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Calibrating hydrological models in ungauged basins: possible use of areal evapotranspiration instead of streamflows

LAKSHMAN NANDAGIRI

Department of Applied Mechanics & Hydraulics, National Institute of Technology Karnataka,
Surathkal, Srinivasnagar PO, Mangalore, Karnataka 575 025, India
lnand@rocketmail.com

Abstract The success of water management policies in developing countries such as India is linked to the accuracy with which variations (temporal and spatial) in available surface and groundwater resources can be quantified. However, sparse hydro-meteorological data networks generating poor quality information content have favoured the use of empirical rather than scientific data-driven approaches in such resource assessments. This situation is likely to continue until such time as recently installed networks, and proposed ones, begin to provide data at the spatial and temporal scales required for the use of operational hydrological models. In such circumstances, these countries are left with no other option but to devise innovative methods that can extrapolate the available data in space and time. The problem of streamflow prediction in ungauged basins is addressed in this paper. Modelling studies carried out in basins located in the humid tropical West Coast region of India are described. We present results with reference to two commonly adopted PUB approaches: (1) regionalization of parameters of a lumped water balance (Thornthwaite-Mather) model, and (2) development and testing of a lumped model with physically-based parameters. Also, we pose the question: can we use areal evapotranspiration values (derived from the Complementary Relationship Areal Evapotranspiration hypothesis) instead of streamflow records to calibrate a hydrological model? This question was explored through application of a simple annual streamflow model to a basin. The model was calibrated separately with streamflows and areal evapotranspiration values and its performance was assessed.

Key words evapotranspiration; hydrological regionalization; model calibration; prediction in ungauged basins; rainfall–runoff modelling; streamflow prediction

INTRODUCTION

The design of a water resources project across a stream/river basin necessarily involves the use of long time series of streamflow records in hydrological analyses relating to storage-yield and flow duration. However, only in extremely rare cases will such records be available at the exact location of the proposed site. In such circumstances, the hydrologist is left with no other option but to "generate" streamflow records from rainfall and other meteorological data or to "synthesize" flows from time series analyses carried out in nearby gauged basins.

Since the former approach of deriving streamflow from rainfall is less cumbersome, the hydrological literature reveals a large number of studies which have addressed this problem. Given the fact that no universal relationship exists between runoff and rainfall, such relationships are usually developed for hydro-meteorologically homogenous regions. In most cases, runoff–rainfall relationships are developed for gauged basins in the region using regression analyses and the regression coefficients are subsequently "regionalized" by relating them to basin physical characteristics so that suitable coefficients may then be derived for ungauged basins. Attempts to improve such regression approaches have been made by including additional variables such as: temperature, antecedent wetness indices, time of the year, etc. Undoubtedly, the accuracy with which streamflow can be estimated will improve as more variables are included, but the increased data requirement will prevent the widespread use of such relationships.

Recent years have seen the emergence of a more sophisticated and accurate approach to streamflow estimation through the use of hydrological models. Such models seek to represent the complex processes involved in the conversion of rainfall input into streamflow output through the use of mathematical descriptions of hydrological processes. Although hydrological models are vastly superior to regression equations, they still need to be calibrated with measured streamflow and model parameters need to be regionalized for application in ungauged basins. With an improvement in our understanding of hydrological processes, the concept of physically-based hydrological modelling has emerged. Such models are designed such that the model parameters retain physical meaning and hence they may be specified *a priori* from the knowledge of basin characteristics. This approach eliminates the need for model calibration with streamflow records.

In this paper the following issues pertaining to the use of hydrological models in estimating streamflow are addressed: (i) regionalization of parameters of a basin-scale water balance model; (ii) development and verification of a physically-based water balance model; and (iii) exploration of an alternative to streamflow records for calibrating hydrological models. In the first two sections of this paper, results with regard to regionalization and a physically-based model are presented for river basins located in the humid tropical West Coast region of Karnataka State, India. In the last section, we explore the possibility of using areal actual evapotranspiration values (derived from the Complementary Relationship Areal Evapotranspiration hypothesis) to calibrate a simple annual hydrological model.

REGIONALIZATION STUDY

In this study, a lumped basin-scale water balance model (named KREC) based on the Thornthwaite-Mather water balance accounting procedure (Dunne & Leopold, 1978) was developed. The model utilizes inputs of rainfall and potential evapotranspiration and gives a continuous output of direct runoff, subsurface runoff, groundwater recharge, baseflow, actual evapotranspiration and streamflow. Table 1 shows the algorithm of the working of the model (Version 1). The model has five unknown parameters: *drc*, *src*, *awc*, *ifc*, *iflag* and *blag*, which need to be determined by calibration with measured streamflow data.

