TR/BR-17/99-2000

FLOOD ESTIMATION BY GIS BASED GIUH APPROACH FOR AJAY BASIN UPTO SARATH GAUGING SITE OF SOUTH BIHAR

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1999-2000

The conventional techniques of derivation of unit hydrographs require historical rainfall-runoff data. In a developing country like India, due to the obvious reasons, adequate runoff data are not generally available for most of the small to medium sized catchments. Indirect inferences through regionalisation are sought for such types of the ungauged catchments. Many times this task of regionalising the hydrological variables becomes very tedious and in certain cases even impossible. The research in the field of fluvial geomorphology has recently picked up and it offers some great opportunities in solving many of the problems facing the hydrologists today. A very complex analysis is required for accurate inferences based on the geomorphological theory. Many investigators have simplified its application to various levels. Attempts have been made to relate the parameters of the conventional conceptual models of instantaneous unit hydrograph (IUH) to the geomorphological characteristics of the catchment. Also, with the developmental activities, most of the catchments have undergone the landuse changes. The landuse changes within the catchment can have significant impact on runoff characteristics. Further, the global atmospheric changes have been responsible for bringing about changes in rainfall patterns. Hence, linking of the geomorphologic parameters with the hydrologic characteristics of the catchment can lead to a simple and useful procedure to simulate the hydrologic behaviour of various catchments, particularly the ungauged ones. In this regard, recently the concept of geomorphological instantaneous unit hydrograph (GIUH) has been introduced; wherein, the characteristics of the instantaneous unit hydrograph are related to the geomorphological and climatic characteristics of the basin.

Based on the aforesaid concept, a mathematical model has been developed at the National Institute of Hydrology; which enables evaluation of the Clark Model parameters using geomorphological characteristics of an ungauged catchment. In this study, the model has been applied for simulating the direct surface runoff (DSRO) hydrographs of the Ajay basin upto Sarath gauging site of South Bihar. The geomorphological characteristics 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. The performance of the GIUH model has been evaluated by employing some of the commonly used error functions. Sensitivity analysis of the GIUH based Clark model has also been conducted in order to examine the effect of the velocity parameter of the GIUH model on the DSRO hydrographs. The study has been carried out by Shri Rakesh Kumar, Dr. Chandranath Chatterjee, Dr. Sanjay Kumar, Shri A. K. Lohani and Shri R. D. Singh, Scientists of the Institute; as per the work programme of the Ganga Plains North Regional Centre, Patna. Technical assistance has been provided by Shri R. K. Nema, SRA and Shri A. K. Sivadas, Technician. It is expected that the GIS approach 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.

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ABSTRACT

The linearity principle of unit hydrograph theory has been widely applied for the simulation of rainfall-runoff process, particularly for small and medium sized catchments. Derivation of unit hydrograph has been extensively investigated by many researchers since Sherman gave the principle of unit graph in 1932. For the gauged catchments the unit hydrographs can be derived by analysing the historical rainfall-runoff records. However, for ungauged catchments some indirect approaches have been used for the derivation of the unit hydrographs. Due to scarcity of data, particularly for small and medium sized catchments, computational and the other constraints, physically based models are very difficult to be implemented. Greater emphasis is now being given to the concept of models based on geomorphological characteristics. Geomorphological instantaneous unit hydrograph (GIUH) is one among the various approaches available for the simulation of flood events, for the ungauged catchments. Many investigators have tried to relate the parameters of the conceptual models to the geomorphological characteristics of the catchments.

In this study, the mathematical model developed at the National Institute of Hydrology for estimation of the Clark model parameters using the geomorphological characteristics of an ungauged basin has been applied for simulation of the direct surface runoff (DSRO) hydrographs of the Ajay basin upto Sarath gauging site of South Bihar. The geomorphological parameters of the Ajay basin 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 estimated 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, (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 computed based on the observed and the simulated DSRO hydrographs. It is observed that the DSRO hydrographs are computed quite accurately by the GIUH based Clark model approach, which simulates the DSRO hydrographs of the basin considering it to be ungauged. Sensitivity analysis of the GIUH based Clark model shows that the peaks of the DSRO hydrographs of the various events increase with increase in the velocity parameter of the model. As estimation of the velocity parameter emerges to be one of the most important factors in this methodology of the GIUH derivation; hence, scope of the further work to be carried out for improving the excess-rainfall intensity and velocity relationship and the concept of determination of regional velocity has also been focussed.

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 non 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 geomorpihc 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. In this study, the geomorphological characteristics of the Ajay basin 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 Ajay river basin (upto Sarath) of South Bihar.

2.0 REVIEW OF LITERATURE

The problem of transformation of rainfall into runoff has been 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 and models for simulation of runoff for the ungauged catchments as described in some of the current studies and the Technical Reports of National Institute of Hydrology (e.g. NIH, 1994-95) 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).

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). 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 GIUH based Clark model 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 based Clark model with the Nash model and the HEC-1 package.

(v) To carry out sensitivity analysis of the velocity parameter of the GIUH based Clark model.

4.0 DESCRIPTION OF THE STUDY AREA

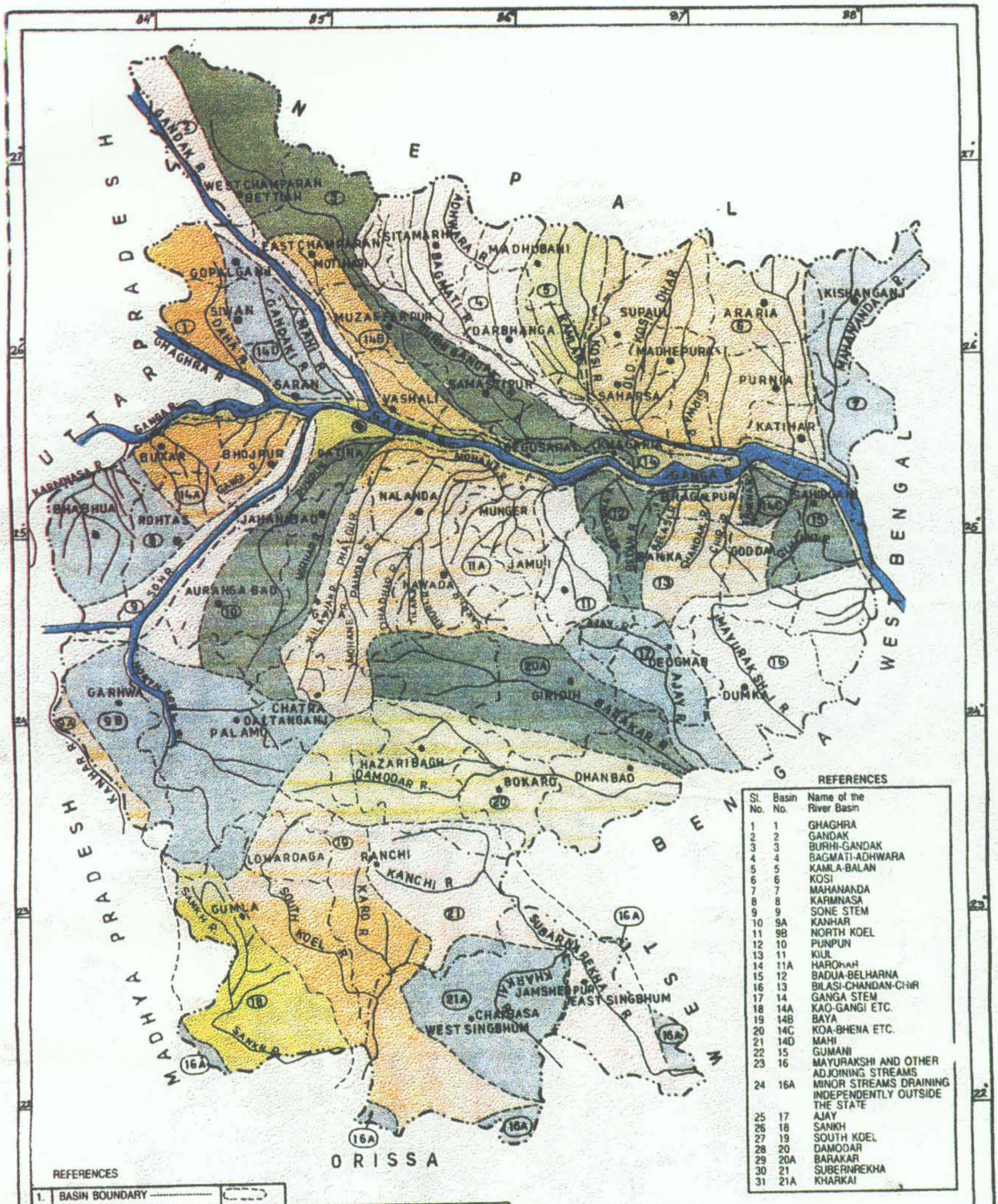
The Ajay river basin, selected for the study is situated between latitudes 24°6'N and 23°50'N and longitudes 86°16'E and 87°5'E and located in the plateau of Santhal Paragana. The Ajay river emerges from forest covered hills of Chakai block in Munger district of Bihar and flows over a length of 132 km in Bihar, enters West Bengal near Kalipahari and falls into Bhagirathi near Katwa. A number of small rivulets like Kedhasa and Darwa join it at the upper reaches. The total length of river including its length in West Bengal is 276 km. The catchment area of the basin in Bihar is 3,554 sq km which is 51.6 per cent of the total basin area. The portion of Ajay river basin lying in Bihar alongwith other river basins of Bihar is shown in Fig. 1.

The river system lies on the north of the Damodar river system and south of Mayurakshi-Babla river system. The Ajay basin covers the areas of four districts consisting of 76.27 per cent of Deoghar district, 17.28 per cent of Dumka district, 5.10 per cent of Munger district and 5.58 per cent of Giridh district in Bihar. The catchment area in Bihar is hilly whereas that in West Bengal is mostly plains. About 7 percent of the total area are under forest and about 63 percent are under cultivation.

The soils in the Ajay river basin have been almost entirely derived from granite gneiss and schists and are mostly yellow and red at the surface except in low lands where olive to olive grey soils may also be found. Most of these soils are sandy and loamy sand specially on uplands, and are, therefore, very light at the surface. But in lowlands, medium textured sandy loam to loam soils are encountered. The average annual rainfall in the catchment varies from 128 cm to 138 cm. The rainfall in plains is more than in the hilly catchment. The monsoon rainfall amounts for about 75 to 80 percent of the annual rainfall in the catchment.

The river flows over recent alluvium in the lower part and is subjected to spilling at moderately high discharge. The upper portion of the Ajay river in West Bengal is protected by embankments on both banks upto the outfall of the Kunur (main tributary in West Bengal). The floods of the Ajay are sudden, flashy and of short duration. There are low pockets in the Ajay-Kunur catchment, which suffer from frequent inundation.

The gauging site, established near village Sarath and about 160 m upstream of Sarath-Madhupur road bridge, is maintained by Water Resources Department, Govt. of Bihar. The geographical location of the site is 24°13'45" N latitude and 60°43' E longitude which is approachable by road in all seasons. The catchment area upto the site is 1, 191.40 sq km. The length of Ajay river upto Sarath gauging site is 82.18 sq. km. For the present study, Ajay river basin upto Sarath forms the study area. Fig 2 shows the index map of the part of Ajay river basin lying in Bihar along with the catchment defined by the Sarath gauging site which forms the study area.



