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HYDRO-CLIMATIC CONCEPTUAL STREAMFLOW MODELLING

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ABSTRACT

What sort of modifications are necessary in order to identify the streamflow response in a changing climate? This is the focus of this chapter. As such the conceptual models for streamflow has a long history. This chapter starts with a brief summary of some of the popular models in the past. In most of the existing approaches, different hydrological processes are conceptualized without considering any time varying watershed characteristics and change in climate. However, these are being considered in the recently developed models. The chapter proceeds to a brief introduction of one such recently developed model, namely Hydro-Climatic Conceptual Streamflow (HCCS) model. Apart from its theoretical background and features, a demonstration of its Graphical User Interface (GUI) is also included. Towards the end of the chapter, applications of HCCS and a few other conceptual models to two rainfed river basins are also included. The GUI of the HCCS model is copyright protected by the Govt. of India but the author can be contacted for its use in academic purposes (Authors' email: rajib@civil.iitkgp.ernet.in; rajibmaity@gmail.com; bhagwatpp@gmail.com).

Key Words: *Conceptual model, Climate, Hydroclimatology, Prediction, Streamflow.*

INTRODUCTION

It is worthwhile to mention at the beginning that the hydrologic models can be classified in several ways depending on different attributes, such as space, time and randomness are considered or not. Based on the rigor of mathematical representations of hydrological processes, three broad categories are – (a) Physically-based models (b) Conceptual models, and (c) Artificial Intelligence (AI) based models. In physically-based models, existing knowledge of all possible hydrological processes is represented through a set of mathematical equations. Examples of some popular physically-based models include System Hydrologique European (SHE) (Abbott et al., 1986a, (b), Better Assessment Science Integrating point and Non-point Sources (BASINS) (EPA, 1998), Soil & Water Assessment Tool (SWAT)(Arnold et al., 1998). The common issue of such models is its requirement of a large number of data and (still)poor performance due to various reasons.

It is indeed true that complex nature of hydrologic cycle is difficult to understand fully. Relatively simple mathematical equations are used in developing different conceptual models that mainly consider only the major hydrological processes of the complex hydrological cycle. In the absence of complete knowledge on any particular processes, simplified means of system concept is used. A system is represented as a set of connected parts that form the whole. Construction of a model relating inputs and outputs is attempted in conceptual models rather than exact representation of the system details. In many cases, exact representation may not be possible. Nevertheless, knowledge of the physical system helps in developing a conceptually clear model. This also forms the basis for selecting the input and output variables in the AI based models. However, the mathematical representation of hydrological processes cannot be inferred easily, if not at all, from such models. Sometimes such models are termed as black/grey box model to draw an analogy to its mathematical transparency.

Conceptual streamflow models have a long evolving history and its initiation is difficult to pin-point. National Weather Service River Forecast System (NWSRFS) can be considered as one of the early initiatives for implementation of the conceptual streamflow model (Anderson, 1974).Afterwards, approximate chronological sequence may include the Institute Royal Meteorology Belgium (IRMB) model (Bultot and Dupriez, 1976), Soil Moisture Accounting and Routing (SMAR) Model (O'Connell et al., 1970; Kachroo, 1992; Tuteja and Cunnane, 1999), Precipitation Runoff Modelling System (PRMS) (Leavesley et al., 1983 and Leavesley et al., 1996), HYDROLOG model (Porter and McMahon, 1976) which was later modified by Chiew and McMahon (1994) to MODifed HYDROLOG (MODHYDROLOG) model, Hydrologiska Byråns Vattenbalansavdelning (HBV) model which was developed at the Swedish Meteorological and Hydrological Institute (SMHI) in 1972 (Bergström, 1980), the Hydrologic Simulation Program-FORTRAN (HSPF) model which is a modified version of Stanford model (Johnson et al., 2003) etc. These models are designed to approximate the general hydrological processes and parametrically parsimonious, the reason for their popularity.

What Do We Need for a Changing Climate?

Response of a watershed in terms of streamflow, ground water recharge and evapotranspiration depends on its operation on the received water (mainly from precipitation). Most of the existing approaches inherently assume a stationarity in other hydroclimatic factors when only rainfall is considered as an input. This may not be a valid assumption under a changing climate. Moreover, different hydrological processes are conceptualized in many, if not most of the, existing approaches without considering the time varying watershed characteristics. As a consequence, consistency (decadal to climatic scale) in the model performance is affected if the climate as well as watershed characteristics are changing gradually that are not accounted for. Hence, in the context of climate change, it is important to consider the information on changing climate and time varying watershed characteristics simultaneously while modelling watershed response. We will discuss Hydro-Climatic Conceptual Streamflow (HCCS) model in this regard.

DETAILS OF HYDROCLIMATIC CONCEPTUAL STREAMFLOW (HCCS) MODEL

Following the category outlined before, the HCCS model is conceptual. It is able to provide the daily variation of streamflow, an estimate of spatially averaged evapotranspiration and an estimate of ground water recharge from the entire catchment. Most significant merit of the model is its applicability for future streamflow simulation using projected climate data in future. This section will provide a brief background of the modelling philosophy. Further, details can be found in Bhagwat and Maity, (2014).

Like many conceptual models, the watershed is treated as a 'system' in the HCCS model. A system receives water in the form of precipitation, processes it internally, and generates various components including streamflow as its 'response'. These responses depends on various time-dependent and time-invariant factors that characterize the watershed. For example, topology and shape of the catchment may be treated as time-invariant factors. On the other hand, rainfall over catchment,wetness condition of the watershed, continuous loss due to evapotranspiration and ground water recharge etc. may be treated as time dependent factors. The approach in HCCS methodology is originated from the SACramento Soil Moisture Accounting (SAC-SMA) Model (Burnash et al., 1973) and the leaky bucket model proposed by Huang et al., (1996) as far as initial water balance equation is concerned.

In HCCS model, the representation of 'System Wetness Condition' (SWC) serves as a proxy for the stored water in the surface and near-surface soil strata (mainly root zone, approximately upto 150 cm) in the form of depression storage, reservoir storage, soil water retention etc. Obviously, the SWC is a time-dependent variable and it is denoted as $V(t)$, where t is the time subscript. It ranges from zero to maximum capacity of the system wetness, which is denoted as $V_{\max}$. It may be defined as the maximum water holding capacity of the watershed in various forms mentioned above. The variable $V(t)$ may change at a faster rate (*e.g.* daily) but the variable $V_{\max}$ varies at a much slower rate over time (*e.g.*, annual to decadal) because it depends on the change in different land use land cover (LULC), such as, urbanization, forest cover, existence of reservoirs etc and combination of spatial distribution thereof.

Consideration of $V_{\max}$ to vary over time in the context of changing climate renders the HCCS model suitable for its application to assess the effect of climate change on streamflow and other water responses. It is established that $V_{\max}$ changes over a multi-year scale and may vary from one watershed to another. A typical example will be shown later in application section.

The temporal evolution of $V(t)$, is expressed as

$$\frac{dV(t)}{dt} = P(t) - E(t) - S(t) - G(t) \qquad \text{...(1)}$$

where $P(t)$ and $E(t)$ at time t are spatially averaged precipitation and evapotranspiration over the watershed respectively. These are expressed in terms of depth unit, represents the streamflow (expressed in depth unit, dividing the total discharge over time dt by the catchment area of watershed). $G(t)$ is the ground water recharge component through deep percolation that joins ground water storage.

When normalized by V_{max}, the factor $V(t)/V_{\max}$ indicates time-varying system wetness condition. Mathematical boundaries of this factor are 0 and 1, where a completely dry and a fully wet system are indicated by 0 and 1 respectively. Various system responses are conceptualized to depend on the system wetness condition, *i.e.*, $V(t)/V_{max}$.Such conceptualizations are explained as follows.

