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DERIVATION OF GIUH FOR SMALL CATCHMENTS IN HARD ROCK REGION

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PREFACE

Rainfall-runoff modeling has been an important area of research in the field of Hydrology. The computation of unit hydrograph characteristics is a major concern for water resources engineers and scientists. Owing to lack of runoff data, indirect inferences through regionalisation are sought for ungauged catchments. Many investigators have tried to relate the parameters of conceptual models to the geomorphological characteristics of a catchment. Geomorphological Instantaneous Unit Hydrograph (GIUH) is a recently developed physically based rainfall-runoff approach for the simulation of hydrographs, especially appropriate for ungauged catchments. Here, the characteristics of the instantaneous unit hydrograph (IUH) are related to the geomorphological characteristics of the basin. A mathematical model developed at National Institute of Hydrology enables the evaluation of parameters of the Clark model for derivation of the instantaneous unit hydrograph (IUH) using geomorphological characteristics of a basin, as proposed by Rodriguez-Iturbe and Valdes.

The GIUH based Clark model approach has been used in this study to check its applicability to hard rock catchments. Since the manual methods for extracting geomorphological parameters from toposheets are tedious, a geographical information system (GIS), ILWIS, is used for this purpose. The model was tested using the rainfall-runoff data of Barchi nala watershed and hypothetical events for Malaprabha catchment upto Khanapur.

This study has been carried out by Mr. Chandramohan T., Scientist C, Mr. B.Venkatesh, Scientist C, and Mr. Sanjay K. Jain, Scientist E under the guidance of Mr. R.D. Singh, Scientist F.

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ABSTRACT

Simulation of rainfall-runoff process for ungauged catchments is one of the most important areas of research in surface water hydrology. A number of well established techniques are currently available for this purpose. Derivation of unit hydrograph has been extensively investigated by many researchers since Sherman introduced the principle of unit hydrograph. These methodologies require historical rainfall-runoff records for a specific period. Therefore, use of geomorphological characteristics of a basin for deriving hydrograph parameters, as proposed by Rodriguez-Iturbe and Valdes, is advantageous for ungauged catchments.

In the present study, the methodology developed at NIH to relate Clark model parameters to geomorphological characteristics has been used to develop unit hydrograph for two hard rock catchments, Barchi nala and Malaprabha upto Khanapur. This model has already been successfully implemented for simulation of flood events in small catchments of Kolar sub-basin of Narmada river and Upper Narmada and Tapi sub-zone.

Since the historical hourly rainfall-runoff data were available for Barchi nala catchment, the GIUH based Clark model methodology was applied to compute and compare the surface runoff hydrographs for few selected rainfall-runoff events. Since hourly rainfall-runoff records were not available for Malaprabha catchment, this methodology was applied for hypothetical events with different equilibrium velocities. The geomorphological parameters and time-area diagram form important input for the GIUH based Clark model and these parameters for each catchment were generated using Geographic Information System (GIS) package ILWIS (Integrated Land and Water Information System). The observed and computed direct surface runoff hydrographs show a reasonable comparison.

INTRODUCTION

The understanding of rainfall-runoff process and the time distribution of runoff are the basic components of water resources planning and design. Mathematical modeling is extensively used to simulate the rainfall-runoff process. Whenever catchments are gauged, event based models can be developed, which may be calibrated and validated for the historical flood events.

The derivation of regional and synthetic unit hydrograph was a great achievement to estimate the unit hydrograph parameters for ungauged catchment. This involves evaluation of representative unit hydrograph parameters and physical characteristics for catchments in a hydrometeorologically homogeneous region. Relationships were developed, by applying multiple linear regression analysis considering one of the unit hydrograph parameters at a time as dependent variable and various catchment characteristics as independent variables. Thereafter, unit hydrograph for an ungauged catchment in that region can be derived using the characteristics of the ungauged catchment. But such relations are not scientifically sound, since the regionalisation of parameters is a tedious task. Hydrological behaviour of many nearby catchments has to be ascertained before being confident about the values of the parameters.

The other approach for developing unit hydrograph for ungauged catchments, utilises geomorphological characteristics. The transformation of the rainfall into runoff is dependent on the surface of a basin and is reflected in the indices that are described by geomorphology of the basin such as its linear, aerial and relief aspects. This approach has many advantages over the regionalisation approach, as it avoids the requirement of computations in the neighbouring gauged catchments. The concept of Geomorphological Instantaneous Unit Hydrograph (GIUH) was introduced by Rodriguez-Iturbe and Valdes (1979), in their pioneering studies on the geomorphologic structure of hydrologic response.

Nature shapes river catchments in an orderly and organised manner. Any river catchment reflects the interdependence of geology, soil characteristics, vegetation, topography, and climate. The quantitative study of channel networks was, originated by Horton (1945). He developed a system for ordering stream networks and derived laws relating the number, length, and catchment area associated with streams of different order and suggested several empirical laws regarding stream numbers, stream lengths, and stream areas for a catchment. The quantitative expressions of Horton's laws are:

(i) law of stream numbers, $N_w/N_{w+1} = R_B$

(ii) law of stream lengths, $L_w/L_{w-1} = R_L$

(iii) law of stream areas, $A_w/A_{w-1} = R_A$

where, N_w is the number of streams of order w, L_w is the mean length of stream of order w, and A_w is the mean area of the catchments of order w. R_B, R_L, and R_A represent the bifurcation ratio, the length ratio, and the area ratio whose values in nature are normally between 3 and 5 for R_B, 1.5 and 3.5 for R_L, and 3 and 6 for R_A (Smart, 1972).

Strahler (1957) slightly revised Horton's classification such that the ordering scheme, unlike Horton's purely topological classification, refers to interconnection and not the lengths, shapes, or orientation of the links comprising a network.

Recently, many attempts have been made to relate the response of a catchment to its morphologic or topologic aspects, using various hypothesis to model both the advection and attenuation effects of a river network. The formalisation by Rodriguez-Iturbe and Valdes and the subsequent refinements by Gupta et al. (1980) and Gupta and Waymire (1983) placed the interpretation of the hydrologic response on new and much more general theoretical grounds.

A new approach, in which the conceptual modeling of IUH is combined with the geomorphologic instantaneous unit hydrograph approach, has been developed at the National Institute of Hydrology. This methodology may be applied for simulation of the flood hydrographs and evaluation of design floods especially for small to medium sized ungauged catchments. Using this method, the estimation of parameters of the conceptual model of IUH is not required to be carried out through the tedious regionalisation process. This approach is formulated by linking the Clark's model parameters with the peak characteristics of the GIUH.

The Geomorphologic Instantaneous Unit Hydrograph (GIUH)

The basic idea of GIUH is that the distribution of arrival times at the basin outlet of a unit instantaneous impulse injected throughout a channel network is affected both by the underlying natural order in the morphology of the catchment and the hydraulic characteristics of the flow along the channels. In the approach of Rodriguez-Iturbe and Valdes, the underlying natural order in the morphology is represented by the Horton ratios, which in turn are based on a classification of the channel network of the catchment according to Strahler's ordering scheme. The holding time of a drop of water within a stream of a given order is represented by means of an exponential law, which is, however, a conceptualisation of true flow dynamics. As a consequence of this last hypothesis, the average holding time of a drop within a stream of a given order is proportional to the average length of all the streams of that order, and the proportionality factor is the flow velocity, which is considered uniform throughout the drainage basin.

The GIUH proposed by Rodriguez-Iturbe and Valdes is based on Shreve's theory (1966) of topologically random networks of a given magnitude and on the state-transition approach (Howard, 1971) coupled with Markov process. In this formulation, the state 'i' identifies the location of an individual drop of water within a stream of order i or in the area drained by a stream of order i. In a drainage network, a transition can only occur from a given state i to some state of higher order j. The probability of that transition is defined as;

p_{ij} = (no. of streams of order i draining into order j / no. of streams of order i)

and the probability of state i is given by,

θ_i = (total area draining directly into the streams of order i / total area of the basin)

To derive a distribution for the travel time to the outlet of an individual particle, it is necessary to hypothesize a holding time distribution for each state of the system. Rodriguez-Iturbe and Valdes assumed that the probability density function of the time spent by a generic drop in a state of order i is,

$f_i(t) = \lambda_i \exp(-\lambda_i t)$.

where λ_i is the reciprocal of the mean holding time in any stream order i. This position is equivalent to treating each order of stream as a linear reservoir.

The application of above equation to all orders of streams including the highest would imply a hydrograph for the whole basin which does not start from zero. To avoid this, the highest order streams are splitted into two streams (ie., two linear reservoirs) in series, each with a travel time probability distribution,

$$f_{\Omega}(t) = \lambda_{\Omega} \exp(-\lambda_{\Omega} t),$$

where $\lambda_{\Omega} = 2\,\lambda_{\Omega}$, ie., each with a mean holding time of $0.5\lambda_{\Omega}^{-1}$. According to Rodriguez-Iturbe and Valdes, only the first, from upstream, of the two 'reservoirs' that represent the highest-order stream (for example, for a third order channel network), receives the drop from all second order streams, a proportion of the first order streams, and those drops draining directly into the third order stream. Using the above equations and Howard's state-transition theory coupled with the Markov process, the probability distribution of the total travel time to the outlet, ie., the GIUH can be derived.

Application of GIS

Geographical Information System (GIS) is a computer based tool for capturing and processing spatial data of geographic nature. The GIS functions for hydrologic and environmental analyses are to manage, automate and display data in digital form for use as input in analytical computer models. Hydrology is an area, which can greatly benefit from integration with GIS.

GIS can be defined as an organised collection of computer hardware, software, and geographic data designed to efficiently capture, store, update, manipulate, analyse, and display all forms of geographically referenced information (Johnson et al. 1992). Once a geographic database is established, its analysis allows us to study real world processes by developing and applying models. Such models illuminate underlying trends in the geographic data and thus make new information available.

GIS is used for the input, storage, manipulation, and display of geographic data. The data input subsystem supports digitizing of analog map or importing of spatial and image data in digital form. Data storage and retrieval functions provide the storage and maintenance of both spatial and related non-spatial data files. Data manipulation functions perform analytical functions such as reclassification, overlay, and neighbourhood analysis tasks. A tabular and graphic output subsystem is used for display of spatial and tabular data.

GIS are rapidly becoming a standard tool for management of resources. The major applications of GIS related to Hydrology includes:

- land use planning and management
- natural resources mapping and management
- land information systems
- urban and regional planning
- management of well log data

The input to GIS may be remotely sensed data, digital models of the terrain, or point or aerial data compiled in the forms of maps, tables or reports. GIS provides a digital representation of watershed characterisation used in hydrologic modeling. GIS can provide the basis for hydrologic modeling of ungauged catchments and studying the hydrologic impact of physical changes within a catchment.

One advantage of the geomorphological instantaneous unit hydrograph (GIUH) approach is the potential of deriving the UH using only the information obtainable from topographic maps or remote sensing, and can be linked with a geographic information system (GIS) and digital elevation model (DEM). The GIUH approach requires the estimation of geomorphological parameters such as R_B, R_L, R_A, time-area diagram, etc., which is a cumbersome process if done manually. So, in order to increase the efficiency of this methodology, GIS can be effectively used.

The GIS software used in the present study is Integrated Land and Water Information System (ILWIS). It was developed at ITC, Enschede, The Netherlands. ILWIS is a GIS that integrates image processing capabilities, tabular data bases and conventional GIS characteristics. Data acquisition from aerospace images, which is an integral part of the system, enables effective monitoring. This is important in regions where data is scarce or difficult to gather.

A conversion program allows the transformation of the remote sensing data, tabular data, raster maps and vector files in several other formats. Analog data can be transformed into vector format by means of a digitizing program. Complex modeling of features can be executed by the 'Map Calculator'. The map calculator includes an easy to use modeling language and the possibility of using mathematical functions and macros. It integrates tabular and spatial databases. Complex procedures can be executed rapidly on portions of study area on the video memory. After evaluation and assessment of results, the procedure can be applied to the entire area. Tabular and spatial database can be used independently and on integrated bases. Calculations, queries and simple statistical analysis can be performed by the Table Calculator. Computational procedures and efficient use of system are improved by the appropriate use of modeling processes. Fast overlay procedures constitute one of the main characteristics of the system.

Image processing capabilities integrated with spatial modeling and tabular database constitute a powerful tool. Together they enable a kind of analysis, which was not possible until recently. ILWIS also incorporates conventional image processing techniques such as filtering, geometric corrections and classification procedures. Special features of interpolation of point data and contour lines are also available to create Digital Elevation Models. Special filters and functions are available to produce slope and aspect maps.

Data processing includes several basic image analysis capabilities, such as histogram manipulation, automatic stretch display, user defined filters, transfer function manipulation and other standard functions. It includes calculation of co-variance and correlation matrices, eigen values and eigen-vectors and other statistics. A user friendly sampling program allows sampling by pixel, feature space plot analysis and sample and class statistics. Several classifier algorithms can be used. Before classifying an entire image, the behaviour of the different classifiers can be compared through an interactive pixel classification routine.

The ILWIS menu is subdivided in several modules and submodules. There are six main modules namely Input, Vector, Raster, Tables, Output and Command. There is not always a one-to-one relationship between menu options and program names and that some menu options can be found in different modules.

LITERATURE REVIEW

Simulation of transformation of rainfall into runoff has been an active area of research throughout the evolution of the science of hydrology. The simplest among all the methodologies is the estimation of an empirical constant, runoff coefficient, which is used to estimate runoff from rainfall. The linearity principle of unit hydrograph theory put forward by Sherman in 1932 has been widely applied for small and medium sized catchments. Large number of conceptual models have been put forward by many researchers where the various interrelated hydrological processes are conceptualised. More sophisticated procedures have also been evolved which are based on the physical concepts of the process in which the rainfall-runoff process is modeled.

The concept of Instantaneous Unit Hydrograph (IUH) suggested by Nash (1957) helped in determining the time distribution process of the excess runoff through a simple two parameter model. Thus, IUH is a purely theoretical concept and represents the unit hydrograph obtained when the unit excess rainfall occurs instantaneously. As the rainfall duration term is eliminated, the IUH indicates storage characteristics of a catchment and it is unique for a catchment. Many conceptual models are available for the derivation of IUH such as Clark model (1945), Zoch model (1934, 1936), Dooge model (1973), models suggested by Laurenson (1964) and Diskin (1972), etc.

The parameters of the types of models mentioned above, are to be calibrated based on the available rainfall-runoff data of a particular basin. But, for ungauged catchments, these parameters need to be determined from the regional relationships correlating the model parameters with physically measurable catchment characteristics. In order to develop unit hydrograph parameters for an ungauged catchment, the concept of regional and synthetic hydrograph was put up by early researchers.

