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DAILY RAINFALL-RUNOFF MODELLING USING A SIMPLE CONCEPUTAL MODEL FOR GUNDLAKAMMA RIVER IN A.P.

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PREFACE

Modelling of catchment response using monthly data does not serve the needs of most applications. To use sufficiently, fine data interval to catch the complete temporal variations of observed flows is impossible and impractical. For most of the catchments, daily data are available for both rainfall and flow. Though daily flow data blur many hydrograph features on small and flashy catchments, don't totally hide them.

Conceptual modelling is one way of undertaking hydrological modelling wherein mathematical representation of physical processes is employed with specific inputs to derive the output. Also, it is important to see that the number of parameters of the model is not high to make the modelling process cumbersome. To make the modelling quick and effective, conceptual models with a few parameters are being preferred. Fewer parameters means quicker optimization and simpler application to any basin.

In this study, a simple 5-parameter model based on the concept of probability distributed method as proposed by Moore (1985) is applied to undertake modelling of the daily runoff over a 9 year period of 1989 to 1997 at Tammavaram in Prakasam district of Andhra Pradesh on the Gundlakamma river. A program in Fortran 77 is developed to undertake automatic optimization of the model to simulate the observed flows using appropriate objective function. This study was undertaken by Mr. S.V.Vijaya Kumar, Scientist 'C' and Mr. U.V.N.Rao, S.R.A., as part of technical work plan of Deltaic Regional Centre, Kakinada. Dr. S K Mishra, Scientist 'E' reviewed this report.

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Abstract

Since 1990's, some new techniques are being applied more widely in solving analytical problems of rainfall-runoff modelling on the readily accessible personal computers. Utilizing the concepts of physics to describe the land phase of hydrological cycle in space and time and computing facilities available hydrological modelling is being made easy and simple. It is important to see that the number of parameters of the model is not so large that modelling the process becomes cumbersome. To make the modelling quick and effective, conceptual models with a few parameters are being preferred.

In this study, a simple 5-parameter model, based on the conceptual of probabilitydistributed method as proposed by Moore (1985) is applied to simulate the daily runoff over a 9-year period of 1989 to 1997 at Tamavaram in Prakasam district of Andhra Pradesh on the Gundlakamma river. A program in Fortran 77 is developed to undertake automatic optimization of the model to simulate the observed flows using a proper objective function. From the calibration and validation of the modelling study, it is found that the model, though a five-parameter one, could respond properly to the rainfall and resulted in a reasonable by efficiency of 72.14% in calibration and 68.25% in validation

INTRODUCTION

Hydrologists are concerned with developing a proper relationship between the rainfall over a catchment and the resulting runoff at the catchment outlet. The link between rainfall and runoff has inspired many research workers and the evaluation of river flow from rainfall has stimulated the imagination and ingenuity of engineers. The availability of high-speed digital computers with large storage for data is now an added advantage. Since 1990's, some new techniques are being applied more widely in solving analytical and numerical engineering problems on the readily accessible personal computers. Utilizing the concepts of physics to describe the land phase of hydrological cycle in space and time and the computing facilities available, hydrological modelling is made easy and simple. Conceptual modelling is one way of undertaking hydrological modelling wherein mathematical representation of physcial process is employed with specific inputs to derive the output. Also, it is important to see that the number of parameters of the model is not so large that modelling the process becomes cumbersome. To make the modelling quick and effective, conceptual models with a few parameters are being preferred. "Fewer parameters" means quicker optimization and simpler application to any basin.

1.1 Hydrological Modelling

Hydrological models can be classified in many ways. Depending upon the phenomenon of importance, they are classified as event-based models i.e., to simulate a flood peak resulting due to a single or multiple storm events or continuous models i.e., to simulate the flow processes over a season or over a number of years preferably to develop rainfall-runoff relationships on daily basis. The other classification is based on the mathematical theory being applied and are classified as 'deterministic' models which seek to simulate the physical processes in the catchment wherein rainfall gets transformed into runoff or 'stochastic' models wherein the hydrological time series of single or several variables such as rainfall, evaporation, stream flow etc., involving distribution in probability are applied. Also, a combined or hybrid models wherein both deterministic and stochastic approaches are selectively being employed are proving to be more successful.