BASED ON SURVEY OF INDIA & NATIONAL ATLAS MAPS

Fig. 1 : Location of Ajay basin along with other river basins of Bihar
(Adapted from 2nd Bihar State Irrigation Commission Report, 1994)

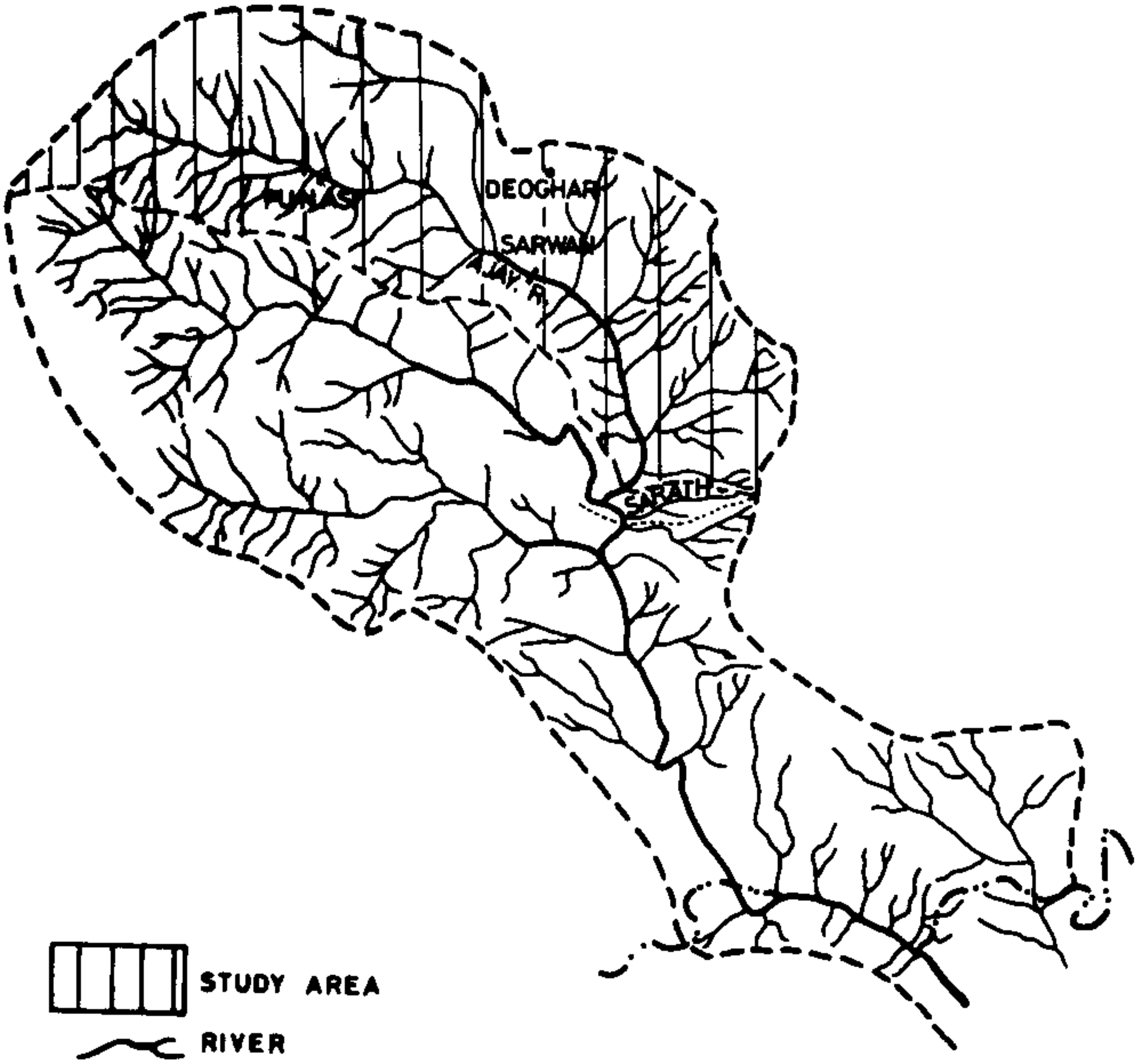


FIG. 2: INDEX MAP OF AJAY RIVER BASIN DEFINED BY
THE SARATH GAUGING SITE

5.0 DATA AVAILABILITY

There are ten raingauge stations located in the sub-basin. These gauging stations are maintained by the Govt. of Bihar. The daily rainfall data at these stations and three hourly runoff data at the gauging site at Sarath have been collected for the years 1977 to 1988 from Hydrology cell, Department of Water Resources, Govt. of Bihar. The locations of the rain gauge stations are shown in the Fig. 3. List of raingauge stations along with their location is given in Table 1. As there is no self-recording raingauge available in the basin, rainfall-pattern for the neareby stations Sabour and Bhagalpur for the same period, are also collected from Indian Meteorolgical Department, Patna and the same were used based on their rainfall data for converting the daily rainfall data into hourly data. For the rainfall-runoff event Nos. 7th and 8th, rainfall data are available only for the Sarath raingauge station and these data have been considered to be applicable for the study area.

Table 1: Location of rain gauge stations

Station	Longitude (E)	Latitude (N)
Batpar	86°20'21"	24°30'39"
Kiajori	86°28'22"	24°29'40"
Bichkorwa	86°22'40"	24°27'12"
Punasi	86°32'16"	24°28'57"
Banka	86°32'26"	24°32'47"
Deoghar	86°45'21"	24°29'18"
Ghasko	86°43'18"	24°23'01"
Sarwan	86°47'26"	24°22'50"
Chamurdaula	86°51'58"	24°20'35"
Sarath	86°50'34"	24°13'57"

Table 2 gives the details of periods of various storms whose rainfall-runoff data have been used in the study. The theissen weights of the raingauge stations in the catchment whose data have been used in the study are given in Table 3.

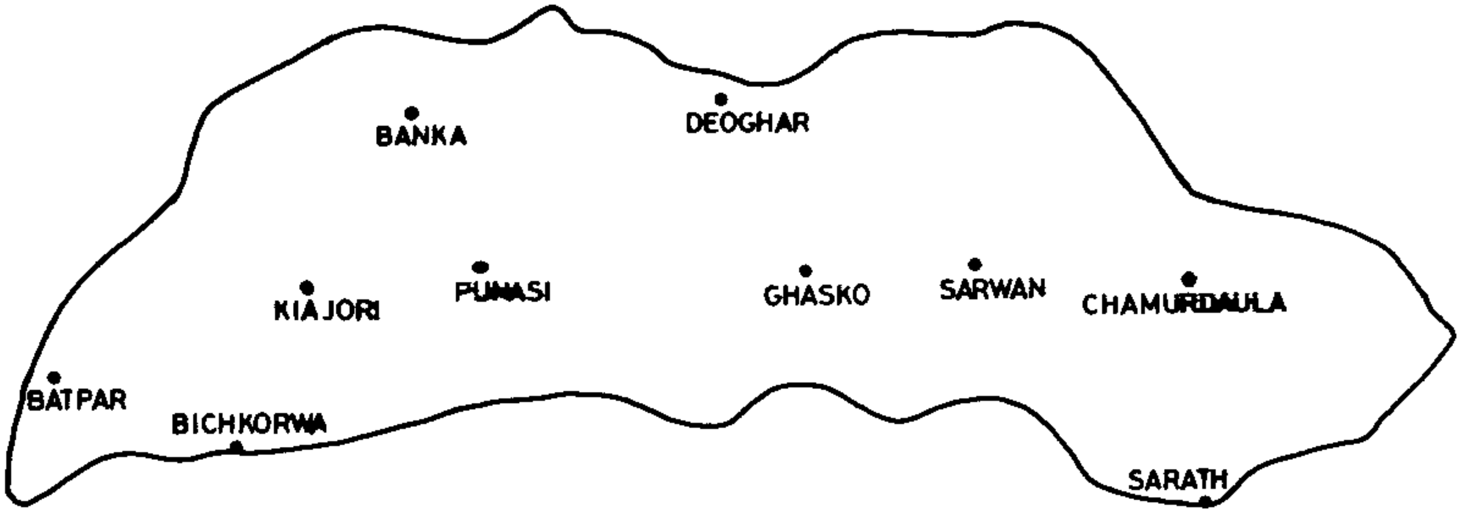


FIG. 3:LOCATION OF THE RAINGAUGE STATIONS FOR AJAY RIVER BASIN UPTO SARATH

Table 2: Periods of various rainfall-runoff events

S. No.	Period of the Events
1	13.08.1977 at 09 hrs. to 13.08.1977 at 20 hrs.
2	05.08.1978 at 21 hrs. to 06.08.1978 at 02 hrs.
3	16.08.1979 at 05 hrs. to 16.08.1979 at 16 hrs.
4	26.08.1980 at 15 hrs. to 26.08.1980 at 07 hrs.
5	23.07.1981 at 09 hrs. to 23.07.1981 at 13 hrs.
6	22.08.1982 at 24 hrs. to 23.08.1982 at 06 hrs.
7	05.08.1983 at 20 hrs. to 06.08.1983 at 09 hrs.
8	03.08.1985 at 13 hrs. to at 03.08.1985 13 hrs.
9	12.09.1987 at 13 hrs. to at 12.09.1987 24 hrs.
10	20.07.1988 at 23 hrs. to at 21.07.1988 04 hrs.

Table 3: Theissen weights of the raingauge stations

Sl.No.	Name of Raingauge station	Theissen weight
1	Kijor	0.15
2	Punasi	0.26
3	Deoghar	0.20
4	Sarwan	0.20
5	Sarath	0.19

6.0 METHODOLOGY

The methodology adopted for preparation of geomorphological data base in Integrated Land and Water Information System (ILWIS), 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.

6.1 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 Ajay river basin upto Sarath 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 methodology adopted for ordering of the streams, measurement of linear and areal aspects, preparation of time area diagram, computation of geomorphological characteristics like bifurcation ratio, length ratio and area ratio for the catchment etc. is described below.

6.1.1 Linear aspects

Computation of the linear aspects such as stream order, stream numbers for various orders, bifurcation ratio, stream lengths for various stream orders and length ratio are described below.

Stream order (u)

For ordering of streams Strahler's method of stream ordering as discussed above has been followed.

Stream number (N_u)

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)

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:

$$R_b = N_u / N_{u+1} \tag{1}$$

It has been very widely used in the derivation of geomorphologic instantaneous unit hydrographs for various catchments.

Stream length (L_u)

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.

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.:

$$R_l = \bar{L}_u / \bar{L}_{u-1} \tag{2}$$

Length ratio is one of the important geomorphologic characteristics. It has been used in the derivation of geomorphologic instantaneous unit hydrographs for various catchments.

6.1.2 Areal aspects

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:

$$A_u = A_l R_a^{u-1} \tag{3}$$

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:

$$A_u = A_l \, R_b^{\,u-1} \, (R_{lb}^{\,u} - 1)/(R_{lb} - 1) \tag{4}$$

Where, A_l 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_l is unknown, so A_l can be computed. The mean areas are computed using value of A_l.

Area ratio (R_a)

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

$$R_a = A_u / A_{u-1} \tag{5}$$

Area ratio is one of the important geomorphologic characteristics. It has been used in the derivation of geomorphologic instantaneous unit hydrographs for various catchments.

6.1.3 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 in this study 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.

$$t = KL / \sqrt{S} \tag{6}$$

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 a proportionality constant. An initial estimate of time of concentration may be made by the Kirpich's formula i.e.

$$t_c = 0.06628\, L^{0.77}\, H^{-0.385} \tag{7}$$

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.

$$K = t_c \sqrt{S_A} / L \tag{8}$$

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 Computation of Excess-Rainfall

The computation of excess rainfall is required for the estimation of direct surface runoff by separating the hydrological abstractions from the rainfall hyetographs. When the rainfall occurs over a 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.

6.3 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:

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

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/Δt, and
u_i = ith ordinate of the IUH.

6.4 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.

Empirical results indicate that 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.

6.5 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.

6.5.1 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 :

$$Q_e = 0.2778 \; i \; A_c \tag{14}$$

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.

6.5.2 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:

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

(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.

6.6 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:

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

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

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

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

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

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

and

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

(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).

6.7 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.

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

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.

6.8 Comparison of DSRO Hydrographs Computed based on GIUH Approach, HEC-1 Package and NASH 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.

6.8.1 HEC-1 package

The HEC-1 model 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 HEC-1 model (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.

6.8.2 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.

6.9 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.

6.9.1 Efficiency (EFF)

Efficiency (EFF) is computed as follows:

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

where, Q_{oi} = ith ordinate of the observed discharge
$\bar{Q}$ = average of the ordinates of observed discharge
Q_{cl} = Computed discharge

6.9.2 Absolute average error (AAE)

Absolute average error (AAE) is computed as follows:

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

where n = No. of ordinates

6.9.3 Root mean square error (RMSE)

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

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

6.9.4 Average error in volume (AEV)

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

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

where Vol_o = Observed runoff volume
Vol_c = Computed runoff volume

6.9.5 Percentage error in peak (PEP)

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

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

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

6.9.6 Percentage error in time to peak (PETP)

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

$$\mathrm{PETP} = \frac{\mathrm{OT_p} - \mathrm{CT_p}}{\mathrm{OT_p}} \mathrm{x}100 \tag{28}$$

where $\mathrm{OT_p}$ = Time to peak of observed discharge
$\mathrm{CT_p}$ = Time to peak of computed discharge

7.0 ANALYSIS AND DISCUSSION OF RESULTS

The analysis carried out and the results of the study for evaluation of the geomorphological characteristics using the GIS software, ILWIS, DSRO estimation by the GIUH based Clark model, comparison of the DSRO hydrographs computed by the HEC-1 package and the Nash model, computation of some of the commonly used error functions for the evaluation of the performance of the GIUH model as well as the sensitivity analysis carried out for GIUH velocity parameter are described below.

