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UNCERTAINTY ANALYSIS OF GIUH BASED CLARK MODEL USING FIRST ORDER ANALYSIS FOR A CATCHMENT OF LOWER GODAVARI SUBZONE 3(f)

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PREFACE

The hydrologic models are complex collections of algorithms combined in such a way as to mathematically mimic some hydrologic system. Users of these models must recognize that uncertainty in the values of the input parameters of these models is one source of uncertainty in the simulations of the hydrologic variables. Parametric uncertainty refers to a lack of knowledge of the exact values for model parameters. Parametric uncertainty can produce considerable uncertainty in the results generated from a hydrologic model. Hydrologic models generally require point or single estimates for model parameters. As modellers we generally provide point estimates but we do so recognizing that we are not sure of the exact values of the parameters. If the uncertainty that exists in a model output due to parametric uncertainty is unacceptably large; then, the uncertainty analysis provides guidance for identifying the parameters which require better estimates. Whatever, resources are available for improved estimation of the parameters; then, those resources may be focused on the parameters which offer the best likelihood for improving the estimates of the model outputs. Further, uncertainty analysis of a modelling effort adds a degree of intellectual honesty to the effort that might otherwise be missing. The modeller recognises that uncertainty exists, and outlines the uncertainty in a quantitative way, which can be communicated to decision makers. Hence, the decision makers are not left with the incorrect impression that a particular result is certain to occur.

In this study, uncertainty analysis has been conducted for the geomorphological instantaneous unit hydrograph (GIUH) based Clark model developed at the National Institute of Hydrology, which enables evaluation of the Clark Model parameters using geomorphological characteristics of an ungauged catchment. The model has been applied for simulating the direct surface runoff (DSRO) hydrographs of the catchment defined by the bridge number 807 of the Lower Godavari Subzone 3 (f). The geomorphological parameters of the catchment which constitute input to this model have been evaluated using the GIS software, ILWIS. The DSRO hydrographs estimated by the GIUH approach have been compared with the observed DSRO hydrographs as well as with the DSRO hydrographs computed by the Nash model and the HEC-1 package. Performance of the GIUH model has been evaluated by employing some of the commonly used error functions. Degree of uncertainty associated with the parameters of the GIUH based Clark model has been quantified. The study has been carried out by Shri Rakesh Kumar, Shri R. D. Singh, Dr. Chandranath Chatterjee, Shri A. K. Lohani and Dr. Sanjay Kumar, Scientists of the Institute as per work programme of the Hydrologic Design Division. Technical assistance has been provided by Shri R.K. Nema, SRA. It is expected that the GIS technique for evaluation of the geomorphological characteristics and the methodology of application of the GIUH based Clark model presented in this report will serve as a suitable procedure for estimation of floods of the ungauged catchments; and the geomorphological parameters of the catchment which have been identified for causing higher degree of unceratinty in derivation of unit hydrograph using the GIUH based Clark model will be evaluated with greater precision in the future flood estimation studies based on the GIUH approach.

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ABSTRACT

Uncertainty analysis outlines the inability to exactly model a real world hydrologic situation even if the best possible estimates of the input parameters of the model are utilized. An added complication with most of the hydrologic models is that in general these models are structured with several uncertain input parameters. The sources of uncertainty in model output are model structure itself and the uncertainty associated with the parameters of the model. Parametric uncertainty refers to a lack of knowledge of the exact values for model parameters. Parametric uncertainty can produce considerable uncertainty in the results generated from a hydrologic model. Hydrologic models generally require point or single estimates for model parameters. As modellers we generally provide point estimates but we do so recognising that we are not sure of the exact values of the parameters. Determining the uncertainty to be assigned to input parameters is one of major hurdles that must be addressed in the overall evaluation of uncertainty associated with hydrologic modelling. Hence, a single best estimate or expected value for each of the parameters should be obtained. Limits on parameters and suggested ranges of parameter values should be investigated. If the parameter is a physically measurable parameter, then the range of its values reported in literature and its variability should be examined with respect to the actual value of the parameter being utilised in a particular modelling study.

In this study, uncertainty analysis has been carried out for the parameters of the mathematical model developed at the National Institute of Hydrology for estimation of the Clark model parameters using the geomorphological characteristics of an ungauged catchment. The model has been applied for simulation of the direct surface runoff (DSRO) hydrographs of the catchment defined by bridge number 807 of the Lower Godavari Subzone 3 (f). The geomorphological parameters of the catchment have been evaluated using the GIS package, Integrated Land and Water Information System (ILWIS). The direct surface runoff hydrographs estimated by the GIUH approach have been compared with the observed direct surface runoff hydrographs as well as with the DSRO hydrographs simulated by the Nash model and the HEC-1 package. The performance of the GIUH model has also been evaluated by employing some of the error functions viz. (i) efficiency (EFF), (ii) absolute average error (AAE), (iii) root mean square error (RMSE), (iv) average error in volume (AEV), (v) percentage error in peak (PEP) and (vi) percentage error in time to peak (PETP) computed based on the observed and the simulated DSRO hydrographs. It is observed that the DSRO hydrographs computed by the GIUH based Clark model approach, which simulates the DSRO hydrographs of the catchment considering it to be ungauged, compare reasonably well with the observed and the simulated DSRO hydrographs.

For carrying out the uncertainty analysis, the geomorphological parameters viz. length ratio (R_L), length of the highest order stream (L_Ω), length of the main stream (L), and the velocity parameter (V) apart from the aforementioned geomorphological parameters, have been considered. Relative sensitivity analysis has been conducted for identifying the parameters of the GIUH based Clark model, which significantly affect peak of the unit hydrograph on the basis of their relative sensitivity coefficients. Uncertainty analysis has been carried out by first order analysis (FOA). Also, upper and lower 95% confidence limits for the peak of the unit hydrograph derived by the GIUH based Clark model have been computed. Uncertainty analysis has been carried out considering the following cases.

(i) Case I – Considering the uncertainty associated with length ratio (R_L), length of the highest order stream (L_Ω), length of the main stream (L) and velocity (V),

(ii) Case II - Considering the uncertainty associated with length ratio (R_L), length of the highest order stream (L_Ω) and Length of the main stream (L), and

(iii) Case III- Considering the uncertainty associated with length ratio (R_L) and length of the highest order stream (L_Ω).

As per Case-I, the uncertainty in the velocity parameter (V) leads to 72.7% uncertainty in peak of the unit hydrograph and it emerges to be the biggest contributor to the uncertainty in estimation of peak of the unit hydrograph. The uncertainty in parameters L_Ω, R_L and L contribute to 15.3%, 8.4% and 3.6% uncertainty in the peak of the unit hydrograph respectively. Hence, the value of the velocity parameter (V) needs to be computed with the highest precision for accurate estimation of the peak of the unit hydrograph derived by the GIUH based Clark model. As uncertainty in L_Ω and R_L, also leads to 15.3% and 8.4% uncertainty in the peak of the unit hydrograph; therefore, effort should be made to estimate these parameters accurately, as well.

As per Case-II, when the three physically measurable geomorphological parameters, viz. R_L, L_Ω and L are considered; the uncertainty in length of the highest order stream of the catchment (L_Ω) leads to 56.0% uncertainty in peak of the unit hydrograph and it emerges to be the biggest contributor to the uncertainty in estimation of peak of the unit hydrograph. The uncertainty in parameters R_L and L contributes to 30.8%, 13.2% uncertainty in the peak of the unit hydrograph respectively. Hence, the values of L_Ω needs to be measured with precision for accurate estimation of the peak of the unit hydrograph derived by the GIUH based Clark model. As uncertainty in R_L leads to 30.8% uncertainty in the peak of the unit hydrograph; therefore, effort should be made to estimate the parameter R_L also as accurately as possible.

As per Case-III, when the two parameters, viz. R_L and L_Ω are considered; the uncertainty in length of the highest order stream of the catchment (L_Ω) leads to 64.5% uncertainty in peak of the unit hydrograph and it emerges to be the biggest contributor to the uncertainty in estimation of peak of the unit hydrograph. The uncertainty in parameter R_L contributes to 35.5% uncertainty in the peak of the unit hydrograph. Hence, the values of both of these geomorphological parameters, L_Ω and R_L need to be precisely measured for accurate estimation of the peak of the unit hydrograph derived by the GIUH based Clark model.

The confidence intervals (CIs) i.e. the intervals which contain the true value of the model output with the indicated degree of confidence or probability have been computed for the 95% confidence level for the three cases assuming that peak of the unit hydrograph is normally distributed. Using the GIUH based Clark model, the actual peak of the unit hydrograph and the time to peak have been estimated as 46.37 cumec and 5 hours respectively. For this peak of the unit hydrograph, the lower and upper 95% confidence limits for Case-I have been computed as 35.33 cumec and 57.41 cumec respectively. The lower and upper 95% confidence limits for Case-II have been computed as 40.60 cumec and 52.14 cumec respectively. The lower and upper 95% confidence limits for Case-III have been computed as 40.99 cumec and 51.75 cumec respectively.

The geomorphological parameters which contribute to higher degree of unceratinty in derivation of unit hydrograph using the GIUH based Clark model as outlined above, are to be estimated more precisely for reducing the uncertainty associated with the flood estimates computed by the GIUH based Clark model. Also, in order to decrease or increase upper and lower confidence limits, the parameters leading to greater uncertainty in the peak of the unit hydrograph need to be estimated more accurately.

1.0 INTRODUCTION

Hydrologists are mainly concerned with evaluation of catchment response for planning, development and operation of various water resources schemes. Wherever, stream gauging is being carried out, such information may be generated utilizing the observed data. Therefore, streamflow synthesis from ungauged catchments has been recognized as one of the important areas of research in the sphere of surface water hydrology. For this purpose, a number of simple techniques involving the use of empirical relationships for computation of the parameters of conceptual models such as synthetic unit hydrographs, or some basic characteristics of streamflow hydrographs such as peak discharge, time to peak and duration of unit hydrograph etc. were developed. Presently, there are a number of well established conceptual or physically based modelling approaches which have been employed for the purpose of simulation of rainfall-runoff process of the various catchments. For application of all such techniques a certain amount of historical data are required. However, due to inadequate stream gauging network availability in most of the Indian catchments, particularly for small catchments it becomes very difficult for such techniques to be directly applicable. In such situations of non availability of data or very poor data availability, the options available are, either to go for regionalization of parameters based on the data available for the gauged catchments in nearby hydrometeorologically similar regions or by using the morphological details available for the ungauged catchments for modelling their hydrological response.

A large number of regional relationships have been developed by many investigators relating either the parameters of unit hydrograph (UH) or instantaneous unit hydrograph (IUH) models with physiographic and climatologic characteristics. Regionalisation of the parameters is, however, a very tedious task to accomplish since the hydrological behaviour of many nearby catchments have to be ascertained before being confident about the values of the parameters. These conventional approaches which are in vogue for estimation of design floods require rainfall-runoff records and the model parameters need to be updated from time to time. Also, in a developing country like India, it is not possible to set up gauging stations for observation of the required data at a large number of sites particularly for the small to moderate size basins because of high cost involved in it. The geomorphological techniques have recently been advanced for hydrograph synthesis, adding a new dimension to hydrologic simulations.

Global atmospheric changes have been responsible for bringing about changes in rainfall patterns. In addition to these, landuse changes within the catchment can have significant impact on runoff characteristics. Thus linking of the geomorphologic parameters with the hydrologic characteristics of the catchment can provide a simple way to understand the hydrologic behaviour of different catchments, particularly the ungauged ones (Bhaskar et al., 1997). As a first step in the direction of using geomorphologic characteristics with the conviction that the search for a theoretical coupling of quantitative geomorphology and hydrology is an area which will provide some of the most exiting and basic developments of hydrology in the future, the concept of Geomorphologic Instantaneous Unit Hydrograph (GIUH) was introduced. The GIUH approach has many advantages over the regionalization techniques as it avoids the requirement of flow data and computations in the neighbouring gauged catchments in the region and updating of the parameters.

The GIUH technique, though appears to be tempting to the practitioners for its use in areas of inadequate or no-data availability situations, it is very difficult if needed to be applied without making a few assumptions. GIUH approach is getting popular because of its direct application to an ungauged catchment without going for tedious method of regionalisation of UH; wherein, the data of storm events for a number of gauged catchments are required to be analysed. In application of GIUH approach, some of the important geomorphological parameters are required to be derived from the toposheets. It is extremely difficult for the user to derive the geomorphological parameters from toposheets, manually. Thus, it discourages the users from adopting GIUH approach. But, now a days geographical information system (GIS) software like ILWIS, ERDAS, ARC/INFO and GRASS etc. are available for derivation of these characteristics in a simplified manner and the GIUH approach may be advantageously applied for estimation and prediction of flood hydrographs.

In GIUH based approach, a unifying synthesis of the hydrological response of a catchment to surface runoff is attempted by linking the instantaneous unit hydrograph (IUH) with the geomorphological parameters of a basin. Equations of general character are derived which express the IUH as a function of Horton's numbers i.e. area ratio (R_a), bifurcation ratio (R_b) and length ratio (R_l) (Strahler, 1957); an internal scale parameter L_W denoting the length of highest order stream; and the peak velocity of streamflow V expected during the storm. The IUH is time varying in character for different storms. The geomorphological theory of unit hydrograph (GIUH) was originated by Rodriguez-Iturbe and Valdes (1979), who rationally interpreted the runoff hydrograph in the frame work of travel time distribution explicitly accounting for geopmorphological stuructre of a basin.

One advantage of the geomorphic instantaenous unit hydrograph (GIUH) approach is the potential of deriving the UH using only the information obtainable from topographic maps or remote sensing, possibly linked with geographic information system (GIS) and digital elevation model (DEM). The input to a 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 provide a digital representation of watershed characterisation used in hydrologic modelling. Hydrologic applications of GIS have ranged from synthesis and characterization of hydrologic tendencies to prediction of response to hydrologic events (Tao and Kouwen,1989). A GIS can provide the basis for hydrologic modelling of ungauged catchments and for studying the hydrologic impact of physical changes within a catchment. The integration of GIS into hydrologic models follows one of the two approaches (a) to develop hydrologic models that operate within a GIS framework (Moore et al.,1987), (b) to develop GIS techniques that partially parameterize existing hydrologic models (Deroo et al.,1989).

An approach which couples the parameters of the Clark model of instantaneous unit hydrograph derivation (Clark, 1945) with the gemogrphologic instantaneous unit hydrograph approach has been developed at the National Institute of Hydrology. The uncertainty in the estimation of the geomorphological parameters of the aforesaid GIUH model can lead to uncertainty in the flood estimates simulated by the model. Hence, there is a need to quantify the uncertainty associated with the input parameters of the GIUH based Clark model.

The uncertainty in the simulation of hydrological variables generally results due to the uncertainty associated with the values of the input parameters of the model and the model structure itself. Model uncertainty has to do with whether or not the model being used actually reflects the processes that are occurring in the field. To a certain degree the models are an approximation to reality and do not duplicate the real world. Different models tend to produce better results in different situations. Model uncertainty has to do with our inability to exactly model a real world hydrologic situation even if we have the best possible estimates for the parameters of the model.

One axiom of stochastic processes is that any function of a random variable is itself a random variable. Thus if any of the variables in input or parameters ($\underline{I}$ and/or $\underline{P}$) are uncertain and known only in a probabilistic sense, then the output ($\underline{O}$) is also uncertain and can be known only in a probabilistic sense. In the context of hydrologic modelling it means that if we are uncertain about $\underline{I}$ or $\underline{P}$, then we are uncertain about $\underline{O}$ as well. Uncertainty is transferred from the inputs to the outputs. An added complication with hydrologic models is that in general there are several uncertain parameters. We must be sure in any uncertainty analysis dealing with more than one variable that we do not violate relationships that exist among the input parameters. If parameters tend to vary together in real life, then we must preserve this joint variability structure in our uncertainty analysis.

While conducting the uncertainty analysis, often the uncertainty we arrive at is surprisingly and disturbingly large. The uncertainty we have been dealing with is parametric uncertainty. Parametric uncertainty refers to a lack of knowledge of the exact values for model parameters. As has been shown, parametric uncertainty can produce considerable uncertainty in the results generated from a hydrologic model. Hydrologic models generally require point or single estimates for model parameters. As modellers we generally provide point estimates but we do so recognising that we are not sure of the exact values of the parameters.

If the uncertainty that exists in a model output due to parametric uncertainty is unacceptably large, the uncertainty analysis will provide guidance as to which parameters require better estimates (less uncertainty). Whatever resources are available for improved estimation can then be focused on those parameters that offer the best likelihood for improving the estimates of the model outputs. An uncertainty analysis of a modelling effort adds a degree of intellectual honesty to the effort that might otherwise be missing. The modeller is recognizing that uncertainty exists and is recognizing it in a quantitative way that can be communicated to decision makers. The decision maker is not left with the incorrect impression that a particular result is certain to occur.

In this study, the geomorphological characteristics of the catchment defined by the bridge number 807 of the Lower Godavari Subzone 3(f) have been evaluated using the GIS software, ILWIS and the Clark model based GIUH has been used for simulation of the flood hydrographs for the storm events of the catchment. Uncertainty analysis has been carried out for quantifying the uncertainty associated with the parameters of the model.

2.0 REVIEW OF LITERATURE

The problem of transformation of rainfall into runoff has been a subject of scientific investigations throughout the evolution of the subject of hydrology. A number of investigators have tried to relate runoff with the different characteristics which affect it. In this regard, the simplest theory proposes to multiply the rainfall with some factor (called the runoff coefficient) to get the runoff. A better way to transform rainfall into runoff is to apply conceptual models in which the various interrelated hydrological processes are conceptualized. More sophisticated procedures are also evolved which are based on the physical concept of the process and try to model this hydrological phenomenon on the basis of physical laws governing them. Many more factors, besides the accuracy, e.g., the availability of data, computing facility, time, resources etc. govern the applicability of a model. The search for suitable models for different conditions still continues and thus more and more mathematical models are being suggested. A review of literature on the event based conceptual models as well as models for simulation of runoff for the ungauged catchments and uncertainty analysis as described in the current literature is given below.

2.1 Event Based Conceptual Models

The approaches utilized to develop linear conceptual models of rainfall-runoff relationship may be classified into three groups. The first group employs a differential equation that supposedly governs the operation of a specified system (Kulandaiswamy, 1964; Chow 1964; Shen, 1965; Chaudhry, 1976; Jackson, 1968; Chow and Kulandaiswamy, 1971, 1982; Singh and Mc Cann, 1979; Mc Cann and Singh, 1980; Te and Kay, 1983). The second group utilizes an arrangement of the so-called conceptual elements, including linear channels and linear reservoirs (Nash, 1957; Dooge, 1959, 1977; Chow, 1964; S Bravo et.al., 1970; Maddaus and Eagleson, 1969; O'Meara, 1968; Singh and Mc Cann, 1980). The third group makes some hypothesis about rainfall-runoff relationship more or less on intuitive grounds (Lienhard, 1964, 1972).

In the second category of the conceptual models Clark (1945) suggested that the unit hydrograph for a watershed due to instantaneous rainfall can be determined by routing its Time-Area-Concentration (TAC) curve through a single linear reservoir. Physically, it is equivalent to Zoch (1934) Model, in which the concept of instantaneous unit hydrograph (IUH) is replaced by one of unit hydrograph. O'Kelly (1955) defined the TAC curve by an isosceles triangle and routed it through a linear reservoir to produce the instantaneous unit hydrograph for the watershed. Thus, O'Kelly model is equivalent to Clark's model except for the definition of TAC curve.

Nash (1957) developed a model based on a cascade of equal linear reservoirs for derivation of the IUH for a natural watershed. This is one of the most popular and frequently used.models in applied hydrology.

Dooge (1959) developed a general unit hydrograph theory, which embraced all previous models as its special cases. The three elements : TAC curves, linear channel and linear reservoir were included in the theory. The basic premise of the Dooge model is that a watershed can be represented by some combination of linear channels and reservoirs. The watershed is drained by a network of channels composed of a complex network of linear channels and linear reservoirs placed in series.

2.2 Models for Ungauged Catchments

The parameters of the models reviewed in previous section are generally calibrated based on the analysis of rainfall-runoff data for gauged catchments. However, these models cannot be calibrated for those catchments which lack such data. Consequently, the parameters of those models for ungauged catchments may be determined from the regional relationships developed by correlating the model parameters with physically measurable catchment characteristics of the gauged catchments. Optimization is one of the most widely used techniques available to calibrate the model for gauged catchments. Frequently, the model parameters are optimized for some selected rainfall-runoff events over a given watershed, using a suitable optimization procedure. The optimized parameter values are then utilized in the model to predict runoff for the rainfall events of interest not used in the calibration process. This approach is obviously not applicable to ungauged watersheds. Further, it has other shortcomings as the optimized parameters can best represent the watershed only for the events used in the calibration. The optimized values change with the change in the events. Also, the extensive amount of data required for calibration is normally lacking and thus prove prohibitive in the widespread use of the model.

The other approach attempts to establish relationships between model parameters and physically measurable watershed characteristics. These relationships are then assumed to hold for ungauged watersheds having similar hydrologic characteristics. Rainfall-runoff relationships for ungauged watersheds have been developed along two complimentary lines: (i) Empirical equations have been developed to relate some individual runoff hydrograph characteristics to watershed characteristics, (ii) Procedures have been developed to synthesize the entire runoff hydrograph from watershed characteristics. Some of these models are reviewed here under.

Bernard (1935) model is perhaps the first attempt to synthesize the unit hydrograph (UH) from watershed characteristics. It assumes that the peak of the UH is immensely proportional to the time of concentration, which in turn is assumed to be proportional to a watershed factor. A distribution graph establishes relation between the effective percentage area contributing and the watershed factor for different days of the storm.

Snyder (1938) established a set of formulae relating the physical geometry of the watershed to three basic parameters of the unit hydrograph. Mc Carthy (1938) related three parameters of 6-hour UH, including the time of rise, the peak discharge, and the base length, to watershed characteristics such as area, overland slopes expressed as the average slope of the hypsometric curve and stream pattern. Taylor and Schwarz (1952), in addition to the watershed characteristics employed by Snyder (1938), introduced the average slope of the main channel. The method of hydrograph synthesis employed by the Soil Conservation Service (SCS) (1971), U.S. Deptt. of Agriculture, uses an average dimensionless hydrograph derived from an analysis of a large number of natural UHs for watersheds varying widely in size and geographical locations.

As mentioned earlier, the Clark model involves determination of the TAC diagram and the storage coefficient. This storage coefficient has been related with the catchment characteristics. The time of concentration was considered to equal the time interval between the end of rain and the point of contraflexure of the hydrograph recession limb. This time base was measured from the recorded floods and not related to watershed characteristics.

Nash (1960) model has two parameters n and K. Nash showed that these parameters were related to the first and second moments of the IUH about the origin. These moments were then correlated empirically with watershed characteristics.

Earlier in India, the design discharges for very small and medium catchments were used to be calculated by well known empirical formulae viz. Dickens, Ryves, Inglis, Ali Nawaz Jung, etc. Later on, to evolve a method of estimation of design flood peak of desired frequency for small catchments, the unit hydrograph approach has been adopted by the Central Water Commission. For this purpose, the country has been divided into 7 major zones which are sub-divided into 26 hydrometeorologically homogeneous subzones. For most of these sub-zones, Central Water Commission has already developed regional formulae for different sub-zones for the derivation of the synthetic unit hydrograph. The unit hydrograph characteristics such as peak (Q_p), time to peak (t_p), W_{50} ,W_{75} ,W_{R50} ,W_{R75} , time base (t_B) etc. have been computed on the basis of physiographic features. These regional formulae enable computation of unit hydrograph for ungauged catchments of the sub-zones. The reports prepared by CWC for different sub-zones (e.g., CWC, 1983 for sub-zone 3c) may be referred in this regard.

The regional unit hydrograph studies have also been carried out for some of the sub-zones by various research and academic organisations besides Central Water Commission. Singh (1984) developed regional unit hydrograph relationship for Lower Godavari sub-zone (3f) relating the parameters of Nash and Clark models with the physiographic characteristics of five gauged catchments in the sub-zone.