The quantitative analysis of drainage network has gone through dramatic advances since the findings of Shreve (1966) which led way for a theoretical foundation of Horton's well known empirical laws and provided a new perspective for many other problems in fluvial geomorphology. Based on these, Rodriguez-Iturbe et al. (1979) introduced the concept of Geomorphological Instantaneous Unit Hydrograph (GIUH) as a step towards linking quantitative geomorphological parameters to stream flow response.

Several investigators have worked towards developing an IUH from the geomorphology of catchments as derived from readily available topographic maps. A majority of the past studies have used conceptual and synthetic unit hydrograph models. Some of the important studies carried out by different investigators are described as follows.

Bernard (1935) accomplished the transformation of rainfall to runoff through the medium of a distribution graph, which was also a function of catchment characteristics. He assumed that the peak of the unit hydrograph was inversely proportional to the time of concentration, given by the length of longest channel divided by the square root of the average catchment slope. McCarthy (1938) and Snyder (1938) correlated the unit hydrograph and the topographic parameters such as area, overland slope, and stream pattern to permit an estimate of unit hydrograph parameters of an ungauged catchment. Clark (1945) suggested that the ordinates of the IUH should be proportional to the derivatives of the time-area concentration curve, at corresponding times in the absence of storage in the catchment. He obtained the IUH from time of concentration t_c, a storage attenuation coefficient R, and a time-area diagram for the catchment.

Taylor and Schwarz (1952) related the lag and peak flow values of the unit hydrograph with the catchment characteristics and duration of rainfall excess empirically. They found that the peak of IUH was a function of main channel slope and the shape of IUH was a function of catchment length. Minshal (1960) pointed out that peak flow and time to peak of the unit hydrograph were dependent upon rainfall intensity and storm pattern. Nash (1960) model has two parameters n and k. He found that these parameters are related to the first and second moments of the IUH about the origin. These moments are then correlated empirically with watershed characteristics (catchment area and slope).

In India, the Central Water Commission adopted unit hydrograph approach for the estimation of design flood peak of desired frequency. For this purpose, the country has been divided into 7 major zones which are further sub-divided into 26 hydrometeorologically homogeneous sub-zones. The CWC has developed regional formulae for different sub-zones for the derivation of synthetic unit hydrograph, relating unit hydrograph characteristics to physiographic features.

Singh (1984) developed regional unit hydrograph relationship for lower Godavari sub-zone (3f) relating Nash and Clark model parameters with catchment characteristics. National Institute of Hydrology (1985) has carried out a regional unit hydrograph study for Narmada basin based on Clark's approach. In this study, the parameters of Clark model were derived using HEC-1.

Huq et al. (1982) developed synthetic unit hydrograph relationships using the data of catchments in Gangetic plains, Mahanadi basin, Krishna basin, and Brahmaputra basin. Relationships were formulated between parameters of unit hydrograph with a suitable combination of physical characteristics of catchment using regression analysis. Mathur and Vijay Kumar (1987) related the physical parameters of twenty small and medium catchments in order to arrive at the most effective combination of the physical parameters for development of the regional unit hydrograph relationships.

Boyd (1978, 1982) developed the linear watershed bounded network (LWBN) model for synthesis of the IUH employing geomorphologic and hydrologic properties of the watershed. The model has a large number of lumped storage parameters most of which are deduced from geographic properties.

Rodriguez-Iturbe and Valdes (1979) and Valdes et al. (1979) introduced the concept of the GIUH by linking the IUH peak discharge (q_p) and time to peak (t_p) with geomorphologic parameters of the catchment and a dynamic parameter (velocity). The approach coupled the empirical laws of geomorphology with the principles of linear hydrologic systems.

The effect of climatic variation is incorporated, by having a dynamic parameter velocity, in the formulation of GIUH. Rodriguez-Iturbe et al. (1982) rationalised velocity as a function of effective rainfall intensity and duration and proceeded to eliminate velocity from the formulation. It led to the development of geomorphoclimatic instantaneous unit hydrograph.

Rosso (1984) related the Horton's order ratios, such as R_B, R_L, and R_A, to the parameters of the Nash IUH model on the basis of geomorphologic model of catchment response. He found that the shape parameter n of the Nash model was dependent on R_B, R_L, and R_A of a catchment.

Zelazinski (1986) gave a procedure for estimating the flow velocity. It involves the development of the relationship between velocity and corresponding peak discharge. A methodology based on trial and error procedures has been suggested for estimating the maximum value of the velocity for each flood event.

Panigrahi (1991) estimated the velocity using the Manning's equation. The methodology involves the estimation of equilibrium discharges and subsequently the corresponding velocity using Manning's equation. The channel cross section at the gauging site, longitudinal slope, and Manning's roughness coefficient are required for the computation of velocity. The methodology has been applied to derive the Nash model parameters using GIUH approach for the Kolar sub-basin.

A new approach of rainfall-runoff modeling based on the geomorphological characteristics has been developed at the National Institute of Hydrology (NIH, 1993). In this approach, the parameters of the Clark model have been estimated using the geomorphological characteristics. This has enabled to determine the complete shape of the IUH by using the formulae given for the peak characteristics of the GIUH. Simultaneously, on the other hand, it has been possible to use the conceptual modeling approach without even requiring to calibrate its parameters on the basis of the observed runoff data. The conceptual model used in this new approach is the Clark model.

This approach was tested on small catchments of Kolar sub-basin of Narmada river (NIH, 1993), Upper Narmada, Tapi sub-zones (NIH, 1995; NIH, 1996) and catchments in Mahi and Sabarmati sub-zone in a GIS environment (NIH, 1999). This methodology links the GIUH equations derived by Rodriguez-Iturbe and Valdes and the parameters of the Clark model.

Yen and Lee (1997) applied the GIUH approach on two hilly watersheds in the eastern United States and two relatively flat slope watersheds in Illiniois. Comparison between the simulated and observed hydrographs for a number of rainstorms indicated the potential of this approach as a useful tool in watershed rainfall-runoff analysis.

Lee and Yen (1997) emphasized the difficulty in determination of travel time, which is actually a hydraulic problem. They used the kinematic wave theory to analytically determine the travel times for overland and channel flows in a stream ordering subbasin system. According to this study, the resultant instantaneous unit hydrograph is a function of the time rate of water input (intensity of rainfall excess), hence the linearity restriction of the unit hydrograph theory is relaxed.

Bhaskar et al. (1997) derived the GIUH and then related to the parameters of the Nash IUH model. They carried out runoff modeling using GIUH for twelve watersheds in the big sandy river basin in eastern Kentucky using ARC/INFO. The hydrological model used to simulate watershed runoff was a geomorphic model called as watershed hydrology simulation (WAHS) model.

Ros and Borga (1997) used digital elevation model data for derivation of the geomorphological instantaneous unit hydrograph for three mountain basins in Italian Alps. A sensitivity analysis was also performed to study the influence of the variability of morphometric property, with respect to threshold area, on the hydrological response obtained.

Lee K.T. (1998) generated design hydrographs by DEM assisted geomorphic runoff simulation. To simplify the time-consuming work involved in geomorphic parameter measurement on topographic maps, the GIUH model was linked with GIS to obtain geomorphic parameters from DEM. In this work, a case study for peak flow analysis in an ungauged watershed was presented. The design storm was applied to the geomorphic runoff simulation-model to obtain the design hydrograph.

STUDY AREA

For the present study, two catchments located in Karnataka, India were selected. These catchments are Malaprabha upto Khanapur, a major tributary of Krishna river and Barchi nala, a small tributary of Kali river.

Barchi Nala Watershed

The Barchi nala watershed upstream of Barchi is located in the leeward side of western ghat and is a sub-basin of Kali river as shown in Figure 1. Barchi nala originates from Thavargatti in Belgaum District at an altitude of about 734 m, 20 km north of Dandeli and flows through North Kanara district of Karnataka State. The catchment is relatively narrow in width and geographical area of the watershed is 21.13 sq. km. The watershed lies between 74°36' and 74°39' East longitudes and 15°18' and 15°24' North latitudes.

High land region consists of dissection of high hills and ridges forming part of the foot hills of western ghats. It consists of steep hills and valleys intercepted with thick vegetation. The slopes of the ghats are covered with dense deciduous forest. This causes the watershed surface to be covered by very thick layer of humus. The brownish and fine grained soils are the principal types of soils found in this area.

The stream gauge site is located near Barchi forest check post, at an elevation of 480 m, where the nala crosses Dandeli-Thavargatti road, about 5 km from Dandeli. The Barchi nala is a 4th order stream. The stream is narrow and deep which is typical of a steep sloped watershed. This stream joins main Barchi river downstream of the gauge site. A full fledged meteorological station, maintained by WRDO, is located near the gauging site. Average annual rainfall for the watershed is 1500 mm with majority of this rainfall occurring during south-west monsoon period.

Malaprabha Catchment upto Khanapur

Malaprabha, which is a sub-basin of Krishna river originates from Kankumbi at an altitude of about 793 m in Belgaum district of Karnataka. Initially the river flows in an

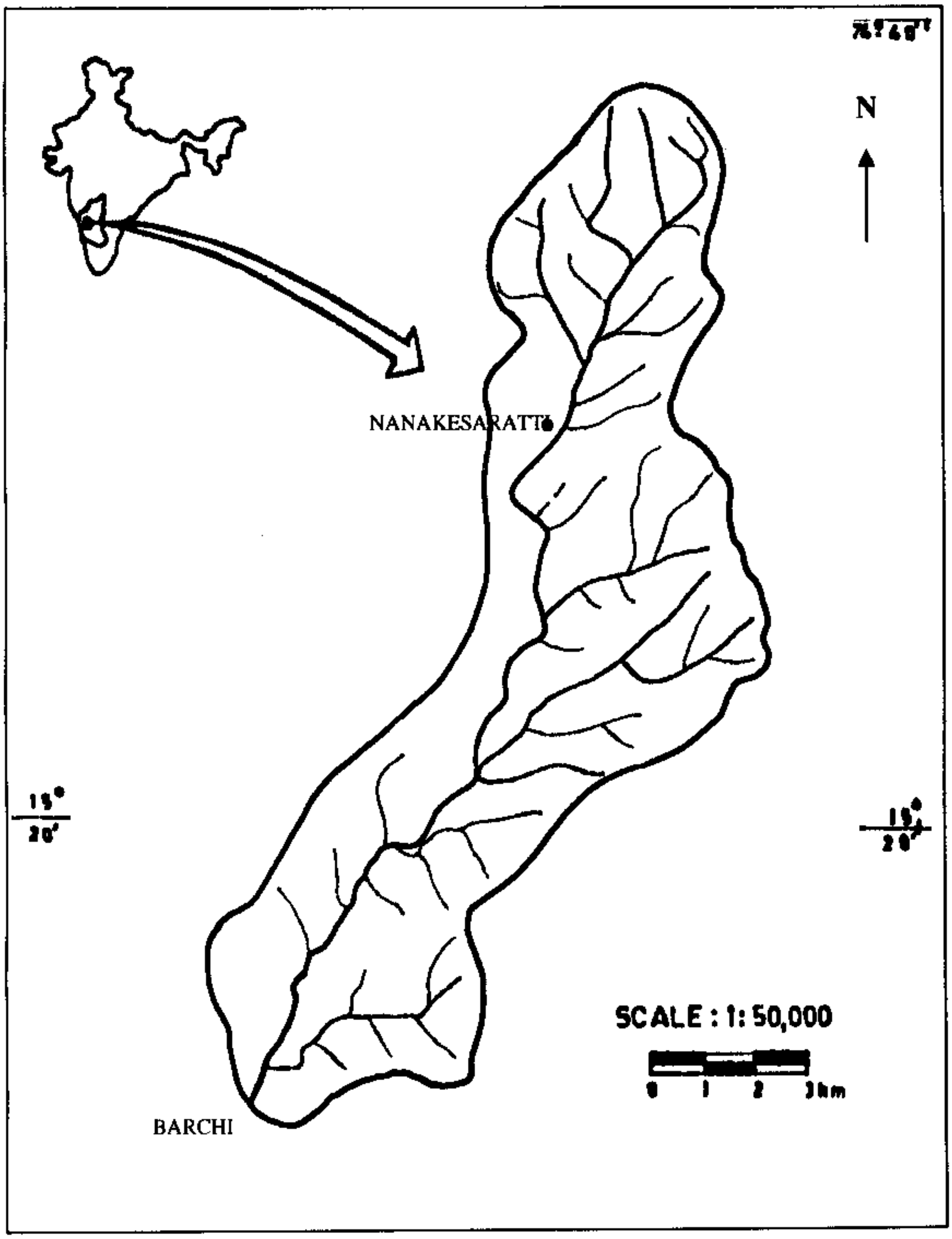

Figure 1. Barchi Nala Catchment

easterly direction and then towards north direction and joins the Krishna at an elevation of about 488 m, after about 300 km from its source.

The catchment area upto Khanapur gauging station, which is the present study area, is 520 km^2. This area lies between 74° 15’ and 74° 35’ East longitudes and 15° 30’ and 15° 45’ North latitudes. Figure 2 shows the Malaprabha river upto Khanapur. This catchment is the major source of water for the Naviluteertha dam, which is situated at about 40 km. downstream of Khanapur. This dam impounds about 1377 MCM water and provides water for irrigation in about 2.17 lakh ha. land.

Geologically, the study area comprises of tertiary basalt, which covers the major part of the basin (96 %); and sedimentary formations of Pre-Cambrian age, which is confined to the south-east part of the catchment.

The soils of the catchment upto Khanapur can be classified into two groups; red loamy soil, which covers a major part of the basin (80%), especially in the upstream region; and medium black soil, which can be seen in the downstream portions. These black soils are usually clayey in texture with low permeability. Generally, the soil thickness within the basin varies between 0.5 m to 10 m.

A major portion of the area is covered by forests (63 % of the total catchment area), which can be seen along western and south-western parts of the study area. Agricultural lands constitute about 17 % of the total area, in the northern part of the basin. The sloppy areas of the catchment are covered by shrubs, which occupies 19 % of the area.

The climate of the Malaprabha upto Khanapur is influenced by the south-west monsoon, which extends from mid June to September. The monsoon rainfall accounts for 91 % of the total rainfall in the basin. The average annual rainfall of the catchment is 2259 mm. The temperature varies between 19.2°C to 29.5°C and the mean evaporation 1496.9 mm. Normally the climate over the catchment is humid. The discharge from the catchment is measured at Khanapur gauge-discharge site, by WRDO, using a, float-type recording gauge. The average annual discharge at Khanapur is 8953.6 cumecs. About 77 % of this flow occur in the month of July and August.