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:

$$R_b = N_u \;/\; N_{u+1} \qquad (29)$$

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:

$$Y = -1.435\, x + 8.429 \qquad (30)$$

The correlation coefficient for this equation is -0.998. From this equation, bifurcation ratio is obtained as 4.20.

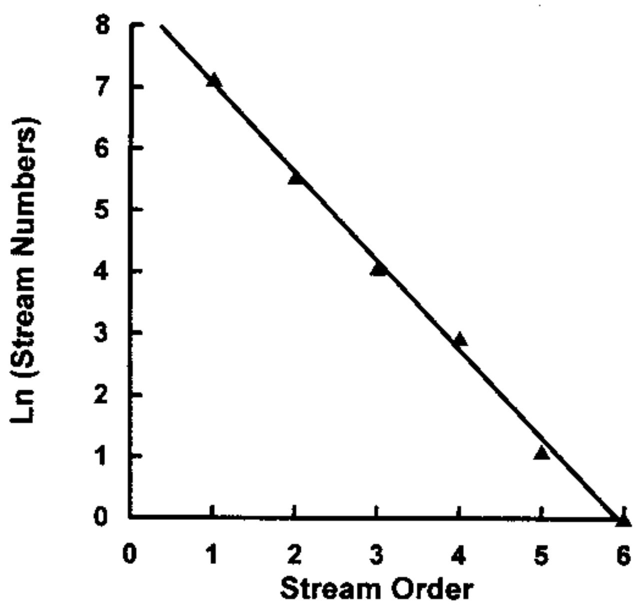


Fig. 5 Variation of stream numbers with stream order for Ajay basin up to Sarath

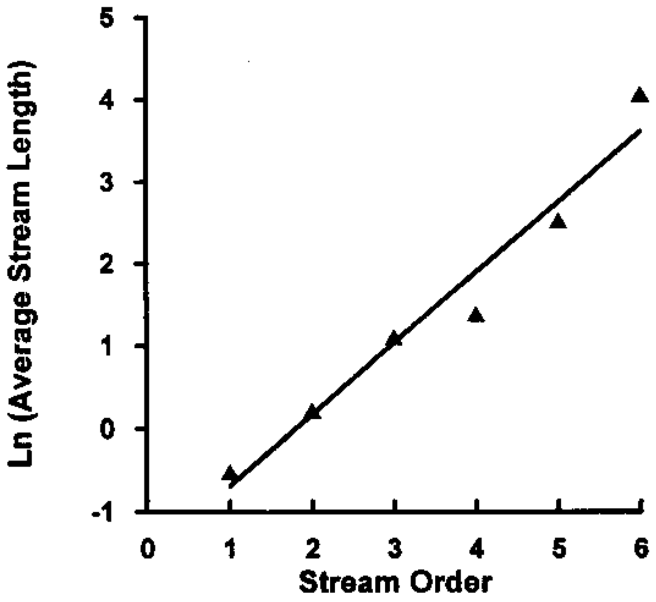


Fig. 6 Variation of mean stream length with stream order for Ajay basin up to Sarath

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.:

$$R_l = \bar{L}_u / \bar{L}_{u-1} \qquad (31)$$

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:

$$Y = 0.865\ x - 1.553 \qquad (32)$$

The correlation coefficient for this equation is 0.979. From this equation, length ratio is obtained as 2.375.

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 is found to be 1191.40 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:

$$A_u = A_1 R_a^{u-1} \qquad (33)$$

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:

$$A_u = A_1\ R_b^{\ u-1}\ (R_{lb}^{\ u} - 1)/(R_{lb} - 1) \qquad (34)$$

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 streams (A_u) of order u, to the area of streams (A_{u-1}) of order u-1, i.e.:

$$R_a = A_u / A_{u-1} \qquad (35)$$

The mean stream area of each order of stream in log domain has been plotted against the order of the streams. Fig. 7 (shown along with Fig. 8) 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:

$$Y = 1.435\,x - 1.526 \qquad (36)$$

The correlation coefficient for this equation is 0.998. From this equation, area ratio is obtained as 4.19.

Table 4 shows the details of stream numbers, length, average length and average areas for streams of various orders for the study area.

Table 4: Details of number, length, mean length and mean area for streams of various orders for Ajay basin upto Sarath

Order of Stream	Number	Length (kms)	Mean Length (kms)	Mean Area (km^2)
1	1266	753.840	0.595	0.913
2	260	325.476	1.250	3.833
3	59	179.569	3.044	16.098
4	19	76.677	4.036	67.612
5	3	38.129	12.709	283.970
6	1	59.667	59.667	1191.400

7.1.4 Length of the main stream (L)

The length of the main stream of Ajay river basin upto Sarath gauging site is measured as 82.18 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 59.667 kilometers.

7.1.6 Preparation of time area diagram (TA)

As described in Section 6.1.3, by substituting values of t_c, L and S_A (S_A is mean slope of the main stream) of the Ajay basin upto Sarath, 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 time interval was measured and these values were tabulated. Fig. 8 shows the plot of time of travel versus cumulative catchment area. Fig. 9 illustrates time area diagram of the study area. For the Ajay catchment defined by the Sarath gauging site, t_c is computed as 15 hours.

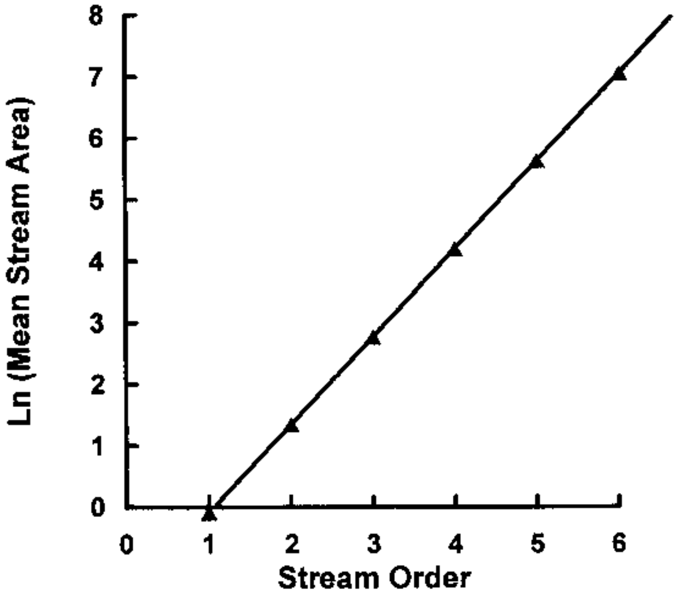


Fig. 7 Variation of mean stream area with stream order for Ajay basin up to Sarath

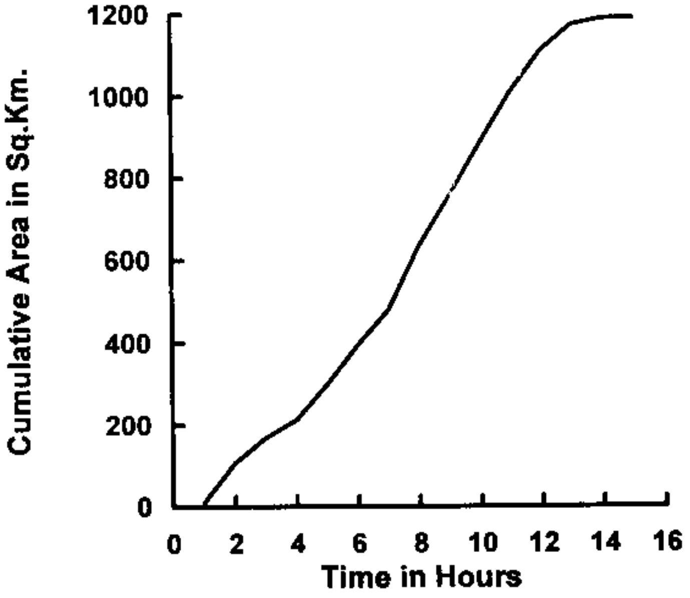


Fig. 8 Time of travel and cumulative area diagram for Ajay basin up to Sarath

7.2 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. 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 IUH 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 the ten 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. 10 to 19).

7.3 Model Application

The methodology described in Section 6, was applied and the model simulations were carried out for the ten 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 Sarath gauging site of the Ajay basin, the approaches for estimation of the velocity under Sections 6.5.1 and 6.5.2 could not be applied in this study. Instead, the model was run by adopting the peak velocity of 2.5 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. Comparisons of the computed unit hydrographs, direct surface runoff (DSRO) hydrographs and the observed DSRO hydrographs as well as some of the error functions evaluated based on these hydrographs were carried out as described below.

7.4 Comparison of the Derived Unit Hydrographs and DSRO Hydrographs

The unit hydrographs have been derived based on the following approaches:

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

(ii) Using the Clark model IUH option of the HEC-1 package (HEC-1) as described in Section 6.8.1.

(iii) Using the Nash IUH model (NASH) as described in Section 6.8.2.

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

7.4.1 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 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 model of HEC-1 and the Nash IUH model have been estimated for each of the ten rainfall-runoff events and the same parameters have been used to compute the DSRO hydrographs of the corresponding ten 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 6.9, 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.

7.4.1.1 Comparison of the derived unit hydrographs based on Approach-I

The parameters of 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 5. It is observed from table 5 that the values of T_c and R for GIUH are identical for all the rainfall-runoff events viz. 9.13 and 8.45 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 storage coefficient (R) and sum of the storage coefficient and 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 0.481 and 0.384 for the GIUH based Clark model and the HEC-1 model for the ten rainfall-runoff events.

Table 6 provides the 1-hour unit hydrographs derived by the GIUH based Clark model, HEC-1 package and Nash IUH model. 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 IUH model for the various rainfall-runoff events are given in Table 7.

Table-5: Parameters of 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	9.13	8.45	8.78	6.07	3.86	2.39
2	9.13	8.45	4.24	9.66	2.31	4.21
3	9.13	8.45	11.57	7.17	3.98	2.86
4	9.13	8.45	10.27	5.52	4.63	2.18
5	9.13	8.45	10.97	6.78	4.80	2.45
6	9.13	8.45	12.01	6.68	4.61	2.64
7	9.13	8.45	10.50	7.03	4.65	2.44
8	9.13	8.45	18.22	3.49	6.19	2.03
9	9.13	8.45	13.38	6.33	5.95	2.30
10	9.13	8.45	6.72	7.85	3.18	2.73

It is seen from Table 7 that the peak of the unit hydrograph and time to peak for GIUH based Clark model are 25.8 cumec and 9 hours respectively. It is observed that the peak of the unit hydrograph for Clark IUH model of HEC-1 package varies from 23.0 to 30.0 cumec and the time to peak varies from 5 to 12 hours. It is also observed that the peak of the unit hydrograph for Nash IUH model varies from 25.3 to 31.5 cumec and the time to peak varies from 6 to 10 hours.