National Institute of Hydrology (1984-85) has carried out a regional unit hydrograph study for Narmada basin based on Clark's approach. In this study the parameters of the Clark model have been derived for each of the sub-basin of Narmada basin using HEC-I package. A regional relationship has been developed in the graphical form relating average value of (t_c + R) for each sub-basin with their respective catchment area. A regional value of R/(t_c + R) along with the graphical relationship has been used to estimate the parameters of the Clark model for ungauged catchment of the Narmada basin.

Although number of such relations are developed with the hope that they will yield satisfactory results when applied to the ungauged basin, these approaches have following limitations:

(i) The catchment for which data is used in a regional study have to be similar in hydrological and meteorological characteristics. However, it is usually difficult to locate catchments strictly satisfying these requirements.

(ii) While establishing such relations, the inherent limitations of the unit hydrograph theory are also being carried out with it. As a result the prevailing method of predicting the discharge hydrograph for a design storm by using the average unit hydrograph will not be appropriate, since the average unit hydrograph does not necessarily reproduce the actual response due to such inherent limitations.

(iii) The relationship evolved are based upon the gauged observations in number of catchments in the region. It is practically very difficult to always have gauged catchments available in adequate numbers in a region to enable the development of such relationships.

(iv) Generally, the data for intense and short duration storms are not available for the derivation of average unit hydrograph for gauged catchments. Hence the average unit hydrograph derived from minor flood events is considered for the regionalisation. It may result in the under estimation of design flood for ungauged catchments.

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 divides a watershed into sub-areas bounded by watershed lines using large-scale topographic maps. The model has a large number of lumped storage parameters. Most of these parameters are deduced from geomorphologic properties.

Rodriguez-Iturbe and Valdes (1979) developed an approach for derivation of the IUH by explicitly incorporating the characteristics of drainage basin composition (Horton, 1945; Strahler, 1964; Smart, 1972). The approach coupled the empirical laws of geomorphology with the principles of linear hydrologic systems. Rodriguez-Iturbe and his associates have since extended this approach by explicitly incorporating climatic characteristics and have studied several aspects including hydrologic similarity. Gupta, Waymire and C.T.Wang (1980) examined this approach, and reformulated, simplified and made it more general.

The effect of climatic variation is incorporated by having a dynamic parameter velocity in the formulation of Geomorphological IUH (GIUH). This is a parameter that must be subjectively evaluated. It is shown (Rodriguez-Iturbe, et.al., 1979) that this dynamic parameter "velocity" of the GIUH can be taken as the velocity at the peak discharge time for a given rainfall-runoff event in a basin. This transforms the time invariant IUH throughout the event into a time invariant IUH in each storm occurrence.

In the derivation of GIUH one of the greatest difficulties involved is the estimation of peak velocity. This is a parameter that must be evaluated for each flood event. Rodriguez et.al. (1982) rationalised that velocity must be a function of the effective rainfall intensity and duration and proceeded to eliminate velocity from the results. It leads to the development of geomorphoclimatic instantaneous unit hydrograph. The governing equations consists of the terms such as the mean effective rainfall intensity, Manning's roughness coefficient, average width, and slope of the highest order stream.

Janusz Zelazinski (1986) gave a procedure for estimating the flow velocity. It involves the development of the relationship between the 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 estimation of the velocity corresponding to it using Manning's equation. It requires the intensity of each rainfall block for the event for the computation of equilibrium discharge. The channel cross-section at the gauging site, longitudinal slope and Manning's roughness are also required during the computation of the velocity. The methodology has been applied to estimate the velocity to derive the Nash model parameters using GIUH approach for the Kolar sub-basin of Narmada basin.

Bhaskar et al. (1997) have presented the study on flood estimation for ungauged catchments using the GIUH. In this study, the GIUH is derived from the watershed geomorphological characteristics and is then related to the parameters of the Nash instantaneous (IUH) model for deriving its complete shape. The model parameters of the GIUH and the Nash IUH model are derived using two different approaches. In the first approach the rainfall intensity during each time interval is allowed to vary; whereas, in the second approach rainfall intensity is averaged over the entire storm period. This methodology has been applied to the Jira subcatchment in eastern India to simulate floods from twelve storm events. Results of both the GIUH approaches and those obtained by using Nash IUH are compared with observed events.

Development of GIUH has potential applications for the estimation of runoff, flood forecasting and design flood estimation, particularly for the ungauged catchments or for the catchments with limited data. Most of the studies available in literature regarding the GIUH approach are synthetic in nature and are in the early stages of research and development. Very few studies are available where its practical applications have been demonstrated. As GIUH approach has many advantages over the traditional method of developing the regional unit hydrograph for the simulation of flood events in the ungauged catchment, it would be appropriate to verify the application of GIUH approach for simulating the flood response of a gauged catchment. In the light of this a new approach of rainfall-runoff modelling based on the geomorphological characteristics has been developed at the National Institute of Hydrology. This technique links the GIUH equations derived by Rodriguez and the parameters of the Clark model. It enables the estimation of parameters of Clark model using the geomorphological characteristics, hydraulic properties of the main stream and storm characteristics. This approach was tested satisfactorily on the Kolar sub-basin of river Narmada (NIH,1993) and on three small catchments of Upper Narmada and Tapi Subzone (Subzone 3c) (NIH, 1995).

2.3 Uncertainty Analysis of Hydrologic Models

Typically hydrologic models are complex collections of algorithms combined in such a way as to mathematically mimic some hydrologic system. One axiom of stochastic processes is that any function of a random variable is itself a random variable. Thus if any of the variables in input or parameters ($\underline{I}$ and/or $\underline{P}$) are uncertain and known only in a probabilistic sense, then the output ($\underline{Q}$) is also uncertain and can be known only in a probabilistic sense. In the context of hydrologic modelling it means that if we are uncertain about $\underline{I}$ or $\underline{P}$, then we are uncertain about $\underline{Q}$ as well. Uncertainty is transferred from the inputs to the outputs.

An added complication with hydrologic models is that in general there are several uncertain parameters. We must be sure in any uncertainty analysis dealing with more than one variable that we do not violate relationships that exist among the input parameters. If parameters tend to vary together in real life, then we must preserve this joint variability structure in our uncertainty analysis. We are talking about the correlation structure among the independent variables. Optimal values of one parameter are dependent to a certain degree on values assigned to the correlated parameters. Correlation and its computation are discussed in Haan (1977), Morgan and Henrion (1990) and Helsel and Hirsh (1992).

While conducting the uncertainty analysis, often the uncertainty we arrive at is surprisingly and disturbingly large. We come face-to-face with the fact that hydrology is an inxact science and we start to realize just how inexact it really is. The uncertainty we have been dealıng with is parametric uncertainty. Parametric uncertainty refers to a lack of knowledge of the exact values for model parameters. As has been shown, parametric uncertainty can produce considerable uncertainty in the results generated from a hydrologic model. Hydrologic models generally require point or single estimates for model parameters. As modellers we generally provide point estimates but we do so recognising that we are not sure of the exact values of the parameters.

If we consider length ratio (R_L) for example, which is used in derivation of unit hydrograph by the GIUH based Clark model in this study, we might estimate R_L as 2.5 but recognize it may be anywhere between 1.5 and 3.5. In uncertainty analysis, we attempt to recognize this uncertainty and to associate weights reflecting our degree of belief that the R_L will have a value in a certain range. We use pdfs to do this. If we are highly confident that the R_L is near 2.5, we use 2.5 as our mean and a small variance. If we are not very sure that 2.5 is a good estimate, we increase the variance. So the shape or spread of the pdf on the parameter reflects our degree of belief or our confidence that the parameter lies in a certain range.

By using Monte Carlo Simulations (MCS), we transform this degree of belief from the parameter itself to the prediction made with a model that relies on that parameter. Obviously if a model output is dependent on the value associated with a parameter, and there is uncertainty as to the correct value of the parameter, there must be an associated uncertainty with the output from the model. Incorporating uncertainty in the modelling effort enables us to specify an expected value for the model output as well as a variance and even to associate probabilities with various intervals in which the output may be. Certainly this type of information can be fed to a decision analysis so that probabilities can be assigned to the consequences of various decisions.

If the uncertainty that exists in a model output due to parametric uncertainty is unacceptably large, the uncertainty analysis will provide guidance as to which parameters require better estimates (less uncertainty). Whatever resources are available for improved estimation can then be focused on those parameters that offer the best likelihood for improving the estimates of the model outputs. An uncertainty analysis of a modelling effort adds a degree of intellectual honesty to the effort that might otherwise be missing. The modeller is recognizing that uncertainty exists and is recognizing it in a quantitative way that can be communicated to decision makers. The decision maker is not left with the incorrect impression that a particular result is certain to occur.

Users of models must recognize that parametric uncertainty is but one source of uncertainty. Another important source is the model itself. Model uncertainty has to do with whether or not the model being used actually reflects the processes that are occurring in the field. To a certain degree the models are an approximation to reality and do not duplicate the real world. Different models tend to produce better results in different situations. Model uncertainty has to do with our inability to exactly model a real world hydrologic situation even if we have the best possible estimates for the parameters of the model. The summary of steps used in an uncertainty analysis is as follows.

2.3.1 Summary of steps used in uncertainty analysis

1. Estimate the best parameter values for the situation being modelled.
2. Define the correlation structure among the input parameters.
3. Estimate the variances of the input parameters.
4. Conduct a sensitivity analysis and select parameters to be used in the uncertainty analysis.

First order Analysis (FOA)

5. Conduct a FOA to estimate the variances for the model inputs of interest.
6. Calculate the fraction of the total variance attributable to each parameter.
7. Assume a pdf for the model output and calculate confidence intervals.

Monte Carlo Simulation (MCS)

8. Determine the pdfs appropriate for the input parameters.
9. Perform a MCS.
10. Calculate the correlation matrix and a multiple regression on the NICS results.
11. Plot the MCS generated outputs as probability plots.
12. Determine appropriate pdfs for the- outputs.
13. Determine confidence intervals on the outputs.

3.0 STATEMENT OF THE PROBLEM

Flood estimation using the geomorphological instantaneous unit hydrograph (GIUH) approach is a new concept in hydrology. Analytical procedures have been established for the derivation of the geomorphological instantaneous unit hydrograph. Such approach may be advantageously applied even for the ungauged catchments as it does not require the observed runoff data, and the geomorphological parameters of the catchment may be easily evaluated from the toposheets of the catchment using the geographical information system (GIS). Two relationships for the peak and time to peak of the geomorphological instantaneous unit hydrograph (GIUH) have been developed. But these relationships do not describe the complete shape of the instantaneous unit hydrograph (IUH).

In some of the studies carried out at the National Institute of Hydrology (e.g. NIH, 1993) and elsewhere the conceptual modelling (e.g. Nash model) has been coupled with the GIUH approach. This has enabled estimation of the complete shape of the IUH by using the relationships developed for the peak characteristics of the GIUH. Hence, it has been possible to use the conceptual modelling approach without even calibrating its parameters on the basis of the observed runoff data. In this study, the Clark model coupled with the GIUH approach viz. Clark model based GIUH approach has been used for estimation of the discharge hydrographs for some of the storm events of the catchment defined by the Bridge No. 807 of the Lower Godavari Subzone 3 (f) and uncertainty analysis of the parameters of the model has been carried out using the relative sensitivity and first order uncertainty analysis.

The main objectives of this study are:

(i) To evaluate the geomorphological parameters of the catchment under study using the GIS package, ILWIS.

(ii) To estimate the direct surface runoff hydrographs of the catchment for some of the storm events using the Clark model based GIUH approach i.e. without using the observed runoff data.

(iii) To compare the direct surface runoff hydrographs estimated by the GIUH approach with the observed direct surface runoff hydrographs.

(iv) To compare the direct surface runoff hydrographs estimated by the GIUH approach with the direct surface runoff hydrographs derived based on Nash and Clark models using the observed runoff data.

(v) To carryout relative sensitivity analysis of the parameters of the GIUH based Clark model.

(vi) To carry out first order uncertainty analysis for GIUH based Clark model and quantify the uncertainty associated with the input parameters of the model.

4.0 DESCRIPTION OF THE STUDY AREA

The catchment defined by bridge number 807 lies in the hydrometeorological region of Lower Godavari Subzone 3(f). Its catchment area is 824.7 square kilometers and length of main stream is 64.25 kilometers. The Subzone 3 (f) is a sub-humid region, which covers parts of areas in the states of Maharashtra, Madhya Pradesh, Andhra Pradesh and Orissa and lies between the longitudes of 17° to 23° east and latitudes of 76° to 83° north. The Subzone 3(f) is covered by the river Godavari in its lower reaches and its tributaries. It constitutes an area of about 56% of the main Godavari basin. The Lower Godavari Subzone 3(f) is essentially a sub-humid region having mean annual rainfall varying between 1000 mm to 1600 mm. Fig. 1 shows the index map of the catchment defined by the bridge number 807 of Lower Godavari Subzone 3(f).

The Lower Godavari Subzone 3(f) has a complex relief. Plains of medium heights upto 150 meters exist near the main Godavari river in its lower reaches. The western part of the subzone and north of Nagpur is the zone of the low plateau in the elevation 300 to 600 meters above mean sea level. The south-east and north-west portions of subzone cover high plateaus in the ranges of 600 to 900 meters above mean sea level and there are hills and higher plateaus ranging from 900 to 1500 meters above mean sea level in the south-eastern part of the subzone.

The Subzone 3(f) has a continental type of climate viz. Cold in winter and very hot in summer. It receives most of its rainfall from the south-west monsoon during the four months of June to September. A small portion of the south-east gets rain from north-east monsoon during November and December besides short duration thunder storms. The average annual temperature varies from 25^0 C to 27.5^0 C over greater part of the subzone. The minimum temperature in the subzone varies from 2.5^0 C to 12.5^0 C. The minimum temperature is recorded in the month of December. The maximum temperature varies from 45^0 C to 47.5^0 C. The maximum temperature is recorded in the month of April.

The broad soil groups in the subzone are red soils. The red soils are further classified into red sandy, red loamy, and red yellow soils. Black soils are classified as deep black, medium black and shallow black soils. More than 50% of the area is covered by forests and only 25% of the area is arable land.

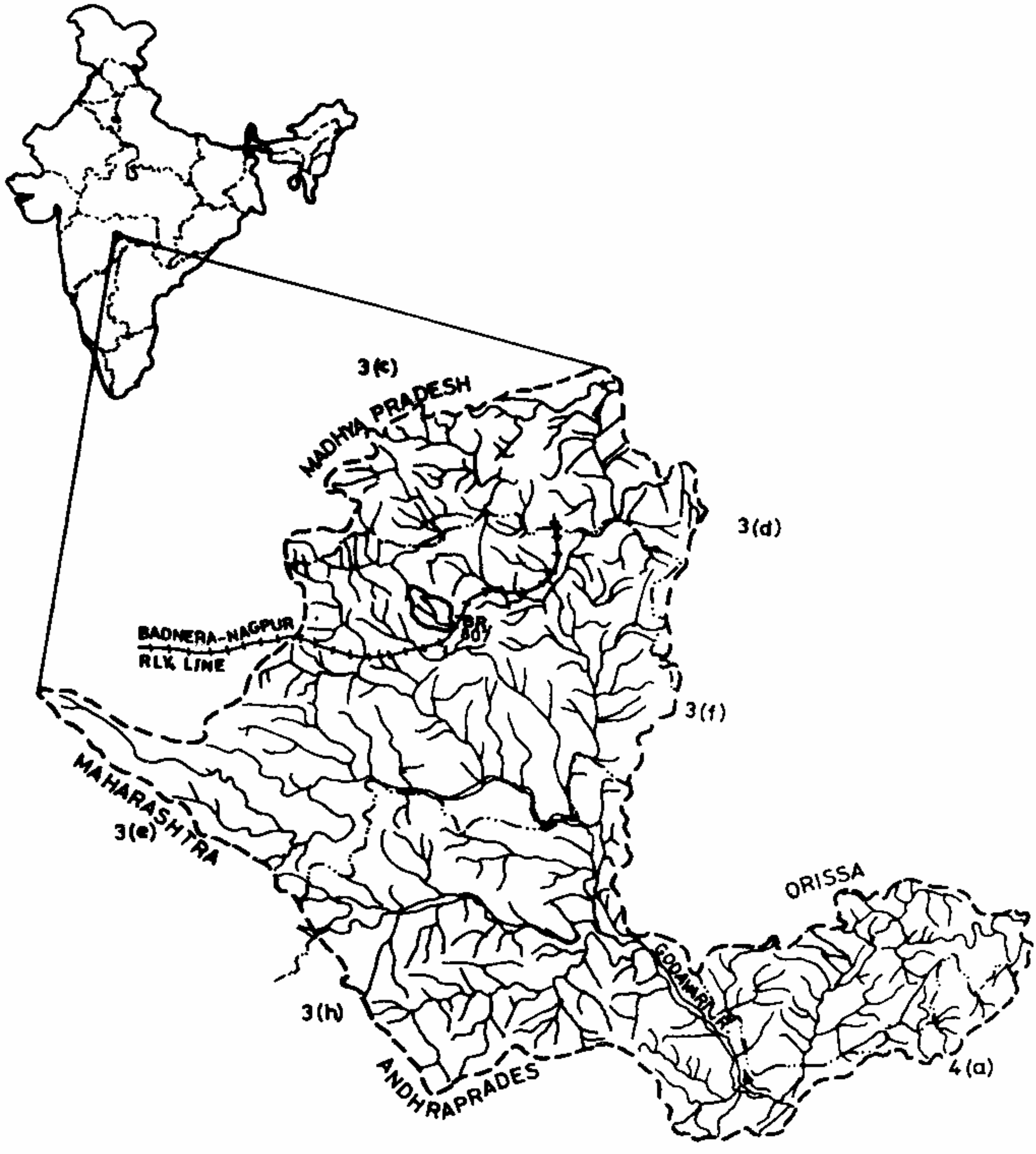


FIG. 1: INDEX MAP OF THE CATCHMENT DEFINED BY THE BRIDGE NO.807 OF LOWER GODAVARI SUB-ZONE 3(f)

5.0 DATA AVAILABILITY

The rainfall and discharge data are available at hourly interval. These data were obtained from Small Catchment Directorate, Central Water Commission, New Delhi. Table 1 gives the details of periods of various storms whose rainfall-runoff data have been used in the study.

Table 1 : Periods of various rainfall-runoff storms for the catchment defined by bridge number 807

S. No.	Period of Storms
1	22.07.1966 at 09 hrs. to 23.01.1966 at 04 hrs.
2	24.07.1967 at 19 hrs. to 25.07.1967 at 17 hrs.
3	06.09.1969 at 01 hrs. to 07.09.1969 at 07 hrs.
4	10.08.1970 at 01 hrs. to 10.08.1970 at 20 hrs.
5	22.06.1971 at 23 hrs. to 23.08.1971 at 12 hrs.
6	22.08.1973 at 12 hrs. to 23.08.1973 at 11 hrs.
7	16.09.1973 at 14 hrs. to 17.09.1973 at 13 hrs.

The names of the raingauge stations lying in the catchment defined by Bridge number 807, whose data have been used in the study and their Theissen weights are given in Table 2.

Table 2 : Names of the raingauge stations and their Theissen weights for the catchment defined by bridge number 807

S.No.	Name of Raingauge	Theissen weight
1	Bazargaon	0.156
2	Mohgaon	0.181
3	Kanholi	0.272
4	Khairee	0.171
5	Gumgaon	0.220

6.0 METHODOLOGY

The methodology adopted for the following aspects of the study is presented below.

(i) Preparation of geomorphological data base in Integrated Land and Water Information System (ILWIS),

(ii) Flood estimation by GIUH based Clark model, comparison of DSRO hydrographs and computation of error functions used for evaluation of the estimated DSRO hydrographs, and

(iii) Uncertainty analysis using the First Order Analysis (FOA)

6.1 Preparation of Geomorpholigical Data Base in ILWIS

The regionalization procedure requires some of the important geomorphological characteristics which are to be evaluated from the toposheets. It is extremely difficult for the user to manually derive the geomorphological parameters from toposheets. Thus, it discourages the users from adopting the various regional approaches. To overcome this difficulty, now a days, geographical information system (GIS) software like ILWIS, ERDAS, ARC/INFO and GRASS etc. are available for derivation of these characteristics in a less time consuming and simplified manner. In this study, the geomorphologic characteristics of the catchment defined by bridge number 807 have been derived using the GIS package i.e. ILWIS. Application of the GIS software like ILWIS makes the computation of the geomorphological parameters easy, less time consuming and accurate. Whereas, the manual methods of the morphometric analysis such as length measurement using thread length, opisometer and rular or area measurement by planimeter or dot grid method are very much time consuming and tedious. The procedure is all the more difficult if the toposheets or maps of higher scales e.g. 1:50,000 are used for derivation of the geomorphological characteristics.

The GIS software Integrated Land and Water Information System (ILWIS) has been developed at ITC, Enschede, the Netherlands. ILWIS integrates image processing capabilities, tabular data bases and conventional GIS characteristics. Data acquisition from aerospace images is an integral part of the system and enables its effective monitoring. A conversion program allows import of remote sensing data, tabular data, raster maps and vector files in several other formats. The map calculator includes an easy to use modelling language and the possibility of using mathematical functions and macros. It integrates tabular and spatial databases. After evaluation and assessment of results, the procedure can be applied to the entire area. Tabular and spatial data bases can be used independently and on an 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 modelling processes. Fast overlay procedures constitute one of the main capabilities of the system. Image processing capabilities integrated with spatial modelling and tabular data bases constitute a powerful tool and 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 DEMs (digital elevation models). Special filters and functions are available for producing slope, aspect maps, data processing, several basic image analysis capabilities such as histogram manipulation, automatic stretch display, user defined filters, transfer function manipulation and other standard functions.

The geomorphological parameters viz. bifurcation ratio (R_B), length ratio (R_L), area ratio (R_A), length of the highest order stream (L_Ω), length of the main steam (L) and time area (TA) diagram of the catchment are required to be evaluated for a catchment for application of the GIUH based Clark model, used in this study. The methodology adopted for estimation of these geomorphological parameters is described below.

6.1.1 Bifurcation ratio (R_B)

For ordering of streams Strahler's method of stream ordering as discussed above has been followed. Through application of ILWIS, the number of streams of each order is stored in a table and for each order the total number of streams was computed. Horton's law of stream numbers states that number of stream segments of each order is in inverse geometric sequence with order number i.e. $N_u = R_B^{u-k}$ where, k is the order of trunk segment, u is the stream order, N_u is the number of stream of order u and R_B is a constant called the bifurcation ratio.

Bifurcation ratio (R_B) is defined as the ratio of stream segments of the given order N_u to the number of stream segments of the next higher order N_{u+1} i.e:

$$R_B = N_u \,/\, N_{u+1} \qquad (1)$$

It has been very widely used in the derivation of geomorphologic instantaneous unit hydrographs for various catchments. The value of R_B for different catchments generally varies from 3 to 5.

6.1.2 Length ratio (R_L)

Horton (1945) defined length ratio (R_L) as the ratio of mean stream length ($\bar{L}_u$) of segment of order u, to mean stream segment length ($\bar{L}_{u-1}$) of the next lower order u-1, i.e.:

$$R_L = \bar{L}_u \,/\, \bar{L}_{u-1} \qquad (2)$$

Length ratio is one of the important geomorphologic characteristics. It has been used in the derivation of geomorphologic instantaneous unit hydrographs for various catchments. The value of R_L for different catchments generally varies from 1.5 to 3.5.

6.1.3 Area ratio (R_A)

The area of the streams of each order was estimated using the area and length relationship (Strahler, 1964). Horton stated that mean drainage basin areas of progressively higher order streams should increase in a geometric sequence, as do stream lengths. The law of stream areas may be mentioned as:

$$A_u = A_1 R_A^{u-1} \quad (3)$$

Here, A_u is the mean area of basin of order u. Areas for different order basins were estimated using the relationship between area of any order and area of highest order as given below:

$$A_u = A_1\, R_B^{\,u-1}\, (R_{LB}^{\,u}-1)/(R_{LB}-1) \quad (4)$$

Where, A_1 is the mean area of first order basin, R_B is the bifurcation ratio and R_{LB} is Horten's term for the length ratio to bifurcation ratio. In this relationship, only A_1 is unknown, so A_1 can be computed. The mean areas are computed using value of A_1.