First, the generated streamflow, $S(t)$, is conceptualized to have a non-linear relationship with the system wetness condition $V(t)$. If non-dimensionalized with respect to their respective maximum possible values which are denoted as V_{max} (as explained earlier) and S_{max}, the assumption is expressed as

$$\frac{S(t)}{S_{max}} = a\left(\frac{V(t)}{V_{max}}\right)^{b'} \quad \text{...(2)}$$

where S_{max} is analogous to Estimated Limiting Value (ELV), defined as the maximum possible magnitude of any hydrologic variable at a given location, based on the best available hydrologic information (Chow et al., 1988).It is shown for a few watershed that a non-linear curve of form, can explain, on an average 93 % (approximate range 74 % to 98 %) of the association between observed $S(t)$ and model estimated $V(t)$ (Bhagwat and Maity, 2014). After rearranging the eqn (2):

$$V(t) = B\ [S(t)]^b \quad \text{...(3)}$$

where $B = \dfrac{V_{max}}{(a\ \ S_{max})^b}$ and $b = 1/b'$.

The component evapotranspiration, $E(t)$, is estimated using following relation

$$E(t) = \frac{E_p(t)\ \ V(t)}{V_{max}} \quad \text{...(4)}$$

where is the potential evapotranspiration and $V(t)$ is the system wetness condition at time t. Substituting $V(t)$ in eqn (4) from eqn (3)

$$E(t) = E_p(t)\ \ \frac{B\left[S(t)\right]^b}{V_{max}} \quad \text{...(5)}$$

Second, the potential evapotranspiration can be estimated from climatic data using many existing methods, such as, Hargreaves method (Hargreaves et al., 1985; Hargreaves, 1994), the Penman-Monteith Method (Monteith, 1965) etc. The Hargreaves method is used in this chapter and developed GUI, which is discussed later.

Third, the ground water recharge component, denoted as, $G(t)$ may vary non-linearly with system wetness condition, $V(t)$ as follows:

$$G(t) = \alpha\ [V(t)]\beta \quad \text{...(6)}$$

However, for simplicity, $\beta = 1$ is assumed. Thus, a linear association is assumed between ground water recharge component and system wetness condition. The validity of this assumption is difficult to ascertain in absence of ground water recharge data. However, such linearity assumption was also made in other successful models, such as leaky bucket model by Huang et al. (1996). It is important to note here that subsequent development of following equations in the HCCS model is also possible without this assumption. This linearity assumption helps to reduce the burden of one parameter (β) only.

Using eqn (3) in eqn (6) with $\beta = 1$, $G(t)$ can be expressed as

$$G(t) = k\,[S(t)]^b \qquad ...(7)$$

where $k = \alpha B$ that indicates the net contribution to ground water recharge from the catchment. The value of k may be positive or negative depending on the net contribution to the ground water is positive or negative from entire catchment. k has no unit.

Expressing the left hand side of eqn (1) in finite difference form,

$$\frac{V(t+1)-V(t)}{\Delta t} = P(t)-E(t)-S(t)-G(t) \qquad ...(8)$$

Substituting the expressions of, $V(t)$ $E(t)$ and $G(t)$ in term of $S(t)$ and rearranging, it reduces to–

$$S(t+1) = \left[\left\{S(t)\right\}^b + \frac{\Delta t}{B}\left\{P(t)-E_p(t)\frac{B\left[S(t)\right]^b}{V_{\max}} - S(t) - k\left[S(t)\right]^b\right\}\right]^{1/b} \qquad ...(9)$$

where the parameters B, b, k and $V_{\max}$ characterize the entire watershed.

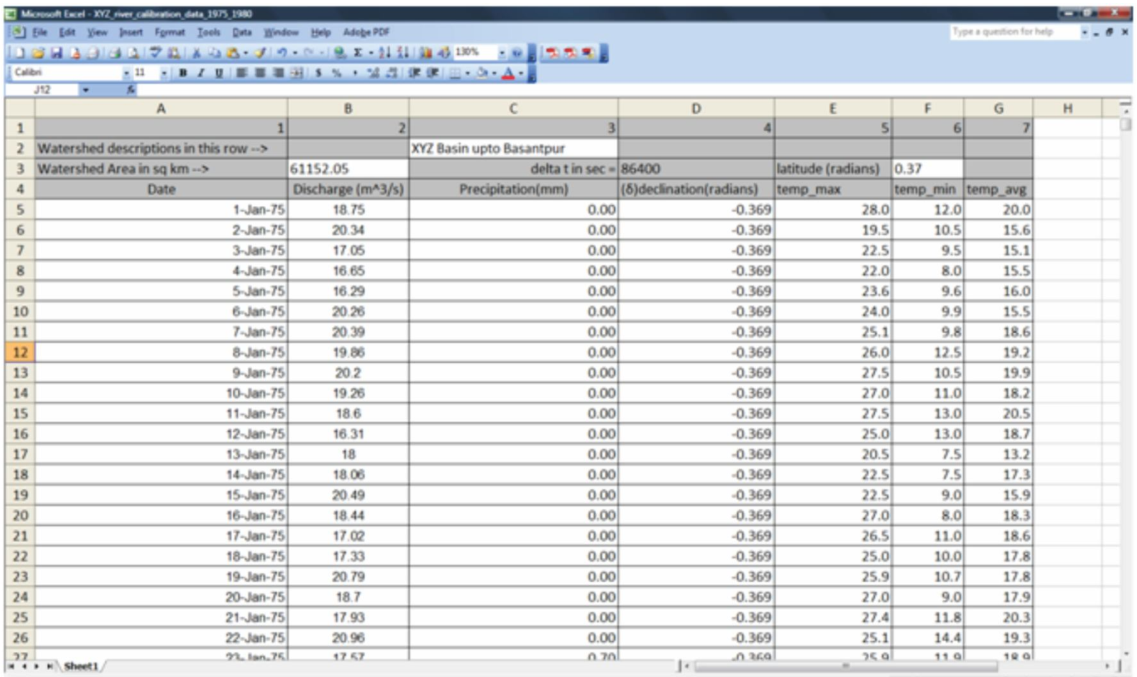
Parameter Estimation, Validation, and Future Projection

Parameter estimation is carried out using the data of rainfall, maximum, minimum and average temperature, and daily streamflow. Model parameters ($V_{\max}$, b, B and k) are estimated using these data during calibration period. These parameters are simultaneously estimated either by an optimization technique, such as simplex algorithm (computationally efficient, but solution may not be optimal always) or grid search technique (best possible solution guaranteed but computationally intensive) keeping the objective function to minimize the Mean Square Error (MSE). The parameter values that provides minimum MSE are obtained. During calibration and validation periods, model performance is investigated through different statistical measures computed between observed and predicted streamflow values.

To investigate the slow change in any parameter over time, parameter estimation is carried out over successive time frames, spanning over several years (say 3-10 years) over the historical period. Apart from depending on the data availability, the length of each time frame should not be too short to obtain an unreliable (noisy) estimate and also, should not be too long to miss (average out) the meaningful temporal trend/pattern, if any. The temporal trend/pattern in the estimated parameter values is modeled and if a trend is found, itis projected in the future. Different cases can be considered while projecting the temporal pattern in future – (1) no further change (latest value is used for future), (2) same trend of change projected to future and (3) change is slower approaching a constant (a non-linear equation may be fitted to observed parameter values in the past and projected to future). However, some of these parameters may not show any linear/ non-linear trend over time.If no such perceptible information on trend is noticed for aparameters, either average value of that parameter over the historical period or the latest information of that parameter can be used.

GRAPHICAL USER INTERFACE (GUI) FOR HCCS MODEL

A Graphical User Interface (GUI) is developed for easy application of the HCCS model. A demonstration is provided in this section to understand and use the GUI.At the outset, the input files are to be prepared in excel spreadsheet following a specified format.The input data required for HCCS model are rainfall, maximum temperature, minimum temperature, average temperature, solar declination and streamflow data. Example file for input data for model calibration (and also for validation) is shown in Figure 1. Similarly, the example file for input data during future streamflow prediction is shown in Figure 2. In these excel files, unhighlighted cells are for user input. Grey highlighted cells should not be changed. There is no restriction on the number of rows to be used. In Figure 2, streamflow values are not known, being in the future. However, the model needs the first day input (For example, 100 m^3/s as shown). This might be a simple guess or the long-term mean as observed in the past. Input files are ready, once all inputs are saved in the respective location.