7.4.1.2 Comparison of observed and computed DSRO hydrographs based on 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 8. 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-6: 1-hour unit hydrographs derived by the GIUH based Clark model, Clark IUH model (HEC-1 package) and Nash IUH model (Approach-I)

Time (hr)	GIUH	HEC				NASH			
		Event 1	Event 2	Event 3	Event 4	Event1	Event2	Event3	Event4
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.1	1.0	3.0	1.0	1.0	1.3	1.8	0.5	4.7
3	2.0	5.0	10.0	3.0	4.0	3.2	13.9	1.4	6.2
4	4.9	10.0	19.0	6.0	9.0	10.9	18.7	5.6	5.8
5	7.9	16.0	26.0	9.0	13.0	18.8	22.8	10.6	12.0
6	11.7	21.0	27.0	12.0	18.0	25.3	25.0	15.8	18.9
7	16.4	26.0	24.0	16.0	23.0	29.6	25.6	20.2	24.8
8	21.3	29.0	22.0	19.0	26.0	31.5	25.2	23.5	28.8
9	24.9	30.0	20.0	22.0	28.0	31.2	23.9	25.3	30.7
10	25.8	28.0	18.0	23.0	29.0	29.4	22.2	25.9	30.6
11	24.1	25.0	16.0	24.0	28.0	26.6	20.3	25.4	29.0
12	21.4	21.0	15.0	24.0	25.0	23.3	18.2	24.2	26.4
13	19.0	18.0	13.0	22.0	21.0	19.9	16.2	22.3	23.3
14	16.9	15.0	12.0	20.0	18.0	16.6	14.3	20.2	19.9
15	15.0	13.0	11.0	17.0	15.0	13.6	12.4	17.9	16.7
16	13.3	11.0	10.0	15.0	12.0	11.0	10.8	15.6	13.7
17	11.9	9.0	9.0	13.0	10.0	8.8	9.3	13.4	11.0
18	10.5	8.0	8.0	11.0	8.0	6.9	7.9	11.4	8.8
19	9.4	7.0	7.0	10.0	7.0	5.4	6.8	9.6	6.9
20	8.3	6.0	6.0	8.0	6.0	4.1	5.7	8.0	5.3
21	7.4	5.0	6.0	7.0	5.0	3.2	4.8	6.6	4.1
22	6.6	4.0	5.0	6.0	4.0	2.4	4.1	5.4	3.1
23	5.8	3.0	5.0	6.0	3.0	1.8	3.4	4.4	2.3
24	5.2	3.0	4.0	5.0	3.0	1.4	2.9	3.5	1.7
25	4.6	2.0	4.0	4.0	2.0	1.0	2.4	2.8	1.3
26	4.1	2.0	3.0	4.0	2.0	0.8	2.0	2.3	0.9
27	3.6	2.0	3.0	3.0	2.0	0.6	1.7	1.8	
28	3.2	2.0	3.0	3.0	1.0	0.0	1.4	1.4	
29	2.9	1.0	2.0	2.0	1.0		1.1	1.1	
30	2.5	1.0	2.0	2.0	1.0		0.9	0.9	
31	2.3	1.0	2.0	2.0	1.0		0.8	0.0	
32	2.0	1.0	2.0	2.0	1.0		0.0		
33	1.8	1.0	2.0	1.0	1.0				
34	1.6	1.0	1.0	1.0	0.0				
35	1.4	0.0	1.0	1.0					
36	1.3		1.0	1.0					
37	1.1		1.0	1.0					
38	1.0		1.0	1.0					
39	0.9		1.0	1.0					
40	0.8		1.0	1.0					
41	0.7		1.0	0.0					
42	0.6		1.0						
43	0.5		1.0						
44	0.5		1.0						
..contd	..contd								
66	0.0								

Table 7: Peak discharge and time to peak of 1-hour unit hydrographs derived by the GIUH based Clark model, HEC-1 package and Nash IUH model for various rainfall-runoff events (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	25.8	9	232.2	30.0	8	240.0	31.5	7	220.5
2	25.8	9	232.2	27.0	5	135.0	25.6	6	153.6
3	25.8	9	232.2	24.0	10	240.0	25.9	9	233.1
4	25.8	9	232.2	29.0	9	261.0	30.6	8	244.8
5	25.8	9	232.2	25.0	9	225.0	26.9	8	215.2
6	25.8	9	232.2	24.0	9	216.0	25.6	8	204.8
7	25.8	9	232.2	25.0	9	225.0	27.4	7	191.8
8	25.8	9	232.2	23.0	12	276.0	27.9	9	251.1
9	25.8	9	232.2	23.0	10	230.0	25.3	10	253.0
10	25.8	9	232.2	28.0	6	168.0	31.1	6	186.6

Table-8: Peak discharge and time to peak of observed DSRO hydrographs and those derived by the GIUH based Clark model, HEC-1 package and Nash IUH 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	363.2	9	318.7	11	372.0	10	393.5	10
2	468.4	6	472.5	10	490.7	6	472.4	7
3	792.0	11	829.9	9	825.2	11	879.5	10
4	808.4	9	715.3	9	803.6	9	859.1	9
5	105.3	8	90.8	9	87.8	9	94.4	8
6	501.9	10	510.8	9	474.5	9	506.0	8
7	399.0	9	397.6	10	386.0	11	422.2	8
8	318.8	13	306.8	11	299.9	14	357.3	11
9	458.3	10	418.1	9	372.2	10	408.7	10
10	161.2	7	169.3	9	184.1	7	206.0	7

7.4.1.3 Comparison of error functions used for evaluation of the computed DSRO hydrographs based on 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 6.9 are given in Table 9. The details regarding the values of the error functions computed for the ten rainfall-runoff events are summarised below.

It is observed from the Table 9 that the values of EFF vary from 38.54 to 94.25 percent for the GIUH based Clark model; 80.14 to 98.28 percent for HEC-1; and 64.28 to 96.10 for Nash model. It is also seen that the values of EFF for HEC-1 are in general 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 utilises only the geomorphological characteristics of the basin.

It is observed that the values of AAE vary from 6.88 to 79.18 for the GIUH based Clark model; 7.64 to 46.60 for HEC-1; and 14.39 to 67.80 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 8.08 to 113.23 for the GIUH based Clark model; 9.91 to 61.28 for HEC-1; and 18.34 to 83.80 for Nash model. It is also seen that the values of RMSE for HEC-1 are lower than those of GIUH based Clark model and the Nash model. It is also seen that the values of AEV vary from 39.74 to 378.23 for the GIUH based Clark model; 41.12 to 386.45 for HEC-1; and 42.34 to 400.05 for Nash model. It is seen that the values of AEV are the lowest for the GIUH based Clark model as compared to the HEC-1 and the Nash model.

It is observed that the values of PEP vary from –13.81 to 5.01 for the GIUH based Clark model; -18.79 to 14.22 for HEC-1; and -10.82 to 27.81 for Nash model. The range of variation of the PEP values is the lowest for the GIUH based Clark model as compared to the HEC-1 and the Nash model.

Table-9: Error functions computed for the DSRO hydrographs estimated by GIUH based Clark model, HEC-1 package and Nash model for the various rainfall-runoff events (Approach-I)

Methods	Error functions for DSRO hydrographs					
	EFF	AAE	RMSE	AEV	PEP	PETP
Event 1						
GIUH	78.38	44.91	58.08	145.72	-12.27	22.22
HEC-1	97.01	18.28	23.36	156.51	2.40	11.11
NASH	95.97	22.42	26.61	162.09	8.34	11.11
Event 2						
GIUH	38.54	79.18	113.23	191.61	0.88	66.67
HEC-1	96.59	20.10	30.07	192.95	4.77	0
NASH	94.13	28.46	37.66	200.67	0.84	16.67
Event 3						
GIUH	91.45	64.62	76.19	378.23	4.78	-18.18
HEC-1	95.51	43.72	59.07	386.45	4.19	0
NASH	91.89	63.41	77.13	400.05	11.05	-9.09
Event 4						
GIUH	86.40	77.63	103.62	333.52	-11.52	0
HEC-1	97.16	40.40	51.75	358.46	-0.59	0
NASH	96.10	45.58	59.31	377.91	6.27	0
Event 5						
GIUH	93.21	6.88	8.08	39.74	-13.81	12.50
HEC-1	90.93	7.64	9.91	41.12	-16.60	12.50
NASH	66.17	14.39	18.34	42.34	-10.32	0
Event 6						
GIUH	94.25	33.42	39.76	206.31	1.77	-10.0
HEC-1	89.10	46.60	57.01	210.89	-5.46	-10.0
NASH	75.39	67.80	83.80	215.44	0.81	-20
Event 7						
GIUH	93.97	26.55	33.54	168.33	-0.34	11.11
HEC-1	95.42	25.57	30.86	175.33	-3.27	22.22
NASH	72.86	55.79	71.86	180.19	5.83	-11.11
Event 8						
GIUH	77.32	44.0	53.07	148.28	-3.75	-15.38
HEC-1	98.28	12.16	20.55	158.27	-5.94	7.69
NASH	64.28	57.95	68.15	159.85	12.07	-15.38
Event 9						
GIUH	78.45	54.91	68.43	164.45	-8.78	-10.0
HEC-1	84.53	43.93	61.28	169.12	-18.79	0
NASH	79.27	48.31	69.99	170.81	-10.82	0
Event 10						
GIUH	48.41	29.69	40.67	83.76	5.01	28.57
HEC-1	80.14	20.85	26.13	87.65	14.22	0
NASH	78.88	21.47	26.89	94.44	27.81	0

7.4.2 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 Clark IUH model option of the 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 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 by taking the geometric mean of the parameters derived for the five rainfall-runoff events viz. event Nos. 1, 2, 3, 6 and 8. While selecting these rainfall-runoff events it has been taken into consideration that some of the high, medium and low events are included for computing the mean parameter values so as to account for the sampling variability. These geometric mean parameter values have been used to derive the unit hydrograph and the DSRO hydrographs for the remaining five independent rainfall-runoff events viz. event Nos. 4, 5, 7, 9 and 10. The error functions, as described in Section 6.9, have been evaluated for the five independent rainfall-runoff events (event Nos. 4, 5, 7, 9 and 10) of the GIUH based Clark model, HEC-1 package and the Nash model considering the observed and the computed DSRO hydrographs.

7.4.2.1 Comparison of the derived unit hydrographs based on Approach-II

For the Clark IUH model of the HEC-1 package, the mean values of T_c and R for the five rainfall-runoff events are computed as 10.96 hours and 6.61 hours by taking the arithmetic mean and 9.88 hours and 6.28 hours by taking the geometric mean. For the Nash model, the mean values of n and k for the five events are computed as 4.19 and 2.83 hours by taking the arithmetic mean and 3.99 and 2.74 hours by taking the geometric mean. The geometric mean values have been considered for carrying out further analysis.

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 are given in Table 10.

Table 10: Peak discharge and time to peak of 1-hour unit hydrographs derived by the GIUH based Clark model, HEC-1 package and Nash IUH model (Approach-II)

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)
25.8	9	232.2	30	8	240.0	26.9	9	242.1

It is seen from Table 10 that out of the three methods of the unit hydrograph derivation, the Q_p and T_p values of the unit hydrographs derived by the Clark model based GIUH approach and the

Nash IUH model are closer as compared to the Q_p and T_p values computed by the Clark IUH model option of the HEC-1 package.

7.4.2.2 Comparison of observed and computed DSRO hydrographs based on Approach-II

In Approach-II, the direct surface runoff (DSRO) hydrographs computed using HEC-1 package and Nash IUH model have been compared with the observed DSRO hydrographs as well as the DSRO hydrographs computed by GIUH based Clark model. The values of peak discharge and time to peak of the DSRO hydrographs for the various rainfall-runoff events are given in Table 11.

Table 11: Values of peak discharge and time to peak of the DSRO hydrographs derived by GIUH based Clark model, HEC-1 package and Nash IUH model (Approach-II)

Run No.	Event No.	OBSERVED		GIUH		HEC-1		NASH	
		Q_p (cumec)	T_p (hr)	Q_p (cumec)	T_p (hr)	Q_p (cumec)	T_p (hr)	Q_p (cumec)	T_p (hr)
1	4	808.4	9	715.3	9	842.1	8	753.1	9
2	5	105.3	8	90.8	9	105.4	7	94.6	9
3	7	399.0	9	397.6	10	462.9	9	415.4	10
4	9	458.3	10	418.1	9	485.4	7	435.7	9
5	10	161.2	7	169.3	9	198.1	8	178.4	9

It is observed from Table 11 that in case of the DSRO hydrographs, the Q_p values estimated by the GIUH based Clark model are closest to the observed Q_P values in the case of two rainfall-runoff events out of the five events. The Clark model option of the HEC-1 package also provides the Q_p values of the DSRO hydrographs closest to the observed Q_p values for the two events. Nash model estimates the DSRO Q_p value closer to the observed Q_p value for one of the events.

7.4.2.3 Comparison of error functions used for evaluation of the computed DSRO hydrographs based on Approach-II

It is seen from Section 7.4.1.3 (Approach-I) that based on the comparison of some of the error functions, HEC-1 package provides higher values of EFF and lower values of AAE and RMSE as compared to the GIUH based Clark model and the Nash model. However, the values of AEV and PEP are lower for the GIUH based Clark model as compared to the HEC-1 package and Nash model.

The values of error functions computed based on the observed and computed DSRO hydrographs for Approach-II are given in Table 12.