1.2 Conceptual models :

It is well known that the movement of water in the land phase of hydrologic cycle is a complex process involving the sub-processes of interception, infiltration, percolation, surface runoff, sub-surface runoff, interflow, baseflow etc., To put it simply the hydrology of a drainage basin, from precipitation through to the stream discharge at the point of interest can be conceived as a series of inter-linked processes of inflows, storages and outflows. In conceptual modelling the catchment processes are described mathematically, and storages are considered as reservoirs for which water budgets are kept. Many conceptual catchment models have been developed over the past. Dawdy and O'Donnel (1965) described the structure and operation of a conceptual model. Nash and Sutcliffe (1970) discussed the principle of river flow forecasting through conceptual models. Blackie and Eeles (1985) discussed in detail about lumped catchment models and parameter optimization for hydrological forecasting.

1.3 Simple conceptual models :

To model catchment response using monthly data would not serve the needs of most of the applications. To use sufficiently fine data interval to catch all the variations of observed flows would be impossible and impractical. For most of the catchments daily data are available for both rainfall and flow. Though daily flow data blur the many hydrograph features on small and flashy catchments, the data don't totally hide them. Daily rainfall and runoff models are fairly commonly used either for generating the flows or for operational purposes, as required. These models try to reproduce the catchment response, as closely as possible, so that they can be used to generate long sequences of flows from rainfall data or show how changes in the catchment may affect runoff. For a good simulation a model and its parameters provide a description of how the catchment respond. A near perfect simulation requires a large number of model parameters. To simulate the model adjusting these parameters either by trial and error may be impossible or by automatic optimization may be computationally difficult. So, a near perfect simulation of observed flows may not be as important as obtaining a response hydrograph that has general features as the observed flows. Relaxing the goodness of fit criteria may enable much more simple models to be used (Bonvoisin & Boorman, 1992). A reasonable number of model parameters are probably around 3 to 5 which should allow adequate simulation, enable fairly confident parameter estimates to be made, ensure no parameters are redundant, provide parameters that have readily understandable functions and hence parameter values that describe major catchment effects.

In this study, a simple 5-parameter model, based on the concept of probability distributed method as proposed by Moore (1985) is applied to simulate the daily runoff over a 9 year period of 1989 to 1997 at Tammavaram in Prakasam district of Andhra Pradesh on the Gundlakamma river. The better performance of the model in the daily rainfall-runoff modelling studies on the Nagavali and the Sarada rivers conducted by Vijayakumar (1995) earlier has encouraged in applying it to this basin too.

2.0 MODEL DESCRIPTION

As mentioned earlier, simple conceptual models are being adopted to simulate daily rainfall runoff now a days. The models consist of a number of stores with model parameter controlling the store sizes and rate of outflows. They use the conceptualization of flow processes with inputs of daily rainfall and pan evaporation to generate runoff. The main components of a model in general are

___a procedure to determine actual evaporation from potential evaporation, derived from pan evaporation or any other methods. The ratio of actual evaporation to potential evaporation is generally taken to be a function of the water content of one of the soil moisture stores. Some models use a linear function i.e., a linear decline in evaporation as soil moisture content falls below some maximum, whilst others use a negative exponential function i.e., the ratio of AE to PE falls slowly at first, but more rapidly as the store empties.

____ a storage accounting procedure to determine the water content of each soil moisture store. Store content at the end of a time step is based on the content at the beginning of the step and on inflow and outflow during the step. The outflow from one store is generally the inflow to another store. Different models have different procedures for determining outflows, usually within prescribed limits e.g. some stores can overflow while others can only drain downwards. Models have different number of stores, which may be combined in different ways.

_____ a runoff generation procedure. This is either as direct surface flow or a baseflow. The former is usually through a saturation excess or infiltration excess model, and the latter as a function of the soil moisture store content.

______ a procedure to route the outflow from appropriate soil moisture stores into flow in the river. This is usually, based on a system of linear reservoirs, one from each store.