	A	B	C	D	E	F	G	H
1	1	2	3	4	5	6	7	
2	Watershed descriptions in this row -->		XYZ Basin upto Basantpur					
3	Watershed Area in sq km -->	61152.05	delta t in sec =	86400	latitude (radians)	0.37		
4	Date	Discharge (m^3/s)	Precipitation(mm)	(δ)declination(radians)	temp_max	temp_min	temp_avg	
5	1-Jan-75	18.75	0.00	-0.369	28.0	12.0	20.0	
6	2-Jan-75	20.34	0.00	-0.369	19.5	10.5	15.6	
7	3-Jan-75	17.05	0.00	-0.369	22.5	9.5	15.1	
8	4-Jan-75	16.65	0.00	-0.369	22.0	8.0	15.5	
9	5-Jan-75	16.29	0.00	-0.369	23.6	9.6	16.0	
10	6-Jan-75	20.26	0.00	-0.369	24.0	9.9	15.5	
11	7-Jan-75	20.39	0.00	-0.369	25.1	9.8	18.6	
12	8-Jan-75	19.86	0.00	-0.369	26.0	12.5	19.2	
13	9-Jan-75	20.2	0.00	-0.369	27.5	10.5	19.9	
14	10-Jan-75	19.26	0.00	-0.369	27.0	11.0	18.2	
15	11-Jan-75	18.6	0.00	-0.369	27.5	13.0	20.5	
16	12-Jan-75	16.31	0.00	-0.369	25.0	13.0	18.7	
17	13-Jan-75	18	0.00	-0.369	20.5	7.5	13.2	
18	14-Jan-75	18.06	0.00	-0.369	22.5	7.5	17.3	
19	15-Jan-75	20.49	0.00	-0.369	22.5	9.0	15.9	
20	16-Jan-75	18.44	0.00	-0.369	27.0	8.0	18.3	
21	17-Jan-75	17.02	0.00	-0.369	26.5	11.0	18.6	
22	18-Jan-75	17.33	0.00	-0.369	25.0	10.0	17.8	
23	19-Jan-75	20.79	0.00	-0.369	25.9	10.7	17.8	
24	20-Jan-75	18.7	0.00	-0.369	27.0	9.0	17.9	
25	21-Jan-75	17.93	0.00	-0.369	27.4	11.8	20.3	
26	22-Jan-75	20.96	0.00	-0.369	25.1	14.4	19.3	
27	23-Jan-75	17.57	0.70	-0.369	25.9	11.9	18.9	

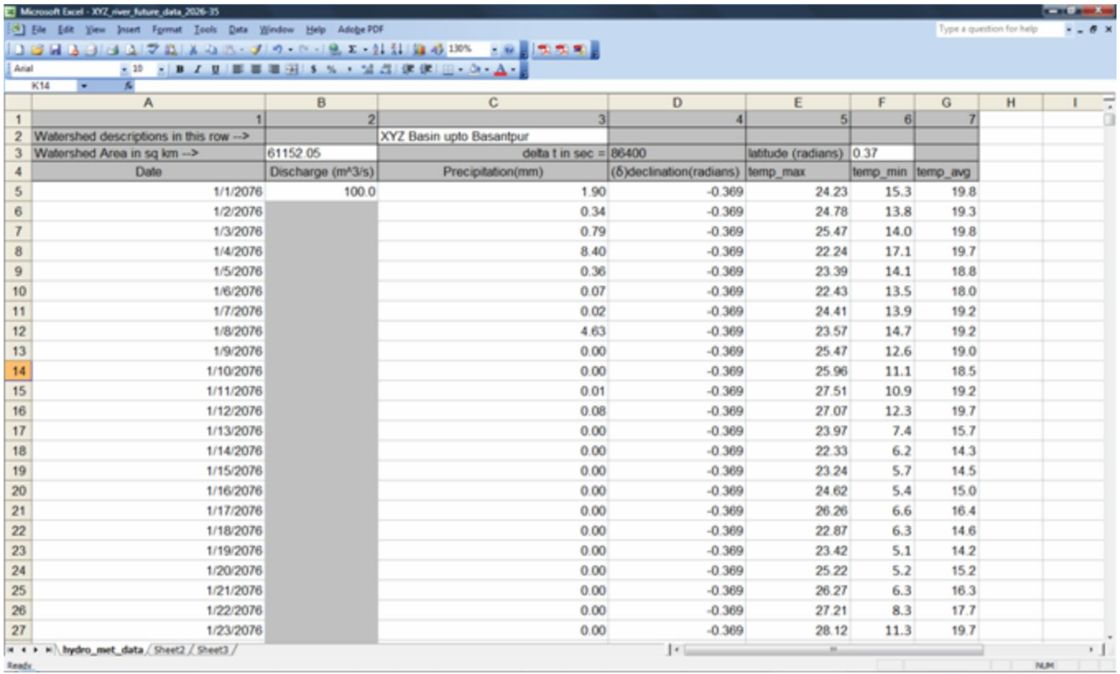
Figure 1. Example File for Model Calibration (and Validation). Unhighlighted cells are for user input. Grey highlighted cells should not be changed. PLEASE DO NOT CHANGE THE ARRANGEMENT ORDER OF THE CELLS. There is no restriction for the number of rows to be used.

Steps to run the GUI:

1. Go to the folder where the software package is installed and double click on HCCS_Model.exe. The GUI for HCCS model will appear as shown in Figure 3.

Model Development:

2. Prepare input data file as discussed before loading. To load the input files, click on the 'LOAD DATA' push button. The path of the selected file will appear beside the 'LOAD DATA' push button.
3. Specify the ranges of model parameters (b, B and k).The step size for parameter estimation in case of grid search technique.Lower the step size longer the time requirement and better the accuracy. Default values are provided in the GUI. Users are free to



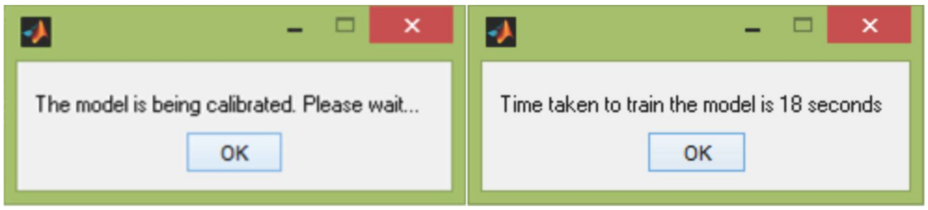
	A	B	C	D	E	F	G
1	1	2	3	4	5	6	7
2	Watershed descriptions in this row -->		XYZ Basin upto Basantpur				
3	Watershed Area in sq km -->	61152.05	delta t in sec =	86400	latitude (radians)	0.37	
4	Date	Discharge (m^3/s)	Precipitation(mm)	(δ)declination(radians)	temp_max	temp_min	temp_avg
5	1/1/2076	100.0	1.90	-0.369	24.23	15.3	19.8
6	1/2/2076		0.34	-0.369	24.78	13.8	19.3
7	1/3/2076		0.79	-0.369	25.47	14.0	19.8
8	1/4/2076		8.40	-0.369	22.24	17.1	19.7
9	1/5/2076		0.36	-0.369	23.39	14.1	18.8
10	1/6/2076		0.07	-0.369	22.43	13.5	18.0
11	1/7/2076		0.02	-0.369	24.41	13.9	19.2
12	1/8/2076		4.63	-0.369	23.57	14.7	19.2
13	1/9/2076		0.00	-0.369	25.47	12.6	19.0
14	1/10/2076		0.00	-0.369	25.96	11.1	18.5
15	1/11/2076		0.01	-0.369	27.51	10.9	19.2
16	1/12/2076		0.08	-0.369	27.07	12.3	19.7
17	1/13/2076		0.00	-0.369	23.97	7.4	15.7
18	1/14/2076		0.00	-0.369	22.33	6.2	14.3
19	1/15/2076		0.00	-0.369	23.24	5.7	14.5
20	1/16/2076		0.00	-0.369	24.62	5.4	15.0
21	1/17/2076		0.00	-0.369	26.26	6.6	16.4
22	1/18/2076		0.00	-0.369	22.87	6.3	14.6
23	1/19/2076		0.00	-0.369	23.42	5.1	14.2
24	1/20/2076		0.00	-0.369	25.22	5.2	15.2
25	1/21/2076		0.00	-0.369	26.27	6.3	16.3
26	1/22/2076		0.00	-0.369	27.21	8.3	17.7
27	1/23/2076		0.00	-0.369	28.12	11.3	19.7