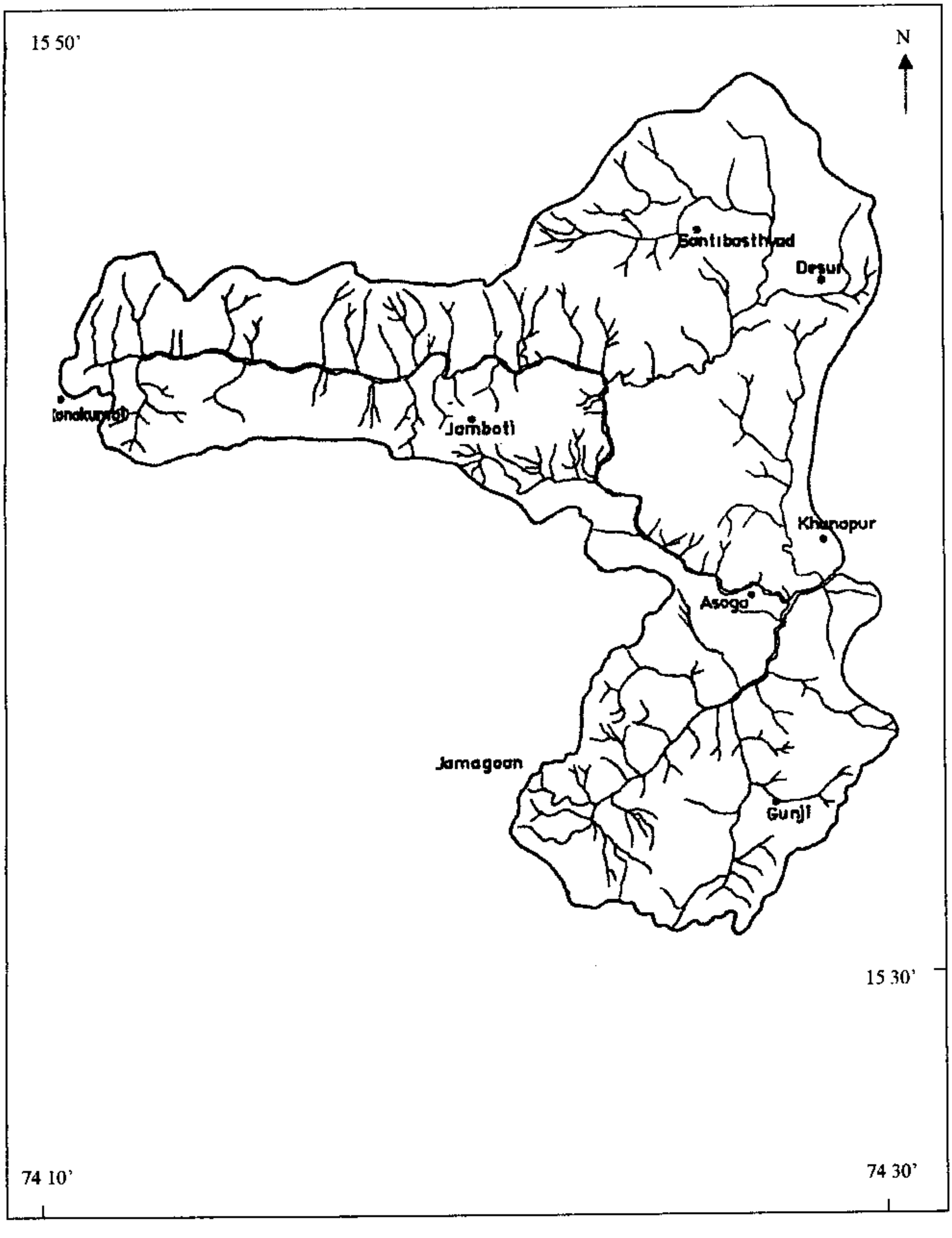

Figure 2. Malaprabha Catchment

METHODOLOGY

Preparation of Data Base in ILWIS

Boundary of the catchments and all the streams were mapped at a scale of 1:50,000 from Survey of India toposheets. Also, a contour map at the same scale was prepared. Both these maps were then converted to digital form using digitization and stored in ILWIS. Digitization, which is the most time consuming part of the analysis, was carried in parts to minimise the digitization errors. Then the digitized maps were corrected for any type of error such as proper joining of the streams, proper overlaying of the segments etc. The ILWIS system then edits the coverage and splits the stream of the higher order automatically at the point where they meet. Individual stream (segment) lengths are computed and stored in the order table along with the order of each stream. The area and perimeter of the basin can be computed after converting segment (boundary) map to polygon map. After converting the contour map into digital form, it was rasterised. Then interpolation from isolines was carried out on this map. This interpolated map gives the elevation at each point (pixel) in the basin.

Evaluation of Geomorphological Characteristics

For stream order, Strahler's ordering system, has been followed. According to this ordering system, which is applied through ILWIS over the entire drainage network of the study area, it is found that the Malaprabha is a 6th order basin and Barchi is a 4th order basin. In the ILWIS system, length of each stream is stored in a table. By adding lengths of each stream of an order, it is possible to get the total stream lengths of each order. The total stream length divided by the number of stream segments (N_w) of that order gives the mean stream length L_w for that order. The plot of logarithm of mean stream length (ordinate) as a function of order (abscissa) yields a set of points lying essentially along a straight line.

Horton's law of stream number states that the number of stream segments of each order is in inverse geometric sequence with order number i.e.

$$N_w = R_B^{w-k} \qquad \text{---------(1)}$$

where, k is the order of trunk segment, w is the stream order, N_w is the number of stream of order w and R_B is a constant called the bifurcation ratio. When logarithm of the number of streams is plotted against order it shows a linear relationship.

Horton inferred that mean drainage basin areas of progressively higher order should increase in a geometric sequence, as do stream lengths. The law of stream areas may written as :

$$A_w = A_1 R_A^{w-1} \qquad \text{---------(2)}$$

where, A_w is the mean area of basin of order w. The areas of fourth and higher order streams were computed by ILWIS. The areas of lower order basin was estimated using the relationship between area of any order and area of highest order as given below:

$$A_w = A_1 R_B^{w-1} (R_{lb}^{w}-1)/(R_{lb}-1) \qquad \text{---------(3)}$$

where, A_1 is the mean area of first order basin, R_b is the bifurcation ratio and R_{lb} is the ratio of length ratio to bifurcation ratio. From this relationship, the only unknown A_1 can be calculated and using the value of A_1, the other mean areas can computed.

Bifurcation, length and area ratios are calculated as the slope of the best fit lines through the plotted points given by the Horton's laws of stream numbers, average lengths and average areas respectively.

Computation of Excess Rainfall

In a catchment, surface runoff occurs only after the abstractions such as interception, evapotranspiration, depression storage, and infiltration have taken place. The rainfall amount which produces surface runoff is termed as rainfall excess. For any rainfall-runoff modeling, the initial step is to estimate rainfall excess by separating the hydrological abstractions from the rainfall hyetograph. Although a number of methods are available for the separation of abstractions, the phi-index method is the simplest and most commonly used. SCS curve number method can also be used for the estimation of rainfall excess, especially for ungauged catchments.

When the phi-index method is used, observed direct surface runoff is used for the estimation of excess rainfall hyetograph. In the cases of ungauged catchments, the phi-index can be estimated by analysing the rainfall-runoff records of flood events of neighbouring catchments having similar hydro-meteorological characteristics.

Preparation of Time-Area Diagram

The time-area diagram is one of the important inputs for running the GIUH based Clark model. It provides the shape of IUH without considering the storage effects of the catchment.

Time of travel (t) through a stream is considered proportional to $L/S^{0.5}$

or $t = kL/S^{0.5}$ ---------(1)

where, t is the time of travel

L is the length of the stream

S is the slope of the stream

k is the proportionality constant

An initial estimate of time of concentration is obtained by the Kirpich's empirical formula, which is given as;

$T_c = 0.0195\, L^{0.77}\, S^{-0.385}$ ---------(2)

where, T_c is the time of concentration in min.

L is the main stream length in meters

S is the mean slope of the main stream in m/m

Substituting the values of L and S in the equation (2) yields the value of time of concentration for the catchment. This value of T_c may be substituted in the equation (1) to get the value of k.

Knowing the value of constant of proportionality k, the equation (1) can be used to calculate time of travel between any two points in the catchment. Starting from the basin outlet, the time of travel can be calculated for various points over the catchment.

All the values of time of travel for different points are marked on the map at their respective locations. Curves of specified time of concentration called isochrones can be drawn through these points by making use of linear interpolation and consideration of elevation contour pattern and stream layout. The DEM data generated from ILWIS are utilized to develop isochronal map for the catchment at hourly interval.

Derivation of Clark Model IUH and D-Hour Unit Hydrograph

The Clark model concept suggests that the IUH can be derived by routing the unit inflow through a single reservoir in the form of time-area diagram, which is constructed from the isochronal map. For the derivation of IUH, the Clark model uses two parameters, time of concentration in hours (T_c), which is the base length of the time area diagram, and storage coefficient in hours (R), of a single linear reservoir in addition to the time area diagram.

The governing equation of IUH, using this model, is given as;

$$u_i = C\, I_i + (1 - C)\, u_{i-1} \qquad \text{---------(3)}$$

where, u_i is the ith ordinate of the IUH

C and (1-C) are the routing coefficients, $C = \Delta t / (R+0.5\, \Delta t)$

Δt is the computational interval in hours

I_i is the ith ordinate of time area diagram

R is the storage coefficient

A unit hydrograph of desired duration (D) can be derived using the following equation;

$$U_i = (1/n)\, \{\, 0.5\, u_{i-n} + u_{i-n} + u_{i-n+1} + \text{----------} u_{i-1} + 0.5\, u_i\, \} \qquad \text{---------(4)}$$

where, U_i is the ith ordinate of unit hydrograph of duration D hour at a computational interval Δt hours

n is the number of computational intervals in duration D hours ($D/\Delta t$)

u_i is the ith ordinate of the IUH

Use of Geomorphological Characteristics

Rodriguez-Iturbe and Valdes (1979) introduced the concept of geomorphologic instantaneous unit hydrograph (GIUH). Their expression yields full analytical, but complicated expressions for the IUH. They suggested that it is adequate to assume a triangular IUH and to specify only the expressions for the time to peak and peak value of the IUH. These expressions are obtained by regression of the peak as well as time to peak of IUH, derived from the analytical solutions for a wide range of parameters with that of geomorphologic characteristics and flow velocities. These expressions are as follows:

$$q_p = 1.31\, R_L^{0.49}\, V/L_\Omega \qquad \text{---------(5)}$$

$$t_p = 0.44\, (L_\Omega /V)(R_B / R_A)^{0.55} (R_L)^{-0.38} \qquad \text{---------(6)}$$

where, L_Ω is the length of the highest order stream in km.

V is the expected peak velocity in m/sec.

q_p is the peak flow in units of inverse hours

t_p is the time to peak in hours

R_B is the bifurcation ratio

R_L is the length ratio

R_A is the area ratio

By multiplying q_p and t_p, we get a dimensionless term,

$$q_p{}^* t_p = 0.5764\, (R_B / R_A)^{0.55} (R_L)^{0.05} \qquad \text{---------(7)}$$

This term is not dependent upon the velocity and thereby on the storm characteristics. It is a function of only catchment characteristics.

Development of Relationship between the Intensity of the Excess Rainfall and the Velocity

For the dynamic parameter velocity, Rodriguez et al. (1979) assumed that the flow velocity at any given moment during the storm can be taken as constant throughout the basin. The characteristic velocity for the basin as a whole changes throughout as the storm progresses. For the derivation of the GIUH, this can be taken as the velocity at the peak discharge for a given rainfall-runoff event in a basin. However, for ungauged catchments, the peak discharge is not known and so this criteria cannot be applied. In such situations, the velocity may be estimated using the relationship developed between the velocity and excess rainfall. Two approaches are available for developing such a relationship, as given below.

Approach 1:

This approach may be utilised when the geometric properties of the gauging section is known and the Manning's roughness coefficient can be assumed with adequate degree of accuracy. The procedure involved in this approach is as below;

(a) Compute cross sectional area, wetted perimeter, and hydraulic radius on the basis of cross sectional details corresponding to different depths.

(b) Assume the frictional slope to be equal to the bed slope of the channel.

(c) Choose an appropriate value of Manning's roughness coefficient for the surface condition of the channel.

(d) Compute the discharge Q using the Manning's equation, corresponding to each depth.

(e) Plot depth v/s discharge and depth v/s area of cross section curves.

(f) Compute the equilibrium discharge (Q_e) corresponding to an excess rainfall intensity i (mm/hr) using the relation, $Q_e = 0.2778\ i\ A$ ---------(8)

where A is the catchment area in sq. km.

(g) Compute the depth corresponding to the equilibrium discharge Q_e using the depth v/s discharge curve.

(h) Compute the area corresponding to the depth computed at step 'g' using the depth v/s area curve.

(i)Compute the velocity V by dividing the discharge Q_e by the area computed at step 'h'.

(j) Repeat steps 'f' to 'i' to find velocity with respect to different intensities of rainfall excess.

(k) Develop the relationship between velocity and rainfall excess intensity in the form, $V = ai^b$ using the method of least squares.

Approach 2:

This approach is based on the assumption that the value of the Manning's roughness coefficient is not available but the velocities corresponding to discharges passing through the gauging section at different depths of water flow are known from the observations. The procedure for this approach is given below;

(a) For different depths of flow, the discharge and the corresponding velocities are known by the observations.

(b) Let these velocities and discharges be the equilibrium velocities V_e and the corresponding equilibrium discharges Q_e.

(c) For these Q_e find the corresponding intensities i of excess rainfall from the expression,

$i = Q_e / 0.2778\ A$ ---------(9)

(d) From the pairs of such V_e and i, develop the relationship between the equilibrium velocity and the excess rainfall intensity in the form, $V = ai^b$, using the method of least squares.

Derivation of Unit Hydrograph using the GIUH Based Clark Model Approach

A new approach has been developed at National Institute of Hydrology (NIH, 1993) for the estimation of the parameters of the Clark model through the use of geomorphological characteristics. The step by step procedure to be followed to derive unit hydrograph for a specific duration using this approach is given below.

(a) Excess hyetograph is computed either by uniform loss rate procedure, by SCS curve number method, or by any other suitable method.

(b) For a given storm, the estimate of the peak velocity V using the highest rainfall excess is made by using the relationship between velocity and intensity of rainfall.

(c) Compute the time of concentration T_c using the equation;

$$T_c = 0.2778\ L / V \qquad \text{---------(10)}$$

(d) Compute the peak discharge (Q_{pg}) of IUH using the equation (5)

(e) Assume two trial values of the storage coefficient of GIUH based Clark model as R_1 and R_2. Compute the ordinates of two instantaneous unit hydrographs by Clark model using the time of concentration T_c obtained from equation (10) and two storage coefficients with the help of equation (3). Compute the IUH ordinates at a very small time interval say 0.1 or 0.05 hrs so that a better estimate of peak value may be obtained.