Table-12: Error functions computed for DSRO hydrographs estimated by the GIUH based Clark model, HEC-1 package and Nash model for the various rainfall-runoff events (Approach-II)

Methods	Error functions for DSRO hydrographs					
	EFF	AAE	RMSE	AEV	PEP	PETP
Run-1 (Event No. 4)						
GIUH	86.40	77.63	103.62	333.52	-11.52	0
HEC-1	89.92	74.75	91.59	356.22	4.17	11.11
NASH	97.66	29.22	47.71	362.64	-6.84	0
Run-2 (Event No. 5)						
GIUH	93.21	6.88	8.08	39.74	-13.81	12.50
HEC-1	58.48	16.70	20.04	49.90	0.09	-12.50
NASH	85.67	9.45	11.84	42.45	-10.17	12.50
Run-3 (Event No. 7)						
GIUH	93.97	26.55	33.54	168.33	-0.34	11.11
HEC-1	75.24	58.99	68.27	177.53	16.01	0
NASH	95.21	25.12	30.57	179.92	4.11	11.11
Run-4 (Event No. 9)						
GIUH	78.45	54.91	68.43	164.45	-8.78	-10.00
HEC-1	19.58	105.98	132.77	170.16	5.92	-30.00
NASH	61.25	66.51	92.58	170.76	-4.94	-10.00
Run-5 (Event No. 10)						
GIUH	48.41	29.69	40.67	83.76	5.01	28.57
HEC-1	81.41	19.95	25.84	90.90	22.91	14.29
NASH	65.01	25.5	34.55	92.46	10.64	28.57

The error functions based on the comparison of the observed DSRO and computed DSRO hydrographs for the three methods, presented in Table 12, show that the values of EFF for the GIUH based Clark model are higher in two cases out of the five rainfall-runoff events. The values of EFF for HEC-1 package are also higher in case of two events while the values of EFF for Nash IUH model are higher in case of only one event. It is seen that the values of AAE and RMSE for the GIUH based Clark model are lower in two cases out of the five rainfall-runoff events. The values of AAE and RMSE for HEC-1 package are also lower in case of two events while the values of AAE and RMSE for Nash IUH model are lower in case of only one event. It is observed that the values of AEV are lower for GIUH based Clark model for all the five rainfall-runoff events. It is also seen that the values of PEP are lower for GIUH based Clark model in two cases. The values of PEP are lower for HEC-1 package in two cases; while, the values of PEP are lower for Nash IUH model in only one case. Thus it is observed that for Approach-II, the GIUH based Clark model provides better DSRO estimates as compared to the HEC-1 package and Nash IUH model.

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

In Approach-III, 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 ten rainfall-runoff events by taking the geometric mean of the parameters derived for the remaining nine out of ten 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. 10; thus excluding the parameter values obtained for the first event. If excess-rainfall hyetograph of event No. 5 has been used for convolution with the unit hydrograph; then, the parameter values of event No. 1 to 4 and 6 to 10 (nine events) have been used to compute the geometric mean values of the parameters. The error functions, as described in Section 6.9, 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.

7.4.3.1 Comparison of derived unit hydrographs based on Approach-III

Table 13 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-III (as mentioned above) for all the ten rainfall-runoff events. Table 14 shows the values of n and K for Nash IUH model for all the ten individual rainfall-runoff events for approach-I and also the arithmetic mean and geometric mean values of n and K for approach-III (as mentioned above) for all the ten 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 15.

Table 13: Mean parameters of Clark IUH Model (HEC-1 Package) derived from historical data (Approach-III)

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	8.78	6.07	10.88	6.72	10.15	6.51
2	4.24	9.66	11.38	6.32	11.00	6.19
3	11.57	7.17	10.57	6.60	9.84	6.39
4	10.27	5.52	10.71	6.78	9.97	6.58
5	10.97	6.78	10.67	6.66	9.90	6.43
6	12.01	6.68	10.52	6.66	9.80	6.44
7	10.50	7.03	10.68	6.62	9.95	6.41
8	18.22	3.49	9.83	7.01	9.36	6.93
9	13.38	6.33	10.36	6.69	9.68	6.48
10	6.72	7.85	11.10	6.53	10.45	6.33

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

Table 14: Mean parameters of Nash IUH Model derived from historical data (Approach-III)

Event No.	NASH model of IUH					
	For individual storm		Arithmetic mean*		Geometric mean*	
	n	K	n	K	n	K
1	3.86	2.39	4.48	2.65	4.31	2.59
2	2.31	4.21	4.65	2.45	4.56	2.43
3	3.98	2.86	4.46	2.60	4.30	2.54
4	4.63	2.18	4.39	2.67	4.22	2.62
5	4.80	2.45	4.42	2.62	4.21	2.58
6	4.61	2.64	4.39	2.62	4.23	2.56
7	4.65	2.44	4.39	2.64	4.22	2.59
8	6.19	2.03	4.22	2.69	4.09	2.64
9	5.95	2.30	4.25	2.66	4.11	2.60
10	3.18	2.73	4.55	2.61	4.40	2.55

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

Table 15: 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	10.67	3.38	5.84	15.00	4.468	16.864
R	6.66	1.59	4.63	8.69	4.05	9.23
Parameters of Nash IUH model						
n	4.42	1.17	2.92	5.91	2.50	6.34
K	2.62	0.61	1.84	3.41	1.62	3.63

The values of T_c and R for the GIUH based Clark model have been estimated as 9.13 hours and 8.45 hours respectively, which are very close to the mean values of these parameters derived from the historical data of all the ten events. As seen from the Table the T_c and R values lie well within 90% confidence limits of these parameters values.

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 16 provides the 1-hour unit hydrographs derived by the GIUH based Clark model, HEC-1 package and Nash model for approach-III. 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-III are given in Table 17.

Table 16: 1-hour unit hydrographs derived by the GIUH based Clark model, Clark IUH model (HEC-1 package) and Nash IUH model (Approach-III)

Time (hr)	GIUH	Clark IUH model (HEC-1)				NASH			
		Event 1	Event 2	Event 3	Event 4	Event1	Event2	Event3	Event4
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0.1	1.0	1.0	1.0	1.0	1.0	1.2	1.0	1.2
3	2.0	4.0	4.0	4.0	4.0	2.5	2.8	2.3	2.3
4	4.9	7.0	7.0	8.0	8.0	5.0	4.5	5.4	5.4
5	7.9	9.0	9.0	10.0	9.0	10.0	9.4	10.7	10.6
6	11.7	13.0	12.0	14.0	14.0	15.5	15.1	16.4	16.2
7	16.4	20.0	18.0	22.0	21.0	20.5	20.4	21.5	21.1
8	21.3	25.0	23.0	26.0	26.0	24.2	24.5	25.2	24.6
9	24.9	29.0	27.0	30.0	29.0	26.4	27.0	27.2	26.7
10	25.8	29.0	29.0	30.0	29.0	27.2	28.0	27.8	27.2
11	24.1	27.0	29.0	27.0	27.0	26.7	27.6	27.0	26.6
12	21.4	24.0	26.0	23.0	23.0	25.3	26.1	25.4	25.1
13	19.0	20.0	22.0	20.0	20.0	23.3	23.9	23.1	23.0
14	16.9	17.0	19.0	17.0	17.0	20.8	21.3	20.6	20.5
15	15.0	15.0	16.0	14.0	15.0	18.3	18.6	17.9	18.0
16	13.3	13.0	14.0	12.0	13.0	15.7	15.9	15.3	15.4
17	11.9	11.0	11.0	11.0	11.0	13.3	13.4	12.8	13.1
18	10.5	9.0	10.0	9.0	9.0	11.2	11.1	10.7	10.9
19	9.4	8.0	8.0	8.0	8.0	9.2	9.0	8.7	9.0
20	8.3	7.0	7.0	7.0	7.0	7.5	7.3	7.1	7.4
21	7.4	6.0	6.0	6.0	6.0	6.1	5.8	5.7	5.9
22	6.6	5.0	5.0	5.0	5.0	4.9	4.6	4.5	4.8
23	5.8	4.0	4.0	4.0	4.0	3.9	3.6	3.6	3.8
24	5.2	4.0	4.0	4.0	4.0	3.1	2.8	2.8	3.0
25	4.6	3.0	3.0	3.0	3.0	2.4	2.2	2.2	2.4
26	4.1	3.0	3.0	3.0	3.0	1.9	1.7	1.7	1.8
27	3.6	2.0	2.0	2.0	2.0	1.5	1.3	1.3	
28	3.2	2.0	2.0	2.0	2.0		1.0	1.0	
29	2.9	2.0	2.0	2.0	2.0		0.7	0.8	
30	2.5	1.0	1.0	1.0	1.0		0.6	0.6	
31	2.3	1.0	1.0	1.0	1.0		0.4		
32	2.0	1.0	1.0	1.0	1.0				
33	1.8	1.0	1.0	1.0	1.0				
34	1.6	1.0	1.0	1.0	1.0				
35	1.4	1.0	1.0	1.0	1.0				
36	1.3	1.0	1.0	1.0	1.0				
37	1.1	1.0	0.0	0.0	1.0				
38	1.0	0.0			0.0				
39	0.9								
40	0.8								
41	0.7								
42	0.6								
43	0.5								
44	0.5								
..contd	..contd								
66	0.0								

Table 17: Peak discharge and time to peak of 1-hour unit hydrographs derived by the GIUH based Clark model, HEC-1 package and Nash model for the various rainfall-runoff events (Approach-III)

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	25.8	9	232.2	29.0	7	203.0	27.2	9	244.8
2	25.8	9	232.2	29.0	8	232.0	28.0	9	252.0
3	25.8	9	232.2	30.0	7	210.0	27.8	9	250.2
4	25.8	9	232.2	29.0	7	203.0	27.0	9	243.0
5	25.8	9	232.2	30.0	8	240.0	27.7	9	249.3
6	25.8	9	232.2	30.0	7	210.0	27.8	9	250.2
7	25.8	9	232.2	30.0	8	240.0	27.5	9	247.5
8	25.8	9	232.2	29.0	7	203.0	27.5	9	247.5
9	25.8	9	232.2	30.0	7	210.0	27.8	9	250.2
10	25.8	9	232.2	30.0	8	240.0	27.3	9	245.7

It is seen from Table 17 that the peak of the unit hydrograph and time to peak for GIUH based Clark model are 25.8 cumec and 9 hours respectively. It is observed that the peak of the unit hydrograph for Clark IUH model of HEC-1 package varies from 29.0 to 30.0 cumec and the time to peak varies from 7 to 8 hours. It is also observed that the peak of the unit hydrograph for Nash IUH model varies from 27.0 to 28.0 cumec and the time to peak is 9 hours. Thus the peak of the unit hydrograph for the GIUH based Clark model is the lowest while the peak of the unit hydrograph for the Clark IUH model of HEC-1 package is the highest.

7.4.3.2 Comparison of observed and computed DSRO hydrographs based on Approach-III

For approach-III, 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. 10 through Fig. 19. The values of peak discharge and time to peak of the DSRO hydrographs for the various rainfall-runoff events are given in Table 18.