Figure 2. Examples File for Input Data for Future Streamflow Prediction. Unhighlighted cells are for user input. Grey highlighted cells should not be changed. PLEASE DO NOT CHANGE THE ARRANGEMENT ORDER OF THE CELLS. There is no restriction for the number of rows to be used.

Figure 3. Opening Screenshot of HCCS Model

specify their own choice on the range of parameters.It is recommended that the ranges should be selected in such a way that the final parameters do not fall on any boundary (lower or upper limits).

3. Click on ‘CALIBRATE MODEL’ push button for model development. A popup window will appear, as shown in Figure 4a, implying model calibration is being carried out. It is not necessary to click on the “OK” button. This will automatically be followed by another popup window (Figure 4b) indicating model calibration is over, showing time taken for model calibration. Click on “OK” in this popup window.



(a) **(b)**

Figure 4. Popup Windows that Appear after ‘CALIBRATE MODEL’ Push Button is Pressed.
(a) Popup Signifying Model Calibration is Being Carried Out.
(b) Popup Indicating Calibration is Complete and the Time Taken.

5. Once model calibration is complete, the estimated parameters are displayed in the ‘Parameter Estimates’ area (Figure 3). The comparison plot (observed and predicted streamflow) and the plot of other two components (Evapotranspiration and Ground water recharge) will be displayed in time series format (Figure 5) upon clicking respective buttons. Some of the model performance measures, such as, Correlation Coefficient (CC), Nash Sutcliffe Efficiency coefficient (NSE), Index of Agreement (D_1) and Root Mean Square Error (RMSE), are incorporated in the GUI itself.These are displayed in the ‘Model Performance’ section. Users can compute other measures as well after exporting the results. To export and save the observed & predicted

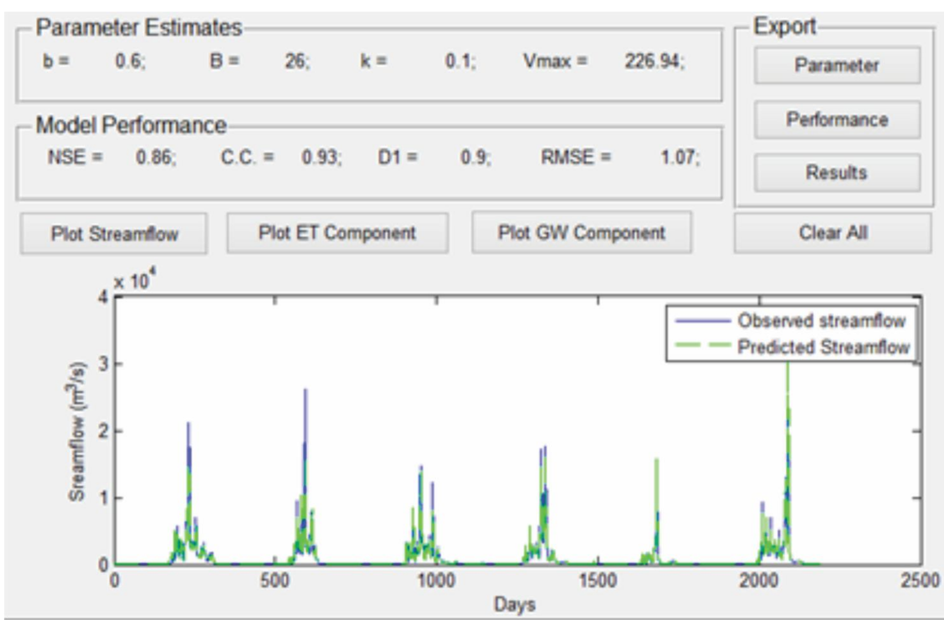


Figure 5. Estimated Parameters, Performance Metrics and Time Series Plots after Completion of Model Calibration. This is basically a part (left, bottom) of Figure 3 after model calibration with a typical example

streamflow click on the 'Results' push button in the 'Export' area. Model parameters and already incorporated performance measures can also be saved using 'Parameter' and 'Performance' push button respectively. Please note that all these exported data is saved in excel sheet (.xlsx format).

6. The 'Clear All' button will reset the GUI to its initial condition. Do not click this if you are using the developed model for 'Model Testing / Future Streamflow Estimation'.

Model Testing / Future Streamflow Estimation:

7. 'Model Testing / Future Streamflow Estimation' section of the GUI has two functions — (*i*) it can either be used to validate the model on new time period (different to the one used in model calibration), and (*ii*) it can be used to estimate the streamflow for some future time duration. The user can make a choice by selecting either of the radio buttons 'Model Testing' or 'Future Streamflow Estimation' shown in Figure 6.

Model Testing:

8. On selecting 'Model Testing', a popup window will appear, asking the user whether to use the parameters estimated during model development as shown in Figure 7a. On selecting 'Yes', the textboxes corresponding to the parameters are automatically filled with the estimated parameters. On selecting 'No', the user is prompted to provide these values after clicking 'OK' as per Figure 7b. However, this option ('No') is recommended to use in special cases, such as, studies like sensitivity analysis or future estimation when the estimated parameters are supposed to change due to changing climate or other issues.

9. Click 'LOAD DATA' (in Model Testing/Future Streamflow Estimation') to load input file for the testing period in the specified format as discussed before. The file path of the file selected is displayed beside the 'LOAD DATA' push button. Click the'Test

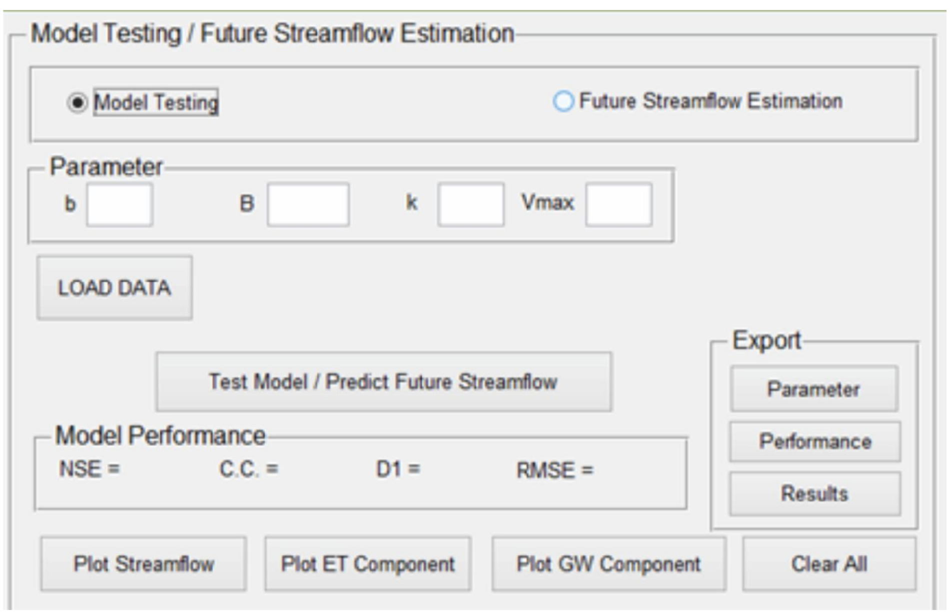


Figure 6. The "Model Testing / Future Streamflow Estimation" Section

Model / Predict Future Streamflow' push button. The pop up windows indicating that testing is in progress and subsequently the time taken are displayed similar to that during model development.

