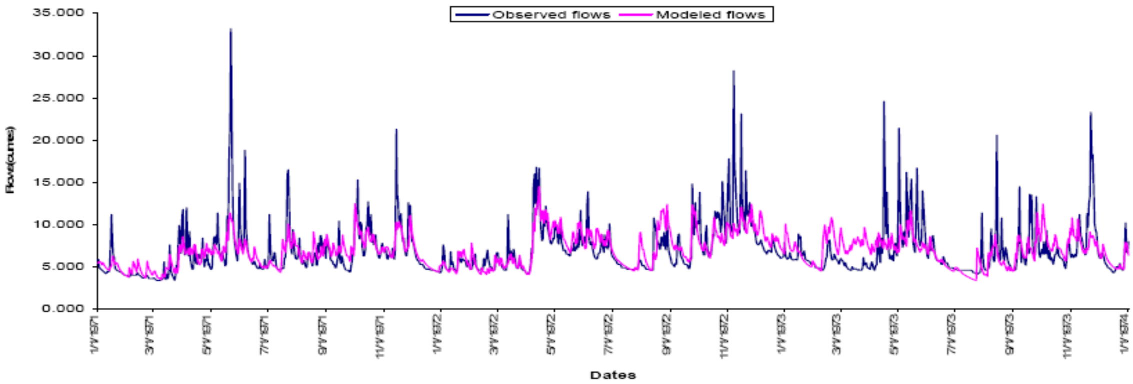

Figure 4.3: Comparison between observed and modelled flows for Nyamugasani sub-catchment

From the results, three subcatchments namely Mubuku, Rwimi and Nyamugasani with R^2 of 0.12, 0.25 and 0.38 respectively gave the poorest R^2 unlike Chambura with 0.51, which is fair. Generally the modelled runoff graphs do not capture the peak flows. This could be because the headwaters of the three catchments are from the Rwenzori Mountains glaciers and snowmelt from snow capped peaks, unlike for Chambura, which is far south.

4.2 Derived Physical Catchment Descriptors (PCDs) and Correlation

Table 4.2 Derived "best" model fit parameters for each catchment

PCD's (Physical catchment descriptors)	Watersheds (Catchments)			
	Mubuku	Rwimi	Nyamugasani	Chambura
Length of main channel(km)	17.45	14.94	35.29	43.34
Average hill slope length (km)	42.14	30.10	24.92	18.92
Basin elevation(m)	2360	1704	1440.0	1491.0
Basin area(Km^2)	261	265	495	674
Longest drainage path(km)	38.85	39.28	65.44	67.61
Drainage density(km/km^{2})	0.149	0.148	0.132	0.100
Major land use (%)	22.42	41.53	31.84	48.07
Major Soil types (%)	45.96	45.87	57.89	43.37

Microsoft -Excel software (CORREL work sheet function) was then used to correlate derived key PCD's and the IHACRES model calibrated results, and the output is as shown in the Table 4.3. Significant correlations at the 5% and above level were found between several PCDs and IHACRES model parameters. Strongest correlations were found with the quickflow proportion (Vq), catchment storage index (1/c), catchment drying constant (TauW) and the temperature modulation factor (f). No significant correlations were found between the drying rate at reference temperature (tw) and PCD's except soil type. Correlations of model parameters with length of main channel, longest drainage path, and drainage area were very similar indicating that no 'new' information may be obtained from computing catchment descriptors beyond catchment area.

The lack of an observed relation between PCDs and the Drying rate at reference temperature (tw) may be related to the seasonal variability in climate of these mountain regions. Observed climate records, typically representative of valley-bottom climates, may not be expected to represent the seasonal variability of basin-averaged temperature and precipitation assumed by the model. It is not to my surprise that there was no significant positive correlation between drainage density and the quick and slow reservoir coefficients. This is obvious that increasing drainage density would reduce the reservoir time constants (, i.e., quicker runoff response).

PCD's	Model parameters					
	f	Vq	Ts	Tq	1/c	tw
Basin area	0.69	0.81	0.59	0.70	0.69	-0.03
Longest drainage path	0.39	0.59	0.29	0.39	0.38	-0.008
Length of main channel	0.57	0.78	0.46	0.56	0.57	0.05
Drainage density	-0.88	-0.88	-0.81	-0.89	-0.88	-0.04
Basin elevation	-0.16	-0.12	-0.11	-0.21	-0.17	-0.31
Average hill slope length	-0.47	-0.37	-0.39	-0.52	-0.47	-0.12
Major land use	0.52	0.50	0.43	0.56	0.52	0.04
Major Soil type	-0.25	-0.66	-0.20	-0.20	-0.25	0.66

From the results above, it can be concluded that generally IHACRES model is satisfactory and the calibrated models were able to reproduce the observed temporal variations in stream flow in the catchment and therefore applicable to Kasese sub-catchments and especially catchments that are far from the influence of snow melt in Rwenzori Mountains. After deriving the DRC–PCD relationships, the relationships should have been validated by simulation of flow and sensitivity analysis at least two or more additional catchments which unfortunately was not done in this study because of the lack of data.

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