(f) Find out the peak discharges Q_{pc1}, Q_{pc2} of the IUH obtained by Clark model for the two storage coefficient R_1 and R_2.

(g) Find out the value of objective function (FCN), using the relation

$$FCN1 = (Q_{pg} - Q_{pc1})^2 \qquad \text{---------(11)}$$

$$FCN2 = (Q_{pg} - Q_{pc2})^2 \qquad \text{---------(12)}$$

(h) Compute the first numerical derivative FPN of the objective function FCN with respect to parameter R as,

$FPN = (FCN1 - FCN2) / (R_1 - R_2)$ ---------(13)

(i) Compute the next trial value of R using the following governing equations of Newton-Raphson method:

$\Delta R = FCN1/FPN$ ---------(14)

and $RNEW = R_1 + \Delta R$ ---------(15)

(j) For the next trial, consider $R_1 = R_2$ and $R_2 = RNEW$ and repeat steps (e) to (i) till any of the following criteria of convergence is achieved.

(i) FCN2 = 0.000001

(ii) no. of trials exceeds 200

(iii) $ABS (\Delta R) / R_1 = 0.001$

(k) The final value of storage coefficient (R_2) obtained above is the required value of the parameter R corresponding to the value of time of concentration for the Clark model.

(l) Compute the instantaneous unit hydrograph (IUH) using equation (3) with the help of final value of storage coefficient, time of concentration and time-area diagram.

(m) Compute the D-hour unit hydrograph (UH) using the relationship between IUH and UH of D-hour, as given by equation (4).

Computation of Direct Surface Runoff using Derived Unit Hydrograph

The direct surface runoff for a storm event whose excess rainfall values are known at D-hour interval are computed using the convolution based on the D-hour unit hydrograph. The convoluted hydrograph ordinates are given as:

$$Q(t) = \Delta t \sum_{i}^{n} [U(D,t-(i-1)\,\Delta t)] * I_i \qquad \text{---------(16)}$$

where

U(D,t) is the ordinate of D hour UH at time t

I_i is the rainfall intensity at ith interval (ie. at time = $\Delta t * i$)

n is the no. of rainfall blocks

Δt is the computational time interval

ANALYSIS AND RESULTS

The objective of this study was to apply the GIUH based Clark model developed at NIH, to Malaprabha basin upto Khanapur and Barchi nala watershed. Since the GIUH approach requires the extraction of geomorphological characteristics of the catchments from toposheets or other types of maps, a geographical information system, ILWIS, was utilised. The various steps followed for the application of this model with their results and discussions are described in the following paragraphs.

Estimation of Geomorphological Parameters

In the present study, GIS technique was used for the stream ordering, calculation of various geomorphological characteristics; number of streams, lengths, and areas of each order stream for both the study areas. These were plotted, as shown in Figure 3 for Barchi and in Figure 4 for Malaprabha. The three constants R_B, $_R$L, and R_A were computed as the slope of the best fit lines and are given in Table 1.

Table 1: Geomorphological Characteristics of the Selected Catchments

Catchment	Stream Order	No. of Streams	Average Length (kms.)	Average Area (sq. kms.)	Constants
Malaprabha upto Khanapur L = 46.50 kms.	1	830	0.82	0.31	$R_B = 4.12$ $R_L = 1.52$ $R_A = 4.77$
	2	210	1.62	1.45	
	3	58	1.82	4.70	
	4	8	7.27	35.19	
	5	2	23.81	247.44	
	6	1	2.35	522.30	
Barchi Nala L = 11.08 kms.	1	39	0.70	0.26	$R_B = 3.45$ $R_L = 1.87$ $R_A = 4.32$
	2	8	1.11	1.37	
	3	2	2.70	5.64	
	4	1	4.18	21.12	

* L is the length of main stream

Preparation of Time-Area Diagram

The lengths and slopes for all streams in the two catchments were calculated with the help of ILWIS GIS. The time of travel from each points within the basin to the outlet was calculated using the method described earlier. These values for all the points were

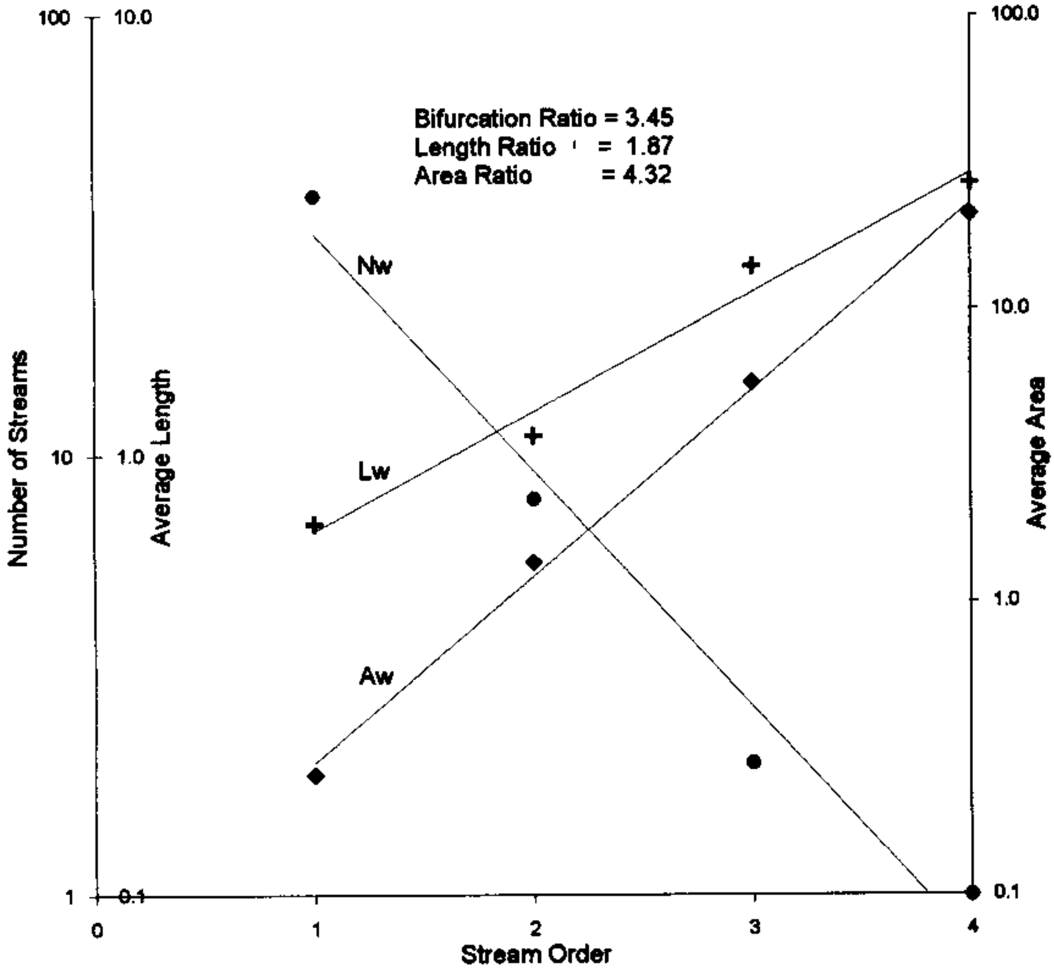

Figure 3 : Plot of Number of Streams (N), Average Length (L) and Average Area (A) Vs. Stream Order for Barchi Nala Catchment

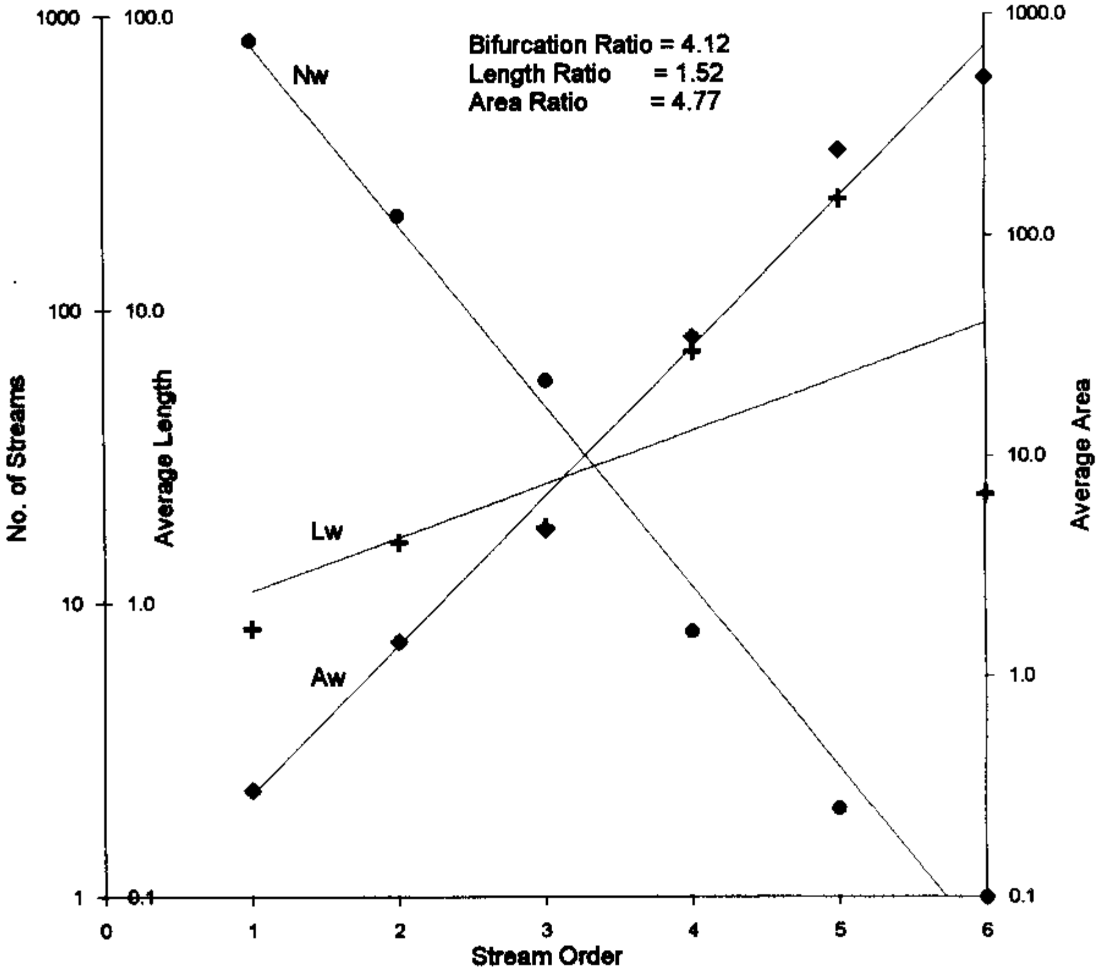

Figure 4 : Plot of Number of Streams (N), Average Length (L) and Average Area (A) Vs. Stream Order for Malaprabha Upto Khanapur

then marked on the digital map in the GIS. Using the interpolation techniques available in the GIS, isochronal maps of equal time of travel was prepared as shown in figures 5 & 6. The area for, each time interval was measured and is presented in Table 2.

Time area diagrams were prepared for the two catchments by taking the contributing area on Y- axis and time of travel on X-axis as shown in Figures 7 and 8.

Table 2: Time of Concentration and Isochronal Areas for the Selected Catchments

Time of Travel (Hrs.)	Cumulative Isochronal Area (Sq. Kms.) for Malaprabha upto Khanapur	Time of Travel (Minutes)	Cumulative Isochronal Area (Sq. Kms.) for Barchi Nala
0 -1	11.4	0 - 15	0.16
1 - 2	18.8	15 - 30	1.34
2 -3	27.9	30 - 45	5.46
3 -4	64.2	45 - 60	9.86
4 - 5	114.7	60 - 75	17.10
5 - 6	143.0	75 - 90	21.12
6 - 7	182.6		
7 - 8	237.0		
8 - 9	289.8		
9 -10	324.2		
10 -11	358.8		
11 - 12	395.4		
12 - 13	432.0		
13 - 14	468.4		
14 - 15	508.7		
15 - 16	522.3		

<u>Development of Relationship between Velocity and Intensity of the Excess Rainfall</u>

The cross sectional details at Barchi and Khanapur were used to develop relationship between equilibrium velocity and rainfall intensity. The approach 1, described in the methodology section was used. The variation of velocity with rainfall intensity for the two catchments are given in Figures 9 and 10 and the following relationships were obtained.