The 5-parameter model used in this study employing the above procedure is described in detail here. The schematic diagram of the model is shown in Fig.1. The model is based on Moore's probability distributed technique (Moore, 1985) and has a soil moisture store with a capacity varying across the basin and a groundwater store. Vijayakumar (1995) applied 5 such simple daily rainfall-runoff models for the Nagavali and for the Sarada catchments along the east coast of India and observed the performance of the 5 parameter model as very efficient. The model is being widely used in flood forecasting (Moore et. al 1990, Moore & Jones, 1991 and Moore 1993). In the model distribution of the soil capacity, C, is represented by the reflected power (or pareto) distribution.

$$F(c) = 1 - 1(1\text{-}C/Cmax)^b \text{ for } 0 \leq C \leq Cmax. \qquad \text{------------ } 2.1$$

Where 'Cmax' is the maximum storage capacity at any point within the basin and 'b' is a dimensionless parameter, which defines the degree of spatial heterogeneity. The maximum amount of water that can be held in storage in the basin, 'Smax', for the reflected power distribution is

$$Smax = \int_0^{C\max} (1\text{-}F(c)).dc \qquad \text{--------------- } 2.2$$

$$= Cmax/(b+1) \qquad \text{----------------}2.3$$

In the model, precipitation is added to the soil moisture and excess precipitation becomes direct runoff which is routed through two cascading linear reservoirs as direct runoff. Evapotranspiration from the soil moisture store occurs at a rate proportional to store contents, as does drainage from the soil moisture store. Baseflow occurs from the groundwater store and is added to the direct runoff to becomes the catchment outflow.

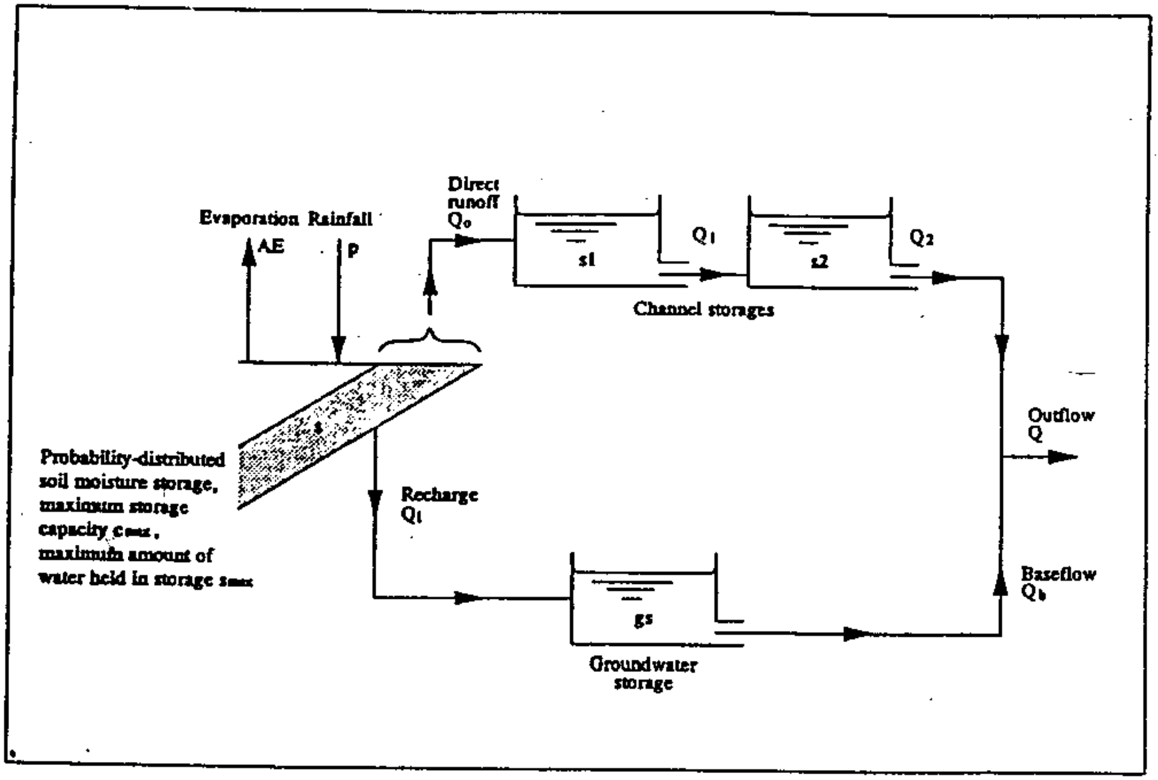

Fig.01-Schematic diagram of the 5 parameter model

The model has five parameters. The maximum storage capacity at any point within the basin 'Cmax'; the average maximum amount of water that could be held in storage over the whole basin 'Smax', a soil drainage coefficient 'Kb', a groundwater discharge coefficient 'Ground' and a channel routing coefficient 'Srout'. The model formulation and the accounting procedure is discussed in detail by Houghton-carr and Arnell (1994) and is briefly presented here:

