INTERNATIONAL CONFERENCE ON WATER RESOURCES, COASTAL AND OCEAN ENGINEERING (ICWRCOE 2015)

Flow Regionalization Under Limited Data Availability - Application of IHACRES in the Western Ghats

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Abstract

Long-term measurements of river stream flow are essential for numerous applications in water resources. In many parts of the world, rivers remain ungauged; stream flow prediction for such ungauged catchment requires information transfer from gauged catchments that are perceived to be hydrologically similar to them. Prediction of stream flows at ungauged catchments is typically performed through the transfer of hydrologic information (e.g., model parameters, hydrologic indices, stream flow values) from gauged to ungauged catchments. This procedure is commonly referred to as regionalization. Hydrologic models have been used extensively for the purpose of transfer of hydrologic model parameters from gauged to ungauged catchments and these models include HBV, IHACRES and PDM.

In the present study, for the purpose of regionalisation, a lumped conceptual model namely, IHACRES has been used. IHACRES is a parsimonious model having six numbers of parameters and requires small data input. The model parameters are used to characterise the daily stream flow of the catchment and are related to the landscape attributes of the catchments. Further, as an offshoot, IHACRES provides for base-flow separation and development of unit hydrograph, which becomes an input in other hydrological works.

In the current paper, the model IHACRES is applied at daily time step to six catchments (Malathi, Hemavathi, Lakshmanthirtha, Yetthinahole, Kadumanehalla and Kumaradhara) in the region of Western Ghats, Karnataka. IHACRES, being parsimonious, requires precipitation and temperature as the only data-input. Information is compiled for physical catchment descriptors using the elevation map of the area (DEM) and relationships are developed between the parameters and the descriptors. These relationships are validated by modelling daily stream flow of a gauged catchment (Nethravathi). This work proves that as an alternative model, IHACRES does well in the domain of flow regionalization with least data inputs.

Keywords: Hydrological modeling; Ungauged catchments; Regionalization; IHACRES; Physical catchment descriptors.

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1. Introduction

The commonly used tools for quantitative decision making in water resources planning and management are essentially data driven, i.e., they are estimated from past stream flow measurements (Beven, 2001). Such tools include: flow duration curves, flood frequency curves, mean annual flood, and unit hydrographs. The accuracy of these quantitative tools is highly dependent on the record length of streamflow measurements that they are derived from. Streamflow measurements are also important for characterizing the hydrologic behaviour of river basins within modelling frameworks, so that future assessments of hydrologic behaviour in response to climate and/or land-use change can be obtained. However, in many parts of India, most of the rivers remain ungauged. This lack of data limits the ability of decision-makers to assess the risks and vulnerabilities of water resources under potential future climate and land-use scenarios and can affect the quality of life of the human population.

The catchments with inadequate stream flow data are classified as ungauged (Sivapalan et al., 2003). Ideally, hydrologic models should be applicable at ungauged catchments since they only require climate data (e.g., rainfall, temperature, etc.) as inputs. Prior to applying the models for stream flow predictions, all the hydrologic models involve calibration of model parameters. Hydrologic models contain parameters in their process representations whose values can only be obtained through calibration with historic stream flow data at a given catchment. Unfortunately, it is not possible to obtain some parameters of models by either measurement or a priori estimation. The problem of obtaining measurable parameters exists because the processes represented in models are based on small scale physical understanding of fluid flow, whereas tremendous heterogeneity exists in soil properties, topography and land-use that is virtually impossible to characterize at the scale of a catchment (Beven, 2001). The need for calibrating hydrologic models is the biggest obstacle for predicting stream flow at ungauged catchments at finer time-scales since they do not have the historic data with which the models can be calibrated.

Prediction of stream flows at ungauged catchments is typically performed through the transfer of hydrologic information (e.g., model parameters, hydrologic indices, stream flow values) from gauged to ungauged catchments (Tara and Caulibly, 2013). This procedure is commonly referred to as regionalization. Hydrologic models that have been used extensively for the purpose of transfer of hydrologic model parameters from gauged to ungauged catchments includes HBV (Merz and Bloschl, 2004), IHACRES (Post and Jakeman, 1999), PDM (as cited in Tara and Caulibly, 2013).