Area ratio (R_A) is defined as the ratio of area of streams (A_u) of order u, to the area of streams (A_{u-1}) of order u-1, i.e.:

$$R_A = A_u / A_{u-1} \quad (5)$$

Area ratio is one of the important geomorphologic characteristics. It has been used in the derivation of geomorphologic instantaneous unit hydrographs for various catchments. The value of R_A for different catchments generally varies from 3 to 6.

6.1.4 Length of the main stream (L)

It is the length of the main stream from its origin to the gauging site. It is used for computing the time of concentration (Eq. 16) as described in Section 6.2.5.

6.1.5 Length of the highest order stream (L_Ω)

The length of the highest order stream is the length in kilometers of the stream of the highest order. It is designated as L_Ω.

6.1.6 Preparation of time-area diagram

The time area diagram illustrates the distribution of travel time of different parts of a catchment. The time area methods were developed in recognition of the importance of the time distribution of rainfall on runoff in the hydrologic design of storage and regulation of works.

Application of GIS makes preparation of the time area diagram of a catchment less time consuming and quite easier. The procedure adopted for derivation of the time area diagram is described below.

The distance from the most upstream point in the basin upto the gauging site, along the main stream is measured. It is assumed that the time of travel between any two points is proportional to the distance and inversely proportional to the square root of the slope between these points i.e.

$$t = KL / \sqrt{S} \qquad (6)$$

Here, t is time of travel, L is the length of the stream, S is the slope of the stream between two points, and K is proportionality constant. An initial estimate of time of concentration may be made by the Kirpich's formula i.e.

$$t_c = 0.06628\ L^{0.77}\ H^{-0.385} \qquad (7)$$

Where, t_c is concentration time in hours, L is the length of stream in kilometers, H is the average slope of the stream. Substituting the values of L and H in the equation (7), the value of t_c is computed. This value of t_c may be substituted in the equation (6), and then it may be rearranged as mentioned here under.

$$K = t_c \sqrt{S_A} / L \qquad (8)$$

By substituting values of t_c, L and S_A (S_A is mean slope of the main stream) in the equation (8), the value of K may be computed. This computed value of constant of proportionality K may be used in the equation (6) for computing time of travel between the two points of the catchment. The time of travel at various locations over the catchment is progressively computed, beginning from the gauging site of the catchment. All the values of the time of travels for each stream were then marked on the map of the catchment. Then, these points are transferred in the digital form. Using interpolation technique a map of time distribution is drawn through these points. From the time distribution map values, a map at a desired interval, e.g. 1-hour is prepared.

6.2 Flood Estimation by GIUH based Clark Model

The methodology adopted for computation of excess-rainfall, derivation of Clark model IUH and D-hour unit hydrograph, GIUH derivation using the geomorphological characteristics, development of relationship between intensity of excess-rainfall and the velocity, derivation of unit hydrograph using the GIUH based Clark model approach, computation of direct surface runoff (DSRO) using the derived unit hydrograph, comparison of DSRO hydrographs computed based on GIUH approach, HEC-1 and NASH model as well as computation of error functions used for evaluation of the estimated DSRO hydrographs is presented below.

6.2.1 Computation of excess-rainfall

Excess rainfall computation is required for estimation of direct surface runoff by separating the hydrological abstractions from the rainfall hyetographs. When the rainfall occurs over catchment not all the rain contributes to the direct surface runoff. A part of the rainfall is abstracted as interception, evapotranspiration, surface depression storage and infiltration. The remaining part of the rainfall termed as excess rainfall contributes to the direct surface runoff. Although, a number of techniques are available for the computation of excess rainfall but the ϕ-index method is one of the simple and quite commonly used technique. Among the other techniques Soil Conservation Service (SCS) curve number method is also very often used for the estimation of the excess rainfall particularly when the catchment is ungauged. In this study, the ϕ-index method has been used for estimation of the excess rainfall hyetographs. The volume of the excess rainfall for a given storm event is assumed to be known. It is computed as the volume of direct surface runoff hydrograph for a given event. The direct surface runoff hydrograph has been computed by separating the baseflow from the observed hydrograph ordinates. The observed direct surface runoff is used only for the estimation of excess rainfall hyetograph and it has not been used further for the derivation of instantaneous unit hydrograph. However, the use of the observed direct surface runoff for the estimation of excess rainfall has to be avoided for the ungauged catchment, as no runoff records would be available for such catchments. In such a situation, the values of ϕ-index can be estimated by analysing the rainfall-runoff records of flood events of the same period of the neighbouring catchments having similar hydrometeorological characteristics. Alternatively, other methods such as SCS method may be applied for estimation of the excess rainfall provided that the land use, soil type, treatment class, hydrologic condition and antecedent soil moisture condition are known for the estimation of runoff curve number.

6.2.2 Derivation of Clark model IUH and D-hour unit hydrograph

The Clark model concept (Clark, 1945) suggests that the IUH can be derived by routing the unit inflow in the form of time-area diagram, which is prepared from the isochronal map, through a single reservoir. For the derivation of IUH the Clark model uses two parameters, time of concentration (T_c) in hours, which is the base length of the time-area diagram, and storage coefficient (R), in hours, of a single linear reservoir in addition to the time-area diagram. The governing equation of IUH using this model is given as:

$$u_i = C\, I_i + (1 - C)\, u_{i-1} \tag{9}$$

where;

u_i = ith ordinate of the IUH

C & (1-C) = the routing coefficients.

and $C = \Delta t / (R + 0.5\,\Delta t)$

Δt = computational interval in hours

I_i = ith ordinate of the time-area diagram

A unit hydrograph of desired duration (D) may be derived using the following equation:

$$U_i = \frac{1}{n}(0.5\,u_{i-n} + u_{i-n+1} + u_{i-n+2} \ldots\ldots\ldots\ldots + u_{i-1} + 0.5\,u_i) \qquad (10)$$

where;

U_i = ith ordinate of unit hydrograph of duration D-hour and at computational interval Δt hours,

n = no. of computational intervals in duration D hrs = $D/\Delta t$, and

u_i = ith ordinate of the IUH.

6.2.3 GIUH derivation using the geomorphological characteristics

Rodriguez-Iturbe and Valdes (1979) first introduced the concept of geomorphologic instantaneous unit hydrograph, which led to the renewal of research in hydrogeomorphology. The expression derived by Rodriguez-Iturbe and Valdes (1979) yields full analytical, but complicated, expressions for the instantaneous unit hydrograph. Rodriguez-Iturbe and Valdes (1979) suggested that it is adequate to assume a triangular instantaneous unit hydrograph and only specify 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 analytic solutions for a wide range of parameters with that of the geomorphologic characteristics and flow velocities.

The expressions are given as:

$$q_p = 1.31\, R_L^{0.43}\, V / L_\Omega \qquad (11)$$

$$t_p = 0.44\,(L_\Omega / V)(R_B / R_A)^{0.55}(R_L)^{-0.38} \qquad (12)$$

where;

L_Ω = the length in kilometers of the stream of order Ω

V = the expected peak velocity, in m/sec.

q_p = the peak flow, in units of inverse hours

t_p = the time to peak, in hours

R_B, R_L, R_A = the bifurcation, length and area ratios given by the Horton's laws of stream numbers, lengths and areas respectively. For natural basins the values for R_B normally ranges from 3 to 5, for R_L from 1.5 to 3.5 and for R_A from 3 to 6 (Smart, 1972).

On multiplying eq. (11) and (12) we get a non-dimensional term $q_p * t_p$ as under.

$$q_p * t_p = 0.5764\,(R_B / R_A)^{0.55}(R_L)^{0.05} \qquad (13)$$

This term is not dependent upon the velocity and thereby on the storm characteristics and hence is a function of only the catchment characteristics. This is also apparent from the expression given above.

6.2.4 Development of relationship between intensity of excess-rainfall and the velocity

For the dynamic parameter velocity (V), Rodriguez and Valdes (1979) in their studies 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 GIUH, this can be taken as the velocity at the peak discharge time for a given rainfall-runoff event in a basin. However, for ungauged catchments the peak discharge is not known and so this criteria for estimation of velocity cannot be applied. In such a situation, the velocity may be estimated using the relationship developed between the velocity and the excess rainfall. The two approaches for developing this relationship, as described in the Technical Report of National Institute of Hydrology (NIH, 1994-95) are presented below.

6.2.4.1 Relationship between intensity of excess-rainfall and the velocity - Approach-I

This approach may be utilized when the geometric properties of the gauging section are known and the Manning's roughness coefficient can be assumed with an adequate degree of accuracy. The steps involved in this approach are as below.

(i) Compute cross-sectional area (A), Wetted Perimeter (P) and hydraulic radius (R) on the basis of cross-sectional details corresponding to different depths.

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

(iii) Choose an appropriate value of Manning's roughness coefficient (n) from the values given in literature (e.g. Chow, 1964) for various surface conditions of the channel.

(iv) Compute the discharge (Q) using the Manning's formula corresponding to each depth.

(v) Plot depth v/s discharge and depth v/s area curves.

(vi) Compute the equilibrium discharge (Q_e) corresponding to an excess rainfall intensity (i in mm/hr) using the relation :

$$Q_e = 0.2778 \; i \; A_c \qquad (14)$$

where, A_c is catchment area in sq. kms.

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

(viii) Compute the area corresponding to the depth computed at step (vii) using the depth v/s area curve.

(ix) Compute the velocity V by dividing the discharge (Q_e) by the area computed at step (viii).

(x) Repeat steps (vi) to (ix) to find velocity with respect to different intensities (e.g., 1, 2, 3 mm/hr. etc.) of rainfall excess.

(xi) Develop the relationship between velocity and rainfall-excess intensity obtained at step (x) in the form: $V = a\, i^b$, using method of least squares.

6.2.4.2 Relationship between intensity of excess-rainfall and the velocity - Approach-II

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 steps involved in this approach are given below.

(i) For different depths of flow the discharge and the corresponding velocities are known by observation.

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

(iii) For these Q_e values, find the corresponding intensities i of excess-rainfall from the expression:

$$i = Q_e / (0.2778\, A_c) \quad (15)$$

(iv) From the pairs of such V_e and i develop the relationship between the equilibrium velocity and the excess rainfall intensity in the form: $V_e = a\, i^b$, using method of least squares. Here, a and b are the regression coefficients.

It is to be noted here that this approach though requires the information of discharges and velocities at the gauging site does not necessarily mean that it can be applied for the gauged catchments only. For the ungauged catchments too, this information may be easily obtained by gauging the stream intermittently for all ranges of depth of flow. This type of information may be gathered without incurring much cost and effort.

6.2.5 Derivation of unit hydrograph using the GIUH based Clark model approach

The step by step explanation of the procedure to derive unit hydrograph for a specific duration using the GIUH based Clark model approach is given here under:

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

(ii) 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 excess (as developed in Section 6.5.1).

(iii) Compute the time of concentration (T_c) using the equation :

$$T_C = 0.2778\, L / V \tag{16}$$

where;
L = length of the main channel, and
V = the peak velocity in m/sec.

Considering this T_c as the largest time of travel find the ordinates of cumulative isochronal areas corresponding to integral multiples of computational time interval with the help of non-dimensional relation between cumulative isochronal area and the percent time of travel. This describes the ordinates of the time-area diagram at each computational time interval.

(iv) Compute the peak discharge (Q_{pg}) of IUH given by equation (11).

(v) 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 time of concentration T_c as obtained in step (iii) and two storage coefficients R_1 and R_2 respectively with the help of equation (11). 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.

(vi) Find out the peak discharges Q_{pc1} and Q_{pc2} of the instantaneous unit hydrographs obtained for Clark model for the storage coefficients R_1 and R_2 respectively at step (v).

(vii) Find out the value of objective function, using the relation:

$$FCN1 = (Q_{pg} - Q_{pc1})^2 \tag{17}$$

$$FCN2 = (Q_{pg} - Q_{pc2})^2 \quad (18)$$

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

$$FPN = \frac{FCN1 - FCN2}{R_1 - R_2} \quad (19)$$

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

$$\Delta R = \frac{FCN1}{FPN} \quad (20)$$

and

$$R_{NEW} = R_1 + \Delta R \quad (21)$$

(x) For the next trial consider $R_1 = R_2$ and $R_2 = R_{NEW}$ and repeat steps (v) and (ix) till one of the following criteria of convergence is achieved.

(a) FCN2 = 0.000001
(b) No. of trials exceeds 200
(c) $ABS(\Delta R)/R_1 = 0.001$

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

(xii) Compute the instantaneous unit hydrograph (IUH) using the GIUH based Clark Model with the help of final values of storage coefficient (R), Time of concentration (T_c) as obtained in the step (xi) and time-area diagram.

(xiii) Compute the D-hour unit hydrograph (UH) using the relationship between IUH and UH of D-hour as given by equation (10).

6.2.6 Computation of direct surface runoff using the derived unit hydrograph

The direct surface runoff (DSRO) 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 computed given as mentioned below.

$$Q(t) = \Delta t \sum_{i}^{n} [U(D, t-(i-1)\Delta t] * I_i \quad (22)$$

where,

$U(D, t)$ = ordinate of D hour unit hydrograph at time t,

I_i = excess-rainfall intensity at ith interval (i.e., at time = $\Delta t * i$),

n = number of excess-rainfall blocks, and

Δt = computational time interval.

6.2.7 Comparison of DSRO hydrographs computed based on GIUH approach, Clark IUH model (HEC-1 package) and Nash IUH model

The DSRO hydrographs computed based on the GIUH based Clark model, HEC-1 package and Nash model have been compared with the observed DSRO hydrographs.

6.2.7.1 HEC-1 package

The HEC-1 package developed by Hydrologic Engineering Center (HEC) of US Corps of Engineers is a well known hydrologic model specially designed for the simulation of flood events in watershed and river basins. In the HEC-1 model, the transformation of rainfall excess to stream flow is accomplished by the unit hydrograph procedure. There are three unit hydrograph methods available in HEC-1, namely Clark's, Snyder's and SCS-method. Because Snyder's method does not give the complete unit hydrograph and SCS-method uses only a single parameter, Clark's method is selected for the present study for the better estimation of the runoff. All the losses, i.e., losses to interception, depression storage and infiltration, referred to as precipitation losses, are incorporated in the program to determine the excess rainfall. Initial and constant loss rate functions are used for the purpose. These loss rate parameters along with Clark's parameters are optimized using parameter optimization technique of the HEC-1 package (HEC-1, 1990).

Clark (1945) suggested that IUH can be derived by routing the unit inflow in the form of time area concentration curve, which is prepared from isochronal map, through a single linear reservoir. There are two parameters of the Clark model viz. the time of concentration (T_c) and storage coefficient (R). The parameter T_c represents the travel time of a water particle from the farthest point in a basin to its outlet; while the parameter R is an attenuation constant which has the dimensions of time. The parameter R is used to account for the effect of storage in the river channel on the hydrograph. Apart from the two parameters, T_c and R, Clark model uses the time area concentration curve also.

6.2.7.2 Nash model concept

Nash (1957) considered that the instantenous unit hydrograph (IUH) could be obtained by routing the instantenous inflow through a cascade of linear reservoirs with equal storage coefficient.

The outflow from the first reservoir is considered as inflow to the second reservoir and so on. The two parameters viz. n and k of the Nash model may be computed by analysing the rainfall runoff data of any catchment. Here n represents number of linear reservoirs and k is the storage coefficient. The value of the parameter n which is a shape parameter is a measure of catchment channel storage required to define the shape of the IUH. The parameter k which is a scale parameter represents the dynamics of rainfall runoff process in the catchment. A larger value of k would indicate a higher value of time to peak of the runoff hydrograph.

6.2.8 Error functions used for evaluation of the computed DSRO hydrographs

The errors functions employed for evaluation of the DSRO hydrographs computed by the GIUH based Clark model approach in comparison with the observed DSRO hydrographs as well as with the DSRO hydrographs estimated by the Nash model and the HEC-1 package viz. (i) efficiency, (ii) absolute average error, (iii) root mean square error, (iv) average error in volume, (v) percentage error in peak and (vi) percentage error in time to peak are mentioned below.

6.2.8.1 Efficiency (EFF)

Efficiency (EFF) is computed as follows:

$$EFF = \frac{\sum_{i=1}^{n}\left(Q_{oi} - \bar{Q}\right)^2 - \sum_{i=1}^{n}\left(Q_{oi} - Q_{ci}\right)^2}{\sum_{i=1}^{n}\left(Q_{oi} - \bar{Q}\right)^2} * 100 \qquad (23)$$

where, Q_{oi} = ith ordinate of the observed discharge

$\bar{Q}$ = average of the ordinates of observed discharge

Q_{ci} = Computed discharge

6.2.8.2 Absolute average error (AAE)

Absolute average error (AAE) is computed as follows:

$$AAE = \frac{\sum_{i=1}^{n}\left|\left(Q_{oi} - Q_{ci}\right)\right|}{n} \qquad (24)$$

where n = No. of ordinates

6.2.8.3 Root mean square error (RMSE)

Root mean square error (RMSE) is computed as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Q_{oi} - Q_{ci})^2}{n}} \tag{25}$$

6.2.8.4 Average error in volume (AEV)

Average error in volume (AEV) is computed as follows:

$$AEV = \frac{(Vol_o - Vol_c)}{n} \tag{26}$$

where Vol_o = Observed runoff volume
Vol_c = Computed runoff volume

6.2.8.5 Percentage error in peak (PEP)

Percentage error in peak (PEP) is computed as follows:

$$PEP = \frac{(Q_{op} - Q_{cp})}{Q_{op}} x100 \tag{27}$$

where Q_{op}= observed peak discharge
Q_{cp} = computed peak discharge

6.2.8.6 Percentage error in time to peak (PETP)

Percentage error in time to peak (PETP) is computed as follows:

$$PETP = \frac{OT_p - CT_p}{OT_p} x100 \tag{28}$$

where OT_p = Time to peak of observed discharge
CT_p = Time to peak of computed discharge

6.3 Uncertainty Analysis of the GIUH based Clark Model

Typically hydrologic models are complex collections of algorithms combined in such a way as to mathematically mimic some hydrologic system. The generic model might be written as:

$$\underline{Q} = f(\underline{I}, \underline{P}, t) + \underline{e} \tag{29}$$

where, $\underline{Q}$ represents the outputs being modelled such as runoff from a catchment, $\underline{I}$ represents the inputs to the model such as rainfall, temperature, etc., $\underline{P}$ represents the parameters required by the model and $\underline{e}$ represents errors associated with the modelling process.

One axiom of stochastic processes is that any function of a random variable is itself a random variable. Thus if any of the variables in $\underline{I}$ and/or $\underline{P}$ are uncertain and known only in a probabilistic sense, then $\underline{Q}$ is also uncertain and can be known only in a probabilistic sense. In the context of hydrologic and water quality modelling it means that if we are uncertain about $\underline{I}$ or $\underline{P}$, then we are uncertain about $\underline{Q}$ as well. Uncertainty is transferred from the inputs to the outputs.

An added complication with hydrologic models is that in general there are several uncertain parameters. We must be sure in any uncertainty analysis dealing with more than one variable that we do not violate relationships that exist among the input parameters. If parameters tend to vary together in real life, then we must preserve this joint variability structure in our uncertainty analysis. We are talking about the correlation structure among the independent variables. Optimal values of one parameter are dependent to a certain degree on values assigned to the correlated parameters. Correlation and its computation are discussed in Haan (1977).

Determining the uncertainty to assign to input parameters is one of the major hurdles that must be addressed in the overall evaluation of uncertainty associated with hydrologic modelling. Using this guidance and our own experience, we must come up with a single best estimate or expected value for each of the parameters. We need to investigate limits on parameters and suggested ranges of parameter values. If the parameter is a physically measurable parameter, we need to look into the literature and see what kind of variability is reported for the parameter. Our goal is to come up with the following quantities in order of priority:

1. Expected value
2. Variance
3. Distributional shape

Typically one might find a table of suggested values that give average values and ranges for the parameters under a variety of conditions. What can be done is to take the suggested values as the expected value or mean parameter estimate. The range might be taken as 2 or 3 standard deviations. For example a table of Manning's n for a natural stream that is winding with pools and riffles might show a minimum of 0.035 and a maximum of 0.050. From this several possibilities are available.

We might assume a uniform distribution with $\alpha = 0.035$ and $\beta = 0.050$. This assumes any value in the interval is as likely as any other and that values outside the interval are not possible. We might assume a triangular distribution with the minimum at 0.035, maximum at 0.50 and mode at 0.042. We might assume a normal distribution with mean = 0.042 and a standard deviation of 0.015/2 or 0.0075. This latter assumption would, of course, allow for values smaller then 0.035 and larger than 0.050. If we can only estimate mean ($\bar{Q}$), we might take coefficient of variation (C_v) = 0.2 or 0.3 and then standard deviation (s) = $C_v \bar{Q}$. $\bar{Q}$ and s are more important than the pdf that is used.

Assessing the correlation structure among parameters is much more difficult. For physical parameters such as bulk density, K_s, %OM, % clay, etc., we might find some field data from which the correlation matrix might be calculated. In other cases we might have to rely on a rational analysis of the parameters. In the case of pseudo physical parameters or parameters designed to describe something physical but which in themselves are not physically measurable, one has to resort to experience and assumptions.

At this point it is apparent that considerable work may be involved in gathering the data required to characterize the uncertainty in each parameter and the parameters as a whole. One would not want to go to all this work unless in fact the parameter was important to the process being modelled. If a parameter has little impact on the output of a model, we don't want to spend a great deal of time estimating that parameter or worrying about uncertainty in that parameter.

6.3.1 Sensitivity analysis

The processes for identifying important parameters include sensitivity analysis. We desire to determine the sensitivity of model outputs to changes in values for model inputs. Two types of sensitivity coefficients are used. One is called an absolute sensitivity coefficient or simply the sensitivity coefficient, S, and the other a relative sensitivity coefficient, S_r. These are given by:

$$S = \frac{\partial O}{\partial P} \qquad\qquad S_r = \frac{\partial O}{\partial P}\frac{P}{O} \tag{30}$$

Where, O and P represent particular model outputs and parameters respectively. S gives the absolute change in O for a unit change in P while S_r gives the % change in O for a 1% change in P. Graphically the terms in these relationships are shown in Fig. 2.