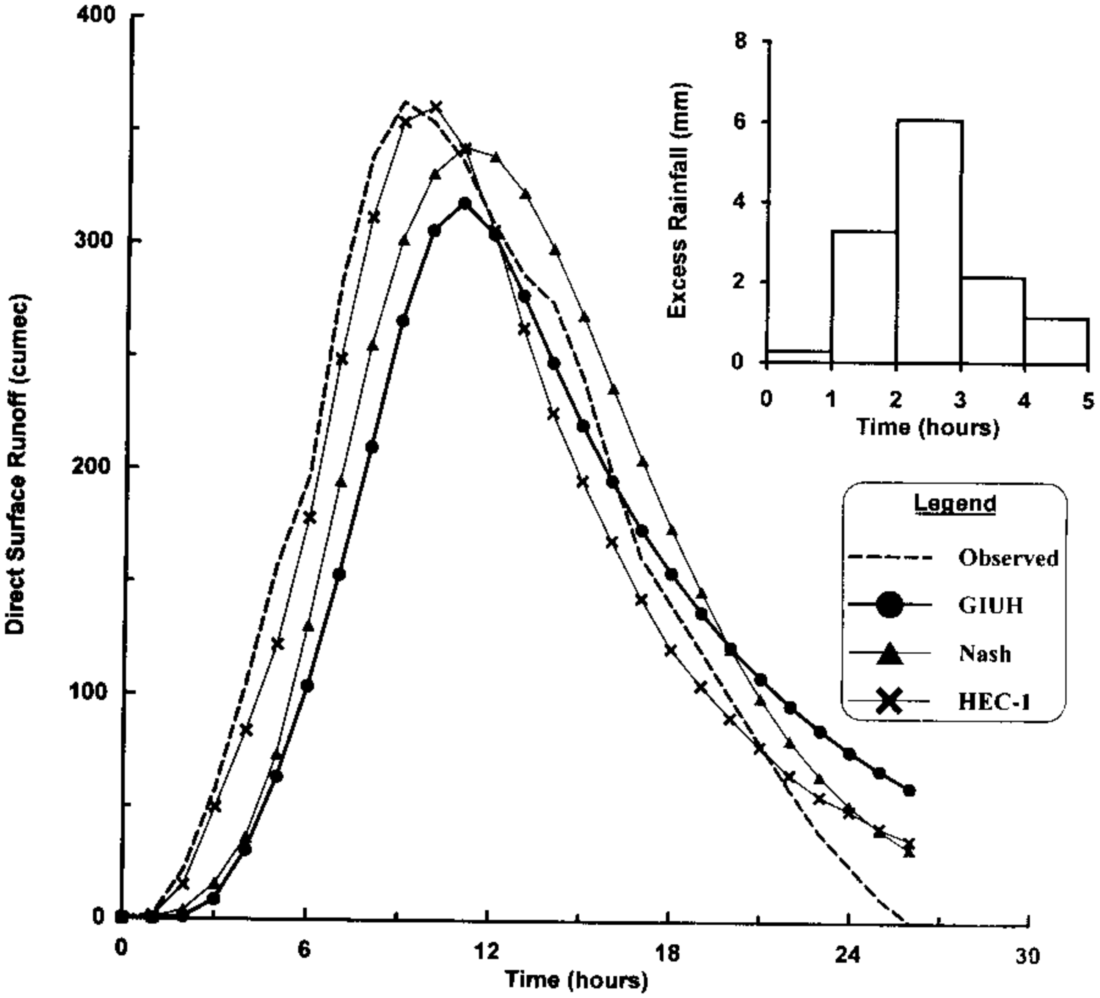


Fig. 10 : Comparison of observed and computed direct surface runoff hydrographs for Ajay basin upto Sarath (Event No. 1)

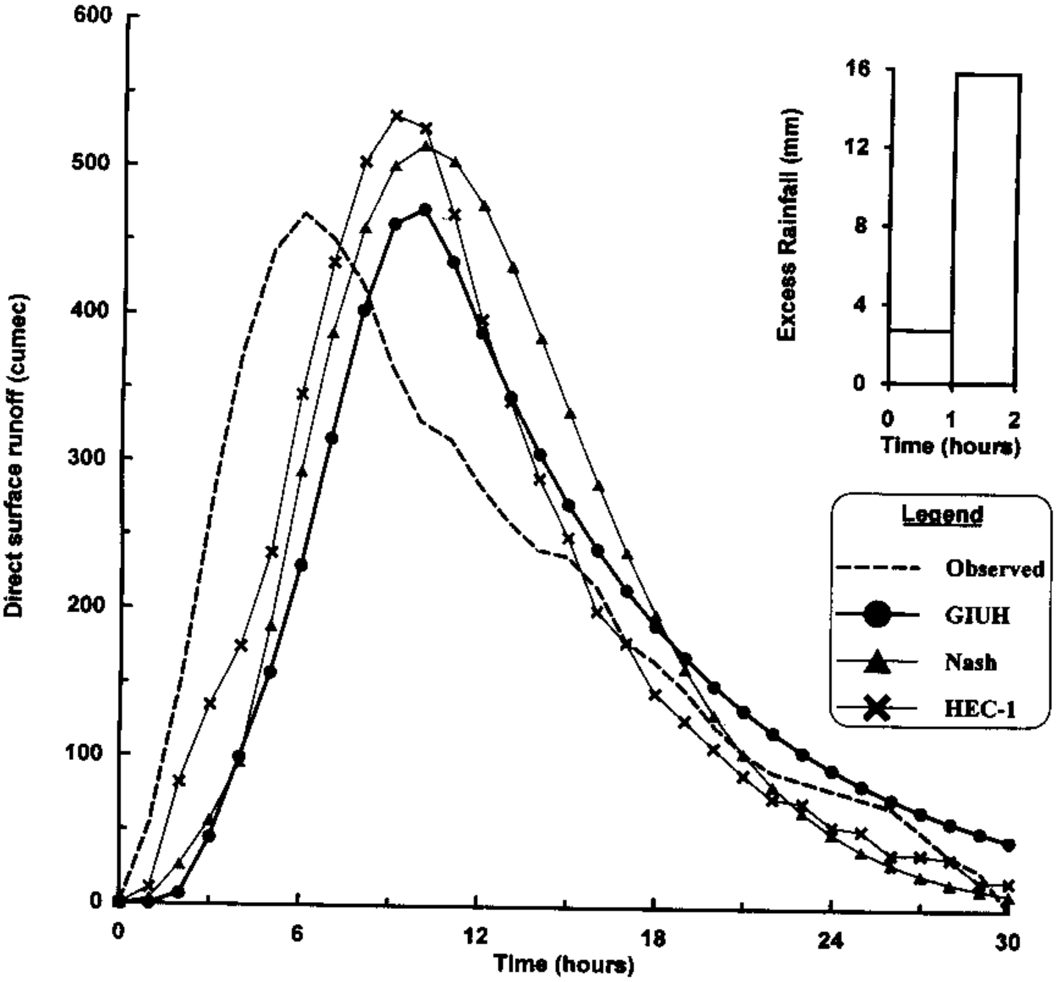


Fig. 11 : Comparison of observed and computed direct surface runoff hydrographs for Ajay basin upto Sarath (Event No. 2)

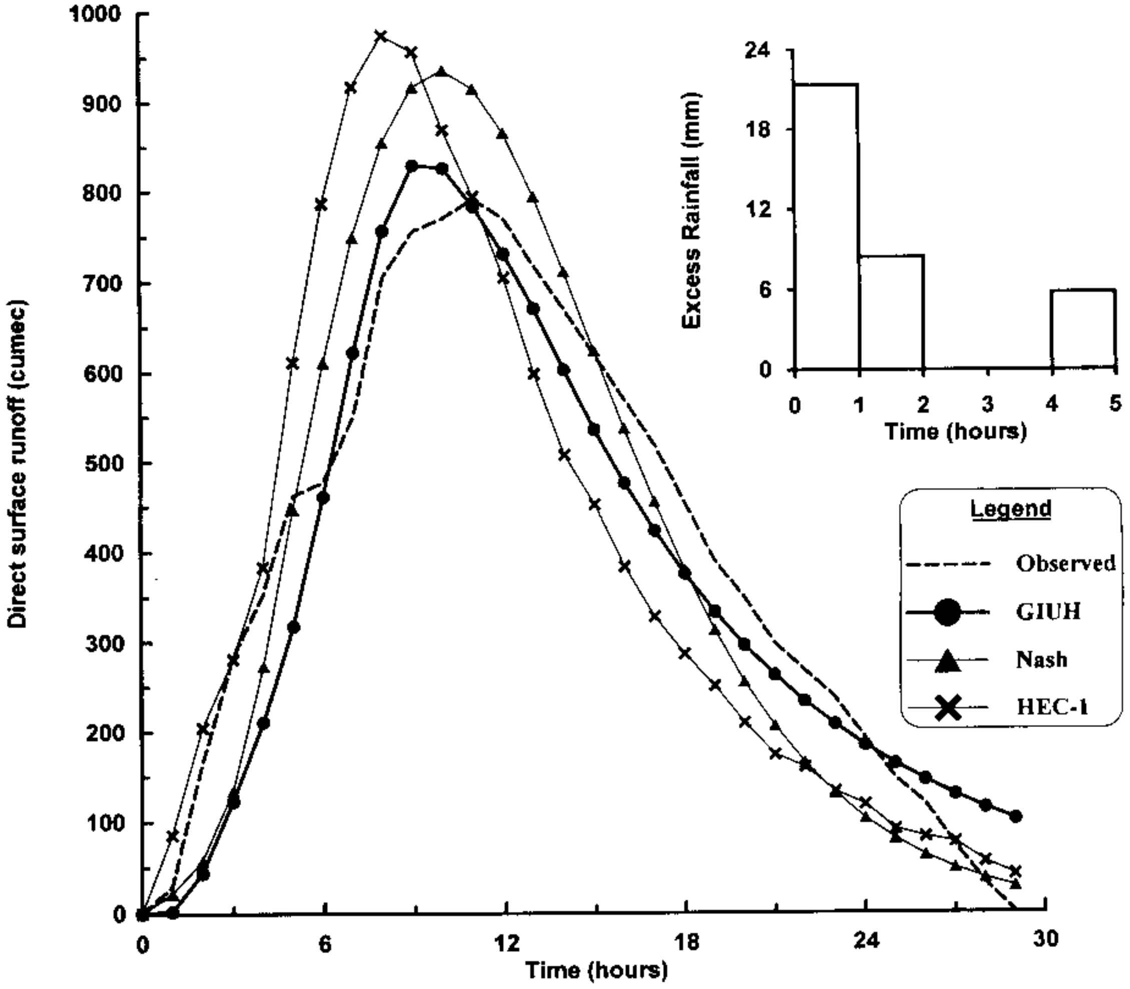


Fig. 12: Comparison of observed and computed direct surface runoff hydrographs for Ajay basin upto Sarath (Event No. 3)

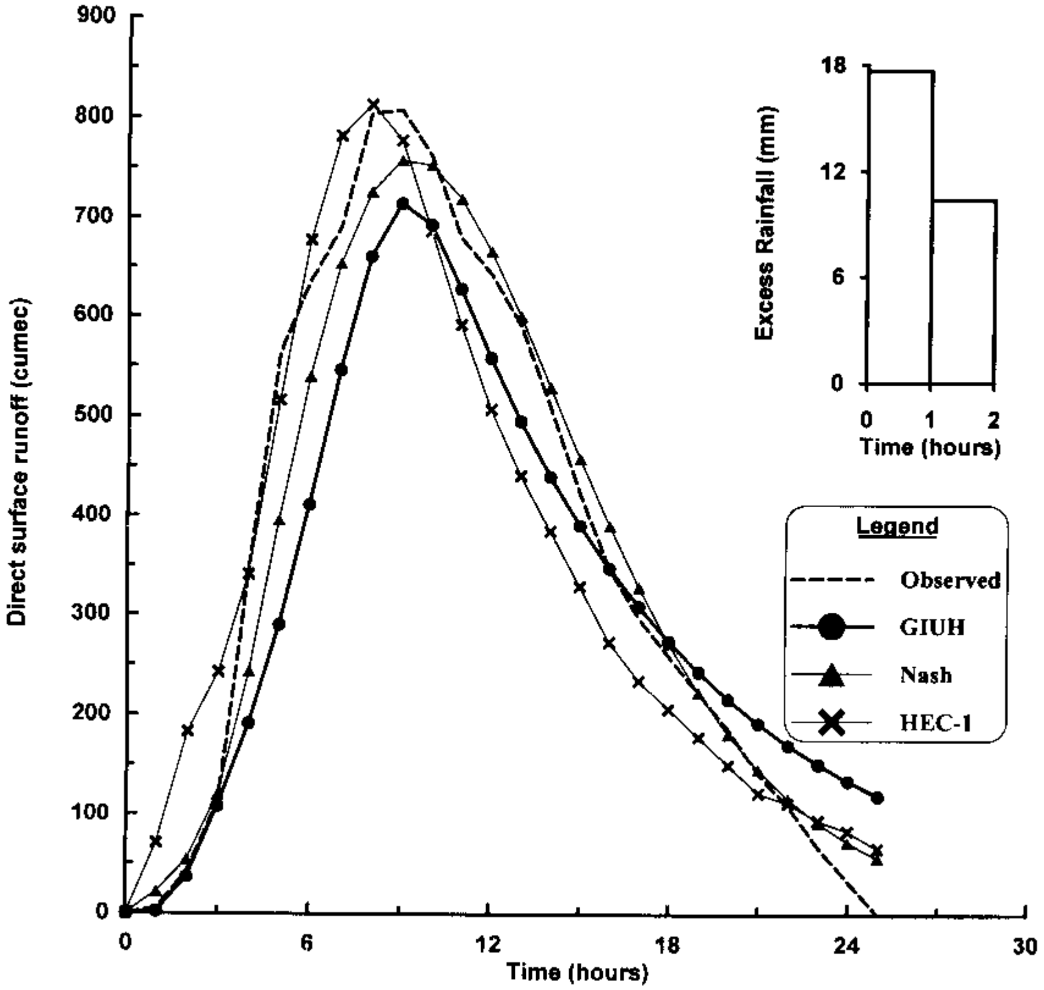


Fig. 13: Comparison of observed and computed direct surface runoff hydrographs for Ajay basin upto Sarath (Event No. 4)