Transfer of model parameters from gauged catchments is essential for implementing hydrologic models at ungauged catchments. However, many models have a tendency towards over-parameterization (Beven and Freer, 2001). The International Association of Hydrological Sciences (IAHS) has launched a long-term research initiative by declaring the years 2003 – 2012 as the IAHS Decade on Predictions in Ungauged Basins (PUB), which is commonly referred to in hydrology community as the PUB initiative (Sivapalan et al., 2003). The aim of this initiative was to increase the awareness about the inadequacies of the current state of science in addressing the PUB problem, and promoting coordinated science strategies that focus on the estimation and reduction of prediction uncertainty in hydrologic systems (Wagener et al., 2004). This provides the motivation for this work on regionalization on flows so as to predict flows in ungauged basins in the region of Western Ghats.

The objective of the present work is to develop a frame work for regionalization of flows in the Western Ghats. This objective accomplish through identifying a lumped rainfall – runoff model as an operational tool within the region of Western Ghats of Karnataka and to develop equations to determine the parameters so as to apply the model at ungauged catchments.

2. The model IHACRES

IHACRES has been developed collaboratively by the Institute of Hydrology and the Centre of Resource and environmental Studies at the Australian National University (CRES at ANU), Canberra. IHACRES comprises a non – linear loss module and a linear unit hydrograph model. In the typical configuration of the non – linear loss module in series with two parallel linear modules, there are six parameters comprising three in each module and is shown in Fig. 1.

The input data required for the model are restricted to time series of rainfall and stream flow and a third variable by which evaporation effects can be approximated. Either temperature or estimates of potential evaporation may be

used as third variable. Data time steps that may be employed for stream flow and rainfall range from one minute to monthly. The time step has to be both consistent during a model run and has to be the same for rainfall and stream flow. And the time step for the third variable is constrained to be the same as that for the rainfall and stream flow data, either daily or monthly.

An assumption is made that, at a particular time step k, there is linear relationship between effective rainfall (u_k) and stream flow (x_k). This allows the application of unit hydrograph theory in which the catchment is represented as a configuration of linear reservoirs acting in series and/or parallel.

In this study the classic redesigned IHACRES version (Croke et al., 2005) has been used. The non-linear loss module converts rainfall (r_k) into an effective rainfall (u_k) by considering both the infiltration rate and evapo-transpiration. In order to obtain the effective rainfall, a catchment wetness index or antecedent precipitation index, representing catchment saturation, is calculated for each time step.

Two modes in which IHACRES can be used is through-

  i.   *Available software packages built around the IHACRES model*

      PC-IHACRES was developed jointly by the Centre for Ecology and Hydrology, Wallingford (a component organisation of NERC) and the Integrated Catchment Assessment and Management Centre (ICAM), Australian National University, Canberra. The original structure of IHACRES uses the exponential soil moisture drying rate index (Littlewood, 1997).

      The Classic Plus version will provide greater choice of model structure, etc., and it is more suitable for certain applications than PC-IHACRES. IHACRES Classic Plus also includes the loss module structure incorporated in PC-IHACRES (Croke et al., 2005).

      IHACRES incorporated by SAGA-GIS, can be used for flow prediction in ungauged catchments.

  ii. *self written program*

      By understanding the methodology used to develop the IHACRES model, self written program can be implemented through programming languages such as MATLAB, C-Programming, etc.,

In the present work, Microsoft excel worksheet is used to write the program and execute the same.
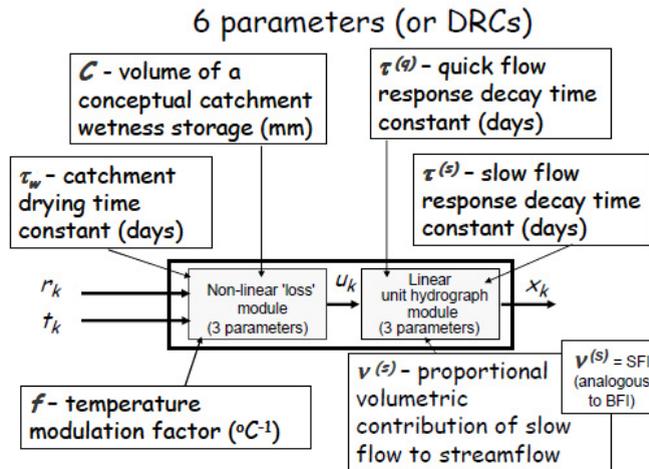