10. Model performance measures with time series plot for model validation period will be displayed. The output variable can be displayed in the plot area by clicking the 'Plot Streamflow', 'Plot ET Component' or the 'Plot GW Component' buttons. The purpose of the rest of the push buttons, *i.e.*, 'Clear All' and the three in 'Export' pane are same as mentioned in 'Model Development' section. Please note that 'Clear All' button in this area, resets only the 'Model Testing/ Future Streamflow Estimation' section. Users need not recalibrate the model for another testing data.

Figure 7. Pop-up Windows Prompting the User to (*a*) Select Whether to Use Parameters Estimated During Model Development. (*b*) On Selecting 'No'Provide User Specified Parameters for Model Testing

Future Streamflow Prediction:

11. On selecting the 'Future Streamflow Prediction' option, the user is prompted to provide parameters estimated for the future time period as shown in Figure 8. After clicking 'OK', the user needs to provide the values in the textboxes.

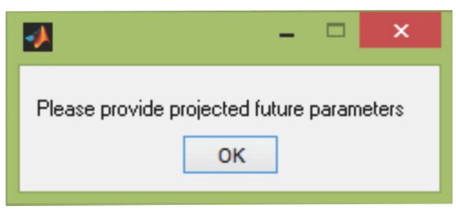


Figure 8. Pop-up Window on Selecting the 'Future Streamflow Prediction' Option.

12. The input file needs to be prepared as discussed before. Rest of the steps are same as model testing. Please note that the performance is not validated since observed data is not available. Hence, performance measures are not displayed as demonstrated in Fig. 9.

APPLICATION OF HCCS TO NARMADA BASIN

In this section, HCCS and a few other conceptual models are applied to a study basin and the results, borrowed from Bhagwat and Maity (2014), are presented.

Study Areas

All the tropical rainfed river basins in Indian Peninsular region are either east flowing or west flowing. Upstream part of two such river basins - Mahanadi (east flowing) and Narmada (west flowing), are considered for demonstration. These basins are shown in Figs.10 (Mahanadi) and 11 (Narmada) respectively. Study area considered in Mahanadi River basin is 61,152 km^2

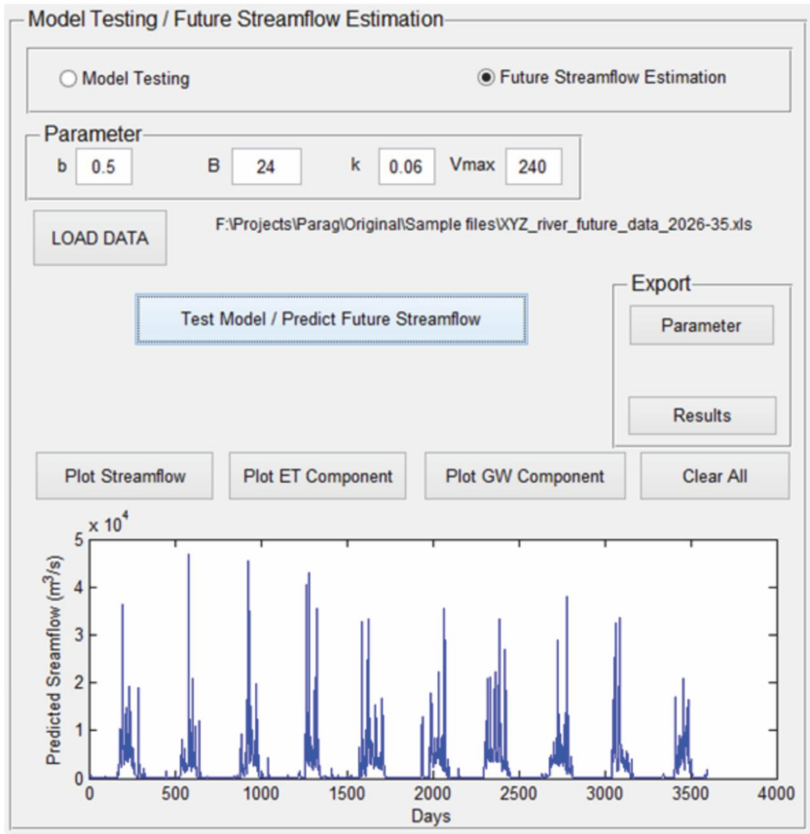


Figure 9. Figure Depicting the GUI when the 'Future Streamflow Estimation' Option is Selected.

up to Bastantpur gauging station and that in Narmada River basin is 25,912 km^2 up to Sandia gauging station.

Data

The daily streamflow data at the outlet of the basins are obtained from the office of Central Water Commission (CWC), India. Data period for Basantpur is from Jan 1, 1973 to Dec 31, 2003 and that for Sandia is from June 1, 1978 to May 31, 2000. There is no missing streamflow data for Basantpur but there are a few missing data is there for Sandia. It is preferable to have a continuous data or some preprocessing of data to fill up the missing values with reasonable accuracy. However, in case of unavoidable situation, the missing data periods can be excluded from analysis.

Spatially averaged daily rainfall and other climate data are prepared using Thiessen polygon method to obtain the spatially averaged values. Daily gridded (1° lat × 1° long) rainfall data is procured from India Meteorological Department (IMD) for Mahanadi basin,. There is no missing data in this. Daily temperature records (maximum and minimum) from two stations (Raipur and Pendra Road) located in the catchment (refer Figure 10) are obtained from National Climatic Data Centre (NCDC) Climate Data Online (*http://www.ncdc.noaa.gov/cdo-web/*). Missing values in temperature data(approximately 250 non-contiguous days out of 31 years) are replaced by the long-term average for that date.

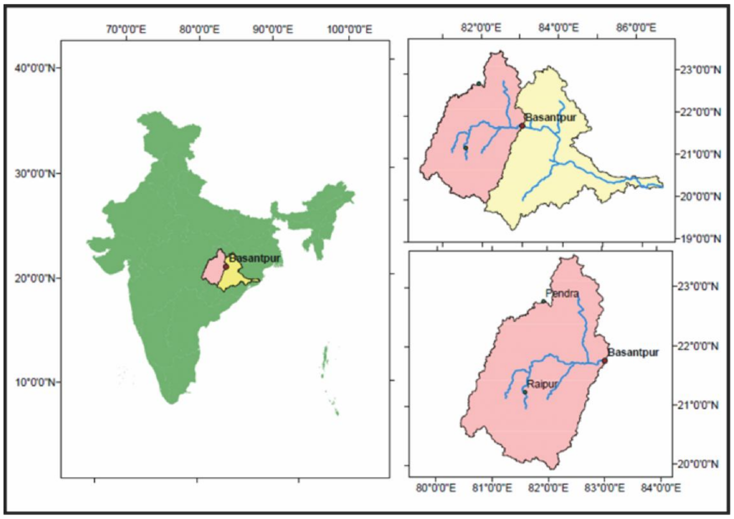


Figure 10. Mahanadi River Basin with the Study Area (up to BasantpurGauging Station)

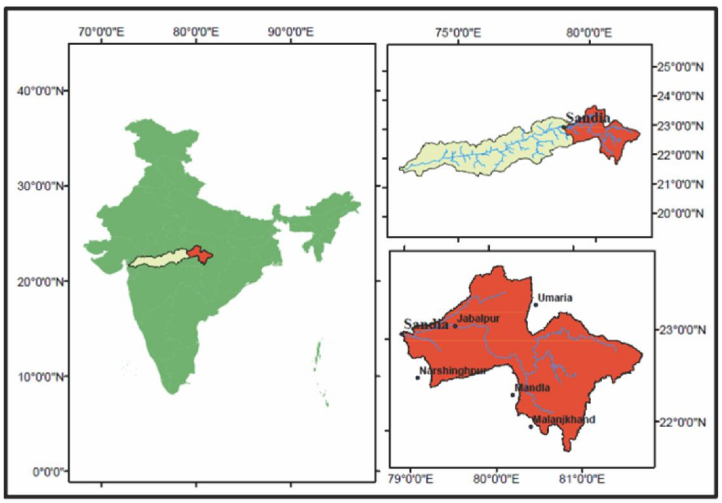


Figure 11. Narmada River Basin with the Study Area (up to Sandia gauging station)

Daily data ofrainfall and temperature are also obtained from IMD for the Narmada basin. These are recorded at five different stations (Jabalpur, Malanjkhand, Mandla, Narshinghpur and Umaria) within or around the basin as shown in Figure 11. Missing values in these data (approximately 150 non-contiguous days out of 23 years), rainfall and temperature data are missing. These values are replaced by the average of other surrounding stations for that date.