For Malaprabha basin upto Khanapur, $V = 1.1857 \, i^{0.3217}$

For Barchi nala watershed, $V = 1.5392 \, i^{0.2881}$

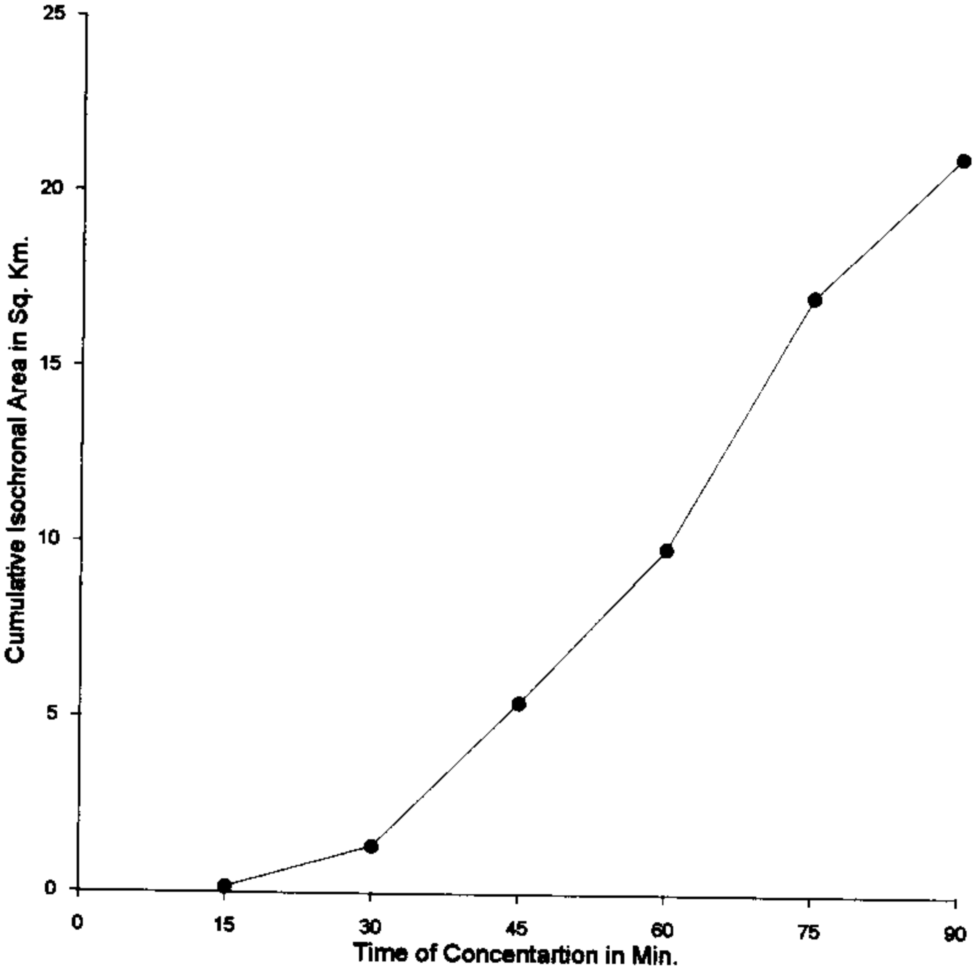

Figure 7 : Time-Area Diagram for Barchi Nala Catchment

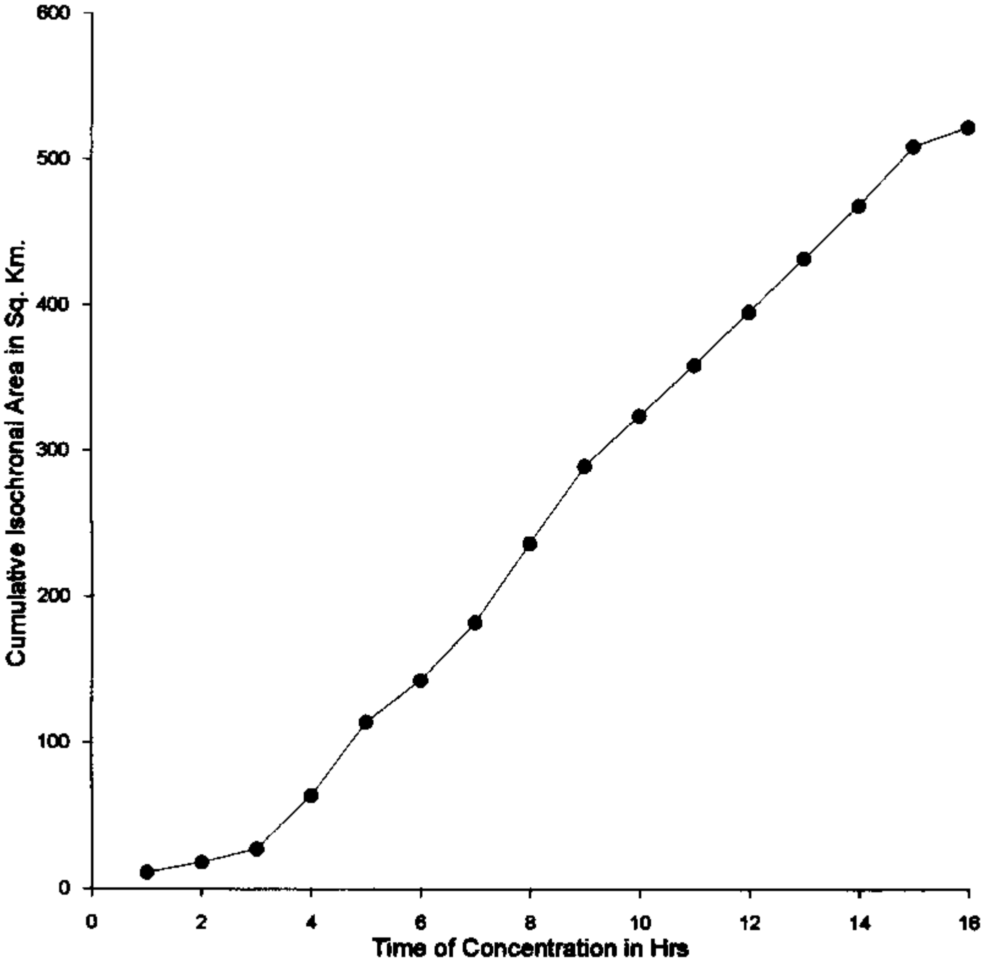

Figure 8 : Time-Area Diagram for Malaprabha Catchment Upto Khanapur

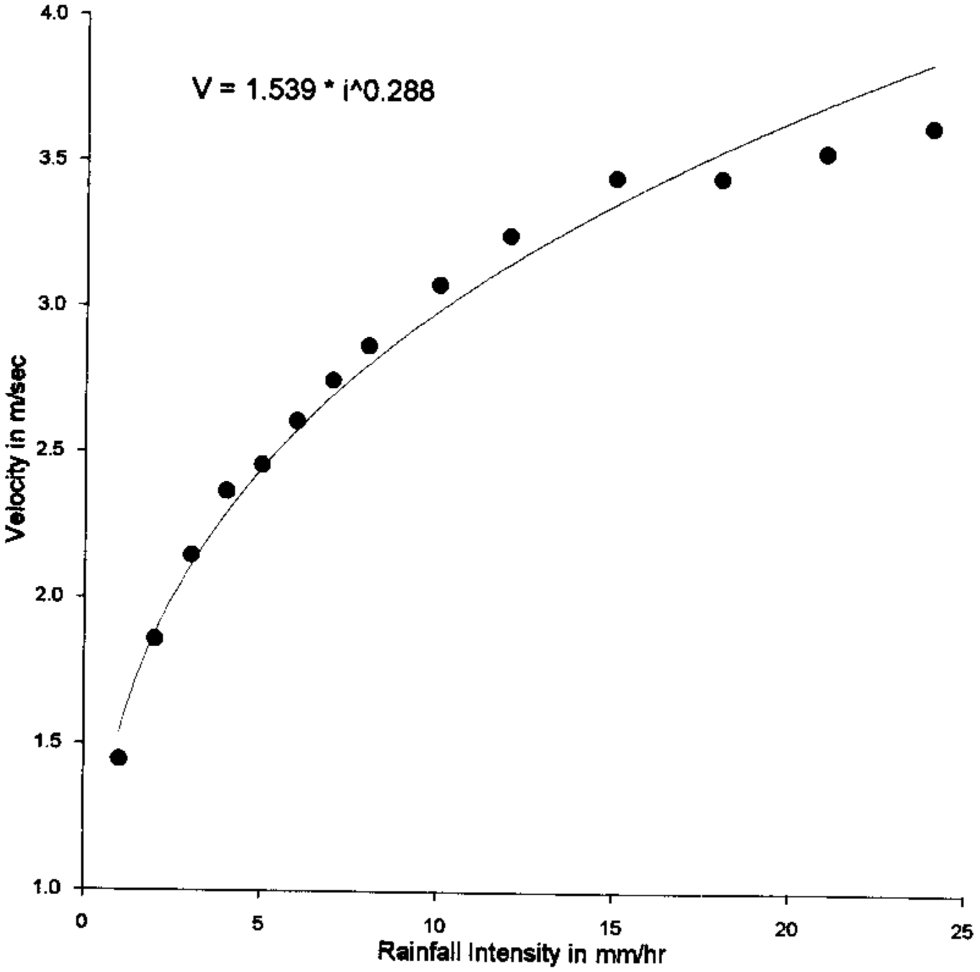

Figure 9 : Variation of Velocity with Rainfall Intensity for Barchi Nala Watershed

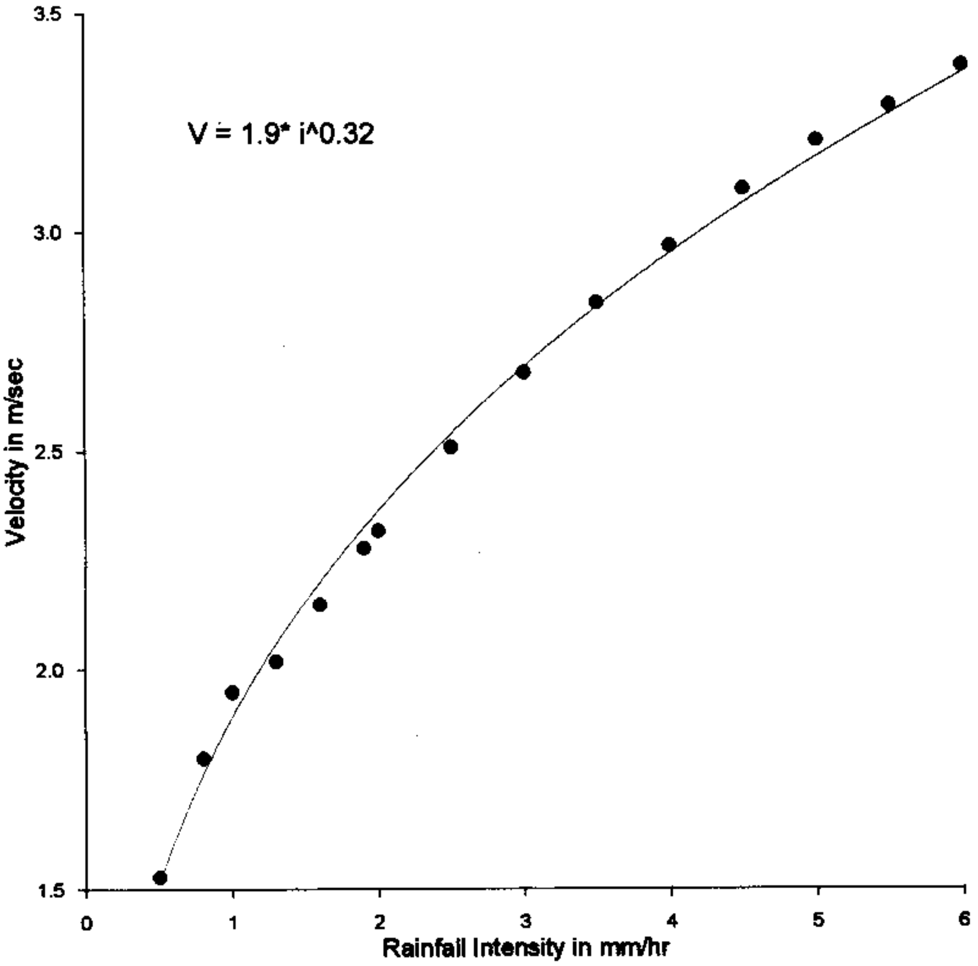

Figure 10 : Variation of Velocity with Rainfall Intensity for Malaprabha Upto Khanapur

Computation of Excess Rainfall Hyetograph

Hourly rainfall-runoff records were available only for the Barchi nala watershed. The events were separated, and the direct surface runoff depths were calculated after deducting the base flow from runoff records. These depths were used to calculate the uniform loss rate (phi index). This phi index was used to compute the rainfall excess hyetograph.

Results and Discussion

The methodology given in the previous section was used to simulate 10 rainfall-runoff events for Barchi nala watershed. A sample Output file has been shown in appendix I. Since hourly records were not available for Malaprabha catchment, the methodology was applied for 11 hypothetical events with assumed values of equilibrium velocity ranging from 0.5 to 3.0 m/sec.

For each event, the peak characteristics and the product of peak discharge and time to peak, given by the GIUH theory and that given by the GIUH based Clark model are tabulated in Table 3. The characteristics for the GIUH based Clark model are given for two computational time intervals (0.05 hr. and 1 hr.). The smaller computational time interval has been used to reduce the error due to discretisation in time domain.

From the table, it can be seen that the product of peak IUH characteristics calculated by GIUH based Clark model methodology is comparable with the product of peak characteristics of IUH obtained by GIUH approach ($Q_{pg}*T_{pg}$), which is a non-dimensional characteristic depending only on the catchment characteristics. This non-dimensional product is thus not dependent on storm characteristics and will be a constant for a catchment. The close proximity of this non-dimensional products between the two methods indicates that the GIUH based Clark model yields IUH with the correct peak characteristics. The results obtained using a smaller time interval of 0.05 hrs. is giving a better comparison. When the computational time interval is taken as 1 hr., the model yields IUH ordinates at 1 hr. interval. But, it is not necessary that the peak characteristics of IUH have to occur exactly at these time intervals. Thus, the differences in the peak characteristics are due to the coarse selection of time interval.

Table 3: Comparison of Peak Characteristics of GIUH and GIUH Based Clark Model IUH for Various Rainfall-Runoff Events

Catchment / Event No.	Equilibrium Velocity m/sec.	Peak Characteristics of GIUH			Peak Characteristics of GIUH based Clark Model – Computational Time Interval 0.05 Hrs.			Peak Characteristics of GIUH based Clark Model - Computational Time Interval 1.0 Hr.		
		Q_{pg}	T_{pg}	$Q_{pg}*T_{pg}$	Q_{pc}	T_{pc}	$Q_{pc}*T_{pc}$	Q_{pc}	T_{pc}	$Q_{pc}*T_{pc}$
Malaprabha										
1	0.50	2.44	32.27	78.79	2.52	25.90	65.30	2.48	26.00	64.46
2	0.75	3.67	21.47	78.79	3.73	17.20	64.23	3.70	17.00	62.92
3	1.00	4.89	16.10	78.79	4.98	12.90	64.27	4.90	13.00	63.72
4	1.25	6.11	12.90	78.79	6.18	10.40	64.01	6.15	10.00	61.52
5	1.50	7.33	10.75	78.79	7.40	8.60	63.65	7.20	9.00	64.81
6	1.75	8.55	9.22	78.79	8.62	7.40	63.76	8.60	7.00	60.18
7	2.00	9.77	8.06	78.79	9.83	6.40	63.42	9.83	6.00	58.99
8	2.25	10.99	7.17	78.79	11.05	5.80	63.54	10.72	6.00	64.33
9	2.50	12.21	6.45	78.79	12.3	5.20	63.96	12.16	5.00	60.82
10	2.75	13.44	5.86	78.79	13.52	4.70	63.53	13.00	5.00	65.02
11	3.00	14.66	5.38	78.79	14.73	4.30	63.36	14.61	4.00	58.45
Barchi										
1	2.53	2.29	1.35	3.08	2.30	1.20	2.76	2.19	1.00	2.19
2	3.02	2.74	1.12	3.08	2.75	1.00	2.75	2.53	1.00	2.53
3	2.50	2.27	1.36	3.08	2.27	1.30	2.84	2.19	1.00	2.19
4	1.90	1.72	1.79	3.08	1.72	1.60	2.76	1.53	2.00	3.06
5	2.38	2.16	1.43	3.08	2.17	1.30	2.82	2.10	1.00	2.10
6	2.62	2.38	1.30	3.08	2.38	1.10	2.74	2.25	1.00	2.25
7	2.49	2.26	1.37	3.08	2.26	1.30	2.83	2.18	1.00	2.18
8	2.01	1.82	1.69	3.08	1.83	1.50	2.83	1.59	2.00	3.19
9	2.56	2.32	1.33	3.08	2.33	1.20	2.79	2.22	1.00	2.22
10	3.83	3.48	0.89	3.08	3.48	0.80	2.79	3.04	1.00	3.04

The values of the peak velocity and GIUH based Clark model parameters for all the events for the two study areas have been tabulated in Table 4. The value for the ratio $R/(R+T_c)$ for each of the events is also given in the table. The variation of velocity and the Clark model parameters for each catchment are as shown in Figure 11 and 12.