This model was applied to nine gauged basins (99–3441 km^2) located in Dakshina Kannada District, Karnataka State, India. For each basin, the model was run on a continuous basis for periods (ranging from a minimum of 6 years to a maximum of 13

Table 1 Algorithms of models used.

KREC Model Version 1			
DR	=	$drc \times P$	
SR	=	$src \times DR$	
EP	=	$P - DR$	
$APWL$	=	$\sum \lvert (EP - PET) \rvert$	for $EP < PET$
	=	0	for $EP > PET$
ST	=	$awc \times \exp\left(-\frac{APWL}{awc}\right)$	for $APWL \neq 0$
	=	$\min\{[(EP - PET) + \mathrm{STt}_{-1}], \mathrm{awc}\}$	for $APWL = 0$
AET	=	PET	for $EP > PET$
	=	$EP + DST$	for $EP < PET$
WS	=	$(EP - PET) + ST_{t\text{-}1} - awc$	for $ST = awc$
	=	0 Otherwise	
IFL	=	$(1 - src) * DR$	
$SSRO$	=	$(1 - iflag)(IFAR + IFL)$	
GWR	=	$WS - IFL$	for $WS > IFL$
	=	0 Otherwise	
BF	=	$(1 - blag)(TAR + GWR)$	
TRO	=	$SR + SSRO + BF$	
KREC Model Version 2			
DR	=	$\frac{(P - 0.3S)^2}{(P + 0.7S)}$ when $P > 0.3S$	
	=	0 otherwise	
EP	=	$P - DR$	
$APWL$	=	$\sum \lvert (EP - PET) \rvert$	for $EP <$ PET
	=	0	for $EP > PET$
ST	=	$awc * \exp\left(-\frac{APEL}{awc}\right)$	for $APWL \neq 0$
	=	$\min\{[(EP - PET) + ST_{t\text{-}1}], awc\}$	for $APWL = 0$
AET	=	PET	for $EP > PET$
	=	$EP + DST$	for $EP < PET$
GWR	=	$(EP - PET) + \mathrm{STt}_{-1} - awc$	for $ST = awc$
	=	0 otherwise	
BF	=	$(1 - blag)(TAR + GWR)$	
TRO	=	$DR + BF$	
abc Model			
I_t	=	$a\,P_t$	
DR_t	=	$(1 - a)\,P_{\mathrm{t}}$	
E_t	=	$b\,I_t$	
BF_t	=	$c\ \ I_t$	
TRO_t	=	$(1 - a + ca)\,P_t$	

years) for which concurrent data of Thiessen weighted rainfall, potential evapotranspiration and measured streamflows were available. An optimization procedure was adopted to arrive at the optimal values of the model parameters such that deviations between simulated and observed streamflows were minimized. Model performance during the calibration phase was assessed by computing several statistics. While the Nash-Sutcliffe prediction efficiencies for the nine basins ranged between 80% and

97%, the correlation coefficients between monthly simulated and observed streamflows ranged between 0.82 and 0.98. Despite the simplicity of the model, these statistics are indicative of their reasonably good performance. An attempt was then made to establish relationships between basin physical characteristics, such as: basin area, stream length, drainage density, vegetation type and percentage cover, and soil type. Due to the limited sample size, statistical relationships between parameters and basin characteristics could not be established. However, we were able to establish broad guidelines for selecting values of the five model parameters in ungauged basins, Table (2).

Table 2 Guidelines for selecting parameters for KREC Model Version 1.

Model parameter		Recommended values			
ifc		250			
drc	Jul	Aug	Sep	Oct	Drainage density
	0.85 – 0.95	0.9 – 0.95	0.8 – 0.9	0.6	>2.5
	0.75 – 0.85	0.9 – 0.95	0.7 – 0.8	0.5	2.0 – 2.5
	0.55 – 0.75	0.8 – 0.95	0.7 – 0.8	0.45	<2
blag		0.35 – 0.45			>2.5
		0.45 – 0.55			2.0 – 2.5
		0.6			<2
			Secondary and scattered vegetation (%)		
iflag		0.35 – 0.45	>80		
		0.45 – 0.55	60 – 80		
		>0.6	<60		