RESULTS AND DISCUSSIONS

Model Calibration and Testing

Model is calibrated with the daily rainfall, maximum temperature, minimum and average temperature, and streamflow data. Model parameters, *i.e.*, V_{max}, b, B and k are estimated during model calibration (model development period). As mentioned before, a minimization of MSE criterion is used to estimate the model parameters. Based on the data length, 3-fold model development and testing is adopted for the Mahanadi river basin and 2-fold model development and testing is adopted for the Narmada river basin. Details of these folds and estimated parameters during these periods are shown in Table 1. Model performance during model development and testing periods can be found in Table 2 in terms of Mean Square Error (MSE), Correlation Coefficient (CC) and Nash-Sutcliffe Efficiency (NSE).

Table 1. Estimated Model Parameters during Different Development Periods

Basin Name	Calibration Period	Model Parameters			
		B	b	k	V_{max}
Mahanadi	Jan 01, 1973 to Dec 31, 1980	22	0.63	0.113	214.0
	Jan 01, 1984 to Dec 31, 1990	98	0.28	0.043	244.4
	Jan 01, 1994 to Dec 31, 2000	48	0.54	0.080	270.3
Narmada	Jun 01, 1978 to May 31, 1987	26	0.57	0.093	315.0
	Jun 01, 1990 to May 31,1997	52	0.44	0.015	316.3

A typical plot showing observed and predicted streamflow for the first model development period (Jan 01, 1973 to Dec 31, 1980) is shown in top panel of Figure 12 for Mahanadi river basin. Results for remaining 2-folds of model development and testing periods for Mahanadi and 2-folds of the same for Narmada basin are shown in Table 2 (comparison plots are not shown). The high value of NSE (range ~ 0.69 to 0.9) and correlation coefficient (range ~ 0.83 to 0.96) indicate the efficacy of the HCCS model.

Other Outputs from HCCS Model

Spatially averaged ground water component and evapotranspiration components can also be estimated from the HCCS model. Typical daily series of these components are shown for the study basins are shown in Figs. 13 and 14. Monthly estimates can also be computed from the daily estimates (not shown). These estimate values are not compared with the observed values due to non-availability of data. However, expected seasonality in the time series of these estimated values is noticed. This matches with the seasonality in Indian hydroclimatology. However, some observations may go contrary to the general experience. For instance, in 1987, the actual evapotranspiration value in October (14.15 mm) is more than that in June (4.06 mm) and July (6.31 mm) for Narmada. It is due to the notably different system wetness condition, $V(t)$ for these months. This due to the fact that the actual evapotranspiration $E(t)$, is conceptualized as a function of potential evapotranspiration ($E_p(t)$) and $V(t)$. For instance, $V(t)$ was found to be very low in July due to the sustained low rainfall. In June (just previous month), total observed rainfall (56.7 mm) was much lower (55%) than that is normally observed (mean = 122.3 mm). Thus, even if, the total observed rainfall in July (299.0 mm) was near normal (mean = 278.3 mm), $E(t)$ was found to be low.

Moreover, it is noticed that the values of ground water component and evapotranspiration components seem to correspond well with each other. This is indeed due to the model structure. As shown in eqn (4), actual evapotranspiration is conceptualized as a function of potential evapotranspiration and system wetness condition.

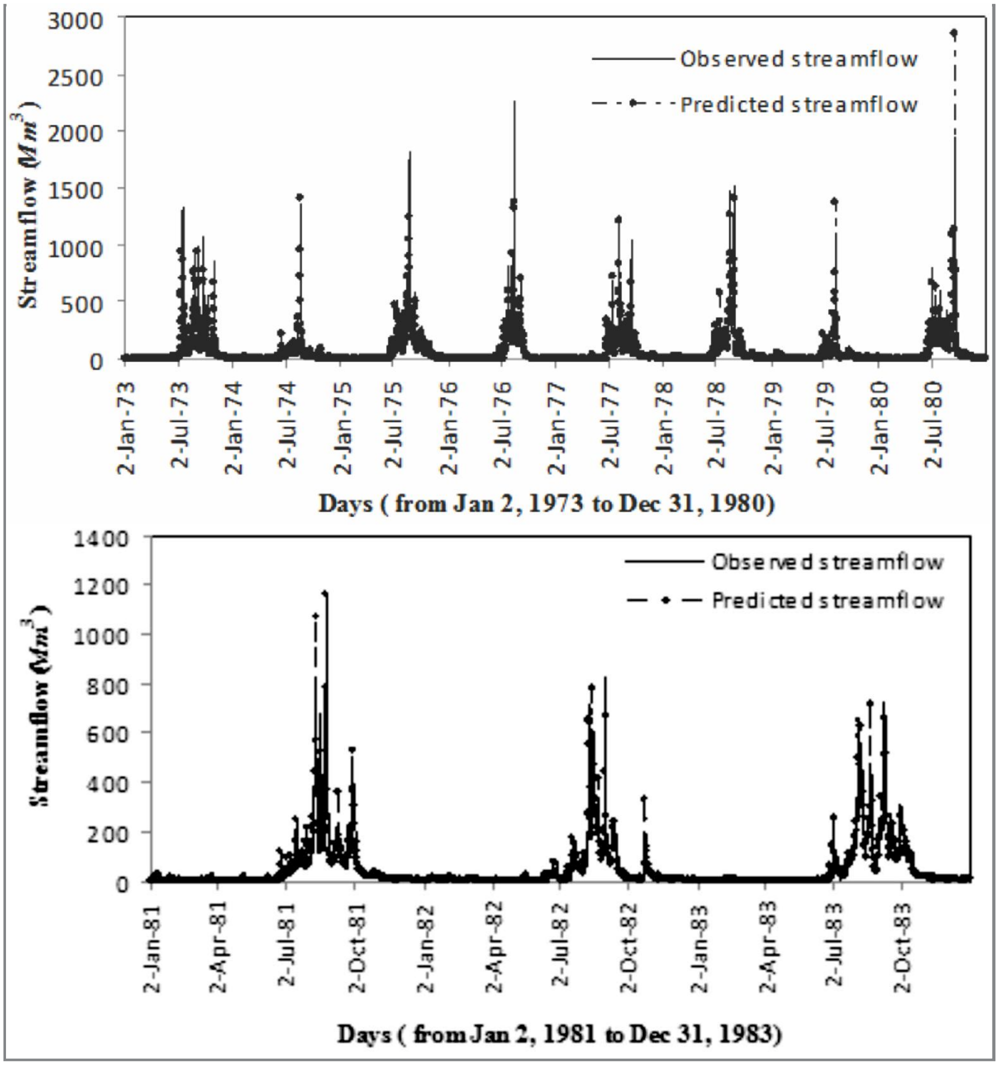
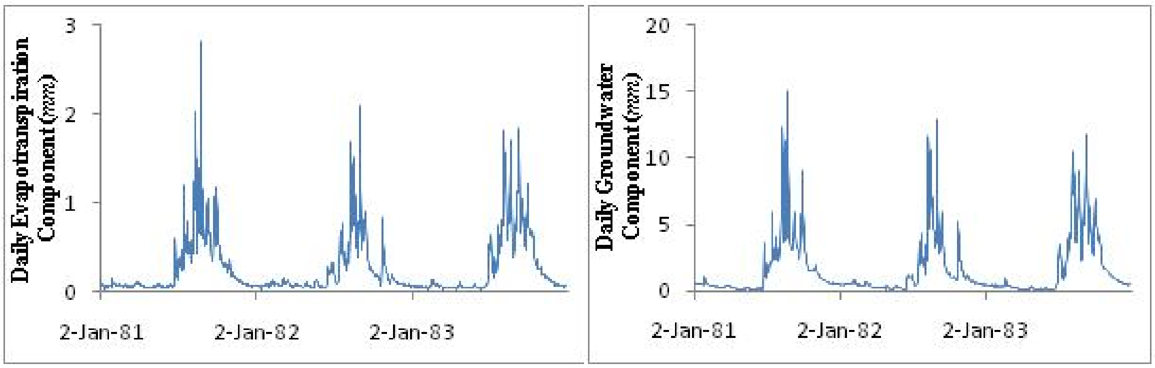