Table 4 shows that the velocity, time of concentration and storage coefficient vary for each event. This is due to the variation in storm characteristics from event to event. So, it shows that this approach is capable of representing the non-linearity in the system caused due to the change in storm characteristics. It is well established, that the ratio,

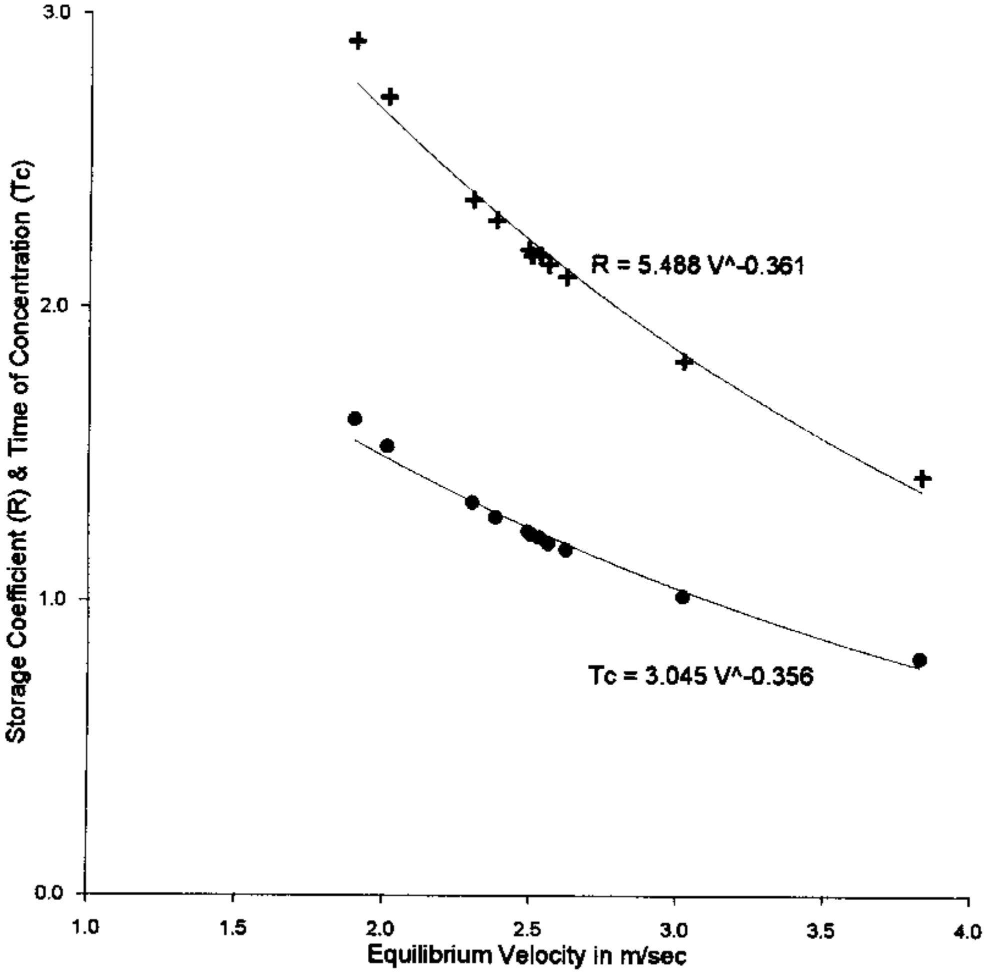

Figure 11: Variation of R and Tc with Equilibrium Velocity for Barchi Nala Catchment

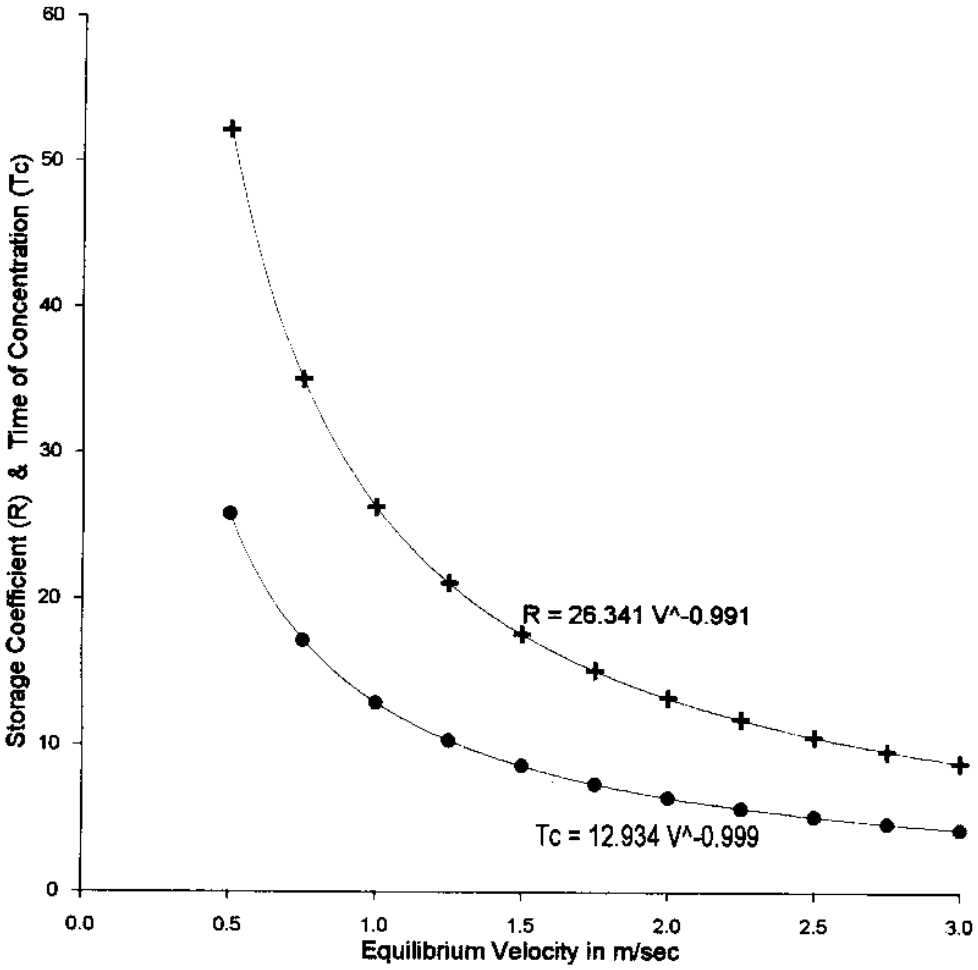

Figure 12: Variation of R and Tc With the Equilibrium Velocity for Malaprabha Catchment Upto Khanapur

R/(Tc+R), is a constant for each catchment and is also valid for the present study as shown in table 4. Once the model is applied for sufficient range of velocity variations, these plots (R-V and T_c-V) can be used for estimating model parameters (R and T_c) for other events, without using the model.

Table 4: GIUH Based Clark Model Parameters for Various Rainfall-Runoff Events for the Catchments

Catchment	Event No.	Velocity m/sec	Time of Concentration T_c Hrs	Storage Coefficient (R)	Ratio $R/(R+T_c)$
Malaprabha upto Khanapur	1	0.50	25.89	52.19	0.6684
	2	0.75	17.22	35.09	0.6708
	3	1.00	12.92	26.31	0.6707
	4	1.25	10.35	21.15	0.6714
	5	1.50	8.63	17.67	0.6720
	6	1.75	7.39	15.15	0.6720
	7	2.00	6.47	13.28	0.6725
	8	2.25	5.75	11.81	0.6724
	9	2.50	5.18	10.59	0.6718
	10	2.75	4.71	9.65	0.6723
	11	3.00	4.31	8.86	0.6725
Barchi Nala	1	2.53	1.22	2.18	0.6415
	2	3.02	1.02	1.82	0.6415
	3	2.50	1.23	2.18	0.6391
	4	1.90	1.62	2.91	0.6418
	5	2.38	1.29	2.30	0.6399
	6	2.62	1.18	2.11	0.6420
	7	2.49	1.24	2.20	0.6395
	8	2.01	1.53	2.72	0.6395
	9	2.56	1.20	2.15	0.6405
	10	3.83	0.81	1.43	0.6400

The unit hydrographs of 1 hr. duration for the two study areas have been derived from the IUH of the GIUH based Clark model. The peak characteristics of the unit hydrograph and the observed and computed direct surface runoff (DSRO) hydrograph are given in Table 5. The observed and computed direct surface runoff hydrographs for Barchi nala watershed for various events, are given in Figures 13 to 22. It can be seen that the observed and computed hydrographs are reasonably comparable for all events except events 1 and 2.

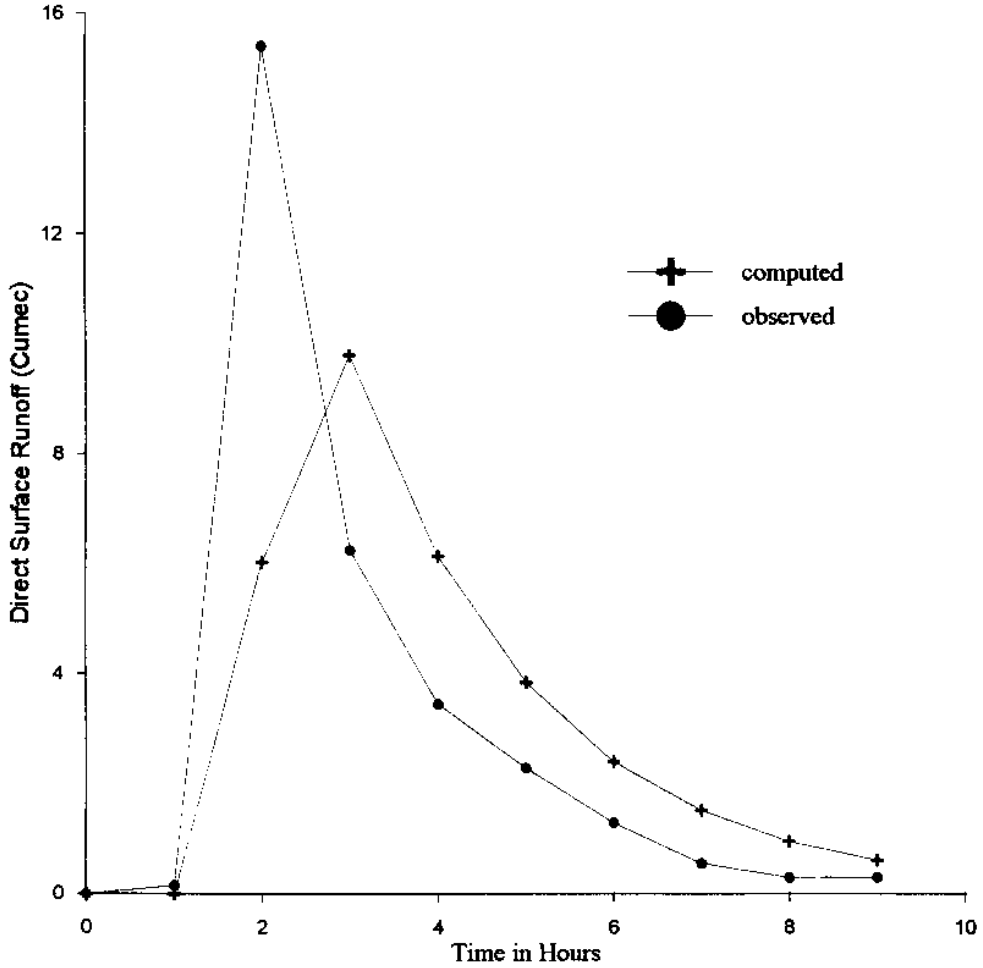

Figure 13 : Comaprison of Observed and Computed DSRO for Event 1 (Barchi Nala)

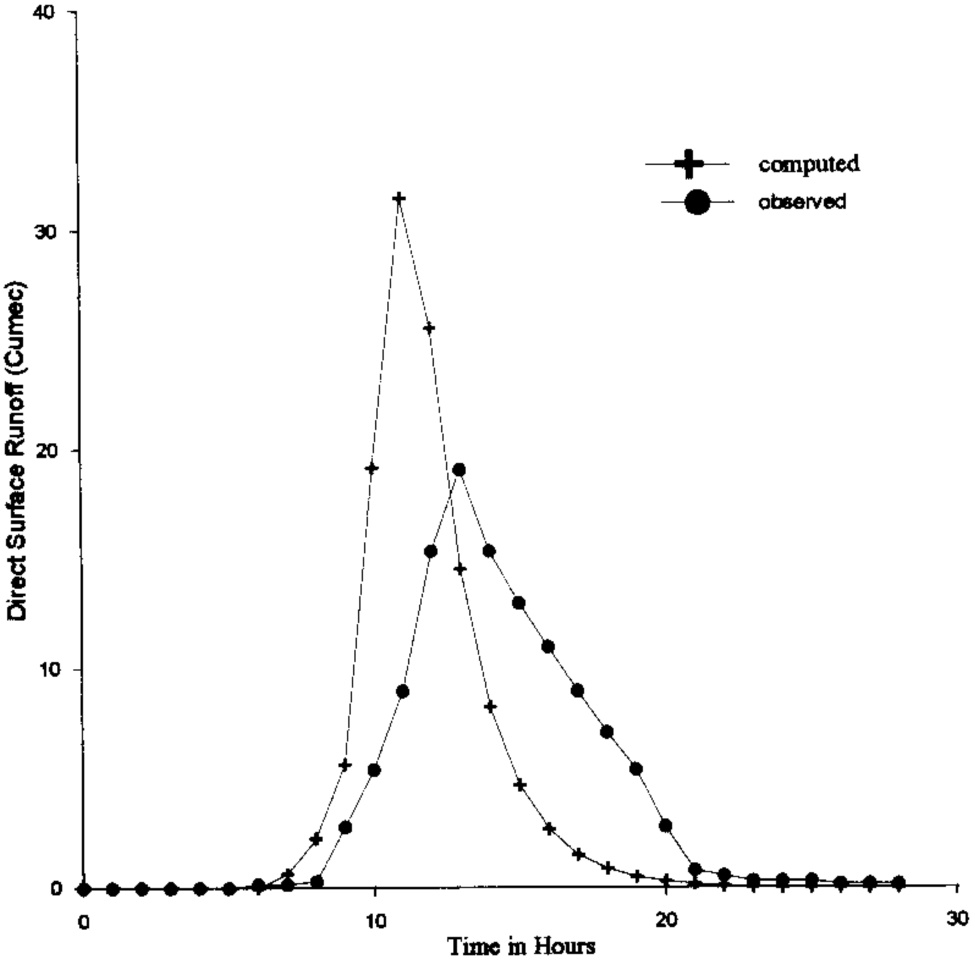

Figure 14 : Comparison of Observed and Computed DSRO for Event 2 (Barchi Nala)