PHYSICALLY-BASED MODEL

In this exercise, the KREC model Version 1 was modified so as to obtain a model structure that yielded parameters which could be assessed from secondary data prior to model application, i.e. a so-called “physically-based” model. Table 1 shows the algorithm of the modified form of the KREC model (Version 2). A major modification involved introduction of the widely used Soil Conservation Services Curve Number (SCS-CN) method for modelling the direct runoff component. This modification not only eliminated cumbersome monthly direct runoff coefficients (*drc*), but also offered the advantage of linking the KREC model to satellite remote sensing data on land use/land cover within a GIS environment. Version 2 has only three parameters: *S* (or *CN*), *awc* and *blag*, which may be fixed up prior to application of the model. While *CN* (Curve Number), based on land use/land cover, hydrological soil type and antecedent wetness conditions, can be readily obtained from standard tables published in the literature, *awc* (available water capacity of the soil profile calculated as the difference in profile water storage at field capacity and permanent wilting point) may be derived from published data on soil hydraulic properties for various soil textural types. The parameter *blag* was estimated using relationships presented by Ram Mohan & Nair (1984) using information on basin slope, soil type and extent and type of forest cover.

This model was applied to the gauged Gurpur River basin (841 km^2) located in the Dakshina Kannada district. Daily rainfall from three raingauge stations were used to calculate basin average rainfall by deriving station weights from a multiple linear regression analysis of annual rainfall obtained as the difference between annual streamflow and actual evapotranspiration, and annual rainfalls recorded at each station. Potential evapotranspiration was derived using the temperature-based Hargreaves-Samani equation. Data from the Indian Remote Sensing Satellite (IRS) was used to produce a land-use map of the basin. The land-use map and a soil map of the basin were then processed with GIS software to yield percentage cover of dominant land-use categories under various soil groups. This information was used to select appropriate values of the *CN* and *awc* parameters for each land-use/soil group category and *blag* for the basin was derived from the relationships suggested by Ram Mohan & Nair (1986).

The KREC model Version 2 was applied separately to each land-use class under each soil group and streamflow was simulated for the period 1976–1986. An area-weighted streamflow was then computed by summing the model simulated streamflows from each category. Figure 1 compares simulated and observed monthly mean streamflows for the test period. Together with a Nash-Sutcliffe coefficient of 0.92 and correlation coefficient of 0.96 between simulated and observed flows during the entire period, this indicates fairly good performance of the model, especially considering the fact that no attempt was made to calibrate the model.

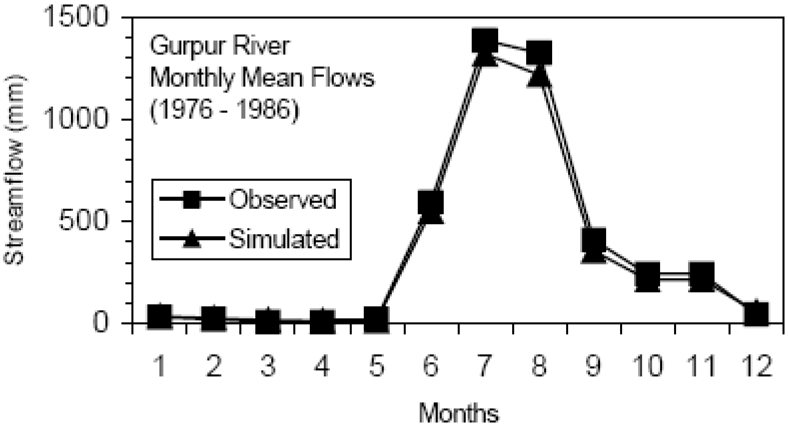

Fig. 1 Comparison between observed and simulated monthly mean flows.

ALTERNATIVE TO STREAMFLOW

Streamflow is the preferred variable with which hydrological models are calibrated. Reasons for this preference are: (i) streamflow represents an integrated response of the basin and accounts for the effect of all the hydrological processes taking place therein, and (ii) streamflow measurements are made at a single point and hence spatial averaging is not an issue. Although attempts have been made to calibrate hydrological models with soil moisture measurements and groundwater levels, difficulties are experienced in converting point measurements into a spatial average with which a lumped model can be calibrated.

In this paper, areal actual evapotranspiration is proposed as an alternative with which hydrological models may be calibrated. Since this variable is representative of the integrated response of the soil–vegetation complex in the basin and since it can be calculated directly as an areal average, it offers the same advantages as streamflow in calibration exercises.