Actual evapotranspiration (AE) is derived from potential evapotranspiration (PE) as

$AE_t = PE_t \{1-e^{(-6.68\, St\text{-}1/Smax)}\}$ ---------------- 2.4

Drainage to the Groundwater store is

$Qi = Kb(S_{t-1}/Smax)$ --------------- 2.5

If rainfall P is less than AE and Qit there is no direct runoff. Otherwise direct runoff does occur. The critical capacity at the end of previous time step 'Cc' below which all the soil moisture goes to storage is calculated from the reflected power (pareto) distribution as

$Cc_{t-1} = Cmax\{1-(1-S_t/Smax)^{(1/(b+1))}\}$ --------------- 2.6

Hence critical capacity, at the end of the present time step is

$Cc_t = Cc_{t-1} + (P_t - AE_t - Qi_t)$ ---------------- 2.7

If Cct is less than Cmax, direct runoff is

$Qo_t = (P_t\text{-}AE_t\text{-}Qi_t) - Smax\{1\text{-}Cc_{t-1}/Cmax)^{b+1} - (1\text{-}Cc_t/Cmax)^{b+1}\}$ --------- 2.8

If Cct is greater than Cmax, direct runoff is

$Qo_t = (P_t\text{-}AE_t\text{-}Qi_t) - (Smax - S_{t-1})$ --------------------2.9

and the soil moisture store is full to Smax.

Baseflow (Q_b) from groundwater storage g_s is

$Qb_t = Grout\ (S_{t-1}/100)$ --------------------2.10

Direct runoff through two cascading reservoir of storage Ss made routed as

$Q = Srout\ (S_s)$ --------------------2.11

Adding the baseflow 'Qb' and direct runoff 'Q' results in the modelled catchment runoff, which can be compared with the observed runoff at the point of interest.

2.1 Optimization

With a model, for any given of parameter set lues, one can estimate modelled flows using input data like, rainfall, evaporation etc., The job of the modelling is to recommended best set of parameters which will closely simulate the observed flows at the particular point of interest on the stream. It can be accompanied either by trail and error or by automatic optimization of the parameter set. There are many criteria to undertake modelling. One technique is by plotting both observed and modeled and selecting the parameters, which give visually better fit. Another one is a numerical technique, in which the parameters are subjected to automatic optimization to achieve a mathematically best fit, indicated by an objective function. Hence the objective function is regarded as a tool to aid fitting and assess the model. If proper limits for parameter set are chosen, this criteria generally results in visually better fit too. In daily rainfall – runoff modelling the following two functions are used as fitting criteria as error functions.

The first objective function is to maximize the sum of the squares of difference of the observed and simulated daily flow during the entire period of simulation i.e.

Minimize $\mathrm{Obj1} = \sum (Q_{obs} - Q_{sim})^2$ ---------------------2.1.1

Which may give a good fit for long periods of low flows.

The second objective function is to minimize the sum of squares of difference of the logarithm of the observed and simulated daily flows i.e.

Minimize $\mathrm{Obj2} = \sum (\log Q_{obs} - \log Q_{sim})^2$ -------------------2.1.2

This objective function prevents the optimization becoming bassed towards larger flows. This function may not be useful when there are no flows during most part of the year.

To undertake automatic optimization Rosenbrock (1960) optimization procedure was invoked to minimize the objective function. The objective function may be used to compare the results from calibration and validation data sets.

2.2 Normalization

Objective function values as explained above are not comparable across different catchments, since they are not normalized. Hence, a suitable technique like NashSutchiffe (1970) efficiency criteria may be used to undertake normalization. The normalization function as per above criteria is

$$Obj3 = Efficiency = 1.0 - Obj1 / \sum (Q_{obs}-Q_{bar})^2 \qquad \text{--------------------2.2.1}$$

Where Obj1 is objective function one as defined above. The denominator is the sum of the square of differences of the daily observed and observed mean daily flow over the period of modelling. Since the objective function one is minimized in the optimization criteria the equation 2.2.1 gives maximum efficiency. The efficiency criterion is biassed towards larger discharges, but is widely used and gives an objective indication of model performance. A perfect agreement between the observed and simulated flows yields an efficiency of 1.0, whilst a negative efficiency represents a lack of agreement, worse than if the simulated flows were replaced with the observed mean daily flows.