Fig. 1. IHACRES modules and dynamic response characteristics (Littlewood, 2003)

3. Study Area and Data Used

In the present study, seven catchments namely Malathi, Hemavathi, Lakshmanthirtha, Yetthinahole, Kadumanehalla, Kumaradhara and Nethravathi are considered. The interest in these catchments is for the reason that they are gauged and initially six catchments namely, Malathi, Hemavathi, Lakshmanthirtha, Yetthinahole, Kadumanehalla and Kumaradhara are considered for the study. Later, the catchment Nethravathi has been used for

validation of the regionalization work. The catchments considered for the study lies well within the Western Ghats. Fig. 2. shows the catchments considered in the present study and its location in boundary of Karnataka map. Some of the special features of the region Western Ghats (Putty and Prasad, 1997; WGEEP, 2011) are its moderate intensity, long duration rainfall; a very thick, highly stable soil mantle on the slopes, even under the grasslands; high infiltration rates permitting very little Hortonian overland flow and resulting in the catchment runoff being dominated by subsurface flow; flow through pipes dominating the subsurface runoff processes in very wet parts of the region; catchment response being influenced by the amount of rainfall, and not the intensity of rainfall; parameter values of channel geomorphology being comparable to only those in areas with much less rainfall.

The input data used in the present study are time series of rainfall, stream flow and mean temperature. Rainfall and stream flow data has been collected from WRC-NIE and the data of temperature from IMD. DEMs of 30m resolution of catchments downloaded from ASTER DEM website http://www.jspacesystems.or.jp

4. Predicting daily streamflow of ungauged catchmnets:

As a first step, IHACRES model is used to simulate rainfall runoff relationship and model parameters are calibrated for each individual catchment. Table-1 shows the model parameter values for the selected catchments. Physical Catchment Descriptors (PCD's) also called as Catchment Attributes are selected for each catchment, shown in table-2. Correlation analysis is carried to explore transferability of model parameters between catchments, based upon catchment characteristics. A significant correlation at 5% and above level is observed among model parameters and several PCD's. An abstract of the significant catchment indices are: Max length of basin Lmax(km), Basin relief ΔH(m), Drainage density Dd, Stream frequency Fs, Bifurcation ratio Rb, Circularity ratio Rc and Relief ratio Rh. A regression based linear relationships are developed between model parameters and catchment attributes. Stepwise method of variable selection is used. Six equations are developed accordingly for the six parameters of the model and the results are tabulated in table-3. Developed equations are evaluated by validating against pseudo ungauged basin. In the hydrological modelling exercise at each of the gauged catchments, a set of optimised model parameters are obtained. This set of model parameters at each catchment are related to the PCD's of the respective catchments. Thus collecting the sets of parameter values and the related sets of PCD's from all the catchments, the parameter values are regressed (multiple linear regression) against the PCD's to develop relations between them.

In the present work, the six model parameters are regressed against selected ten PCD's. Possibilities are there such that a single parameter might not be dependent on all the selected PCD's. Multiple linear Regression analysis provides the means to identify the significant independent variables on which the parameter (dependent variable) under consideration depends. The process of selecting the significant independent variables is termed as Variable Selection (Freund and Wilson, 2003). Filtering of variables is necessary to identify those that are most important in explaining a process. In many applications this translates into obtaining a good regression using a minimum number of independent variables. MLR analysis without variable selection would remain incomplete. Statistical packages like SPSS, SAS, etc, can be used in MLR analysis which includes the process of variable selection.
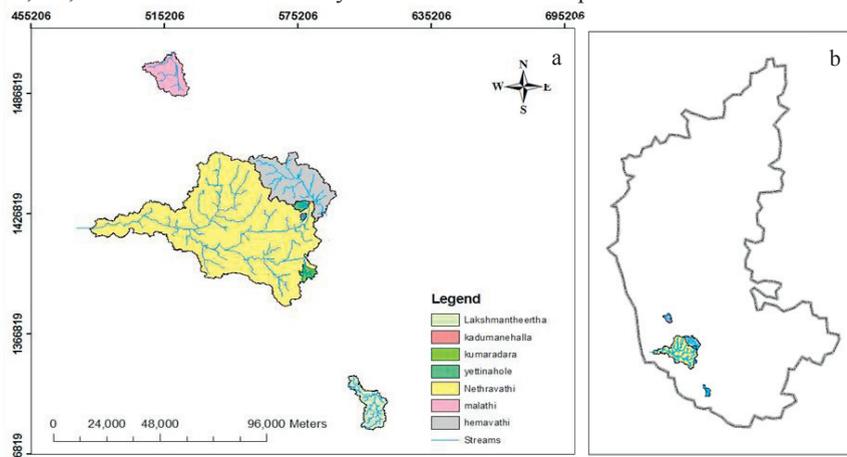