Obviously for most hydrologic models, numerical procedures must be used since analytic partial derivatives can not be obtained. Thus one has to approximate the above derivatives by:

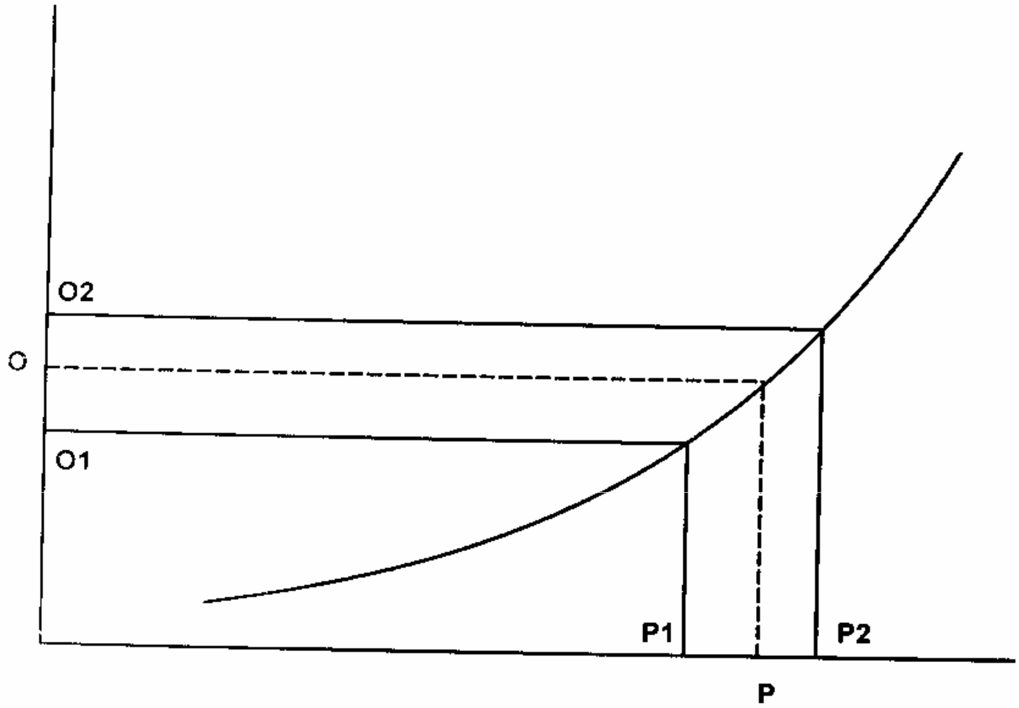


Fig. 2: **Definitions for numerical derivatives**

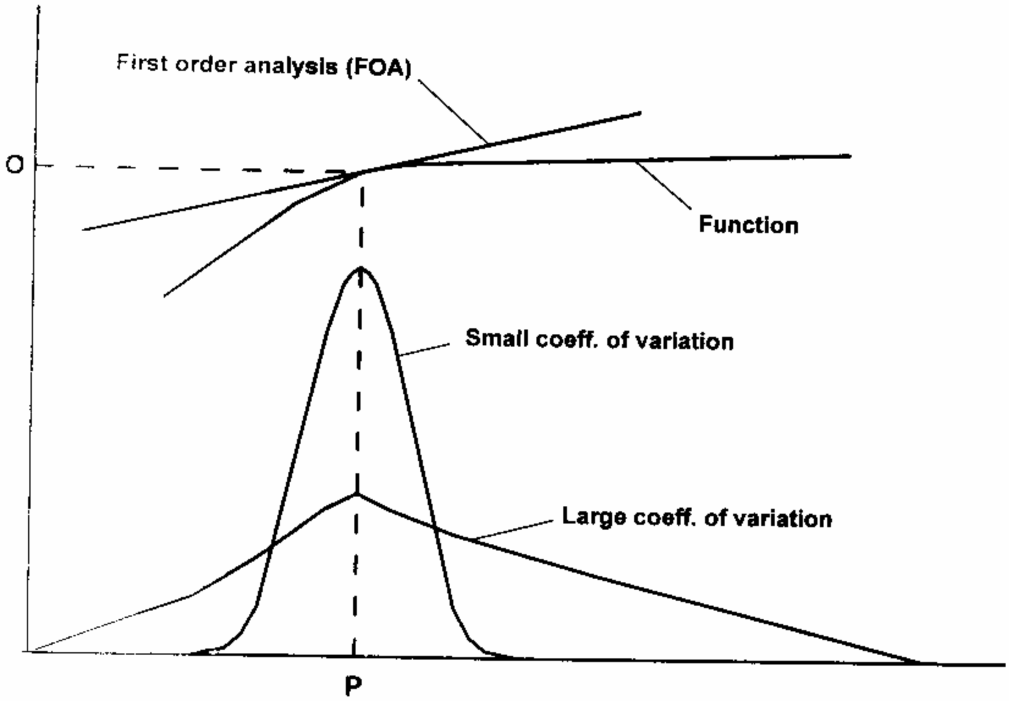


Fig. **3: First order analysis (FOA) considerations**

$$S = \frac{O_2 - O_1}{P_2 - P_1} \qquad S_r = \frac{O_2 - O_1}{P_2 - P_1} \frac{P}{O} \tag{31}$$

Where, P is given by $(P_1 + P_2)/2$ and O is given by $(O_1 + O_2)/2$. When evaluating these partial derivatives, all other parameters are set at their expected values. The derivatives are also taken about the expected value of P.

The relative sensitivity coefficients may be preferred since they are dimensionless and can be compared across parameters while the absolute sensitivity coefficients have units of output over input and can not be directly compared across noncommensurate parameters. Parameters can be ranked on the basis of their relative sensitivity coefficients and only the most sensitive ones retained for further analysis.

6.3.2 First order analysis (FOA)

As has been previously indicated, FOA can be used to estimate the variance of a function or model in terms of the variance of the various parameters that go into the model. FOA equations are relatively simple to apply; however, the basic assumptions that are made must be kept in mind. Again these assumptions are that $f(X^0)$ is nearly linear and that $(x_i - x_i^0)$ is small for I = 1 to n. This latter assumption is often expressed in terms of a C_v being less than 0.2 or some other fixed value.

We can put the results of the above development of FOA in terms of hydrologic modelling using the notation previously adopted for a general hydrologic model.

$$\bar{O} = \bar{f}(\bar{I}, \bar{P}, t) + \bar{e} \tag{32}$$

Where, $\underline{O}$ represents model outputs and $\underline{P}$ represents the parameters of interest. The resulting estimates for the mean and variance are:

$$E(\underline{O}) = \underline{f}(\bar{\underline{I}}, \bar{\underline{P}}, t) \tag{33}$$

$$\mathrm{Var}(\underline{O}) = \sum_{i=1}^{p} \left[\left(\frac{\partial \underline{f}(\underline{I}, \underline{P}, t)}{\partial P_i} \right)^2 \right]_{\bar{\underline{P}}} \mathrm{Var}(P_i) + 2 \sum_{i=1}^{p} \sum_{j=i+1}^{p} \left[\frac{\partial \underline{f}(\underline{I}, \underline{P}, t)}{\partial P_i} \frac{\partial \underline{f}(\underline{I}, \underline{P}, t)}{\partial P_j} \right]_{\bar{\underline{P}}} \mathrm{Cov}(P_i, P_j) \tag{34}$$

The expression for the variance appears to be quite complex and is useless the parameters are independent. The last term of the Variance expression contains Cov (Pi, P_j). If P_i and P_j, are independent then this term is zero. If P_i and P_j for all i and j are independent, then the Variance expression reduces to:

$$\mathrm{Var}(\underline{O}) = \sum_{i=1}^{p}\left[\left(\frac{\partial f(\underline{I},\underline{P},t)}{\partial P_i}\right)^2\right]_{\overline{\underline{P}}} \mathrm{Var}(P_i) \qquad (35)$$

Recognizing the definition of the absolute sensitivity coefficients given by Eq. 31, this becomes

$$\mathrm{Var}(\underline{O}) = \sum_{i=1}^{p} S_i^2 \mathrm{Var}(P_i) \qquad (36)$$

Where S_i is the absolute sensitivity with respect to P_i.

The fraction of the total variance due to the ith parameter is given by:

$$F_i = \frac{S_i^2 \mathrm{Var}(P_i)}{\sum_{i=1}^{p} S_i^2 \mathrm{Var}(P_i)} \qquad (37)$$

F_i can be used to identify which parameters are the largest contributors to uncertainty in the output based on the FOA. It may be noticed that F_i combines parameter uncertainty in terms of parameter variance and the sensitivity of the model to the parameter. Thus FOA has some very attractive features. Unfortunately, the Taylor series expansion we use is truncated and thus is only an approximation for E(O) and Var(O). FOA is said to be valid for those situations where the model is nearly linear in the parameters of interest and the C_v, on P_i is small. This can be seen from Fig. 3 (shown along with Fig. 2).

We also note that FOA produces only estimates for the E(O) and Var(O). If we want to look at probabilities of the O being in certain ranges, we must make pdf regarding the O. For example if we take O to be normally distributed with a mean of E(O) and a variance of Var(O), we can calculate probabilities of O in any range and we can put confidence intervals on O. Other pdf assumptions can be made as well. FOA is computationally efficient requiring only 2p+ 1 model runs for a model in which p parameters are under consideration. For example, with 6 parameters, 13 model runs are required (Personal communication with Prof. C. T. Haan).

6.3.3 Confidence intervals (CIs)

Confidence intervals, CIs, in the context of the discussion of uncertainty in hydrologic modelling, are defined as intervals that contain the true value of the model output with the indicated degree of confidence or probability. Thus, the 90 % CI is the interval that we conclude has a 90% chance of containing the true model output. The CIs are bounded by the confidence limits, CL. Obviously the CIs and CLs depend on the estimated values of the model parameters and the pdf that is assumed. When using FOA it is necessary to assume a distribution on the model outputs to compute CIs. This interpretation of CIs is somewhat at odds with a statistician's interpretation. In actuality, the true value for the model output is not a random variable - it is a fixed constant. The CIs are random variables and may vary from sample to sample. The statistician prefers to say that the α% CIs are intervals calculated in such a manner that α% of the time, the resulting intervals will contain the true value. If Q is assumed to be normally distributed, then 90% CIs may be computed. For example, the CIs may be computed so that there is a 5% chance of a value larger than the upper CL and a 5% chance of a value below the lower CL. The upper confidence limit, CL is:

$$Q_u = Q + \sigma_Q * Z_{0.95} \quad (38)$$

and the lower confidence limit, CL is

$$Q_l = Q + \sigma_Q * Z_{0.05} \quad (39)$$

7.0 ANALYSIS AND DISCUSSION OF RESULTS

The analysis carried out and results of the study for following aspects are presented below.

(i) Evaluation of geomorphological data base in Integrated Land and Water Information System (ILWIS),

(ii) Flood estimation by GIUH based Clark model, comparison of the DSRO hydrographs computed by the HEC-1 package and the Nash model as well as computation of error functions used for evaluation of the estimated DSRO hydrographs, and

(iii) Relative sensitivity as well as uncertainty analysis using the first order analysis (FOA)

7.1 Evaluation of Geomorphological Characteristics using ILWIS

The boundary of the catchment, stream network and contours have been mapped using Survey of India toposheets in the scale of 1:50,000. Procedure of digitization was adopted to convert these maps into digital form and storing in ILWIS. Digitization which is the most time consuming part of the analysis, was carried in parts to minimise the digitization errors. The digitized map was corrected for any type of errors such as correcting joining of the streams and appropriate overlaying of the segments etc. The system then edits the coverage and splits the stream of the higher orders automatically at the points where these streams join. Length of each stream is computed by default and stored in the order table alongwith the order of each stream. Fig. 4 shows drainage network map of the study area for the six order streams of the catchment. The area and perimeter of the basin can be computed after converting the boundary map to polygon map. The contour map was rasterized after converting it to digital form. Then interpolation from isolines was carried out on this map for computation of elevation at each point (pixel) of the catchment.

7.1.1 Bifurcation ratio (R_B)

Bifurcation ratio (R_B) is defined as the ratio of stream segments of the given order N_u to the number of stream segments of the next higher order N_{u+1} i.e:

$$R_B = N_u \; / \; N_{u+1} \tag{40}$$

The logarthim of the number of streams is plotted against order of streams, which is observed to be a linear relationship, as shown in Fig. 5. The best fit equation for this relationship is obtained as:

$$Y = -1.474\,x \; + \; 8.571 \tag{41}$$

The correlation coefficient for this equation is –0.989 and bifurcation ratio is obtained as 4.366.

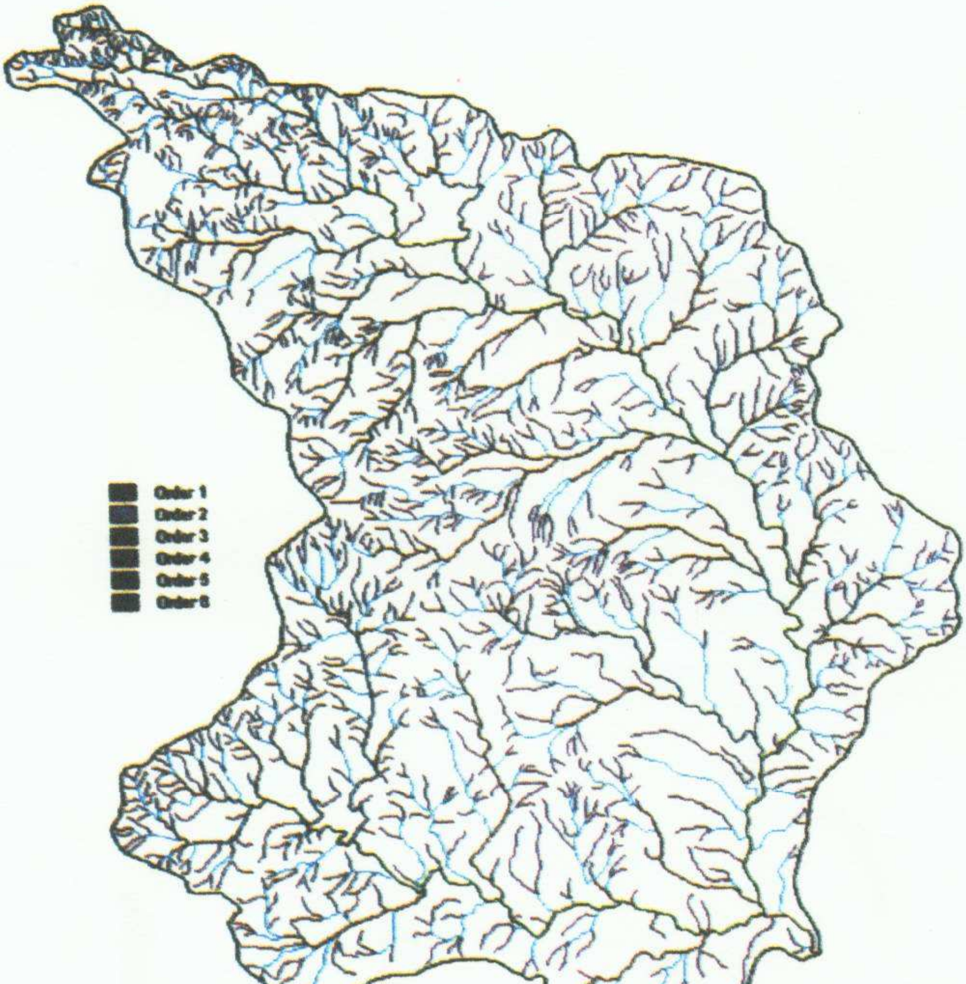


Fig. 4 : Drainage network map of the catchment defined by bridge number 807 of Lower Godavari Subzone 3(f)

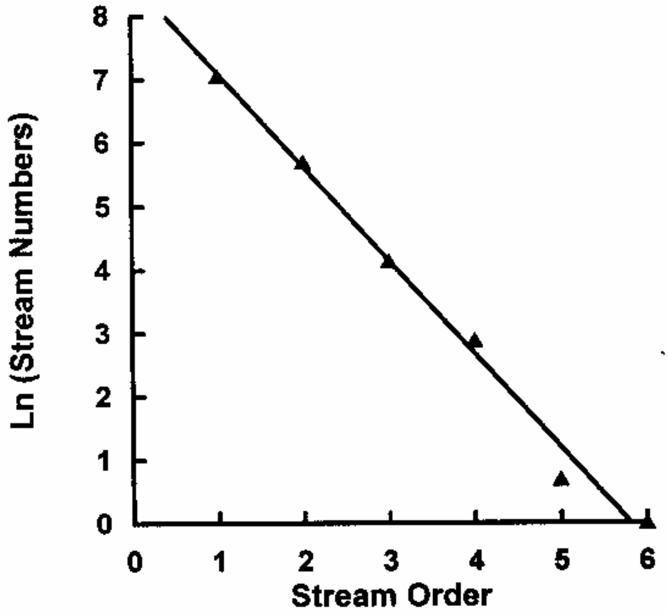


Fig. 5 Variation of stream numbers with stream order

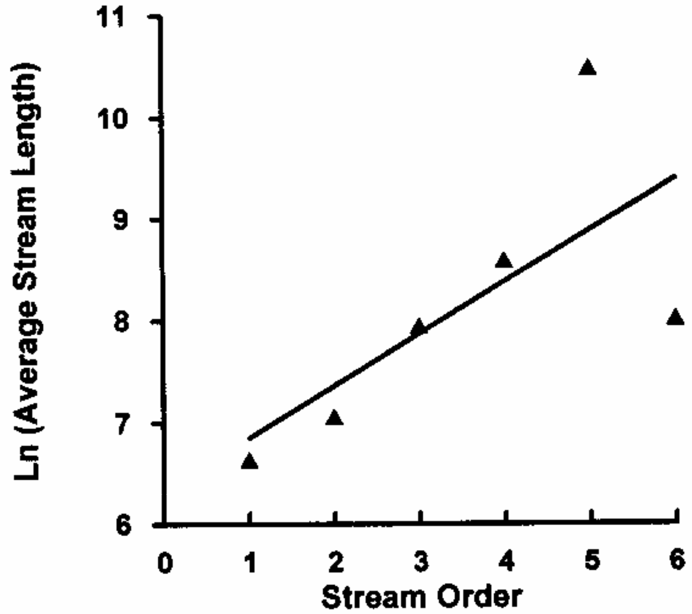


Fig. 6 Variation of mean stream length with stream order

7.1.2 Length ratio (R_L)

The length ratio (R_L) is defined as the ratio of mean stream length ($\bar{L}_u$) of segment of order u, to mean stream segment length ($\bar{L}_{u-1}$) of the next lower order u-1, i.e.:

$$R_L = \bar{L}_u / \bar{L}_{u-1} \qquad (42)$$

Length of each stream is stored in a table. Then after adding length of each stream for a given order, the total stream length of each order (L_u) is computed. The total stream length divided by the number of stream segments (N_u) of that order gives the mean stream length L_u for that order. The mean stream length of each order in log domain has been plotted against the order of the streams. Fig. 6 (shown along with Fig. 5) shows that the plot of logarithm of mean stream length as a function of stream order gives a straight line. Equation of the best-fit line is obtained as:

$$Y = 0.509\, x + 6.343 \qquad (43)$$

The correlation coefficient for this equation is 0.495. From this equation, length ratio is obtained as 1.664.

7.1.3 Area ratio (R_A)

The area of the catchment was computed by converting the map of the catchment into polygon form. The area of the catchment defined by bridge No. 807 is found to be 824.7 square kilometers. However, the area of streams of various orders could not be computed by ILWIS. The area of the streams of each order was estimated using the area and length relationship (Strahler, 1964). Horton stated that mean drainage basin areas of progressively higher order streams should increase in a geometric sequence, as do stream lengths. The law of stream areas may be mentioned as:

$$A_u = A_1 R_A^{u-1} \qquad (44)$$

Here, A_u is the mean area of basin of order u. Areas for different order basins were estimated using the relationship between area of any order and area of highest order as given below:

$$A_u = A_1\, R_B^{\,u-1} (R_{LB}^{\,u}-1)/(R_{LB}-1) \qquad (45)$$

Where, A_1 is the mean area of first order basin, R_B is the bifurcation ratio and R_{LB} is Horten's term for the length ratio to bifurcation ratio. In this relationship, only A_1 is unknown, so A_1 can be computed. The mean areas are computed using value of A_1.

Area ratio (R_A) is defined as the ratio of area of streams (A_u) of order u, to the area of streams (A_{u-1}) of order u-1, i.e.:

$$R_A = A_u / A_{u-1} \tag{46}$$

The mean stream area of each order of stream in log domain has been plotted against the order of the streams. Fig. 7 shows that the plot of logarithm of mean stream area as a function of stream order gives a straight line. Equation of the best fit line is obtained as:

$$Y = 1.473\,x - 2.127 \tag{47}$$

The correlation coefficient for this equation is 0.495. From this equation, area ratio (R_A) is obtained as 4.362.

Table 3 shows the details of stream numbers, length, average length and average areas for streams of various orders for the study area.

Table 3: Details of number, length, mean length and mean area for streams of various orders

Order Of Stream	Number	Length (kms)	Mean Length (kms)	Mean Area (km²)
1	1163	893.100	0.768	0.520
2	299	347.300	1.162	2.272
3	63	179.200	2.844	9.916
4	18	96.372	5.353	43.284
5	2	71.557	35.778	188.930
6	1	3.027	3.027	824.700

7.1.4 Length of the main stream (L)

The length of the main stream of the catchment defined by the bridge No. 807 is measured as 64.25 kilometers.

7.1.5 Length of the highest order stream (L_Ω)

The length of the highest order stream is the length in kilometers of the stream of the highest order. It is designated as L_Ω. In the present study, the length of the highest order, i.e., the sixth order stream is estimated as 3.027 kilometers. As the total length of the main river is 64.25 kilometers, hence, it has been considered appropriate to use the average length of the fifth and sixth order as L_Ω which is computed as 19.40 kilometers. This is because the length of the sixth order stream is too small to govern the process of generation of runoff for this catchment and the significance of the mean length of the next highest order viz. fifth order streams needs to be accounted for.

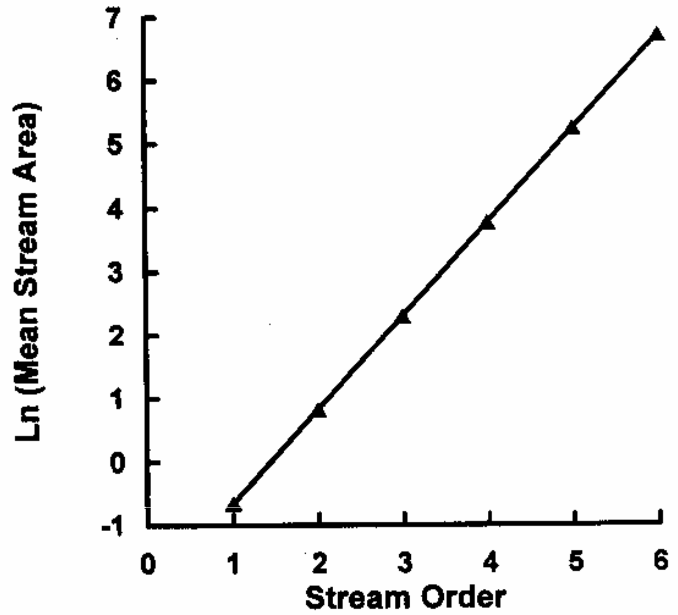


Fig. 7 Variation of mean stream area with stream order

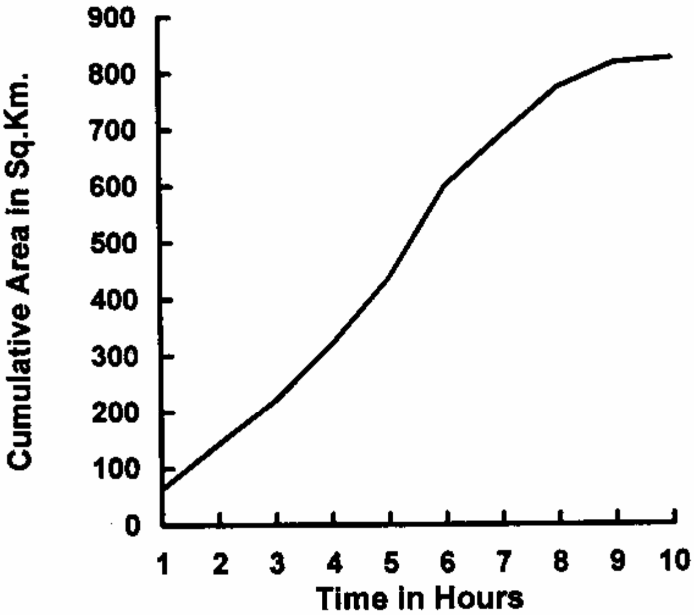


Fig. 8 Time of travel and cumulative area diagram

7.1.6 Preparation of time area diagram (TA)

As described in Section 6.1.6, by substituting values of t_c, L and S_A (S_A is mean slope of the main stream) of the catchment defined by the bridge No. 807, in the equation (8), the value of K was computed. This computed value of constant of proportionality K was used in the equation (6) for computing time of travel between the two points of the catchment. The time of travel at various locations over the catchment was progressively computed, starting from the gauging site of the catchment. All the values of the time of travels for each stream were then marked on the map of the catchment. Then, these points were transferred in the digital form. Using interpolation technique a map of time distribution was drawn through these points. From the time distribution map values, a map at an interval of 1-hour was prepared. For preparing the time area diagram of the catchment, the area for each of the time interval was measured and these values were tabulated. Fig. 9 shows the digital elevation model (DEM) of the study area. Fig. 8 (shown along with Fig. 7) shows the plot of time of travel versus cumulative catchment area. Fig. 10 illustrates time area diagram of the study area. For the catchment defined by the bridge No. 807, t_c is computed as 10 hours.