3.0 STUDY AREA :

The Gundlakamma river basin is a medium river of about 264 kms length taking its origin from the Nallamalai hills in Mallamalai forest near Gundla brahmeswaram village, Longitude 76046'E and Latitude 15040'N in Nandyal taluka of Kurnool district at altitude of 680 metres. It flows through deep ravines and thickly grown natural forests and hilly tracts upto Cumbum tank situated in Cumbum village in Prakasam district. The river flows generally in northeast direction upto the confluence of Konduleru river, then takes a turn towards east upto the confluence of Konkeru at Pittambanda village. It turns southeast and flows at a uniform slope till it joins Bay of Bengal near Pallipalem village. The river's total catchment area is 8195 km2, including the area drained by its tributaries. Jamaleru, Venumuleru, Mekaleru, Teegaleru, Duvvaleru, Rallavagu, Konduleru, Pasupaleru, Konkeru, Chilakaleru, Voleru etc., The Gundlakamma basin is bounded by Vogeru vagu, Romperu on East side, by Nallamalai hill range on the western side, Krishna basin on the northern side and Musi river basin on the southern side and flowing eastwards into Bay of Bengal.

About 50 km from its source, the Gundlakamma receives the waters of the tributary Jampaleru from the eastern side of the Eastern ghats and joins on left side of Gundlakamma. About 52 km from this point Gundlakamma receives waters from Teegaleru from western side. After another 6.4 km it meets Rallavagu from westwards. After 17.6 km from this point it receives Konduleru from the north. After 25.6 km from

Teegaleru from western side. After another 6.4 km it meets Rallavagu from westwards. After 17.6 km from this point it receives Konduleru from the north. After 25.6 km from this confluence it receives waters from Konkeru river from North. About 49 km from the mouth, it is joined by Chilakaleru. Mixed red and black soils on upper reaches, red sandy soils in the middle part and a mixture of coastal alluvium and coastal sandy soils in the lower reaches.

3.1 Drainage

The Gundlakamma river originates and initially flows over different formations of Cuddapah super group which occupies more than half of the basin. From about Vinukonda onwards the river cuts across the rocks and enters the coastal plains. The predominant drainage patterns in the Gundlakamma are paralle, sub-parallel, radial and peripheral. The annular drainage is observed around dome structures of Eshwarakuppam, Vellatur and Ipur. In the northern part of Yandrapalli and around Darsi dendritic patterns are observed. The important physiographic features of the basin are Nallamalai Range, Sagileru Valley, Veligonda range, Nellore payanghat (Pediment low land), East Coastal Plain, Palco-channels and palco beaches (ancient beach ridges). The Gundlakamma is a 9th order stream according to Strahler's classification according to Rao & Babu (1995). The main tributaries of the Gundlakamma are, the Ralla Vagu, the Mekaleru the Vemuleru, the Jampaleru, the Tegaleru, the Konduleru, the Duvvaleru. The basin has an 'axe' shape (Fig.2). The maximum length of the crescent shaped basin is 201 km and maximum width is 91.73 km in the middle. From source upto 29th km the gradient is 23.675 m/km. There are three falls in bed level in this stretch. From 29th km to the mouth the gradient is 7.136 m/km. The catchment area upto Tammavaram G/D site is about 7831 sq.km.

During monsoon season Gundlakamma occasionally swells into floods. The maximum flow recorded at CWC G/D site at Tammavaram is 3607 cumecs and minimum flow recorded is 0.10 cumecs.

3.2 Climate :

The Climate of coastal part of the study area may be broadly classified under tropical coastal type and rest is of steppe type. According to Koppan the climate is tropical Savannah in upper part and dry season in high sun period in the rest of the area. The daily mean temperature is about 27.5 0C. Mean maximum temperature is around 32.5 0C.

Fig. 02 Basin map of the Gundlakamma river