Figure 12. Observed and Predicted Streamflow for First Development Period (Jan 02, 1973 to Dec 31, 1980) and Corresponding Testing Period (Jan 02, 1981 to Dec 31, 1983) for Mahanadi River Basin

Table 2. Model Performance Statistics for Development and Testing Periods. Testing Period Values are Shown in Parentheses.

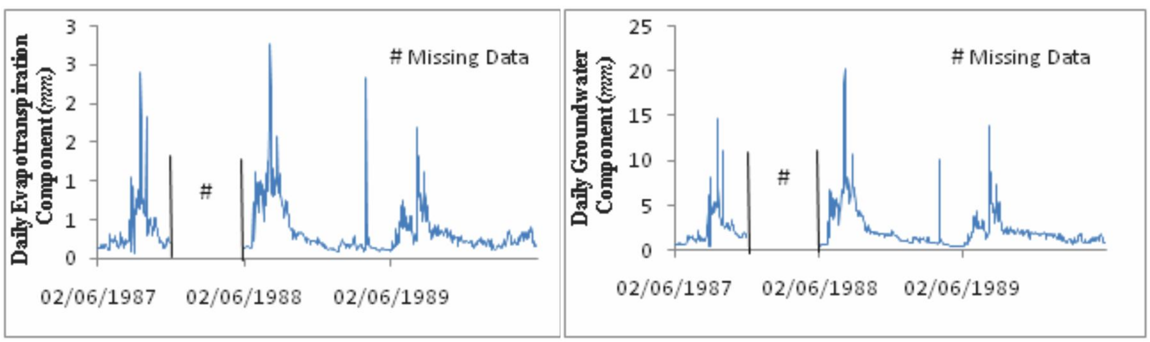
Basin Name	Development Period (Testing Period)	Performance Statistics		
		MSE	CC	NSE
Mahanadi	Jan 01, 1973 to Dec 31, 1980 (Jan 01, 1981 to Dec 31, 1983)	1.133 (0.379)	0.93 (0.94)	0.86 (0.88)
	Jan 01, 1984 to Dec 31, 1990 (Jan 01, 1991 to Dec 31, 1993)	0.546 (0.601)	0.93 (0.95)	0.87 (0.90)
	Jan 01, 1994 to Dec 31, 2000 (Jan 01, 2001 to Dec 31, 2003)	0.551 (1.513)	0.94 (0.88)	0.88 (0.77)

Narmada	Jun 01, 1978 to May 31, 1987 (Jun 01, 1987 to May 31, 1990)	4.43(2.77)	0.83(0.86)	0.69(0.72)
	Jun 01, 1990 to May 31, 1997 (Jun 01, 1997 to May 31, 2000)	4.66(7.20)	0.90(0.96)	0.81(0.86)



Days (From Jan 2, 1981 to Dec 31, 1983) **Days (From Jan 2, 1981 to Dec 31, 1983)**

Figure 13. Estimate of Evapotranspiration (left) and Ground Water (right) Component for Mahanadi River Basin for the period Jan, 1981 to Dec, 1983



Days (From Jun 2, 1987 to May 31, 1990) **Days (From Jun 2, 1987 to May 31, 1990)**

Figure 14. Estimate of Evapotranspiration (left) and Ground Water (right) Component for Narmada River Basin for the period Jun, 1987 to May, 1990

Comparative Performance of other Conceptual Models

As mentioned before, there are other existing conceptual models, e.g. Australian Water Balance Model (AWBM) (Boughton, 1993; Boughton and Carroll, 1993), Sacramento model (Burnash et al., 1973), SIMplifiedHYDrolog (SIMHYD) (Porter, 1972; Porter and McMahon, 1975; 1976), Soil Moisture Accounting and Routing (SMAR) model (O'Connell et al., 1970) and Tank Model (Sugawara, 1967; Sugawara et al., 1974). Details of these models and software package can be obtained from Rainfall Runoff Library (RRL) (available at *http://www.toolkit.net.au/Tools/RRL*). However, basic difference between HCCS and these models is in its consideration of time-varying characteristics and capability to consider climate variability as input. It is also true that the performance of AI based machine learning approaches are found to overshadow the performance of other modeling approaches. However, the assumption of stationarity is the biggest question for such models considering the changing climate and watershed condition. However, comparison with AI based machine-learning approach is not included in this chapter. One such comparison with Least Square-Support Vector Regression (LS-SVR) (Suykens et al., 2002)can be found in Bhagwat and Maity (2014). For a brief demonstration in this chapter, the performances of other conceptual models are shown in Table 3a and 3b. The merit of considering time-varying characteristics in HCCS model can be revealed by comparing the performances (Tables 3a,3b and 2) with HCCS (Table 2).

Table 3a. Performances of Other Conceptual Models (AWBM, Sacramento and SimHyd) During Different Model Development and Testing Periods (within parentheses)

Basin Name	Development Period (Testing Period)	AWBM			Sacramento			SimHyd		
		MSE	CC	NSE	MSE	CC	NSE	MSE	CC	NSE
Mahanadi	Jan 01, 1973 to Dec 31, 1980 (Jan 01, 1981 to Dec 31, 1983)	2.10 (0.88)	0.86 (0.86)	0.74 (0.71)	2.56 (1.13)	0.83 (0.85)	0.68 (0.63)	2.69 (0.99)	0.82 (0.83)	0.66 (0.68)
	Jan 01, 1984 to Dec 31, 1990 (Jan 01, 1991 to Dec 31, 1993)	1.08 (1.47)	0.86 (0.85)	0.73 (0.72)	1.11 (1.72)	0.85 (0.82)	0.73 (0.67)	1.20 (1.68)	0.84 (0.82)	0.71 (0.68)
	Jan 01, 1994 to Dec 31, 2000 (Jan 01, 2001 to Dec 31, 2003)	1.44 (2.60)	0.85 (0.79)	0.70 (0.63)	1.47 (3.64)	0.85 (0.75)	0.70 (0.47)	1.38 (2.90)	0.85 (0.77)	0.71 (0.58)
Narmada	Jun 01, 1978 to May 31, 1987 (Jun 01, 1987 to May 31, 1990)	6.04 (7.41)	0.76 (0.67)	0.57 (0.49)	6.85 (7.18)	0.73 (0.67)	0.52 (0.43)	6.04 (6.98)	0.76 (0.69)	0.58 (0.44)
	Jun 01, 1990 to May 31, 1997 (Jun 01, 1997 to May 31, 2000)	6.04 (7.41)	0.76 (0.67)	0.57 (0.49)	6.85 (7.18)	0.73 (0.67)	0.52 (0.43)	6.04 (6.98)	0.76 (0.69)	0.58 (0.44)