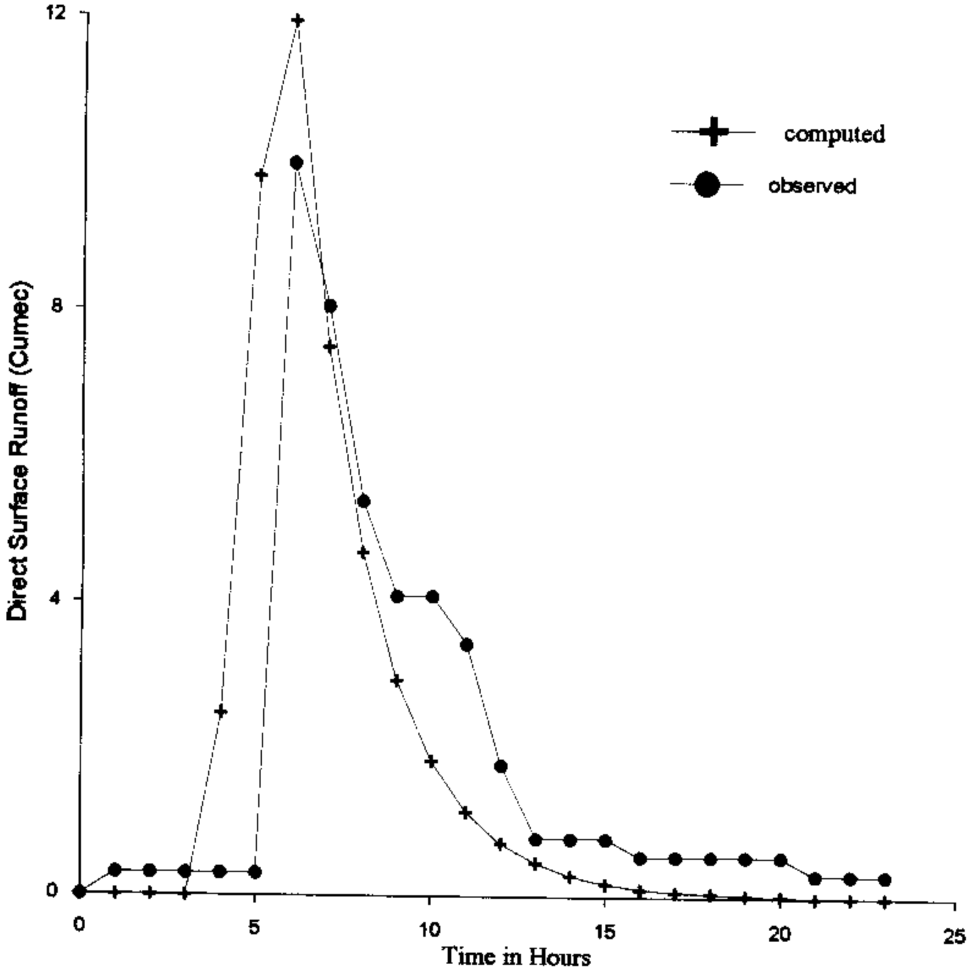

Figure 15 :Comparison of Observed and Computed DSRO for Event 3 (Barchi Nala)

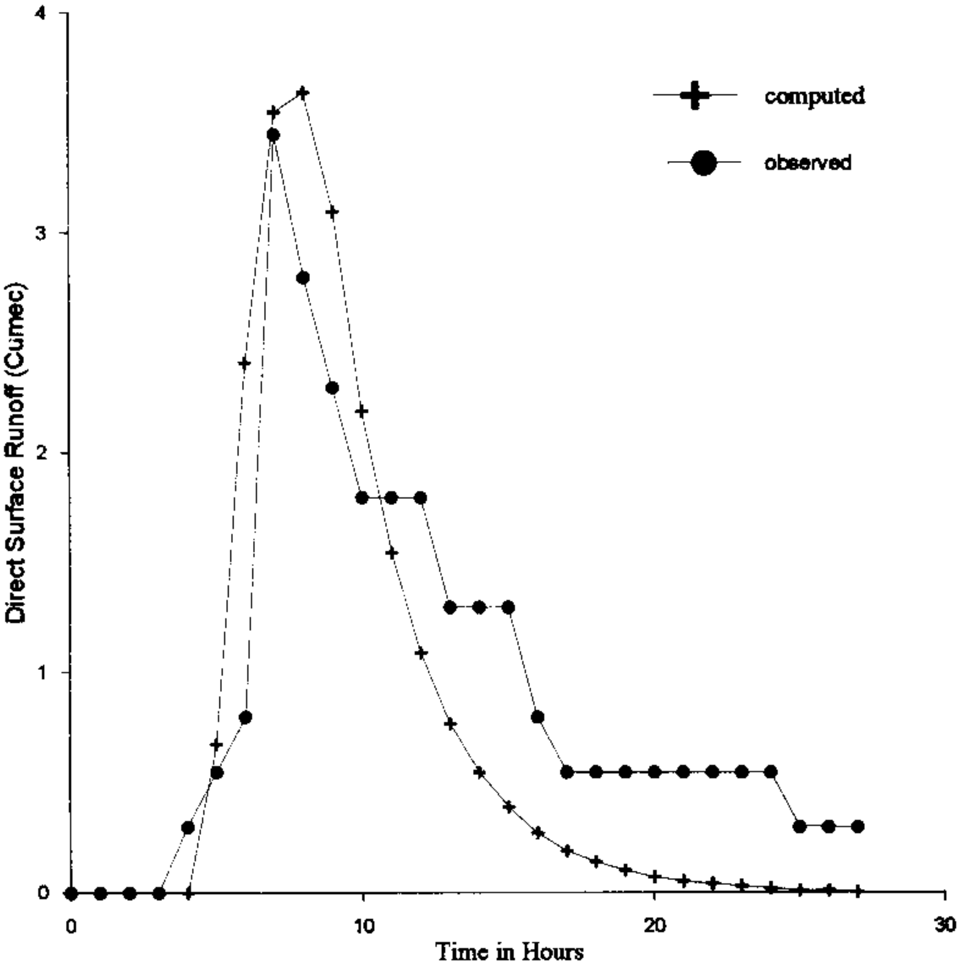

Figure 16 : Comparison of Observed and Computed DSRO for Event 4 (Barchi Nala)

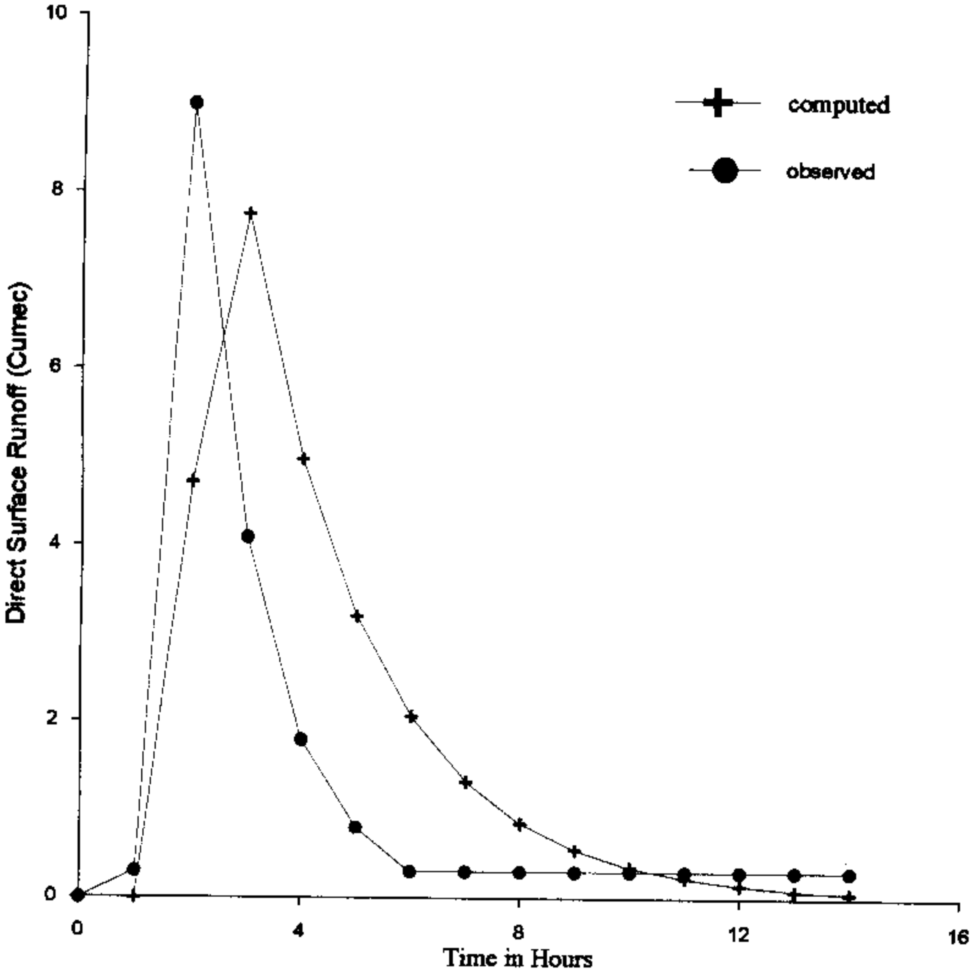

Figure 17: Comparison of Observed and Computed DSRO for Event 5 (Barchi Nala)

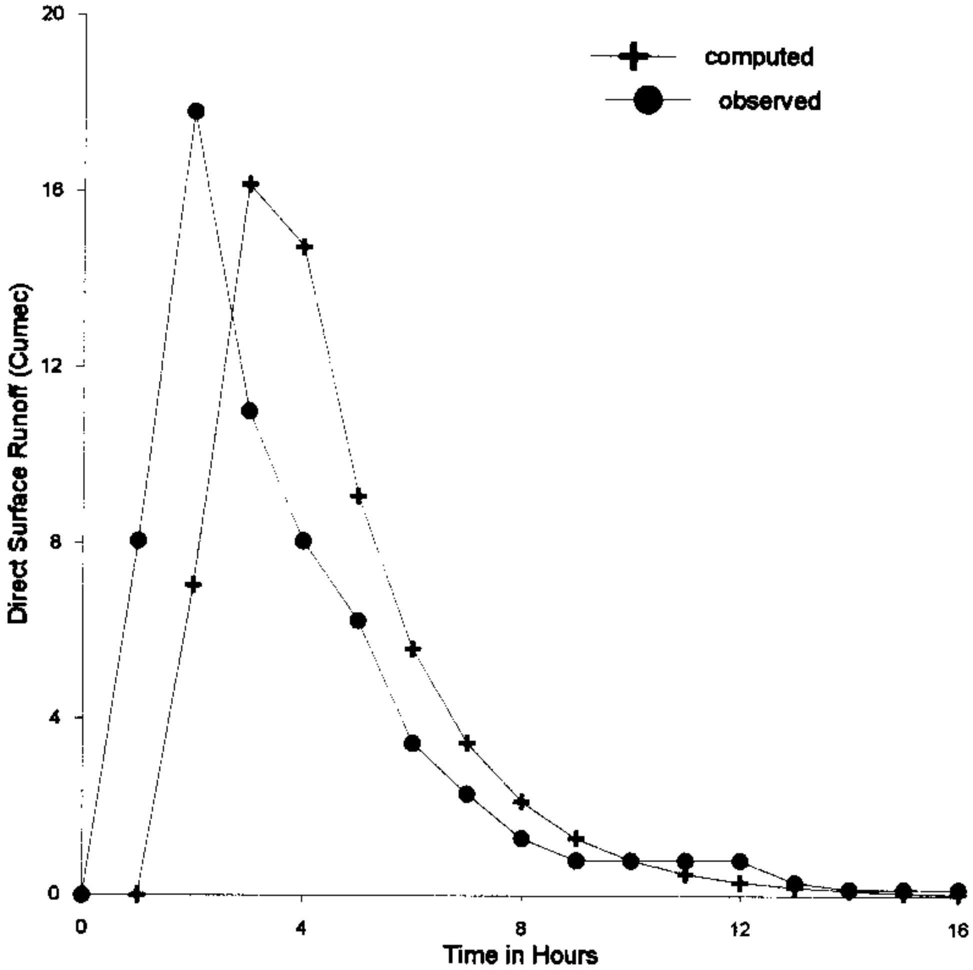

Figure 18: Comaprison of Observed and Computed DSRO for Event 6 (Barchi Nala)

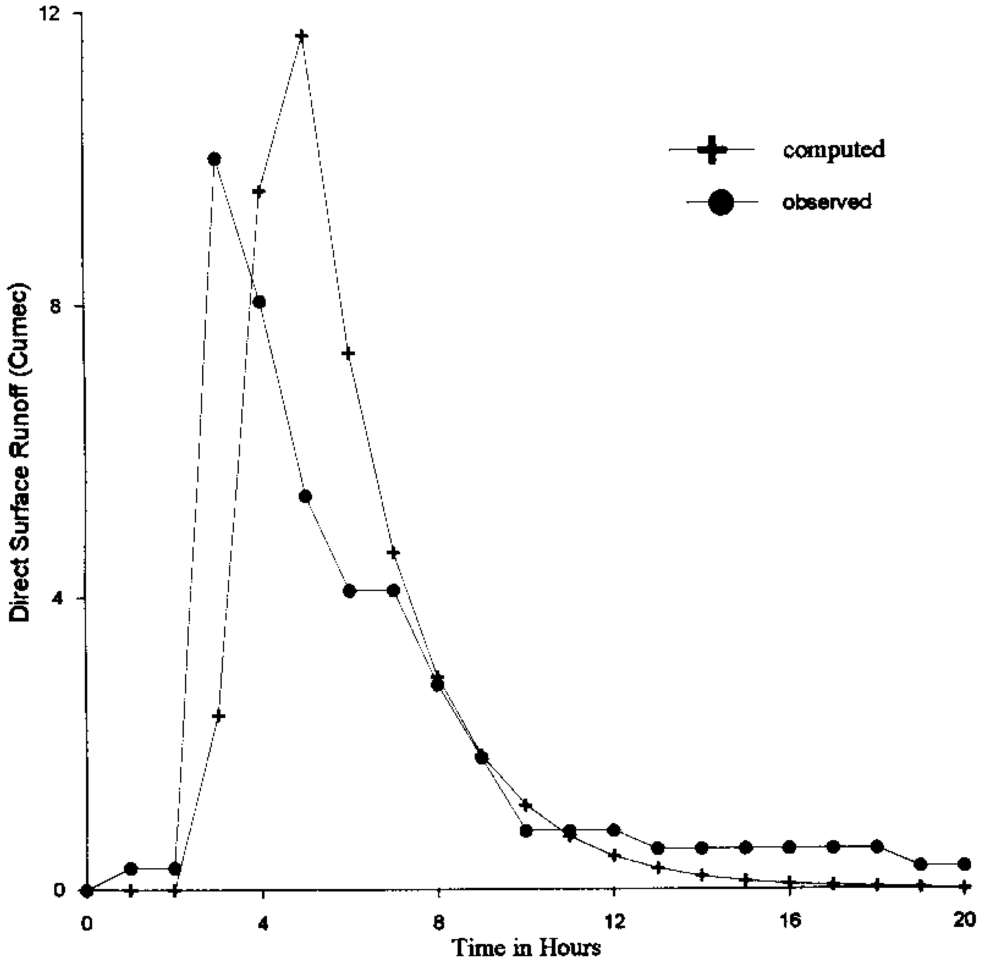

Figure 19: Comparison of Observed and Compted DSRO for Event 7 (Barchi Nala)