Fig. 2. Location of catchments used in the present study- a) Relative positions of catchments b) Location of catchments in the State of Karnataka

Table 1. Model parameter values

Sl no	Basin name	c (mm)	f (per degree centigrade)	tw (days)	ts (days)	tq (days)	vs
1	Hemavathi	0.000966	0.8	43	21.221	0.99	0.324
2	Kadumanehalla	0.000467	0.6	61	28.512	0.88	0.407
3	Kumaradhara	0.000335	0.7	130	19.465	0.957	0.55
4	Lakshmantheertha	0.001095	2.4	38	11.046	0.495	0.606
5	Malathi	0.001102	0.5	19	47.686	0.546	0.277
6	Yettinahole	0.001294	3.5	62.5	25.296	1.078	0.522

Volume of a conceptual wetness storage (*c*) is in mm,

Temperature modulation factor (*f*) is in per degree celcius,

Catchment drying time constant (tw)

Quick flow response decay time constant(t_q) is in days,

Slow flow response decay time constant (t_s) is in days and

Proportional volumetric contribution of slow flow to streamflow (v_s).

Table 2. Physical Catchment Descriptors

Sl no	Physical Catchment Descriptors	Basin Name					
		Hemavathi	Kadumane halla	Kumara dhara	Lakshman theertha	Malathi	Yettina hole
1	Area (km^2)	631.65	7.59	34.75	212.69	241.62	27.56
2	Perimeter (m)	188126.00	17511.00	36622.00	144893.00	93714.00	25682.00
3	Length of main stream (m) L_s	53045.40	4540.24	10980.00	17126.23	22868.38	8739.97
4	Maximum length of basin (km) L_{max}	32.18	3.62	8.50	28.13	23.86	8.25
5	Drainage density D_d	0.65	2.44	1.54	2.04	0.66	1.62
6	Stream frequency F_s	0.45	3.67	2.82	2.40	0.39	2.07
7	Bifurcation ratio R_b	1.86	5.66	4.80	4.44	4.20	8.11
8	Basin Relief ΔH	530.00	318.00	591.00	778.00	367.00	413.00
9	Relief ratio R_h	13.12	87.75	69.53	27.66	15.38	59.41
10	Circularity ratio R_c	0.12	1.39	3.23	0.12	0.13	3.33

Table 3. Developed regression equations

Sl no	Developed Equation	R^2 value
1	$c = 1.61 \times 10^{-6}(\Delta H)$	0.799
2	$f = 0.305\ (R_b)$	0.764
3	$\tau_w = 30.822\ (R_c)$	0.794
4	$t_q = 0.152\ (R_b)$	0.859
5	$t_s = 4.633\ (R_b)$	0.742
6	$v_s = 0.001\ (\Delta H) +\ 0.029\ (R_b) -\ 0.005\ (L_{max})$	0.999

5. Results and discussions:

The self written program of the model IHACRES using MS – Excel is executed for continuous flow of monsoon months on selected gauged catchments. The results output were in the form of hydrographs of observed flow, modelled flow, quick flow and slow flow. The resultant hydrographs are shown in Fig. 3. to Fig. 8. The Nash-Sutcliff coefficients for the catchments Hemavathi, Kadumanehalla, Kumaradhara, Lakshmantheertha, Malathi and Yettinahole are 0.83, 0.45, 0.60, 0.69, 0.84 and 0.81 respectively. It is observed that these coefficients are generally good for the modelled catchments. This proves that the IHACRES model is applicable to these catchments and in general to Western Ghats. However for the catchment Kadumanehalla, the Nash-Sutcliff coefficient is comparatively lower possibly due to the presence of some extreme discharge values (outliers) and the possibility of IHACRES not capable of capturing such extreme non-linearity's. Such outliers are also present in the hydrographs of other catchments such as Kumaradara and Yettinahole.