Table 3b. Performances of Other Conceptual Models (SMAR and Tank model) During Different Model Development and Testing Periods (within parentheses)

Basin Name	Development Period (Testing Period)	SMAR			Tank Model		
		MSE	CC	NSE	MSE	CC	NSE
Mahanadi	Jan 01, 1973 to Dec 31, 1980 (Jan 01, 1981 to Dec 31, 1983)	2.76 (1.77)	0.82 (0.71)	0.65 (0.66)	2.87 (1.44)	0.82 (0.79)	0.64 (0.53)
	Jan 01, 1984 to Dec 31, 1990 (Jan 01, 1991 to Dec 31, 1993)	1.38 (1.98)	0.82 (0.80)	0.66 (0.62)	1.91 (2.58)	0.81 (0.79)	0.53 (0.50)
	Jan 01, 1994 to Dec 31, 2000 (Jan 01, 2001 to Dec 31, 2003)	2.34 (4.44)	0.75 (0.65)	0.52 (0.36)	1.63 (3.30)	0.83 (0.74)	0.66 (0.52)
Narmada	Jun 01, 1978 to May 31, 1987 (Jun 01, 1987 to May 31,1990)	8.02 (8.08)	0.66 (0.61)	0.44 (0.35)	5.87 (6.79)	0.77 (0.69)	0.59 (0.46)
	Jun 01, 1990 to May 31, 1997 (Jun 01, 1997 to May 31,2000)	11.90 (33.9)	0.74 (0.86)	0.53 (0.37)	12.52 (33.87)	0.71 (0.70)	0.51 (0.35)

Future Streamflow Variation

In this section, application of HCCS model is demonstrated for the assessment of future streamflow variation using projected climate and time-varying watershed characteristics. The same watersheds are considered for this purpose to compare the current streamflow variation with the future streamflow variations over different months in the year.

Temporal change in Model Parameters and Streamflow Assessment under Future Climate

Among different parameters, temporal change of V_{max} is a very important aspect to be considered in hydroclimatic modeling to study the variation of streamflow under a changing climate and also the changing characteristics of watershed. Maximum System Wetness Capacity (V_{max}) and its variation over time are the unique characteristics of a particular watershed due to a combination of human activities (urbanization, deforestation, construction of reservoirs etc.) and effect of climatic change over the basin. These aspects are already investigated and explained in Bhagwat and Maity (2014) with the help of LANDSAT data from Earth Science Data Interface (ESDI), Global Land Cover Facility (available at *http://glcfapp.glcf.umd.edu:8080/esdi/*). It is also recommended that a data length of successive 5 to 10-year periods can be considered to assess the change of V_{max} over time.Here the steps to project the parameters are explained with a trend line approach. An example to project V_{max} in the future is discussed in the subsequent sections. Similar procedure can be followed for other parameters as well.

Step 1 : The values of V_{max} for successive 5-year periods (with one or two periods of different lengths) are estimated.

Step 2 : In general, the estimates may remain same over successive time periods or may exhibit an overall increasing/decreasing trend in V_{max} with or without fluctuations. Linear as well as logarithmic trend lines for the historical change in the estimates of V_{max} are fitted. Refer to Figure 15 for a typical example showing the change of V_{max} over time (for Narmada), fitted with linear and logarithmic trend lines.The variable X denotes the mid-point of the period.

Step 3 : Either of following three cases may be considered to estimate the changes in future–

(*i*) remain constant (line 1 – untouched henceforth);

(*ii*) increase with the same linear trend observed in the past (line 2 – business-as-usual scenario); and

(*iii*) increase at a faster rate than that observed in the past (line 3 – Intense water management/ utility activity in terms of construction of reservoirs).

These lines are also plotted in Figure 15. Quantification of the growth rate of the trend line is indeed very difficult. It depends on the policy makers' decision for the basin. For example, if a new reservoir is constructed, the V_{max} for the basin will increase. Urbanization will results in more imperviousness that may lead to lesser V_{max}. Hence, it is difficult to quantify the growth rate. However, it can be projected in future if an overall trend of change is found and a specific assumption in the growth rate can be made for the entire catchment. Here we demonstrate the future projection by adopting a logarithmic trend line that makes an assumption of a continuous increase over time but at a slower rate as time pass by. Please note that a logarithmic growth rate (and no change also) is used in the analysis; continuous rate of increase is not adopted. The

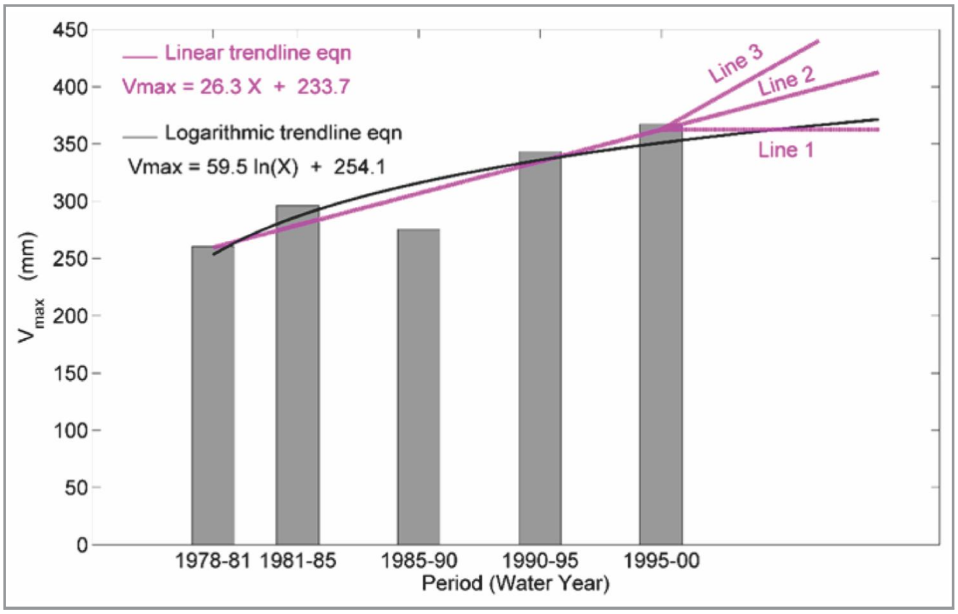


Figure 15. Change of V_{max} Over Time for Narmada River Fitted with Linear and Logarithmic Trend Lines

logarithmic growth rate is estimated from the historical trend as explained before.On the other hand,a logarithmic trend line indicates a continuous increase over time but at a slower rate in the future.

Step 4 : Daily rainfall and temperature data (Maximum and Minimum) for future climate scenario are obtained. With this data and project parameters, possible future streamflow variation for different possible cases, *e.g.*, 'no further change' and 'logarithmic growth' etc. are carried out.

CLOSING REMARKS

This chapter provides a brief account on conceptual models for streamflow assessment. Apart from the existing models, necessary modifications in order to identify the streamflow response in a changing climate are explained. Ability to consider the hydroclimatic inputs and time-varying watershed characteristics are found to be necessary for a changing climate condition and analysis of streamflow variation under future climate. In this context application of HCCS model is demonstrated. Performance of the proposed HCCS model is found to be promising for both the study basins used for demonstration. While comparing the performance of the proposed HCCS model with the performance of other popular conceptual models and with LS-SVR (one of the popular AI based machine learning approaches), it is found that the overall performance of HCCS model is better in general and remarkably better in some cases.

In addition, the proposed model is also able to provide additional overall (spatially averaged) estimates of ground water recharge component and evapotranspiration component from the entire catchment. Though these estimates are not compared with the observed values (due to non-availability), seasonality in these estimates is visible, which is matching with the reality for Indian hydroclimatology.

The parameter that controls the time-varying watershed characteristics is conceptualized in this model. Procedure to project this parameter to the future with different assumptions on change in watershed characteristics is also explained. Using the projected climate data, demonstration is provided to apply the HCCS model for future period and to assess the streamflow variation under future climate.

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