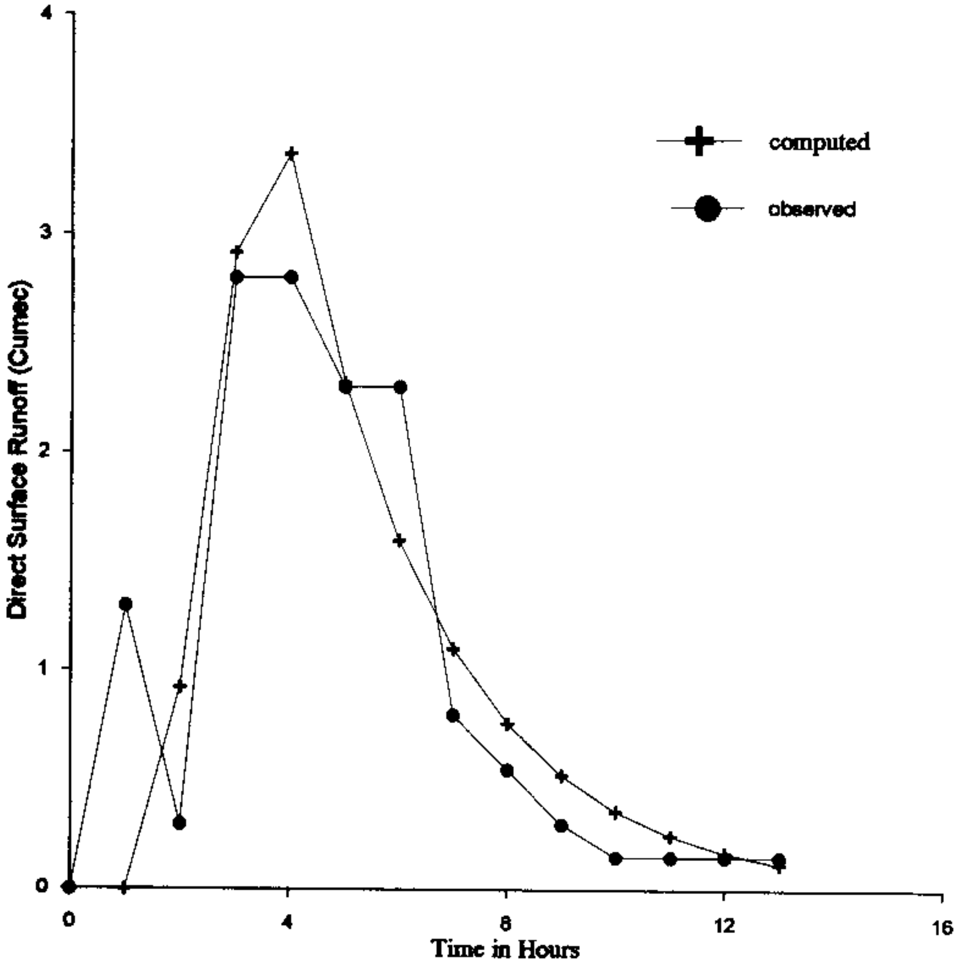

Figure 20 : Comparison of Observed and Computed DSRO for Event 8 (Barchi Nala)

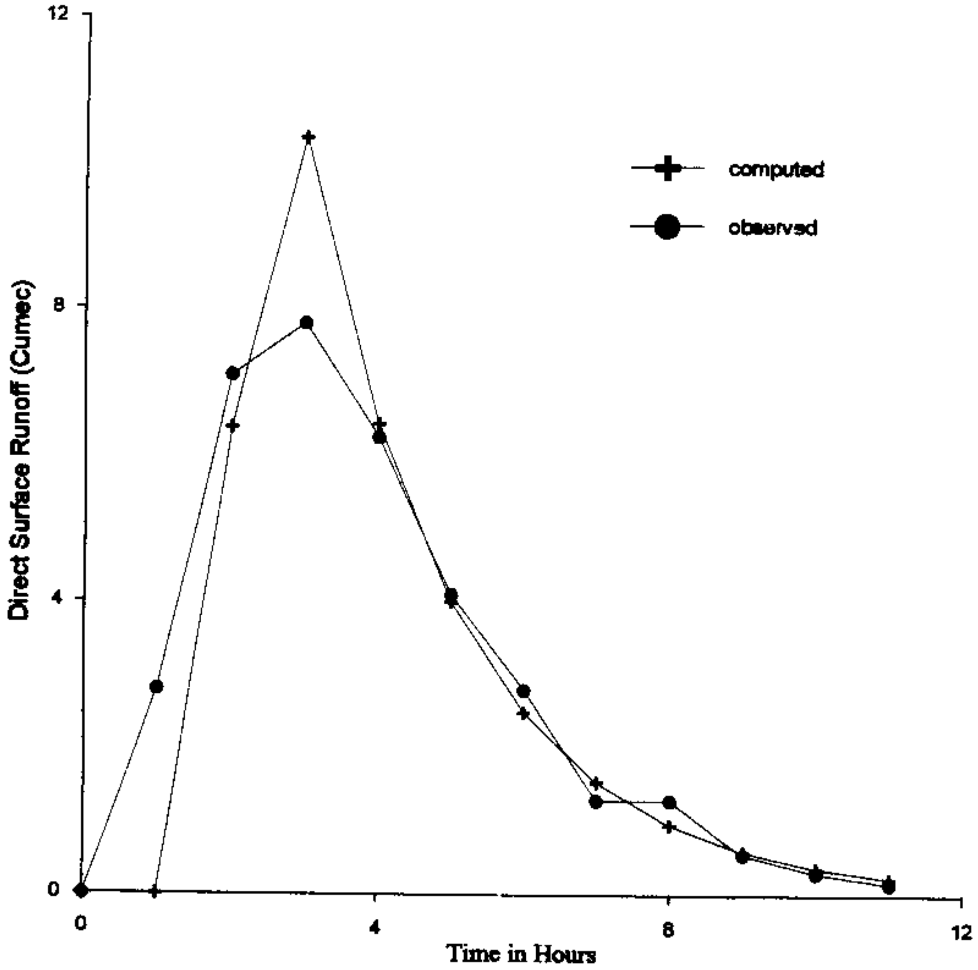

Figure 21: Comparison of Observed and Computed DSRO for Event 9 (Barchi Nala)

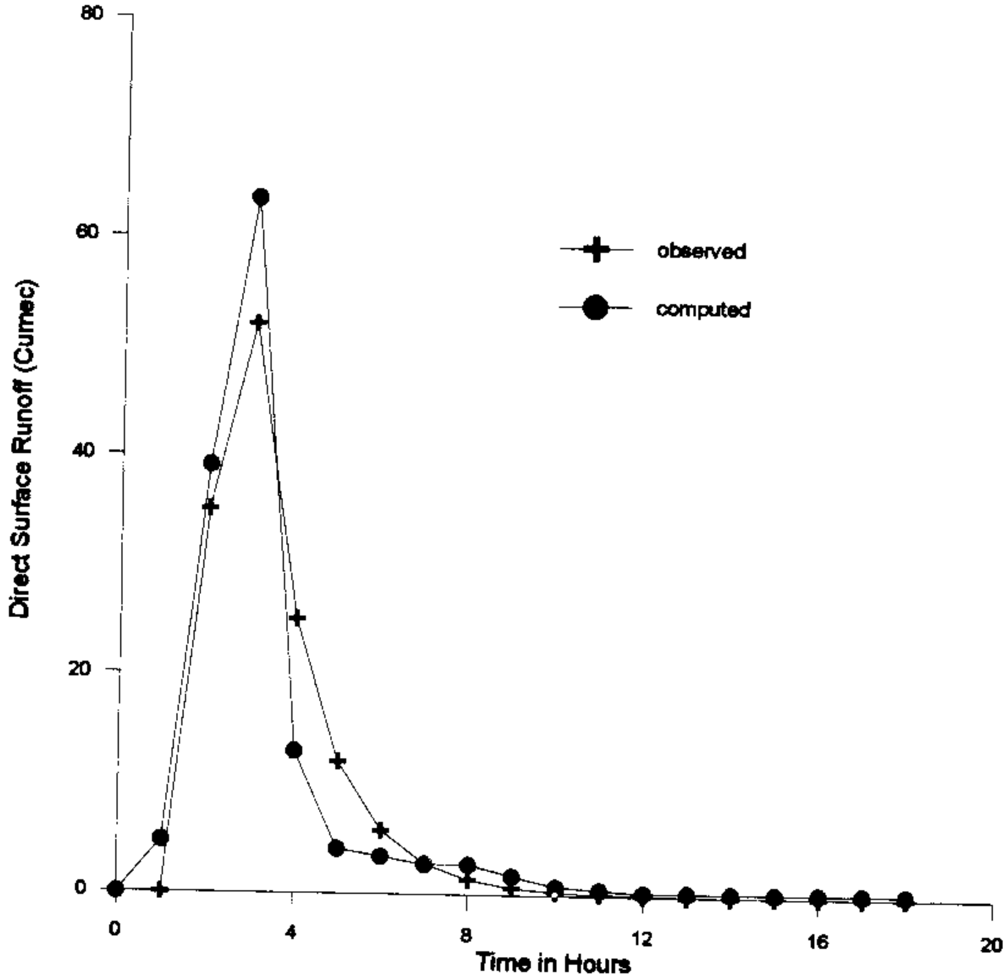

Figure 22: Comaprison of Observed and Computed DSRO for Event 10 (Barchi Nala)

Table 5: Peak Characteristics of GIUH Based Clark Model UH and Observed and Computed DSRO for the Catchments

Catchment / EventNo.	Peak Characteristics of UH		Peak Characteristics of DSRO			
	Peak Dis.	Time to Peak	Observed SRO		Estimated SRO	
			Qp	Tp	Qp	Tp
Malaprabh						
a	2.46	27.00			0.44	27.00
1	3.65	18.00	No obs. data	No obs. Data	2.77	18.00
2	4.81	14.00			10.10	14.00
3	6.01	11.00			27.59	11.00
4	7.00	10.00			61.27	10.00
5	8.32	8.00			125.51	8.00
6	9.48	7.00			229.02	7.00
7	10.29	7.00			377.00	7.00
8	11.62	6.00			617.70	6.00
9	12.36	6.00			920.66	6.00
10	13.83	5.00			1400.9	5.00
11						
Barchi						
1	1.78	2.00	15.40	2.00	9.80	3.00
2	1.98	2.00	19.10	13.00	31.50	11.00
3	1.78	2.00	10.00	6.00	11.90	6.00
4	1.30	3.00	3.50	7.00	3.60	8.00
5	1.72	2.00	9.00	2.00	7.80	3.00
6	1.82	2.00	17.80	2.00	16.20	3.00
7	1.77	2.00	10.00	3.00	11.70	5.00
8	1.35	3.00	2.80	3.00	3.40	4.00
9	1.80	2.00	7.80	3.00	10.30	3.00
10	2.25	2.00	63.50	3.00	52.00	3.00

CONCLUSIONS

Geomorphological parameters, rainfall-runoff records and equilibrium velocity values were used in this study to apply GIUH based Clark model to Barchi nala and Malaprabha upto Khanapur. A Geographical Information System, ILWIS was used to derive the geomorphological characteristics and preparation of time area diagram.

For the study, the historical rainfall-runoff records were not available, for Malaprabha catchment (upto Khanapur), to verify GIUH based Clark model approach. However, using assumed velocity values, the unit hydrograph ordinates were calculated using GIUH based Clark model considering the existing rainfall patterns in the basin.

The following conclusions have been drawn from the study:

- Various geomorphologic characteristics such as length of main stream, catchment area, bifurcation ratio, length ratio and area ratio have been evaluated using ILWIS GIS. The estimation of these parameters can be handled easily and more accurately using GIS system which otherwise is very tedious using manual methods.

- For the Barchi nala watershed, the computed and observed direct surface runoff hydrographs were found to be reasonably comparable. Since the watershed is small in size and steep in slope, the time of concentration and storage coefficient values are very small. This results in a sudden rise and quick attainment of peak discharge values for the watershed.

- The ratio $R/(R+T_c)$ has a unique value for each catchment. This ratio may therefore be computed for a catchment and subsequently used for employing simple Clark model also.

- For the GIUH approach, velocity is one of the important parameters. The GIUH based Clark model approach provides different unit hydrographs for different events considering the storm characteristics. This indicates that the methodology is capable of simulating the non-linear response to different events. However, this capability is limited in the sense that only the highest rainfall intensity block is used to get the equilibrium velocity.

- The greatest limitation of the equations suggested by Rodriguez-Iturbe and Valdes and subsequent modifications by various other authors is in respect of the absence of a well defined approach for estimation of the value of the kinematic parameter, ie., velocity. The peak discharge is estimated corresponding to the highest rainfall block. This methodology needs to be improved so as to consider the whole pattern of rainfall distribution for the estimation of peak velocity. However, despite the above deficiency, the model can be used with a fair degree of accuracy. The computation of rainfall excess hyetograph is also a weak link in this methodology, since phi-index method considers a uniform loss rate. Accurate estimation of rainfall excess hyetograph is necessary since the equilibrium velocity and the computed model parameters are greatly dependent on the maximum rainfall hyetograph block.

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