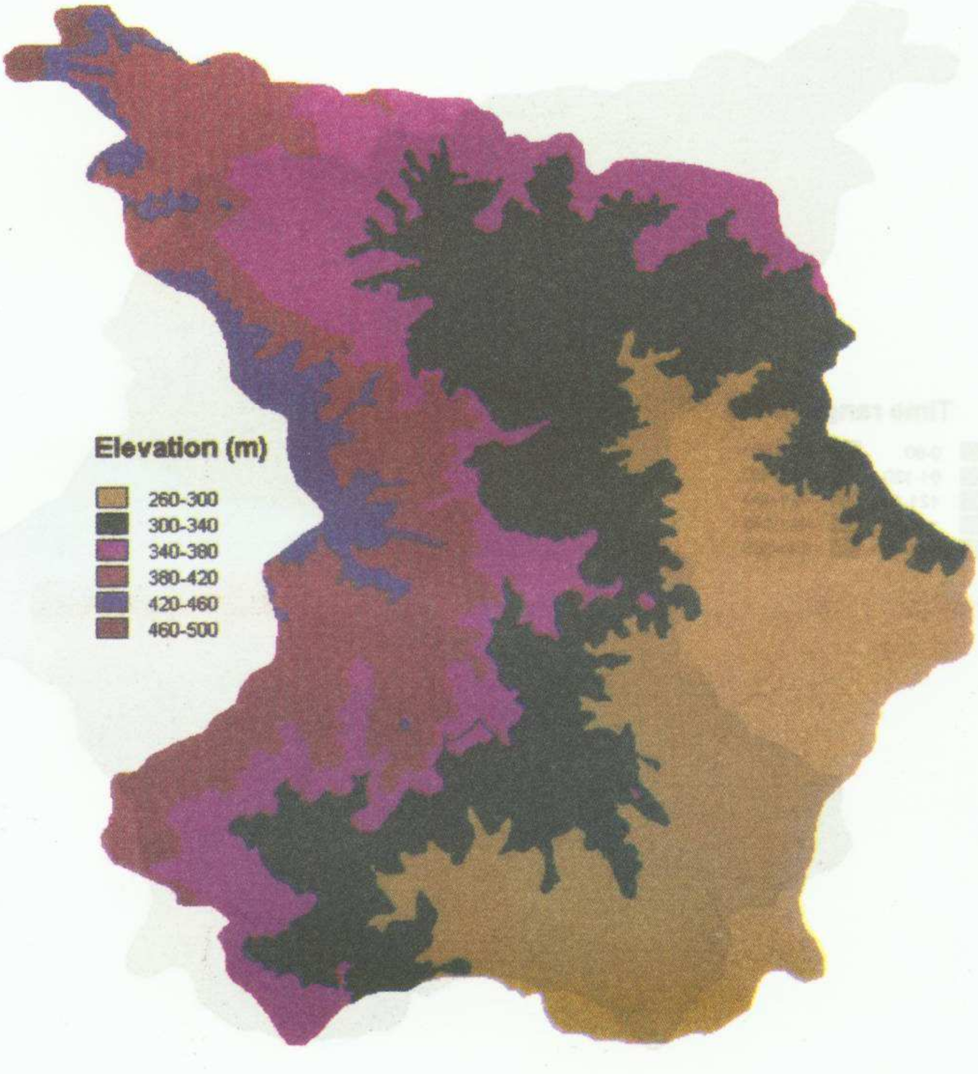


Fig. 9 : Degital Elevation Model (DEM) for the catchment defined by bridge number 807 of Lower Godavari Subzone 3(f)

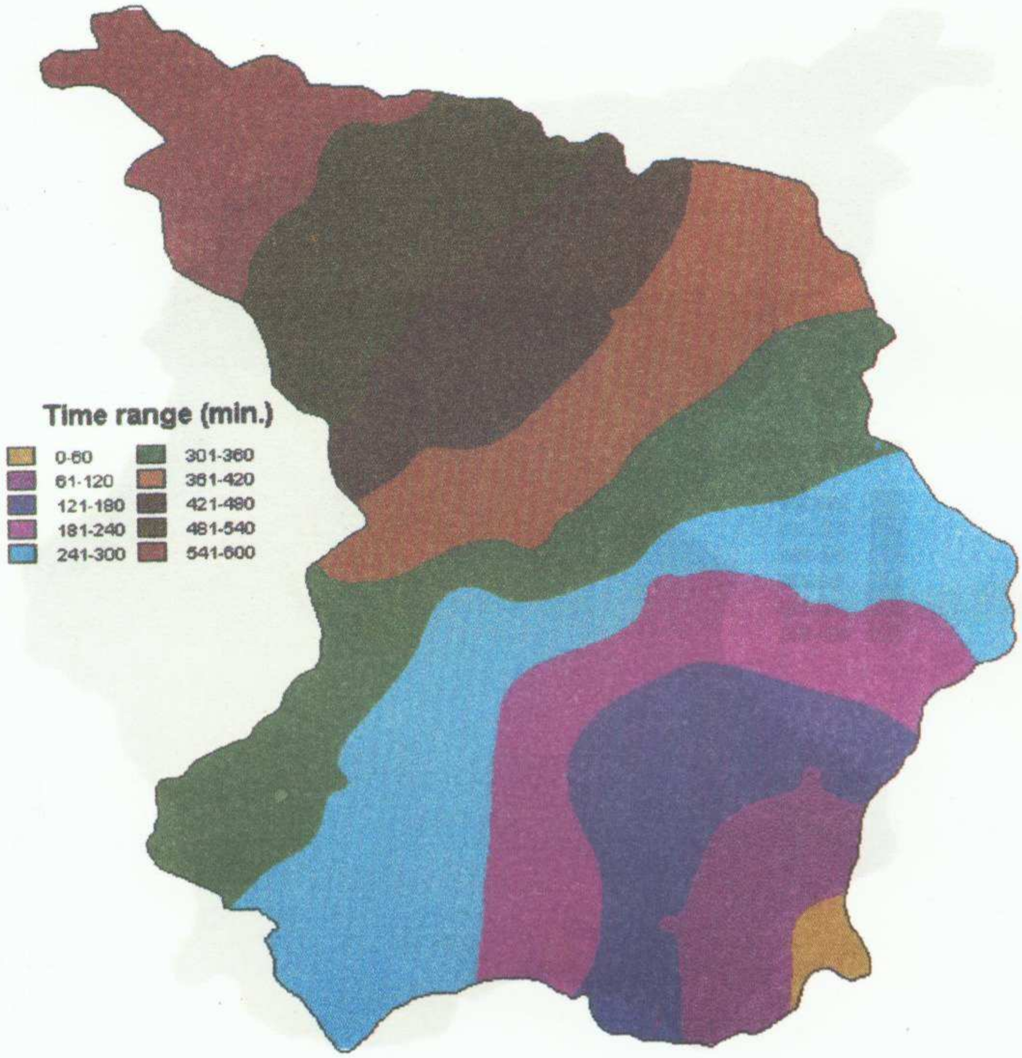


Fig. 10 : Time area diagram of the catchment defined by bridge number 807 of Lower Godavari Subzone 3(f)

7.2 Flood Estimation by GIUH based Clark Model

The analysis carried out and results obtained for computation of excess-rainfall, derivation of Clark IUH model and D-hour unit hydrograph, GIUH derivation using the geomorphological characteristics, development of relationship between intensity of excess-rainfall and the velocity, derivation of unit hydrograph using the GIUH based Clark model approach, computation of direct surface runoff (DSRO) using the derived unit hydrograph, comparison of DSRO hydrographs computed based on GIUH approach, HEC-1 and NASH model as well as computation of error functions used for evaluation of the estimated DSRO hydrographs is presented below.

7.2.1 Computation of excess-rainfall hyetographs

The average rainfall for the study area was computed using the Theissen polygon method. The ϕ-index approach was applied for estimation of excess rainfall. The direct surface runoff (DSRO) was computed by subtracting the baseflow from the observed discharge of the corresponding rainfall-runoff events. The procedure for computation of excess rainfall and DSRO has been described in Section 6.2.1. The observed direct surface runoff data have been used for comparing the flood hydrographs computed by the Clark model based GIUH approach and computation of parameters of the Nash model (Nash, 1957) of the instantaneous unit hydrograph (IUH) derivation and direct surface runoff hydrographs by the HEC-1 package; which have also been used for comparison of the direct surface runoff hydrographs computed by the GIUH approach. In all, the rainfall-runoff data of seven events were analyzed. The excess rainfall hyetographs for the corresponding rainfall events are shown along with the figures showing the comparisons of the computed and observed DSRO hydrographs (Figs. 11 to 17).

7.2.2 Model application

The methodology described in Section 6.2, was applied and the model simulations were carried out for the seven rainfall-runoff events. As the geometric properties of the gauging section and the Manning's roughness coefficient for the basin under study as well as the velocities corresponding to discharges passing through the gauging section at different depths of water flow are not known for the catchment defined by bridge number 807, the approaches for estimation of the velocity under Sections 6.2.4.1 and 6.2.4.2 could not be applied in this study. Instead, the model was run by adopting the peak velocity of 2.75 m/sec, which is based on the information obtained from the field engineers about the normally prevailing velocity at the gauging site under study, during the occurrence of the type of rainfall-runoff storms which have been considered in this study. The unit hydrographs have been derived based on the following three methods:

(i) GIUH based Clark model (GIUH) considering the basin as ungauged.

(ii) Using Clark IUH model option of HEC–1 package (HEC-1) as described in Section 6.2.7.1.

(iii) Using the Nash model of IUH derivation (NASH) as described in Section 6.2.7.2.

The unit hydrographs derived based on the above three methods have been used for convolution of the excess rainfall hyetographs for the seven rainfall-runoff events. The comparisons of the unit hydrographs and the DSRO hydrographs have been carried out employing the following two approaches.

7.2.3 Comparison of observed and computed DSRO hydrographs using GIUH based Clark model, HEC-1 package and Nash IUH model (Approach-I)

In this approach, the unit hydrographs derived using the GIUH approach have been compared with the unit hydrographs computed using Clark IUH model option of HEC-1 package (referred as HEC-1 in this report) and Nash IUH model (referred as NAHS). Also the DSRO hydrographs derived using the GIUH based Clark model approach (referred as GIUH) been compared with the DSRO hydrographs computed using HEC-1 package and Nash IUH model as well as with the observed DSRO hydrographs. The parameters of the Clark model of HEC-1 and the Nash IUH model have been estimated for each of the seven rainfall-runoff events and the same parameters have been used to compute the DSRO hydrographs of the corresponding seven rainfall-runoff events. Thus, the parameters of the HEC-1 package and the Nash IUH model have been computed for a particular rainfall-runoff event and these parameters have been used to reproduce the same DSRO hydrograph. The error functions, as described in Section 6.2.8, have been evaluated for the GIUH based Clark model, HEC-1 package and the Nash IUH model considering the observed and the computed DSRO hydrographs.

7.2.3.1 Comparison of the derived unit hydrographs (Approach-I)

The parameters of the GIUH based Clark model, Clark IUH model (HEC-1 package) and the Nash IUH model for the various rainfall-runoff events are given in Table 4. It is observed from table 4 that the values of T_c and R for GIUH are identical for all the rainfall-runoff events viz. 6.49 and 1.159 respectively. This is because the parameters of GIUH depend on the geomorphological characteristics and the velocity. The parameter velocity has been considered same for all the events in the absence of cross-sectional details of the gauging site and manning's 'n'. The ratio between the storage coefficient (R) and sum of the storage coefficient and the time of concentration, (T_c), i.e. $R/(T_c+R)$ has a unique value for a particular catchment. Its average value has been computed as 0.152 and 0.429 for GIUH based Clark model and HEC-1 model for the seven rainfall-runoff events. Table 5 provides the 1-hour unit hydrographs derived by the GIUH based Clark model, HEC-1 package and Nash model.

Table-4: Parameters of the GIUH based Clark model, Clark IUH model (HEC-1 package) and Nash IUH model for the various rainfall-runoff events (Approach-I)

Event No.	GIUH		HEC-1		NASH	
	T_c	R	T_c	R	n	K
1	6.490	1.159	6.08	2.50	4.02	1.35
2	6.490	1.159	3.89	1.60	5.31	0.70
3	6.490	1.159	2.88	2.50	3.44	1.18
4	6.490	1.159	3.91	1.41	3.93	0.82
5	6.490	1.159	2.45	2.77	2.74	1.46
6	6.490	1.159	4.90	2.97	7.62	0.76
7	6.490	1.159	1.05	3.71	1.34	3.48

Table-5: 1-hour unit hydrographs derived by the GIUH based Clark model, HEC-1 package and Nash model (Approach-I)

Time (hr)	GIUH	HEC-1				NASH			
		Event1	Event2	Event3	Event7	Event1	Event2	Event3	Event7
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	2.8	4.0	10.0	11.0	27.0	1.5	2.3	6.3	31.0
3	13.6	13.0	34.0	36.0	48.0	12.6	27.2	30.7	35.4
4	26.2	23.0	54.0	51.0	37.0	27.4	56.5	45.9	32.0
5	36.7	33.0	54.0	43.0	28.0	36.2	57.9	45.1	27.0
6	46.4	37.0	37.0	29.0	21.0	37.0	41.1	36.0	22.0
7	45.4	36.0	19.0	19.0	16.0	32.4	23.4	25.3	17.7
8	31.6	28.0	10.0	13.0	12.0	25.7	11.5	16.3	14.1
9	16.0	19.0	5.0	9.0	9.0	18.9	5.1	10.0	11.1
10	6.3	12.0	3.0	6.0	7.0	13.2	2.1	5.8	8.7
11	2.5	8.0	1.0	4.0	6.0	8.8	0.8	3.3	6.8
12	1.0	6.0	1.0	3.0	4.0	5.7	0.3	1.8	5.2
13	0.4	4.0	0.0	2.0	3.0	3.6	0.1	1.0	4.1
14	0.2	2.0		1.0	2.0	2.2	0.0	0.5	3.1
15		2.0		1.0	2.0	1.3		0.3	2.4
16		1.0		1.0	1.0	0.8		0.1	1.9
17		1.0		0.0	1.0	0.5		0.1	1.4
18		0.0			1.0	0.0		0.0	1.1
19					1.0				0.8
20					0.0				0.6
21					0.0				0.5
22					0.0				0.0

The values of peak discharge (Q_p), time to peak (T_p) and their product (Q_p* T_p) for 1-hour unit hydrographs derived by the GIUH based Clark model, HEC-1 package and Nash model for the various rainfall-runoff events are given in Table 6.

Table 6: Peak discharge and time to peak of 1-hour unit hydrographs derived by the GIUH based Clark model, HEC-1 package and Nash model (Approach-I)

Event No.	GIUH			HEC-1			NASH		
	Q_p (cumec)	T_p (hr)	Q_p T_p (cumec-hr)	Q_p (cumec)	T_p (hr)	Q_p T_p (cumec-hr)	Q_p (cumec)	T_p (hr)	Q_p T_p (cumec-hr)
1	46.4	5	232.0	37.0	5.0	185.0	37.0	5.0	185.0
2	46.4	5	232.0	54.0	3.0	162.0	57.9	4.0	231.6
3	46.4	5	232.0	51.0	3.0	153.0	45.9	3.0	137.7
4	46.4	5	232.0	57.0	3.0	171.0	61.8	3.0	185.4
5	46.4	5	232.0	50.0	3.0	150.0	44.7	3.0	134.1
6	46.4	5	232.0	38.0	5.0	190.0	44.4	6.0	266.4
7	46.4	5	232.0	48.0	2.0	96.0	35.4	2.0	70.8

7.2.3.2 Comparison of observed and computed DSRO hydrographs (Approach-I)

The direct surface runoff (DSRO) hydrographs computed by the GIUH based Clark model were compared with the observed DSRO hydrographs as well as the DSRO hydrographs computed by the Nash model of IUH derivation and the DSRO hydrographs computed using the HEC-1 package. The values of peak discharge and time to peak of the DSRO hydrographs for the various rainfall-runoff events are given in Table 7. It is observed that the Clark model based GIUH approach estimates the DSRO hydrographs reasonably well as compared to the observed DSRO hydrographs as well as the DSRO hydrographs computed by the Nash model and the HEC-1 package. The GIUH approach considers the catchment under study as ungauged; while, DSRO computations of the Nash model and HEC-1 package are based on the observed data of each of the events.

Table-7: Peak discharge and time to peak of observed DSRO hydrographs and those derived by the GIUH based Clark model, HEC-1 package and Nash model for the various rainfall-runoff events (Approach-I)

Event No.	OBSERVED		GIUH		HEC-1		NASH	
	Q_p (cumec)	T_p (hour)	Q_p (cumec)	T_p (hour)	Q_p (cumec)	T_p (hour)	Q_p (cumec)	T_p (hour)
1	360.3	7	460.5	6	366.6	6	365.5	5
2	543.8	6	419.0	8	459.0	6	470.8	6
3	478.3	5	486.4	8	469.4	6	476.3	7
4	324.5	5	258.4	6	311.5	5	327.5	4
5	402.1	4	389.6	6	389.7	4	367.6	4
6	247.0	8	265.7	11	241.1	10	273.4	11
7	1391.0	4	1546.4	6	1278.4	6	1169.5	6

7.2.3.3 Comparison of error functions used for evaluation of the computed DSRO hydrographs (Approach-I)

The values of the errors functions computed for evaluation of the DSRO hydrographs for the GIUH based Clark model approach, HEC-1 package and the Nash model viz. (i) efficiency, (ii) absolute average error, (iii) root mean square error, (iv) average error in volume, (v) percentage error in peak and (vi) percentage error in time to peak as described in Section 6.2.8 are given in Table 8. The details regarding the values of the error functions computed for the seven rainfall-runoff events are summarised below.

It is seen from the Table 8 that the values of EFF vary from 29.10 to 82.97 percent for the GIUH based Clark model; 80.14 to 97.76 percent for HEC-1; and 79.95 to 96.67 for Nash model. It is also seen that the values of EFF for HEC-1 are higher than those of GIUH based Clark model and the Nash model. In general, EFF values are higher for the DSRO hydrographs computed by HEC-1 package and Nash model as compared to those of the GIUH based Clark model. This is because these models utilise the observed runoff data for computation of the DSRO hydrographs; whereas, the GIUH based Clark model considers the basin as ungauged and utilizes only the geomorphological characteristics of the basin.

It is seen that the values of AAE vary from 30.77 to 357.24 for the GIUH based Clark model; 12.86 to 130.86 for HEC-1; and 17.11 to 136.28 for Nash model. It is also seen that the values of AAE for HEC-1 are lower than those of GIUH based Clark model and the Nash model. It is also observed that the values of RMSE vary from 37.88 to 455.04 for the GIUH based Clark model; 27.11 to 189.96 for HEC-1; and 28.16 to 182.89 for Nash model. It is also seen that the values of RMSE for Nash model are in general lower than those of GIUH based Clark model and the HEC-1 package. It is also seen that the values of AEV vary from 91.48 to 487.64 for the GIUH based Clark model; 90.40 to 478.75 for HEC-1; and 91.23 to 478.41 for Nash model. It is seen that the values of AEV are the lowest for HEC-1 as compared to the GIUH based Clark model and the Nash model.

It is seen that the values of PEP vary from –22.94 to 27.80 for the GIUH based Clark model; -15.59 to 1.74 for HEC-1; and –15.93 to 10.69 for Nash model. The range of variation of the PEP values is the lowest for the HEC-1 as compared to the GIUH based Clark model and the Nash model.

Table-8: Error functions computed based on the observed and computed DSRO hydrographs for the various rainfall-runoff events (Approach-I)

Methods	Error functions for DSRO hydrographs					
	EFF	**AAE**	**RMSE**	**AEV**	**PEP**	**PETP**
			Event 1			
GIUH	82.97	42.09	53.14	143.37	27.80	-14.29
HEC-1	96.74	16.86	27.11	142.99	1.74	-14.29
NASH	95.59	17.49	38.42	142.47	1.43	-28.57
			Event 2			
GIUH	68.70	73.37	99.11	159.57	-22.94	33.33
HEC-1	96.15	22.17	45.04	159.02	-15.59	0
NASH	96.67	20.82	35.73	159.34	-3.41	0
			Event 3			
GIUH	68.02	62.53	100.32	165.40	1.69	60.00
HEC-1	92.49	33.43	54.71	164.62	-1.87	20.00
NASH	92.71	27.89	49.76	164.75	-0.43	40.00
			Event 4			
GIUH	29.10	88.53	99.53	133.01	-20.39	20.00
HEC-1	97.76	12.86	33.80	134.80	-4.03	0
NASH	95.73	17.11	28.16	135.07	0.9	-20.00
			Event 5			
GIUH	29.93	83.22	112.15	156.80	-3.13	50.00
HEC-1	95.10	23.93	38.61	154.11	-3.10	0
NASH	93.15	26.50	36.16	155.28	-8.60	0
			Event 6			
GIUH	82.65	30.77	37.88	91.48	7.56	37.50
HEC-1	87.89	23.54	32.80	90.40	-2.39	25.0
NASH	79.95	29.20	42.22	91.23	10.69	37.50
			Event 7			
GIUH	-33.72	357.24	455.04	487.64	11.16	100.00
HEC-1	80.14	130.86	189.96	478.75	-8.10	50.00
NASH	80.21	136.28	182.89	478.41	-15.93	50.00

7.2.4 Comparison of observed and computed DSRO hydrographs using GIUH based Clark model, HEC-1 package and Nash IUH model (Approach-II)

In Approach-II, the unit hydrographs derived using the GIUH approach have been compared with the unit hydrographs computed using HEC-1 package and Nash IUH model. Also the DSRO hydrographs derived using the GIUH approach have been compared with the DSRO hydrographs computed using HEC-1 package and Nash IUH model as well as with the observed DSRO hydrographs. The parameters of the Clark IUH model of HEC-1 and the Nash model have been estimated for all the seven rainfall-runoff events by taking the geometric mean of the parameters derived for the remaining six out of seven rainfall-runoff events each time by excluding the rainfall-runoff event whose excess rainfall hyetograph has been used for convolution with the unit hydrograph derived by the aforementioned geometric mean parameter values. For example, the geometric mean values of the Clark and Nash IUH models for convolution with the excess-rainfall data of the first rainfall-runoff event have been computed by taking the geometric mean of the parameters derived for the nine rainfall-runoff events viz., event No. 2 to event No. 7; thus excluding the parameter values obtained for the first event. If excess-rainfall hyetograph of event No. 4 has been used for convolution with the unit hydrograph; then, the parameter values of event No. 1 to 3 and 5 to 7 (six events) have been used to compute the geometric mean values of the parameters. The error functions, as described in Section 6.2.8, have been evaluated for the GIUH based Clark model, HEC-1 package and the Nash IUH model considering the observed and the computed DSRO hydrographs as desribed below.

7.2.4.1 Comparison of derived unit hydrographs (Approach-II)

Table 9 shows the values of T_c and R for HEC-1 package for all the ten individual rainfall-runoff events for approach-I and also the arithmetic mean and geometric mean values of T_c and R for approach-II (as mentioned above) for all the seven rainfall-runoff events. Table 10 shows the values of n and K for Nash IUH model for all the seven individual rainfall-runoff events for approach-I and also the arithmetic mean and geometric mean values of n and K for approach-II (as mentioned above) for all the seven rainfall-runoff events. The arithmetic mean parameters of HEC-1 package (Clark IUH model) and Nash IUH model derived from the historical data and their 90% and 95% confidence limits are given in Table 11.