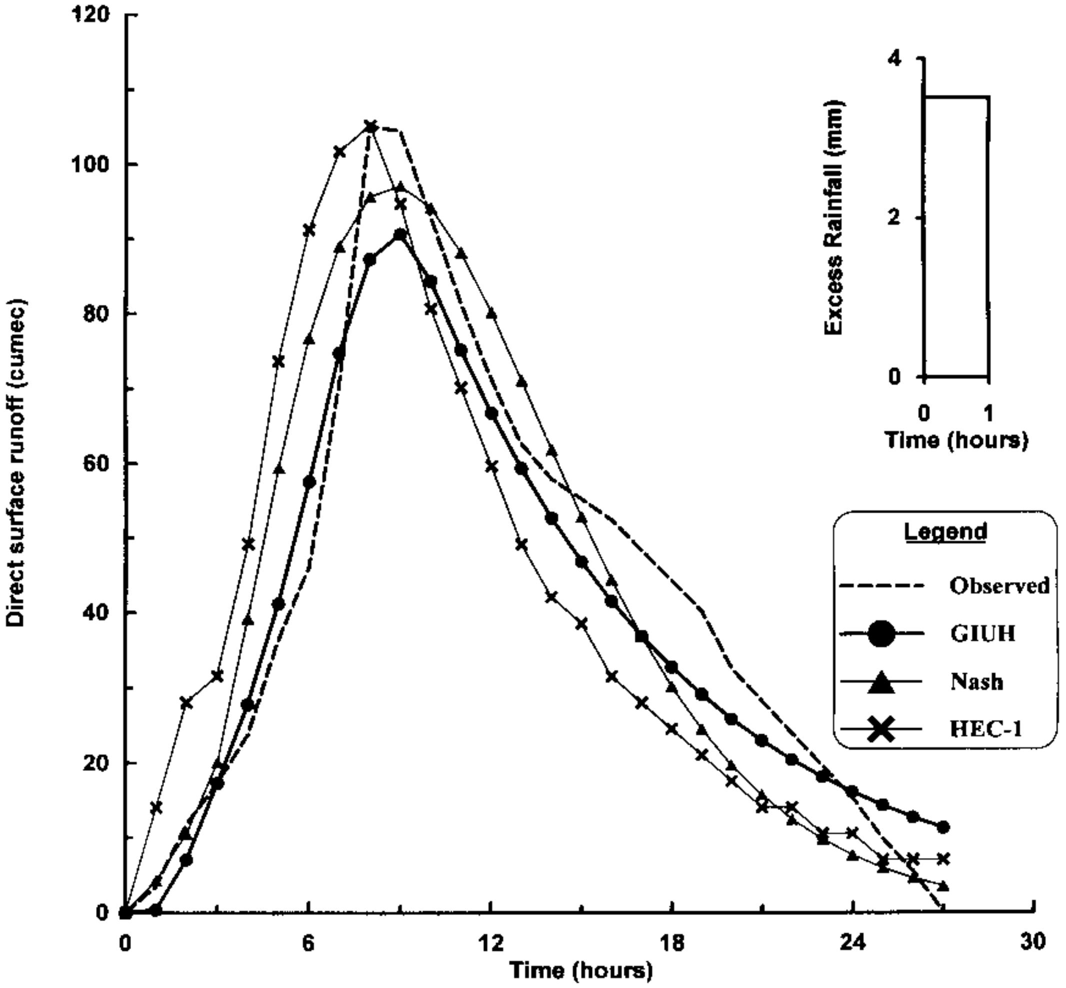


Fig. 14: Comparison of observed and computed direct surface runoff hydrographs for Ajay basin upto Sarath (Event No. 5)

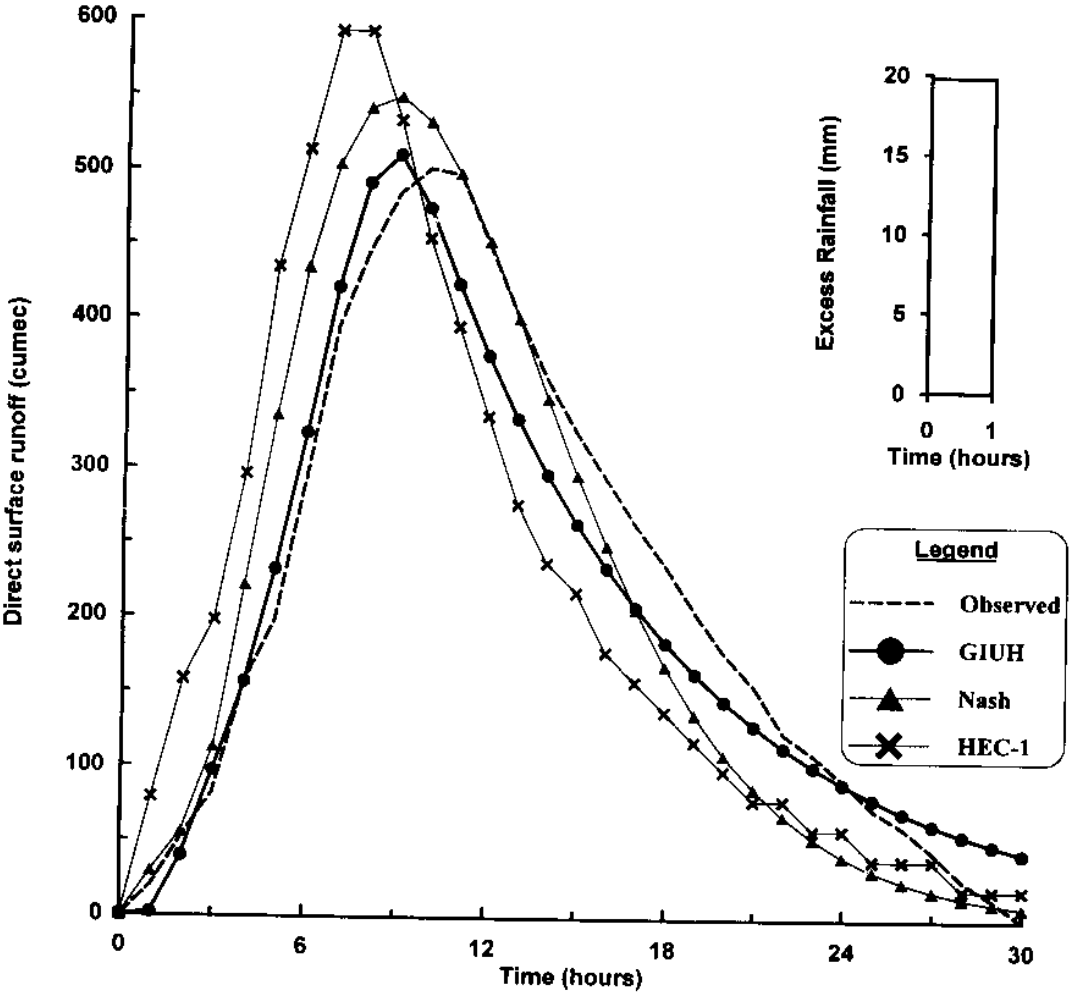


Fig. 15: Comparison of observed and computed direct surface runoff hydrographs for Ajay basin upto Sarath (Event No. 6)

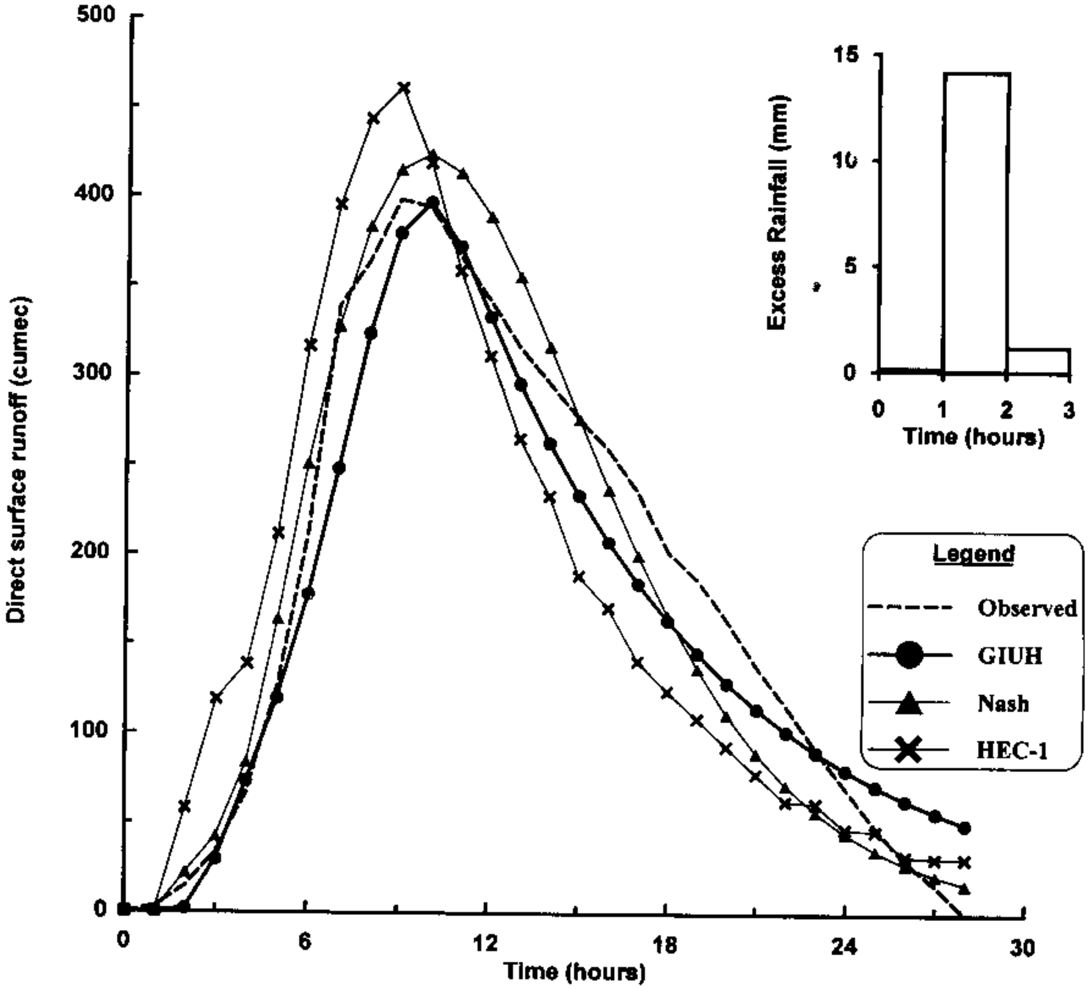


Fig. 16: Comparison of observed and computed direct surface runoff hydrographs for Ajay basin upto Sarath (Event No. 7)