The areal actual evapotranspiration suggested in this paper is a product of the Complementary Relationship Areal Evapotranspiration (CRAE) approach. This approach utilizes only meteorological data to produce estimates of actual evapotranspiration from large areas (characteristic length 1 km to 10 km) and thereby avoids the need for information on the soil–vegetation complex. Based on the initial concept proposed by Bouchet (1964), the CRAE approach has been expanded by Brutsaert & Stricker (1979) and Morton (1983). Subsequently this approach has been applied over a range of temporal and spatial scales to estimate actual evapotranspiration from a variety of soil–vegetation complexes (e.g. Ben Asher, 1981; Ali & Mawdsley, 1987; Parlange & Katul, 1992, Nandagiri, 1997). Attempts have also been made to integrate CRAE estimates of evapotranspiration into basin-scale hydrological models (e.g. Kite & Kouwen, 1992; Doyle, 1990).

In this study, areal actual evapotranspiration (E) was estimated using the following equation suggested by Brutsaert & Stricker (1979):

$$E = (2\alpha - 1)\,\frac{\Delta}{\Delta + \gamma} R_n \quad \frac{\gamma}{\Delta + \gamma} f(u)(e_a \quad e_d) \tag{1}$$

where Δ is the slope of the saturation vapour pressure *vs* temperature curve at air temperature (T), γ is the psychrometric constant, R_n is net radiation, $f(u)$ is a function of windspeed (u), α is the Priestley-Taylor constant and ($e_a - e_d$) is the vapour pressure deficit.

In order to investigate the possibility of using areal evapotranspiration in calibration, we formulated a simple annual water balance model, the abc model, the algorithm of which is shown in Table 1. This model uses only annual basin average rainfall as input and yields annual values of actual evapotranspiration and streamflow. The unknown parameters of the model are: *a*, *b* and *c*. Two approaches to determining these parameters were tried: (i) calibration with streamflow data and (ii) calibration with areal evapotranspiration values. This exercise was carried out for the Nethravathi River basin (3441 km^2) located in the Dakshina Kannada district, Karnataka, India for the period 1972 to 1986. Thiessen weighted rainfall from observations at 17 raingauges, measured streamflows and areal evapotranspiration values calculated using equation (1) with data from a nearby meteorological station, were used in the analysis. Figure (2) compares measured streamflows with those estimated by the model with

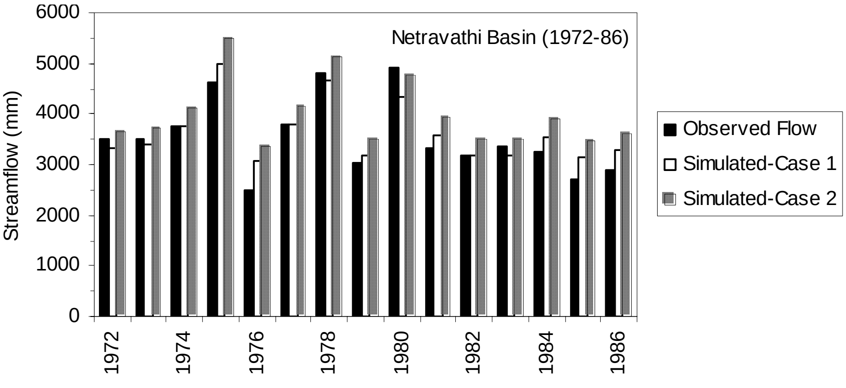

Fig. 2 Comparison of streamflow simulations with abc model calibrated with measured streamflow (Case 1) and areal ET (Case 2).

Case 1: parameters calibrated with measured streamflows, and Case 2: parameters calibrated with areal evapotranspiration.

The fairly good comparison between the simulations obtained by both calibration approaches indicates the feasibility of our proposal that areal evapotranspiration values, obtained quite easily from regularly recorded meteorological data, may be used to calibrate a hydrological model in ungauged basins. Future research must concentrate on refining this methodology and exploring calibration exercises with models operating on small time steps.

CONCLUSIONS

Streamflow data is crucial in hydrological analyses related to the design of water resources projects. Invariably, the hydrologist is posed with the problem of estimating streamflow, since more often than not, project sites do not coincide with gauge and discharge sites. This is especially true in developing countries such as India where the density of river gauging sites is extremely low. In such situations, the hydrologist has to devise innovative methods of utilizing whatever hydro-meteorological data is available and come out with a reasonably accurate estimate of streamflow. A few such innovative methods are demonstrated in this paper. Future research on the topic of "Predictions in Ungauged Basins" (PUB) must no doubt concentrate on improving the density and quality of hydro-meteorological networks, but until such time as these networks become operational, there is an urgent need to standardize procedures for estimating streamflow from secondary data.

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