One of the special features of IHACRES is that it provides for separation of base flows through the concept of two-storage function- one taking care of quick flow component (surface runoff) and the other taking care of slow flow component (base flow). Fig. 3.b – 8.b shows also the quick flow and slow flow hydrographs. It is observed that in some catchments, slow flow is quite appreciable and can also approach negligible values. This feature of IHACRES by itself can be used to study base flows from different catchments.
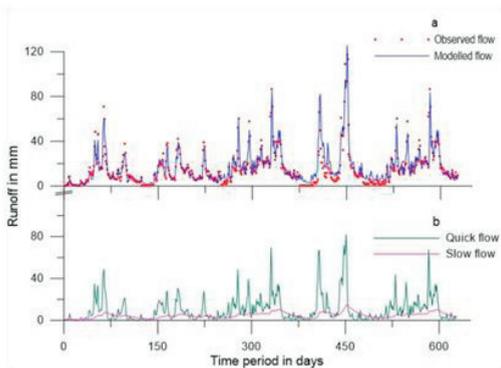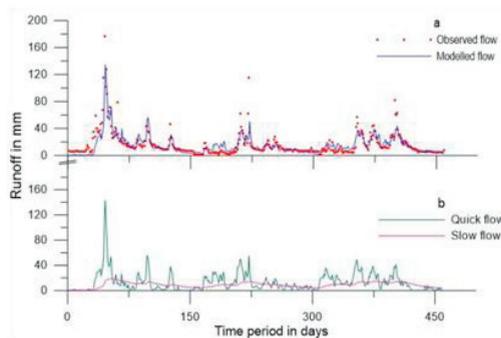

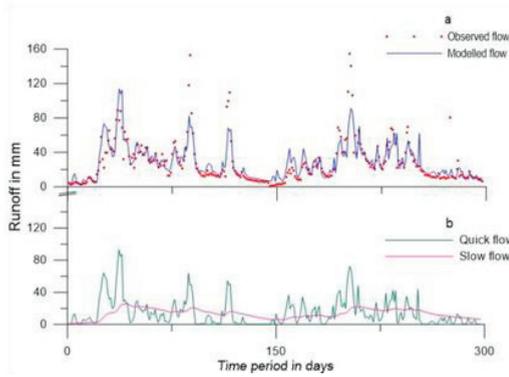Fig. 3. Hemavathi   Fig. 4. Kadumanehalla
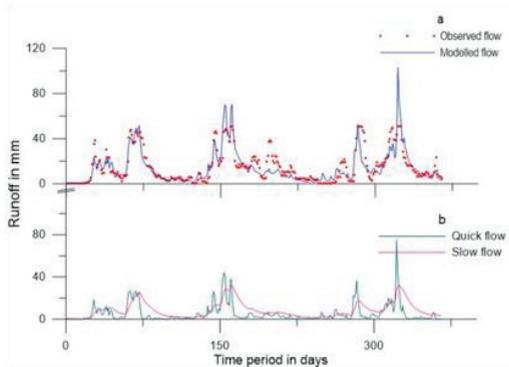
Fig. 5. Kumaradhara
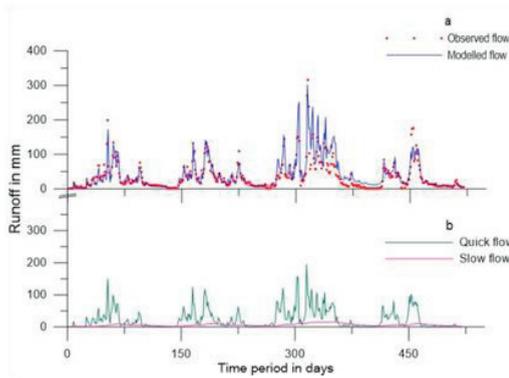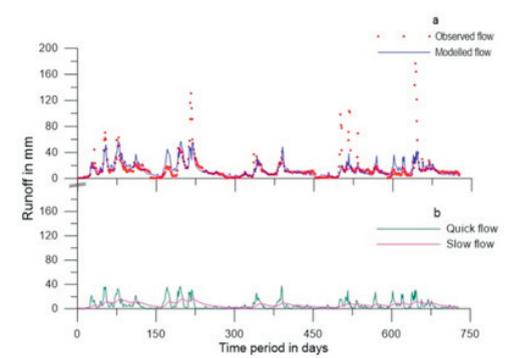

Fig .6. Lakshmantheertha

Fig. 7. Malathi

Fig. 8. Yettinahole

Developed equations are validated in two ways-

Case-1: Application of the developed equations on one of the catchments from which the equations are derived.