Table 9: Mean parameters of Clark IUH Model (HEC-1 Package) derived from historical data (Approach-II)

Event No.	Clark model of IUH (HEC-1 package)					
	For individual storm		Arithmetic mean*		Geometric mean*	
	T_c	R	T_c	R	T_c	R
1	6.08	2.50	3.18	2.49	2.86	2.36
2	3.89	1.60	3.55	2.64	3.09	2.54
3	2.88	2.50	3.71	2.49	3.24	2.36
4	3.91	1.41	3.54	2.68	3.08	2.59
5	2.45	2.77	3.79	2.45	3.33	2.32
6	4.90	2.97	3.38	2.42	2.97	2.29
7	1.05	3.71	4.02	2.29	3.84	2.21

***Arithmetic/Geometric mean values based of the parameters T_c and R of the remaining storms.**

Table 10: Mean parameters of Nash IUH Model derived from historical data (Approach-II)

Event No.	NASH model of IUH					
	For individual storm		Arithmetic mean*		Geometric mean*	
	n	K	n	K	n	K
1	4.02	1.35	4.06	1.40	3.55	1.17
2	5.31	0.70	3.85	1.51	3.39	1.31
3	3.44	1.18	4.16	1.43	3.65	1.20
4	3.93	0.82	4.08	1.49	3.57	1.28
5	2.74	1.46	4.28	1.38	3.79	1.16
6	7.62	0.76	3.46	1.50	3.19	1.29
7	1.34	3.48	4.51	1.05	4.27	1.00

***Arithmetic/Geometric mean values based of the parameters n and K of the remaining storms.**

Table 11: Mean parameters of Clark and Nash IUH models derived from the historical data and their 90% and 95% confidence limits

Parameter	Mean	Standard Deviation	Confidence level = 90%		Confidence level = 95%	
			Lower limit	Upper limit	Lower limit	Upper limit
Parameters of Clark IUH model (HEC-1 package)						
T_c	3.59	1.65	1.48	5.70	0.88	6.30
R	2.49	0.79	1.48	3.50	1.19	3.79
Parameters of Nash IUH model						
n	4.06	1.99	1.51	6.61	0.79	7.33
K	1.39	0.97	0.15	2.63	-0.21	2.99

The values of R and T_c the GIUH based Clark model have been estimated as 1.16 hours and 6.49 hours respectively. The arithmetic mean values of R and T_c for the seven events for the HEC-1 package are 2.49 hours and 3.59 hours respectively. The R and T_c values of the GIUH based Clark model are quite close to the 95% confidence limits of the R and T_c values of the HEC-1 package computed based on the historical data. A lower value of R which is a storage coefficients reflects a higher peak value of the DSRO hydrograph and a lower value of T_c reflects a lower time to peak of the DSRO hydrograph. On the other hand, a higher value of R which is a storage coefficients reflects a lower peak value of the DSRO hydrograph and a higher value of T_c reflects a higher time to peak of the DSRO hydrograph.

The value of the Nash IUH model parameter n which is a shape parameters is a measure of catchment channel storage required to define the shape of the IUH. A lower value of n results in higher peak of unit hydrograph because there is less storage for attenuating the peak flow; on the other hand a higher value of n leads lower unit hydrograph peak as it signifies higher storage for attenuating the peak flow. The parameter K of the Nash IUH model, which is a scale parameter, indicates the dynamics of the rainfall-runoff process of the catchment. A smaller K value reflects a lower time to peak of the runoff hydrograph and a larger K value reflects a higher time to peak of the runoff hydrograph.

Table 12 provides the 1-hour unit hydrographs derived by the GIUH based Clark model, HEC-1 package and Nash model for approach-II. The values of peak discharge (Q_p), time to peak (T_p) and their product (Q_p* T_p) for 1-hour unit hydrographs derived by the GIUH based Clark model, HEC-1 package and Nash model for the various rainfall-runoff events for approach-II are given in Table 13.

Table 12: 1-hour unit hydrographs derived by the GIUH based Clark model, HEC-1 package and Nash model (Approach-II)

Time (hr)	GIUH	HEC-1				NASH			
		Event1	Event2	Event3	Event7	Event1	Event2	Event3	Event7
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	2.8	13.0	11.0	11.0	10.0	5.5	5.2	4.3	2.8
3	13.6	42.0	37.0	37.0	30.0	28.6	25.6	24.7	22.5
4	26.2	54.0	51.0	53.0	48.0	44.8	40.5	41.5	43.3
5	36.7	42.0	43.0	45.0	49.0	45.3	42.5	44.3	48.2
6	46.4	27.0	29.0	29.0	34.0	36.8	36.3	37.7	40.6
7	45.4	18.0	19.0	19.0	22.0	26.2	27.4	28.0	29.0
8	31.6	12.0	13.0	12.0	14.0	17.1	19.1	19.0	18.5
9	16.0	7.0	9.0	8.0	9.0	10.5	12.6	12.1	10.9
10	6.3	5.0	6.0	5.0	5.0	6.2	7.9	7.3	6.1
11	2.5	3.0	4.0	3.0	3.0	3.5	4.8	4.3	3.2
12	1.0	2.0	3.0	2.0	2.0	1.9	2.9	2.4	1.6
13	0.4	1.0	2.0	1.0	1.0	1.0	1.7	1.3	0.8
14	0.2	1.0	1.0	1.0	1.0	0.5	0.9	0.7	0.4
15	0.0	1.0	1.0	1.0	1.0	0.3	0.5	0.4	0.2
16		0.0	1.0	0.0	0.0	0.1	0.3	0.2	0.1
17			0.0			0.1	0.2	0.1	0.0
18						0.0	0.0	0.1	
19								0.0	

Table 13: Peak discharge and time to peak of 1-hour unit hydrographs derived by the GIUH based Clark model, HEC-1 package and Nash model (Approach-II)

Event No.	GIUH			HEC-1			NASH		
	Q_p (cumec)	T_p (hr)	$Q_p T_p$ (cumec -hr)	Q_p (cumec)	T_p (hr)	$Q_p T_p$ (cumec -hr)	Q_p (cumec)	T_p (hr)	$Q_p T_p$ (cumec -hr)
1	46.4	5	232.0	54.0	2	108.0	45.3	4	181.2
2	46.4	5	232.0	51.0	2	102.0	42.5	4	170.0
3	46.4	5	232.0	53.0	2	106.0	44.3	4	177.2
4	46.4	5	232.0	51.0	2	102.0	42.4	4	169.6
5	46.4	5	232.0	53.0	2	106.0	44.8	4	179.2
6	46.4	5	232.0	55.0	2	110.0	44.6	3	133.8
7	46.4	5	232.0	49.0	3	98.0	48.2	4	192.8

7.2.4.2 Comparison of observed and computed DSRO hydrographs (Approach-II)

The direct surface runoff (DSRO) hydrographs computed by the GIUH based Clark model were compared with the observed DSRO hydrographs as well as the DSRO hydrographs computed by the Nash model of IUH derivation and the DSRO hydrographs computed using the HEC-1 package as shown in Fig. 11 through Fig. 17. The values of peak discharge and time to peak of the DSRO hydrographs for the various rainfall-runoff events are given in Table 14. It is observed that the Clark model based GIUH approach estimates the DSRO hydrographs reasonably well as compared to the observed DSRO hydrographs as well as the DSRO hydrographs computed by the Nash model and the HEC-1 package. The GIUH approach considers the catchment under study as ungauged; while, DSRO computations of the Nash model and HEC-1 package are based on the observed data of each of the events.

Table-14: Peak discharge and time to peak of observed DSRO hydrographs and those derived by the GIUH based Clark model, HEC-1 package and Nash model for the various rainfall-runoff events (Approach-II)

Event No.	OBSERVED		GIUH		HEC-1		NASH	
	Q_p (cumec)	T_p (hour)	Q_p (cumec)	T_p (hour)	Q_p (cumec)	T_p (hour)	Q_p (cumec)	T_p (hour)
1	360.3	7	460.5	6	492.5	3	450.4	4
2	543.8	6	419.0	8	405.9	5	381.4	7
3	478.3	5	486.4	8	474.6	6	461.7	7
4	324.5	5	258.4	6	267.6	3	240.2	5
5	402.1	4	389.6	6	413.2	3	371.6	5
6	247.0	8	265.7	11	301.5	8	278.2	9
7	1391.0	4	1546.4	6	1461.6	6	1507.0	7

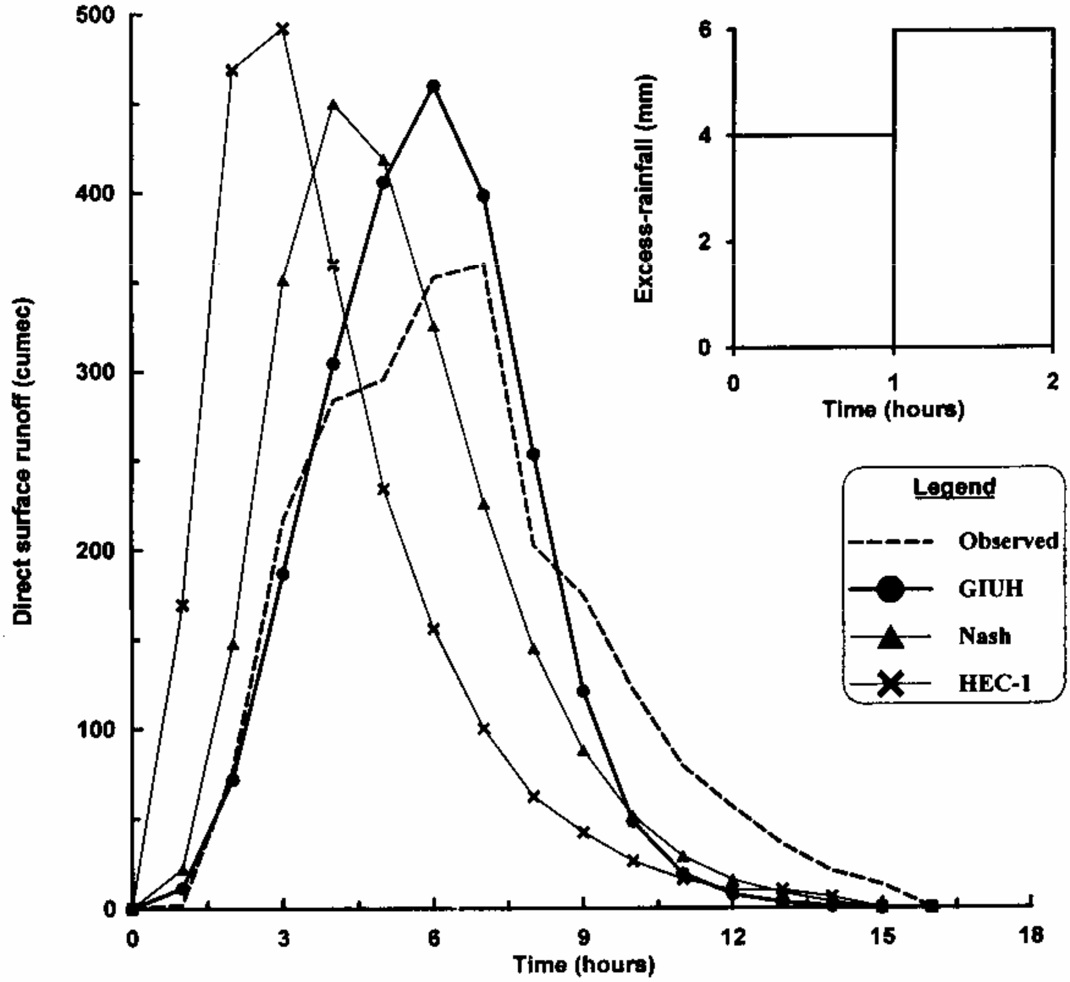


Fig. 11 : Comparison of observed and computed direct surface runoff hydrographs for catchment upto bridge No. 807 (Event No. 1)

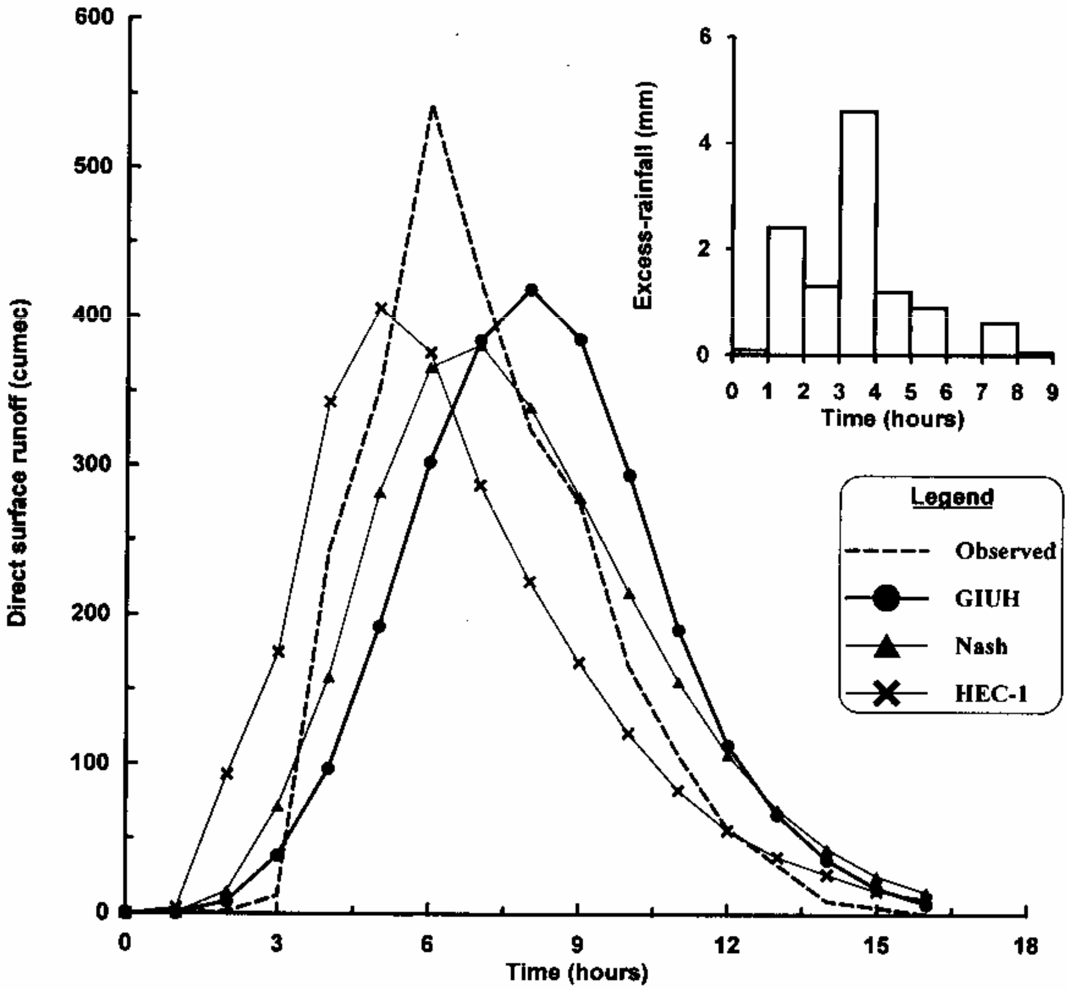


Fig. 12: Comparison of observed and computed direct surface runoff hydrographs for catchment upto bridge No. 807 (Event No. 2)

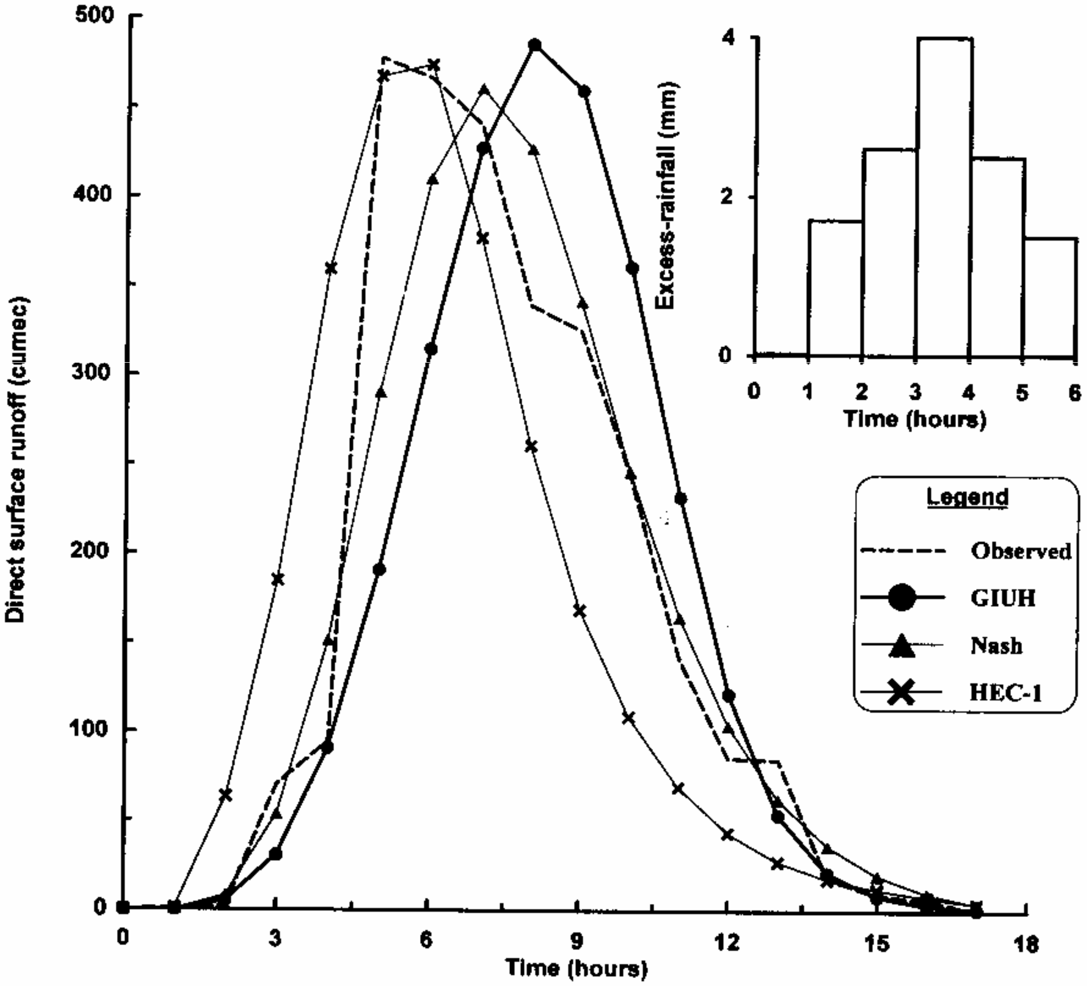


Fig. 13: Comparison of observed and computed direct surface runoff hydrographs for catchment upto bridge No. 807 (Event No. 3)

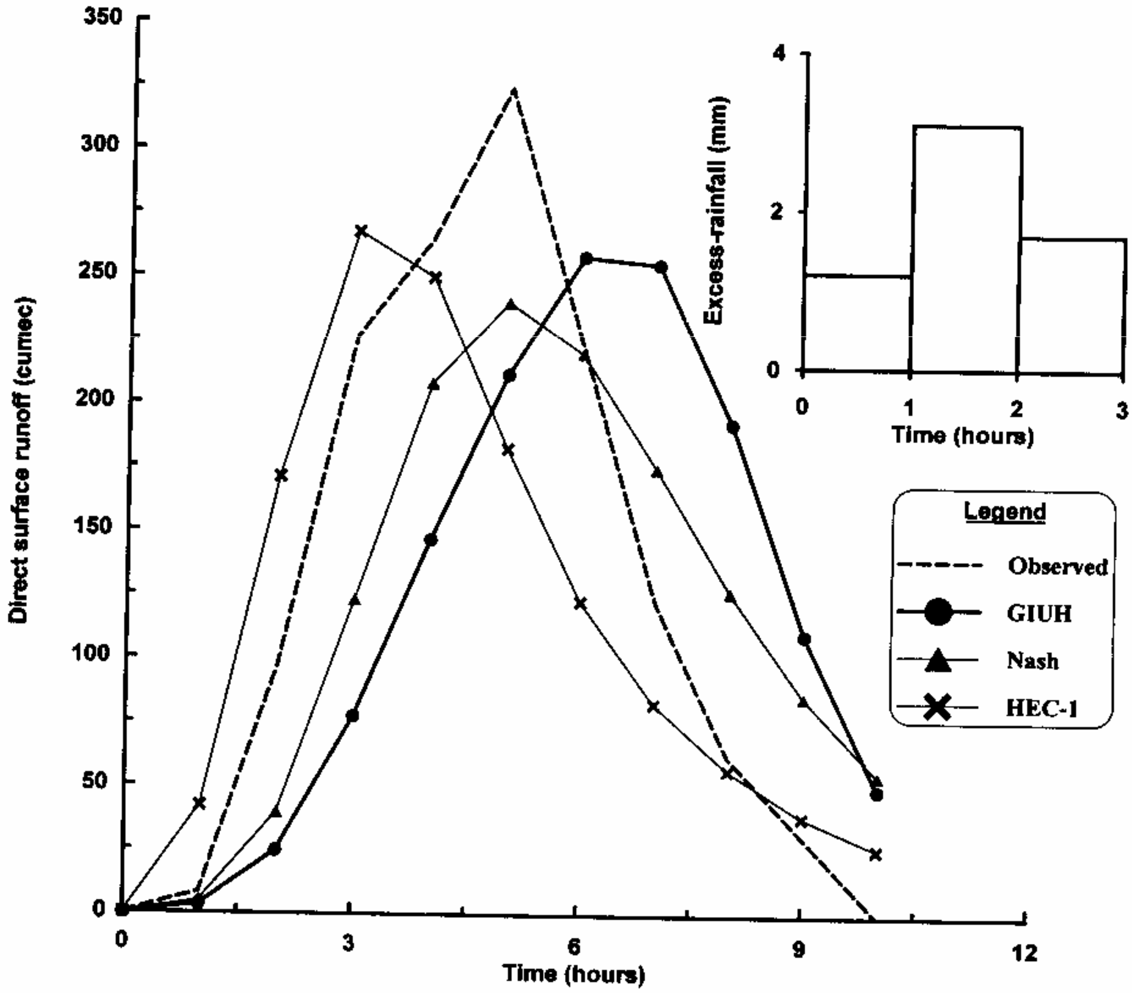


Fig. 14 : Comparison of observed and computed direct surface runoff hydrographs for catchment upto bridge No. 807 (Event No. 4)

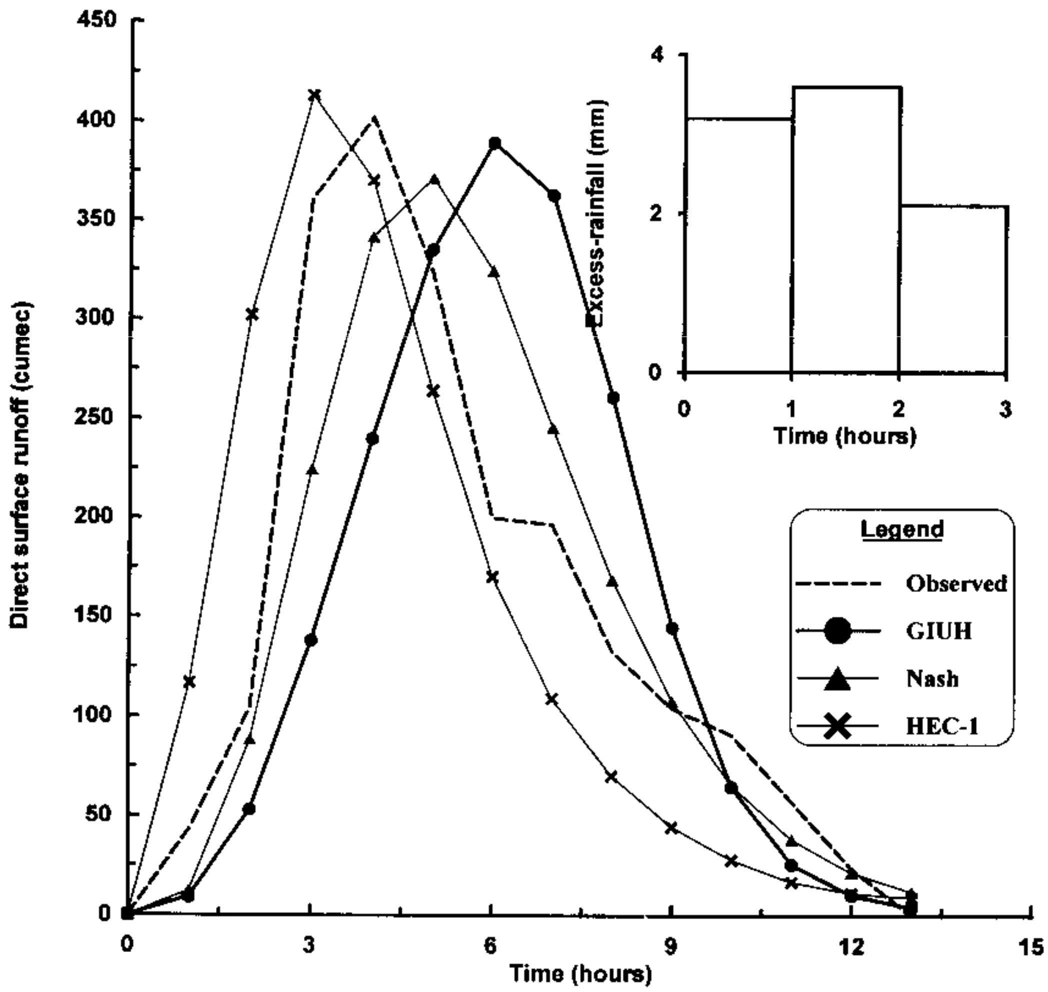


Fig. 15: Comparison of observed and computed direct surface runoff hydrographs for catchment upto bridge No. 807 (Event No. 5)