Case-2: Application of the developed equations on an independent catchment. This independent catchment is not one among the catchments from which the regression equations are developed.

The catchment adopted for Case-1 is Kadumanehalla (7.59 km2) and for Case-2 is Nethravathi (3440 km2). The parameter values for Case - 1 and Case – 2 are shown in table-4. Adopting these parameter values the output generated on executing the IHACRES model for Case-1 and Case-2 are shown in Fig. 9. and Fig. 10.

It is observed from that the Nash-Sutcliff coefficient in Case-1 for the catchment of Kadumanehalla (Fig. 9.) is 0.67 and in Case-2 for the catchment of Nethravathi (Fig. 10.) is 0.72 which shows that the fits are fairly good. Also on visual inspection the modeled discharges closely fit the observed ones. This proves that the process of regionalization of flows using IHACRES model is success and it is applicable to the catchments of Western Ghats.

Table 4. Parameter values obtained using developed regression equations

Model Parameters	Kadumanehalla	Nethravathi
c (mm)	0.00051198	0.0009821
f (per degree centigrade)	1.73	1.90015

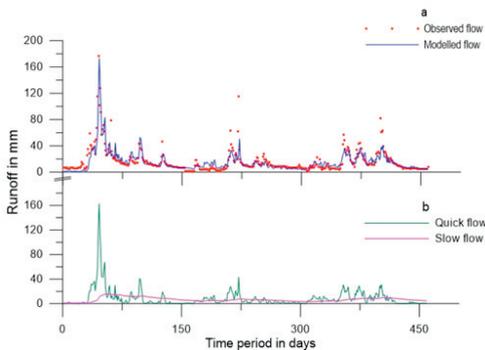|		
τ_w (days)	42.813	13.438
t_s (days)	26.23	0.947
t_q (days)	0.86	28.86
v_s	0.464	0.276

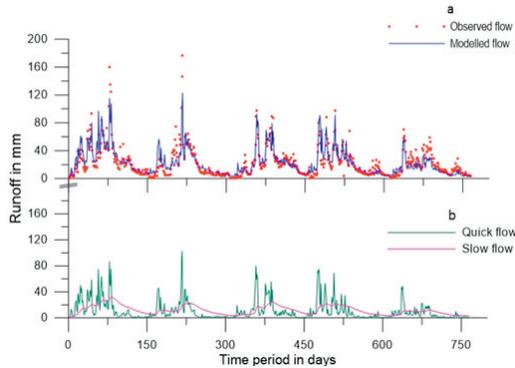Fig. 9. Hydrographs for the catchment Kadumanehalla (validation results)

Fig. 10. Hydrographs for the catchment Nethravathi (validation results)

6. Conclusions:

The performance of the model IHACRES is tested first and the results suggests that the IHACRES model could simulate the flows reasonably well. The peak flows could not be simulated properly - the results of the study to some extent may be influenced by the quality of data as these have been used as such.

In the discharge hydrographs of the catchments considered for this study, the base flow part is quite appreciable and is prominent. An important feature of IHACRES is that it captures this base flow separately (as slow flow component). This feature of IHACRES by itself can be used to study base flows from different catchments.

The linear dependency of the model parameters (of IHACRES) on PCDs are tested through correlation analysis. The results shows that the model parameters depends linearly either directly or indirectly on area of the basin, perimeter of the basin, maximum length of a stream in a basin, elevation, number of streams and stream order.

The work on regionalization of flows should follow up with a rigorous MLR analysis to identify those PCDs that are insignificant in the relation to the parameter. This was the case in the present study as many of the PCDs were identified as not impacting on the parameter values.

The developed regression equations between model parameter values and PCDs have been used in IHACRES model and validated at two different scales - at a smaller scale for a small catchment of Kadumanehalla (7.59 km2) and at a larger scale for a bigger catchment of Nethravathi (3440 km2). This gives the confidence to use this work to find the flows at ungauged catchments in the vicinity of the catchments adopted in this study (basically in Western Ghats).

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