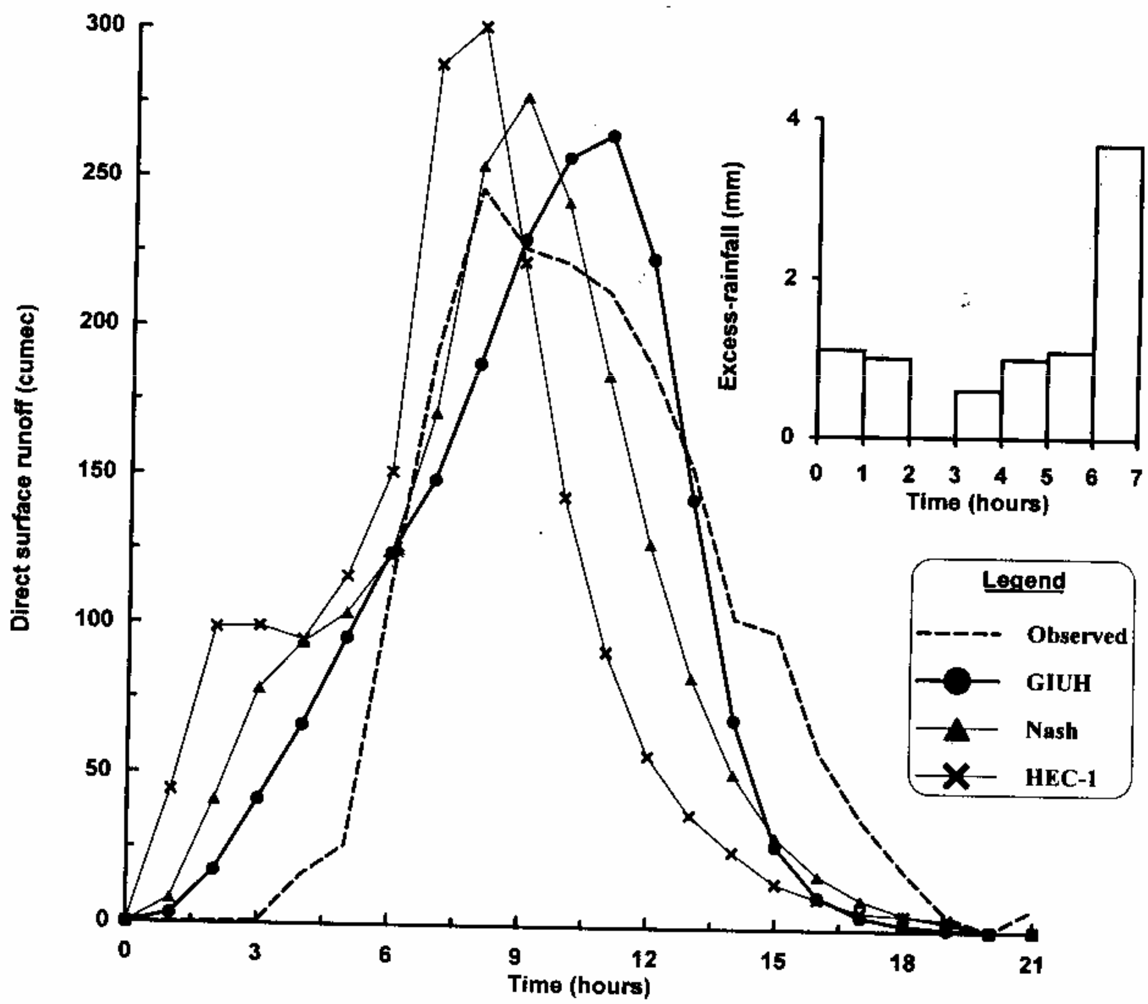


Fig. 16: Comparison of observed and computed direct surface runoff hydrographs for catchment upto bridge No. 807 (Event No. 6)

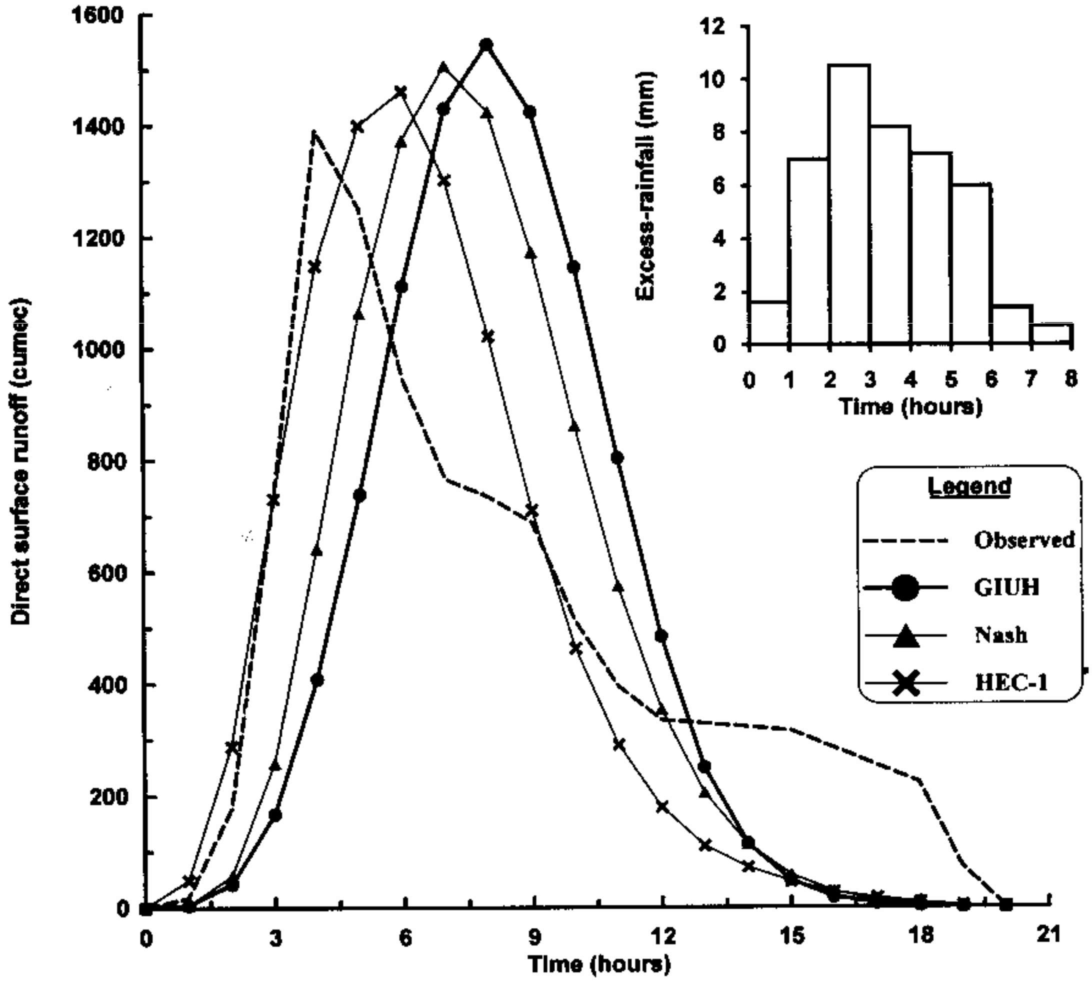


Fig. 17: Comparison of observed and computed direct surface runoff hydrographs for catchment upto bridge No. 807 (Event No. 7)

7.2.4.3 Comparison of error functions used for evaluation of the computed DSRO hydrographs (Approach-II)

The values of the errors functions computed for evaluation of the DSRO hydrographs for the GIUH based Clark model approach, HEC-1 package and the Nash model viz. (i) efficiency, (ii) absolute average error, (iii) root mean square error, (iv) average error in volume, (v) percentage error in peak and (vi) percentage error in time to peak as described in Section 6.2.8 are given in Table 15.

The error functions based on the comparison of the observed DSRO and computed DSRO hydrographs for the three methods, presented in Table 15, show that the values of EFF for the GIUH based Clark model are higher in two cases out of the seven rainfall-runoff events. The value of EFF for HEC-1 package are also higher in case of one event while the values of EFF for Nash IUH model are higher in case of four events. It is seen that the values of AAE and RMSE for the GIUH based Clark model are lower in two cases out of the seven rainfall-runoff events. The values of AAE for HEC-1 package are lower in case of two events while the values of AAE for Nash IUH model are lower in case of three events. It is seen that the values of RMSE for the HEC-1 package are lower in case of one event while the values of RMSE for Nash IUH model are lower in case of four events.

It is observed that the values of AEV are lowest for HEC-1 package for all the seven rainfall-runoff events. It is also seen that the values of PEP are lower for GIUH based Clark model in three cases. The values of PEP are lower for HEC-1 package in the remaining four cases; Thus it is observed that as per Approach-II, the GIUH based Clark model, which considers the basin under study as ungauged; in general, provides DSRO estimates with comparable accuracy with the HEC-1 package and Nash IUH model which utilise the historical data.

Table-15: Error functions computed based on the observed and computed DSRO hydrographs (Approach-II)

Methods	Error functions for DSRO hydrographs					
	EFF	AAE	RMSE	AEV	PEP	PETP
Event 1						
GIUH	82.97	42.09	53.14	143.37	27.80	-14.29
HEC-1	-61.42	122.67	164.14	134.60	36.69	-57.14
NASH	59.80	65.07	82.72	142.66	25.00	-42.86
Event 2						
GIUH	68.70	73.37	99.11	159.57	-22.94	33.33
HEC-1	76.14	64.93	90.01	151.64	-25.36	-16.67
NASH	86.06	45.19	66.04	157.93	-29.86	16.67
Event 3						
GIUH	68.02	62.53	100.32	165.40	1.69	60.00
HEC-1	71.73	63.25	97.42	155.94	-0.77	20.00
NASH	90.28	32.38	60.43	164.36	-3.48	40.00
Event 4						
GIUH	29.10	88.53	99.53	133.01	-20.39	20.00
HEC-1	70.54	48.56	71.46	123.99	-17.54	-40.00
NASH	73.22	53.66	68.80	127.75	-26.00	0
Event 5						
GIUH	29.93	83.22	112.15	156.80	-3.13	50.00
HEC-1	68.40	59.96	81.48	148.11	2.76	-25.00
NASH	80.23	43.30	67.20	155.50	-7.59	25.00
Event 6						
GIUH	82.65	30.77	37.88	91.48	7.56	37.50
HEC-1	32.31	62.67	75.29	86.29	22.05	0
NASH	75.45	36.28	45.81	90.94	12.65	12.50
Event 7						
GIUH	-33.72	357.24	455.04	487.64	11.16	100.00
HEC-1	63.58	186.34	258.35	466.35	5.07	50.00
NASH	11.57	290.78	383.76	485.72	8.34	75.00

7.3 Uncertainty Analysis of the GIUH based Clark Model

In hydrologic models in general there are several uncertain parameters. In any uncertainty analysis dealing with more than one variable relationships that exist among the input parameters should not be violated. Determining the uncertainty to assign to input parameter is one of the major hurdles that must be addressed in the overall evaluation of uncertainty associated with hydrologic modelling. Hence, a single best estimate or expected value for each of the parameters should be obtained. Limits on parameters and suggested ranges of parameter values should be investigated. If the parameter is a physically measurable parameter, then the range of its values reported in literature and its variability should be examined with respect to the actual value of the parameter being utilised in a particular modelling study.

If for example, length ratio (R_L) is considered for derivation of unit hydrograph by the GIUH based Clark model, and its value is evaluated as 1.66; then, it may be realised that its value lies anywhere between 1.5 and 3.5 for various catchments as described in Section 6.1. In uncertainty analysis, we attempt to recognize this uncertainty and to associate weights reflecting our degree of belief that the R_L will have a value in a certain range. If we are highly confident that the R_L is near 1.66, we use 1.66 as our mean and a small variance. If we are not very sure that 1.66 is a good estimate, we increase the variance. So the shape or spread of the pdf on the parameter reflects our degree of belief or our confidence that the parameter lies in a certain range.

The geomorphological parameters used in estimation of peak of the unit hydrograph derived by the GIUH based Clark model are:

(i) Length ratio (R_L)
(ii) Length of the highest order stream (L_Ω)
(iii) Length of the main stream (L)

Apart from these, the velocity parameter (V) is also used for estimation of peak of the unit hydrograph derived by the GIUH based Clark model.

7.3.1 Sensitivity analysis

In conducting sensitivity analysis, it is desired to determine the sensitivity of model outputs to changes in values for model inputs. There are two types of sensitivity coefficients which are used. One is called an absolute sensitivity coefficient or simply the sensitivity coefficient (S) and the other a relative sensitivity coefficient (S_r). The relative sensitivity coefficients may be preferred in comparison to the absolute sensitivity coefficients; since, they are dimensionless and can be compared across the parameters, while the absolute sensitivity coefficients have units of output over input and can not be directly compared across noncommensurate parameters. Parameters can be ranked on the basis of their relative sensitivity coefficients and only the most sensitive ones retained for further analysis.

In the present study, relative sensitivity coefficients have been computed for the four parameters, viz. R_L, L_Ω, L and V. For the study area the values of these parameters i.e. R_L is evaluated as 1.66, L_Ω is measured as 19.40 km, L is measured as 64.25 km and V is adopted as 2.75 m/s. With these parameter values, peak of the unit hydrograph is estimated as 46.37 cumec and the time to peak is 5 hours. For conducting the relative sensitivity analysis, the peak of the unit hydrograph and the time to peak are computed for various values of these four parameters; by varying only one of these parameters at a time and adopting the actual aforesaid values for the remaining three parameters, as shown in Tables 16 through 19.

Table 16: Variation of unit hydrograph peak and time to peak with length ratio (R_L)

Sl. No.	Length ratio (R_L)	UH peak (cumec)	Time to peak (hour)
1	1.328	43.67	6
2	1.411	44.21	6
3	1.494	44.67	6
4	1.577	45.52	5
5	1.660	46.37	5
6	1.743	47.18	5
7	1.826	47.97	5
8	1.909	48.69	5
9	1.992	49.36	5

Table 17: Variation of unit hydrograph peak and time to peak with length of highest order stream (L_Ω)

Sl. No.	Length of highest order stream (L_Ω) (km)	UH peak (cumec)	Time to peak (hour)
1	17.46	50.33	5
2	18.43	48.36	5
3	19.40	46.37	5
4	20.37	44.61	6
5	21.34	43.69	6

Table 18: Variation of unit hydrograph peak and time to peak with length of main stream (L)

Sl. No.	Length of main stream (L) (km)	UH peak (cumec)	Time to peak (hour)
1	57.83	49.24	5
2	61.04	47.86	5
3	64.25	46.37	5
4	67.46	46.38	6
5	70.68	46.02	6

Table 19: Variation of unit hydrograph peak and time to peak with velocity parameter (V)

Sl. No.	Velocity (V) (m/s)	UH peak (cumec)	Time to peak (hour)
1	2.2000	38.31	7
2	2.3375	40.82	6
3	2.4750	43.58	6
4	2.6125	45.38	6
5	2.7500	46.37	5
6	2.8875	49.56	5
7	3.0250	52.24	5
8	3.1625	54.30	5
9	3.3000	55.03	5

The values of relative sensitivity coefficients S_r computed for the four parameters are given in Table 20. It is observed that parameters V and L_Ω are more sensitive and L and R_L are relatively less sensitive in computing peak of the unit hydrograph by the GIUH based Clark model.

Table 20: Values of relative sensitivity coefficients (S_r) for the four parameters

Sl. No.	Parameter	Parameter value	Relative Sensitivity coefficient (S_r)
1	R_L	1.66	0.307
2	L_Ω	19.40 km	-0.716
3	L	64.25 km	-0.348
4	V	2.75 m/s	0.901

7.3.2 Uncertainty analysis (First Order Analysis)

In the present study, uncertainty analysis has been carried out by first order analysis (FOA) as described in Section 6.3.2, considering the following cases:

(i) Case I – Considering the uncertainty associated with Length ratio (R_L), Length of the highest order stream (L_Ω), Length of the main stream (L) and velocity (V),

(ii) Case II - Considering the uncertainty associated with Length ratio (R_L), Length of the highest order stream (L_Ω) and Length of the main stream (L), and

(iii) Case III- Considering the uncertainty associated with Length ratio (R_L) and Length of the highest order stream (L_Ω)

7.3.2.1 Considering the uncertainty associated with R_L, L_Ω, L and V (Case-I)

In the present study, length ratio (R_L) is evaluated as 1.66. The length of the highest order stream (L_Ω) is measured as 19.40 km. The length of the main stream (L) is measured as 64.25 km and the value of parameter velocity (V) is adopted as 2.75 m/s. The peak of the unit hydrograph and the time to peak are computed for various values of these four parameters; by varying only one of these parameters at a time and adopting the actual aforesaid values for the remaining three parameters, as shown in Tables 16 through 19, presented in Section 7.3.1. The values of standard deviation (σ), variance (σ^2) and coefficient of variation (C_v) for the range of the four parameters, R_L, L_Ω, L and V considered in the study (as given in Tables 16 through 19) are shown in Table 21.

Table 21: Values of standard deviation (σ), variance (σ^2) and coefficient of variation (C_v) for the range of the four parameters (R_L, L_Ω, L and V)

Sl. No.	Parameter	Standard deviation (σ)	Variance (σ^2)	Coefficient of variation (C_v)
1	R_L	0.227	0.052	0.137
2	L_Ω	1.534	2.352	0.079
3	L	5.079	25.800	0.079
4	V	0.377	0.142	0.137

Figures 18 through 21 show the variation of peak of the unit hydrographs with variation in the values of R_L, L_Ω, L and V respectively.

Following the methodology discussed in Section 6.3.2, the values of uncertainty in peak of the unit hydrograph estimated by the GIUH based Clark model caused by uncertainty in the values of the paramaters of the model viz. R_L, L_Ω, L and V are computed as given in Table 22. Fig. 22 shows the uncertainty associated with each of these parameters.

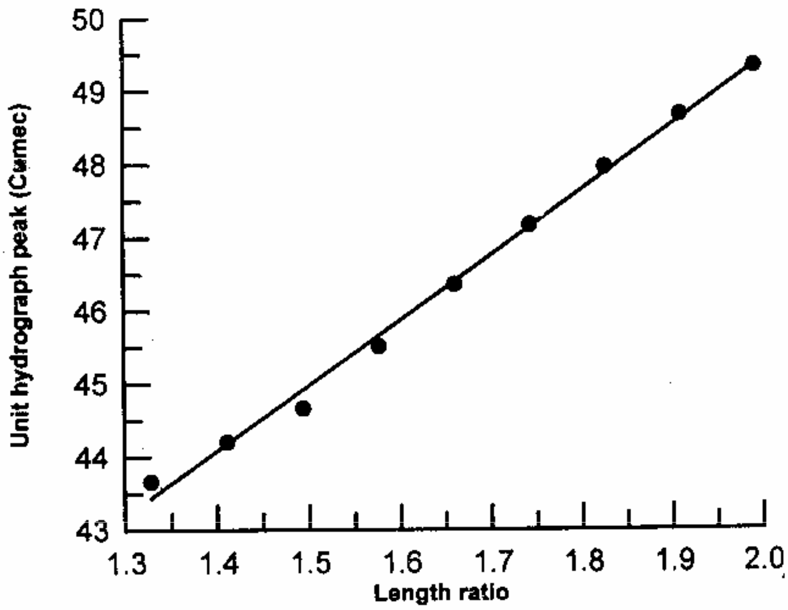


Fig. 18: Variation of peak of unit hydrograph derived by the GIUH approach with length ratio

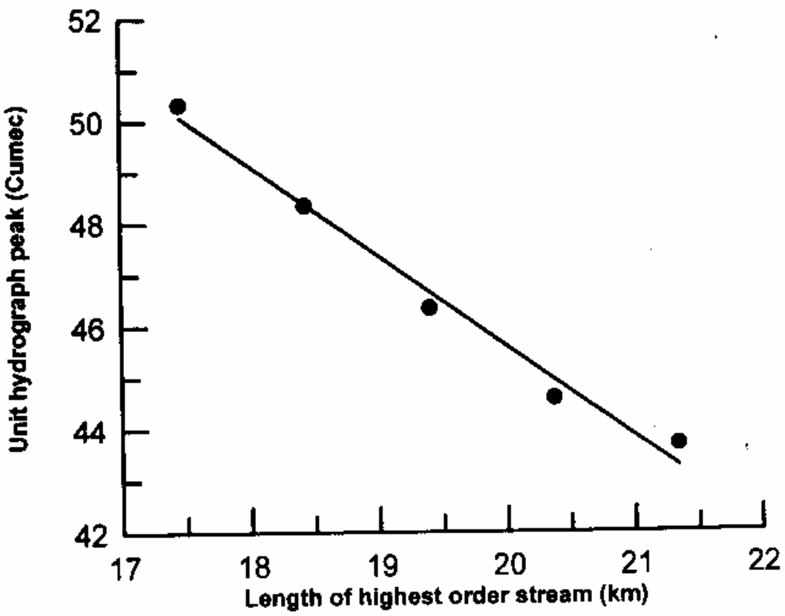


Fig. 19: Variation of peak of unit hydrograph derived by the GIUH approach with length of highest order stream

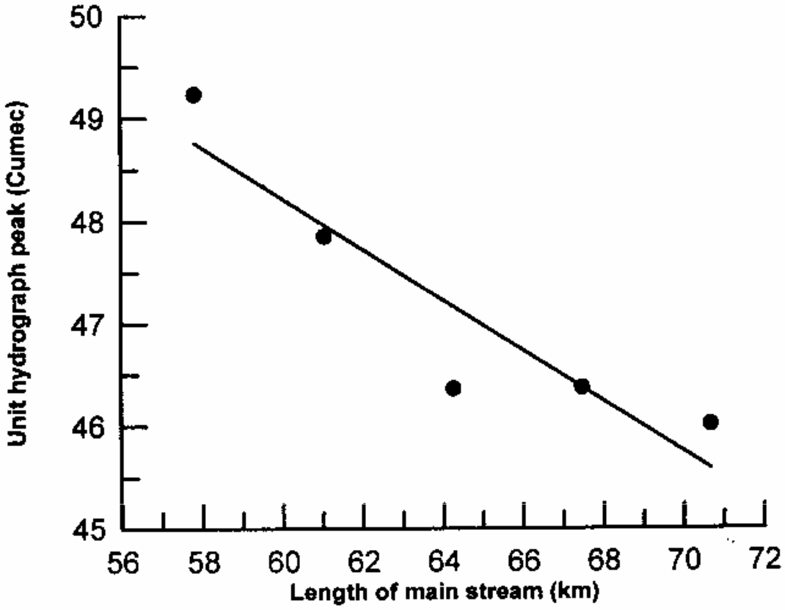


Fig. 20: Variation of peak of unit hydrograph derived by the GIUH approach with length of main stream

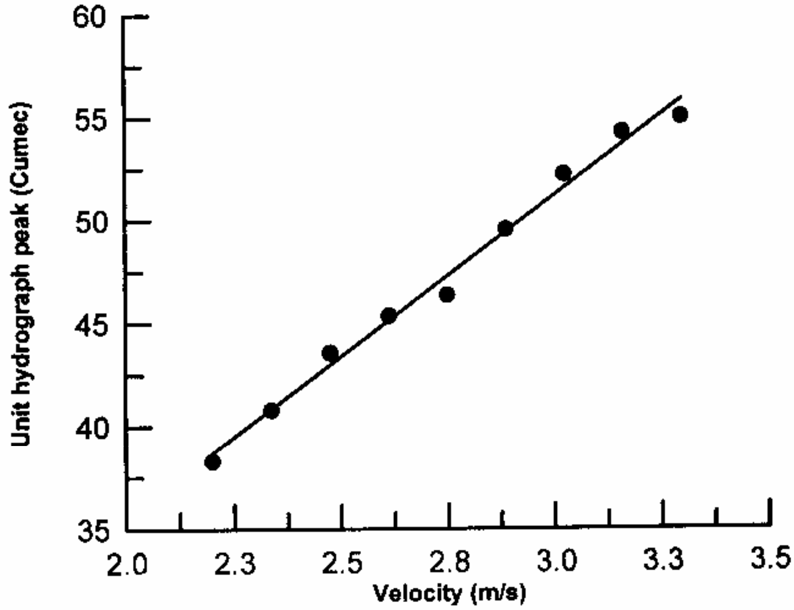


Fig. 21: Variation of peak of unit hydrograph derived by the GIUH approach with velocity parameter

Fig. 22 : Uncertainty associated with the various parameters of the GIUH based Clark model (Case-I)

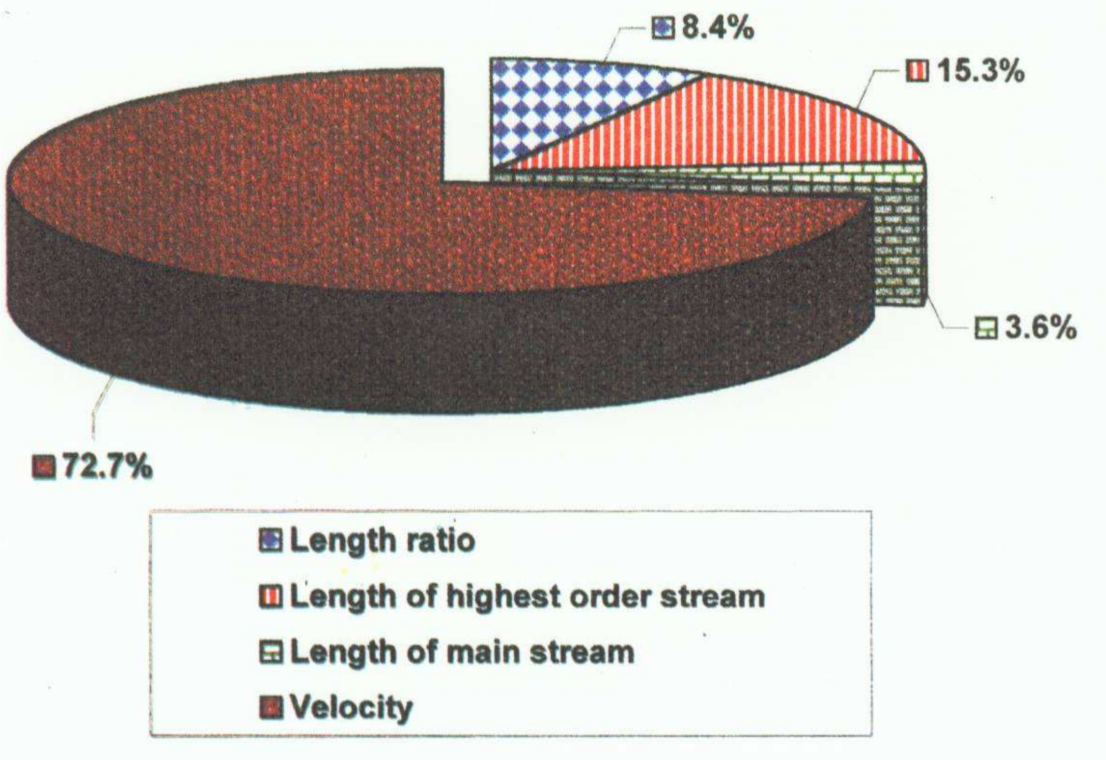


Table 22: Values of uncertainty (F_l) in peak of unit hydrograph caused by uncertainty in R_L, L_Ω, L and V

Sl. No.	Parameter	Uncertainty in peak of UH	
		F_l	Values (%)
1	R_L	F_{RL}	8.4
2	L_Ω	$F_{L\Omega}$	15.3
3	L	F_L	3.6
4	V	F_V	72.7

From the above analysis carried out as per Case-I when the four parameters, viz. R_L, L_Ω, L and V are considered; it is apparent that the peak of the unit hydrograph computed by the GIUH based Clark model for the catchment defined by the bridge No. 807 is quite uncertain. The uncertainty in the velocity parameter (V) leads to 72.7% uncertainty in peak of the unit hydrograph and it emerges to be the biggest contributor to that uncertainty. The uncertainty in parameters L_Ω, R_L and L contributes to 15.3%, 8.4% and 3.6% uncertainty in the peak of the unit hydrograph respectively. Hence, the value of the velocity parameter (V) needs to be estimated with the highest precision for accurate estimation of the peak of the unit hydrograph derived by the GIUH based Clark model. As uncertainty in L_Ω and R_L, also leads to 15.3% and 8.4% uncertainty in the peak of unit hydrograph; therefore, effort should be made to estimate these parameters accurately, as well.

7.3.2.2 Considering the uncertainty associated with R_L, L_Ω and L (Case-II)

As the GIUH based Clark model provides a procedure for estimation of unit hydrograph for an ungauged catchment; hence, the velocity (V) is not a physically measurable parameter for the ungauged catchment. Therefore, the above procedure as outlined in Section 7.3.2.1 is repeated considering only the parameters, R_L, L_Ω and L which are physically measurable inputs to the GIUH based Clark model. The values of uncertainty in peak of the unit hydrograph estimated by the GIUH based Clark model caused by uncertainty in the values of the paramaters of the model viz. R_L, L_Ω and L are computed as given in Table 23. Fig. 23 shows the uncertainty associated with each of these parameters.

Table 23: Values of uncertainty (F_l) in peak of unit hydrograph caused by uncertainty in R_L, L_Ω and L

Sl. No.	Parameter	Uncertainty in peak of UH	
		F_l	Values (%)
1	R_L	F_{RL}	30.8
2	L_Ω	$F_{L\Omega}$	56.0
3	L	F_L	13.2

Fig. 23 : Uncertainty associated with the various parameters of the GIUH based Clark model (Case-II)

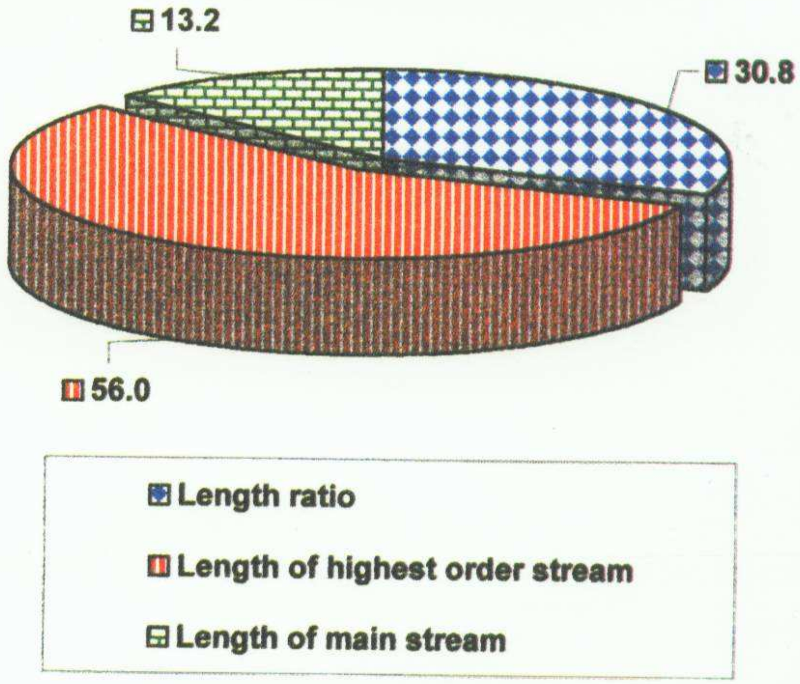
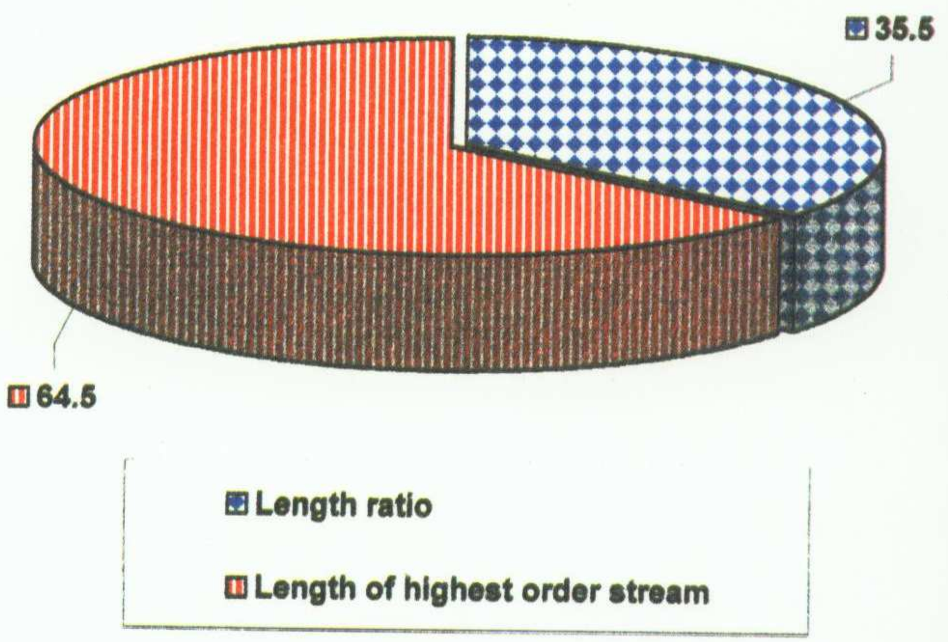


Fig. 24 : Uncertainty associated with the various parameters of the GIUH based Clark model (Case-III)



From the above analysis carried out as per Case-II when the three physically measurable parameters, viz. R_L, L_Ω and L are considered; it is seen that the peak of the unit hydrograph computed by the GIUH based Clark model for the catchment defined by the bridge No. 807 is quite uncertain. The uncertainty in length of the highest order stream of the catchment (L_Ω) leads to 56.0% uncertainty in peak of the unit hydrograph and it emerges to be the biggest contributor to that uncertainty. The uncertainty in parameters R_L and L contributes to 30.8%, 13.2% uncertainty in the peak of the unit hydrograph respectively. Hence, the values of L_Ω needs to be measured with precision for accurate estimation of the peak of the unit hydrograph derived by the GIUH based Clark model. As uncertainty in R_L also leads to 30.8% uncertainty in the peak of the unit hydrograph; therefore, effort should be made to estimate the parameter R_L as accurately as possible.

7.3.2.3 Considering the uncertainty associated with R_L and L_Ω (Case-III)

The above procedure as outlined in Section 7.3.2.1 is also repeated considering only the parameters, R_L and L_Ω. The values of uncertainty in peak of the unit hydrograph estimated by the GIUH based Clark model caused by uncertainty in the values of the paramaters of the model viz. R_L and L_Ω are computed as given in Table 24. Fig. 24 (shown along with Fig. 23) shows the uncertainty associated with each of these parameters.

Table 24: Values of uncertainty (F_i) in peak of unit hydrograph caused by uncertainty in R_L and L_Ω

Sl. No.	Parameter	Uncertainty in peak of UH	
		F_i	Values (%)
1	R_L	F_{RL}	35.5
2	L_Ω	$F_{L\Omega}$	64.5

From the above analysis carried out as per Case-III when the two parameters, viz. R_L and L_Ω are considered; it is observed that the peak of the unit hydrograph computed by the GIUH based Clark model for the catchment defined by the bridge No. 807 is quite uncertain. The uncertainty in length of the highest order stream of the catchment (L_Ω) leads to 64.5% uncertainty in peak of the unit hydrograph and it emerges to be the biggest contributor to that uncertainty. The uncertainty in parameter R_L contributes to 35.5% uncertainty in the peak of the unit hydrograph respectively. Hence, the values of both of these geomorphological parameters, L_Ω and R_L need to be precisely measured for accurate estimation of the peak of the unit hydrograph derived by the GIUH based Clark model.

7.3.3 Confidence intervals (CIs)

Confidence intervals (CIs) are defined as intervals that contain the true value of the model output with the indicated degree of confidence or probability. Thus, the 95 % CI is the interval that has a 95% chance of containing the true model output. The CIs are bounded by the confidence limits (CL). Obviously the CIs and CLs depend on the estimated values of the model parameters and the pdf that is assumed.

In the present study, CIs have been computed for the three cases as discussed in Section 7.3.2. The values of the upper and lower 95% confidence limits, assuming that the peak of the unit hydrograph (Q_P) estimated by the GIUH Clark model is normally distributed, have been computed and presented in Table 25 for the three cases. Figs. 25 through 27 show the upper and lower 95% confidence limits of the peak of the unit hydrograph (Q_P) for the three cases.

Table 25: Values of upper and lower confidence limits for the peak of the unit hydrograph (Q_P) for the three cases for 95% confidence level

Confidence limits	Values of peak of the unit hydrograph (Q_P)		
	Case-I	Case-II	Case-III
Lower	35.33	40.60	40.99
Upper	57.41	52.14	51.75

This implies that for case-I with the considered variability in the parameters V, R_L, L_Ω, and L, there are 95% chances that the peak of the unit hydrograph computed by the GIUH based Clark model lies between 35.33 cumec and 57.41 cumec.

Similarly for case-II, with the considered variability in the parameters R_L, L_Ω, and L, there are 95% chances that the peak of the unit hydrograph computed by the GIUH based Clark model lies between 40.60 cumec and 52.14 cumec.

Again, for case-III with the considered variability in the parameters R_L and L_Ω, there are 95% chances that the peak of the unit hydrograph computed by the GIUH based Clark model lies between 40.99 cumec and 51.75 cumec.

In order to increase or decrease the upper and lower confidence limits, the parameters leading to higher uncertainty in the peak of the unit hydrograph need to be estimated more accurately.

Fig. 25 : Lower and upper 95% confidence limits for peak of the unit hydrograph (Case-I)

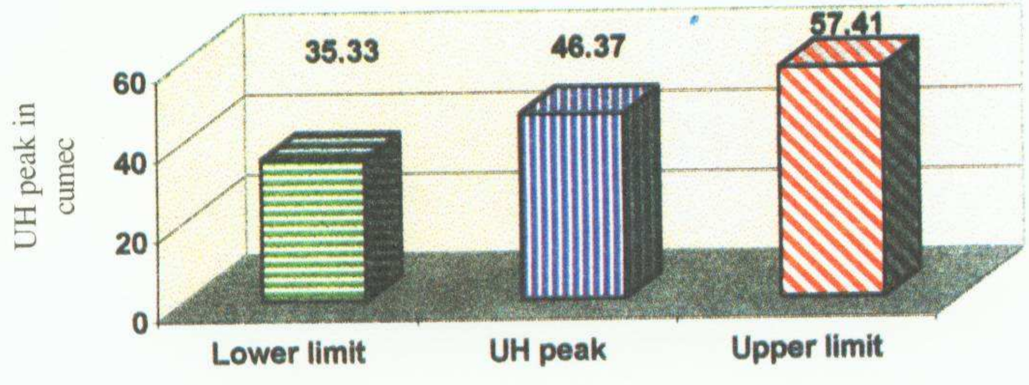


Fig. 26 : Lower and upper 95% confidence limits for peak of the unit hydrograph (Case-II)

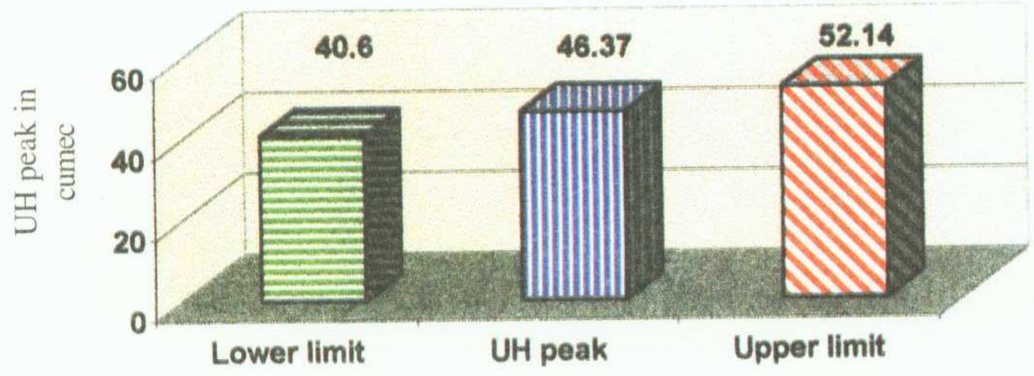
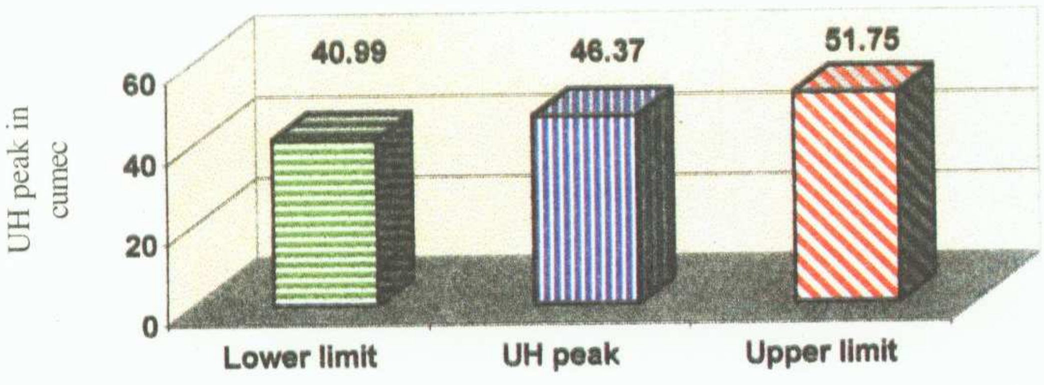


Fig. 27 : Lower and upper 95% confidence limits for peak of the unit hydrograph (Case-III)



8.0 CONCLUSIONS

In this study, (i) the geomorphological parameters of the GIUH based Clark model for the catchment defined by the bridge number 807 of Lower Godavari Subzone 3(f) have been evaluated using the GIS package (ILWIS), (ii) DSRO hydrographs estimated by the GIUH based Clark model have been compared with the observed as well as with the DSRO hydrographs computed by the HEC-1 package and the Nash model, and (iii) relative sensitivity as well as uncertainty analysis using the first order analysis (FOA) have been carried out for quantifying the uncertainty associated with the input parameters of the GIUH based Clark model. On the basis of this study, the following conclusions may be drawn.

(i) Manual estimation of geomorphological parameters is a tedious and cumbersome process and often discourages the field engineers from developing the regional methodologies for solving various hydrological problems of the ungauged catchments or in limited data situations. At times, it also leads to erroneous estimates. On the other hand, modern techniques like the GIS serve as an efficient approach for storage, processing and retrieval of large amount of database. Its spatial modelling and tabular databases constitute a powerful tool for the data analysis. Also, the database created and stored in GIS system may be updated as and when required.

(ii) The parameters of the GIUH based Clark model viz. T_c and R have been estimated satisfactorily by using the geomorphological parameters of the catchment defined by bridge number 807 of Lower Godavari Subzone 3(f), instead of the observed rainfall-runoff data, as the catchment has been considered as an ungauged catchment under the GIUH approach.

(iii) Comparison of the error functions reveals that the GIUH based Clark model approach estimates the DSRO hydrographs reasonably well as compared to the observed DSRO hydrographs as well as the DSRO hydrographs computed by the Nash model and the HEC-1 package. The GIUH approach considers the catchment under study as ungauged; while, DSRO computations of the Nash model and HEC-1 package are based on the observed data of each of the rainfall-runoff events.

(iv) Relative sensitivity coefficients computed for the four parameters, viz. R_L, L_Ω, L and V are 0.307, -0.716, -0.348 and 0.901 respectively. It is observed that parameters V and L_Ω are more sensitive and L and R_L are relatively less sensitive in computing peak of the unit hydrograph by the GIUH based Clark model.

(v) The uncertainty analysis carried out as per Case-I, when four parameters viz. R_L, L_Ω, L and V are considered shows that the velocity parameter (V) leads to 72.7% uncertainty in peak of the unit hydrograph and it emerges to be the biggest contributor to the uncertainty in estimation of peak of the unit hydrograph. The uncertainty in parameters L_Ω, R_L and L contribute to 15.3%, 8.4% and 3.6% uncertainty in the peak of the unit hydrograph respectively. Hence, the value of the velocity parameter (V) needs to be computed with the highest precision for accurate estimation of the peak of the unit hydrograph derived by the GIUH based Clark model. As uncertainty in L_Ω and R_L, leads to 15.3% and 8.4% uncertainty in the peak of the unit hydrograph; therefore, effort should also be made to estimate these parameters accurately.

(vi) As per Case-II, when the three physically measurable geomorphological parameters, viz. R_L, L_Ω and L are considered; the uncertainty in length of the highest order stream of the catchment (L_Ω) leads to 56.0% uncertainty in peak of the unit hydrograph and it emerges to be the biggest contributor to the uncertainty in estimation of peak of the unit hydrograph. The uncertainty in parameters R_L and L contributes to 30.8%, 13.2% uncertainty in the peak of the unit hydrograph respectively. Hence, the values of L_Ω needs to be measured with precision for accurate estimation of the peak of the unit hydrograph derived by the GIUH based Clark model. As uncertainty in R_L leads to 30.8% uncertainty in the peak of the unit hydrograph; therefore, effort should be made to estimate the parameter R_L also as accurately as possible.

(vii) As per Case-III, when the two parameters, viz. R_L and L_Ω are considered; the uncertainty in length of the highest order stream of the catchment (L_Ω) leads to 64.5% uncertainty in peak of the unit hydrograph and it emerges to be the biggest contributor to the uncertainty in estimation of peak of the unit hydrograph. The uncertainty in parameter R_L contributes to 35.5% uncertainty in the peak of the unit hydrograph. Hence, the values of both of these geomorphological parameters i.e. L_Ω and R_L need to be precisely measured for accurate estimation of the peak of the unit hydrograph derived by the GIUH based Clark model.

(viii) The confidence intervals (CIs) have been computed for the 95% confidence level for the three cases assuming that peak of the unit hydrograph is normally distributed. Using the GIUH based Clark model, the actual peak of the unit hydrograph and the time to peak have been computed as 46.37 cumec and 5 hours respectively. For this peak of the unit hydrograph, the lower and upper 95% confidence limits for Case-I have been computed as 35.33 cumec and 57.41 cumec respectively. The lower and upper 95% confidence limits for Case-II have been computed as 40.60 cumec and 52.14 cumec respectively. The lower and upper 95% confidence limits for Case-III have been computed 40.99 cumec and 51.75 cumec respectively.

(ix) The geomorphological parameters which contribute to higher degree of uncertainty in derivation of unit hydrograph using the GIUH based Clark model as outlined above, are to be estimated more precisely for reducing the uncertainty associated with the flood estimates computed by the GIUH based Clark model. Also, in order to decrease or increase the upper and lower confidence limits, the parameters leading to greater uncertainty in the peak of the unit hydrograph need to be estimated more accurately.

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