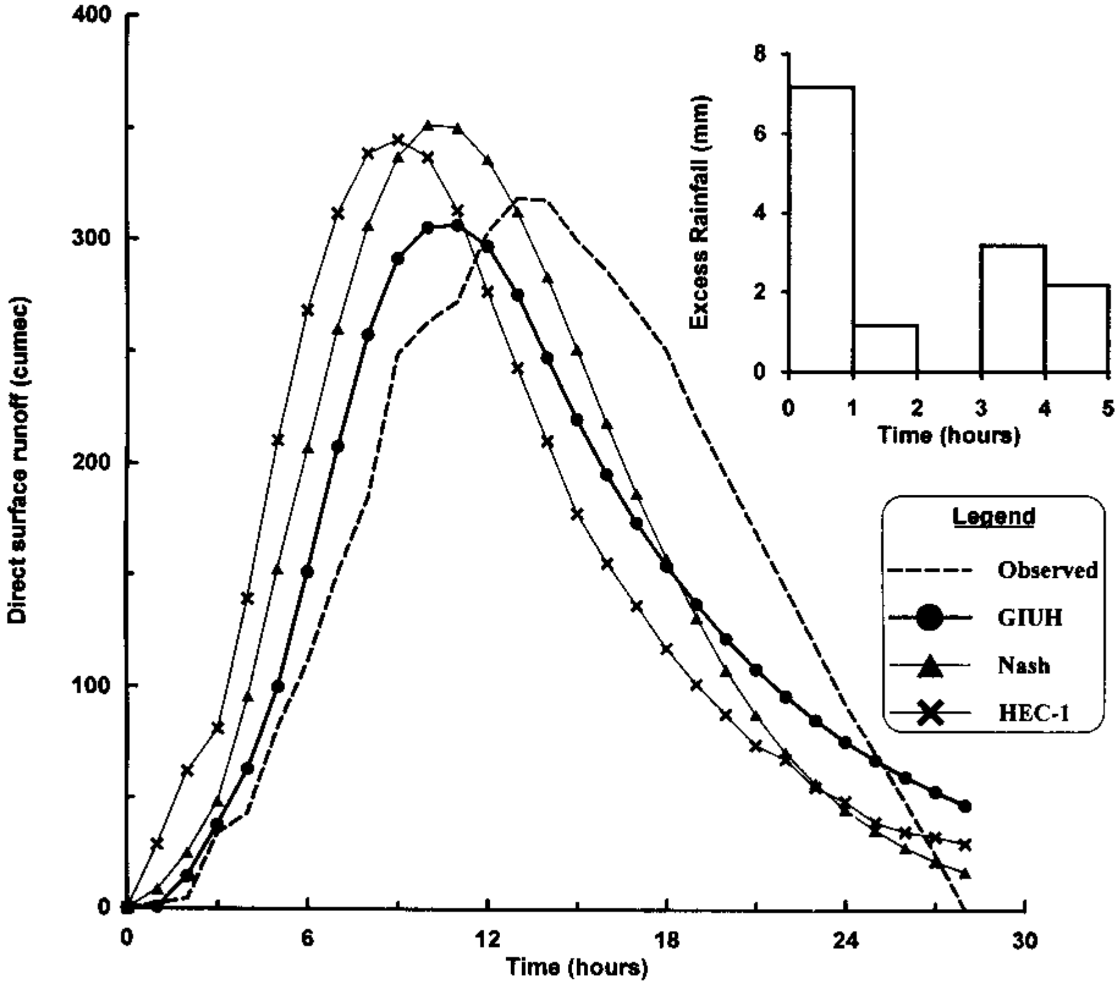


Fig. 17: Comparison of observed and computed direct surface runoff hydrographs for Ajay basin upto Sarath (Event No. 8)

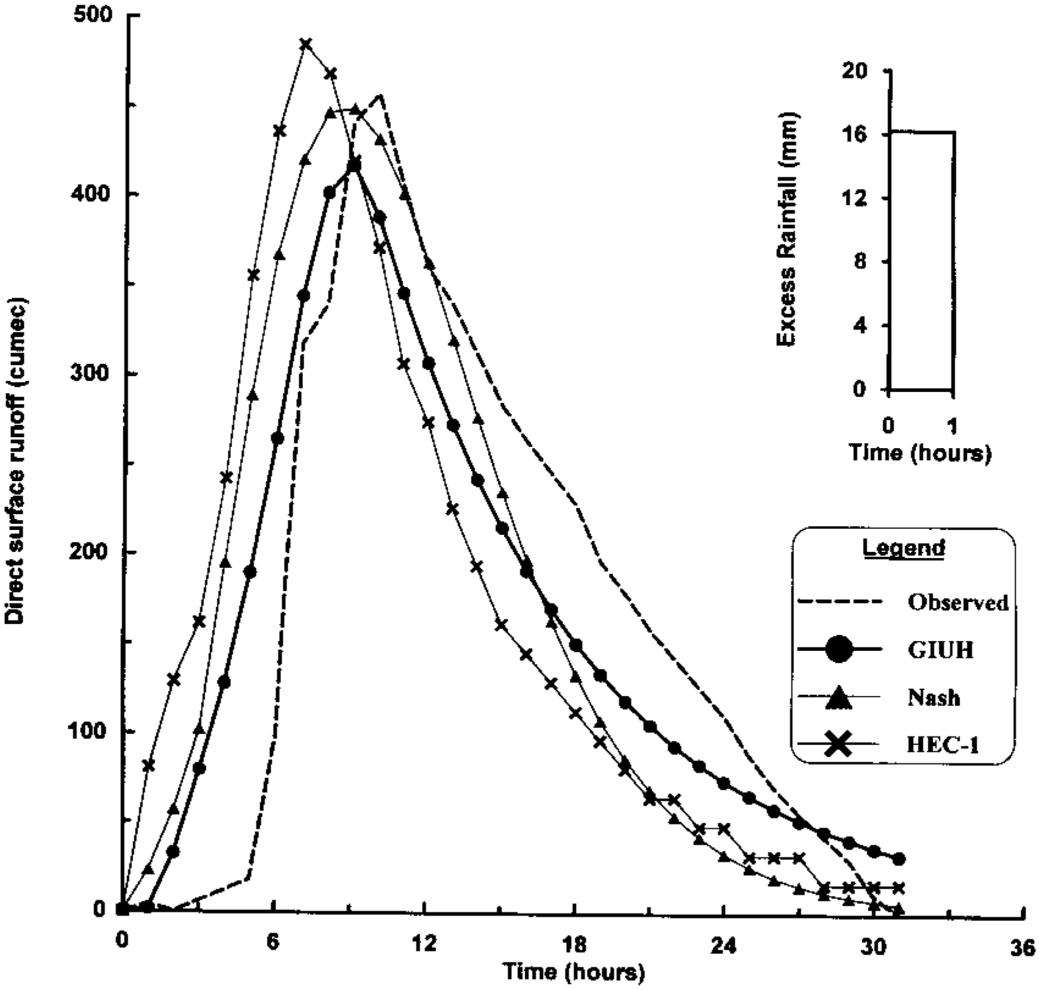


Fig. 18: Comparison of observed and computed direct surface runoff hydrographs for Ajay basin upto Sarath (Event No. 9)

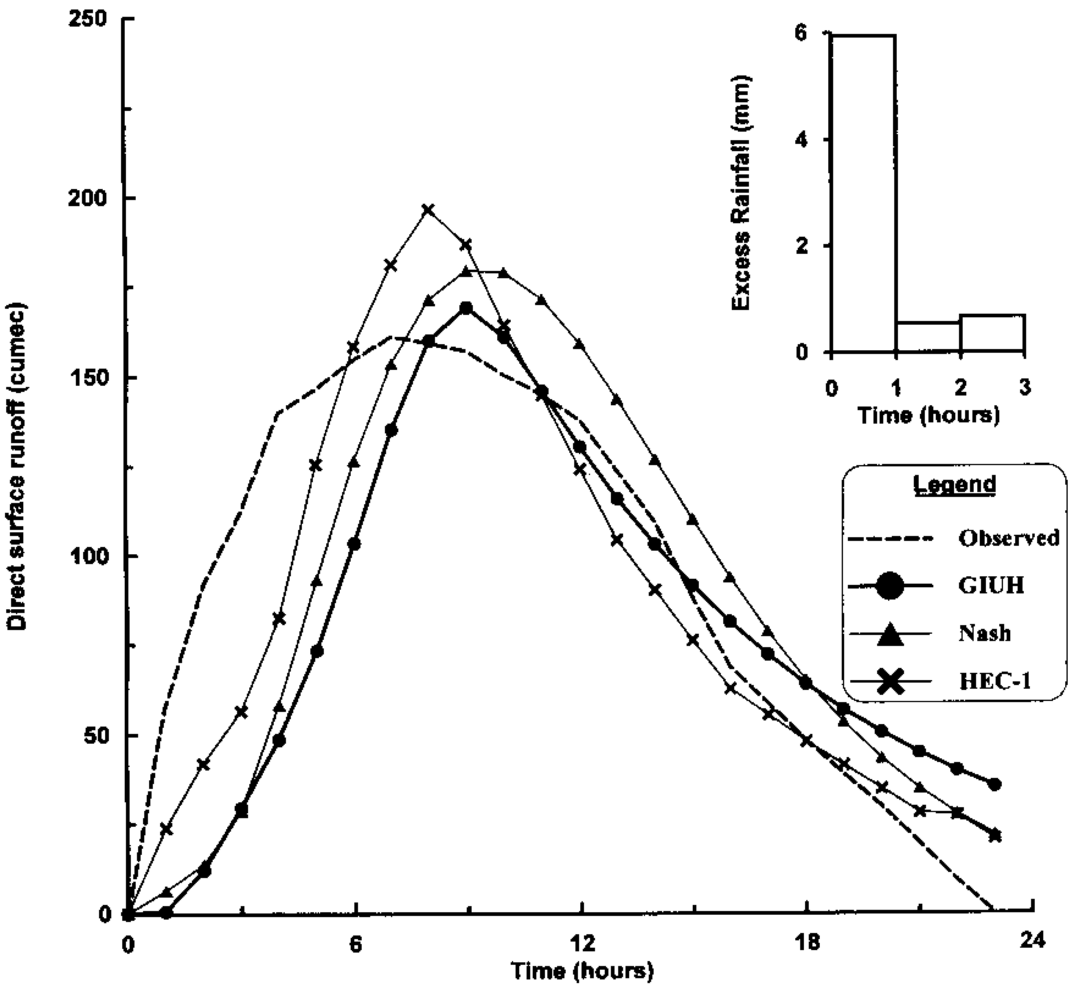


Fig. 19: Comparison of observed and computed direct surface runoff hydrographs for Ajay basin upto Sarath (Event No. 10)

Table 18: Peak discharge and time to peak of observed and computed DSRO hydrographs for the various rainfall-runoff events (Approach-III)

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	363.2	9	318.7	11	361.2	10	343.3	11
2	468.4	6	472.5	10	535.8	9	515.8	10
3	792.0	11	829.9	9	975.1	8	936.4	10
4	808.4	9	715.3	9	814.0	8	758.5	9
5	105.3	8	90.8	9	105.4	8	97.2	9
6	501.9	10	510.8	9	593.1	7	549.7	9
7	399.0	9	397.6	10	461.7	9	424.7	10
8	318.8	13	306.8	11	345.2	9	352.0	10
9	458.3	10	418.1	9	485.4	7	449.8	9
10	161.2	7	169.3	9	196.7	8	179.6	9

It is observed from Table 18 that the Clark model based GIUH approach estimates peak of the DSRO hydrographs closer to the observed DSRO peak in six cases out of ten rainfall-runoff events. It is also observed that the Clark IUH model of HEC-1 package estimates peak of the DSRO hydrographs closer to the observed DSRO peak in three cases; whereas, the Nash IUH model estimates peak of the DSRO hydrographs closer to the observed DSRO peak in only one case.

7.4.3.3 Comparison of error functions used for evaluation of the computed DSRO hydrographs based on Approach-III

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 6.9 are given in Table 19.

The error functions based on the comparison of the observed DSRO and computed DSRO hydrographs for the three methods, presented in Table 19, show that the values of EFF for the GIUH based Clark model are higher in five cases out of the ten rainfall-runoff events. The values of EFF for HEC-1 package are also higher in case of three events while the values of EFF for Nash IUH model are higher in case of two events. It is seen that the values of AAE and RMSE for the GIUH based Clark model are lower in five cases out of the ten rainfall-runoff events. The values of AAE and RMSE for HEC-1 package are also lower in case of three events while the values of AAE and RMSE for Nash IUH model are lower in case of two events. It is observed that the values of AEV are lower for GIUH based Clark model for all the ten rainfall-runoff events. It is also seen that the values of PEP are lower for GIUH based Clark model in six cases. The values of PEP are lower for HEC-1 package in three cases; while, the values of PEP are lower for Nash IUH model in only one case. Thus it is observed that for Approach-III, the GIUH based Clark model provides better DSRO estimates as compared to the HEC-1 package and Nash IUH model.

As discussed above, out of the three methods, the GIUH based Clark model provides the best DSRO estimates for five cases, the HEC-1 package provides the best DSRO estimates for three cases and the Nash model provides the best DSRO estimates for two cases out of the ten rainfall-runoff events. But when only two methods viz. HEC-1 package and Nash model are compared; then it is seen that the Nash model provides better DSRO estimates for seven cases as compared to the HEC-1 package; whereas, HEC-1 package provides better DSRO estimates for only three cases as compared to the Nash model. Thus, it is observed that the GIUH based Clark model which considers the basin under study as ungauged, estimates the DSRO hydrographs more accurately for the Ajay basin of South Bihar upto Sarath gauging site as compared to the HEC-1 package and Nash IUH model. The performance of the HEC-1 package and the Nash model for estimation of the DSRO hydrographs may be considered as comparable.

Table-19: Error functions computed for DSRO hydrographs estimated by the GIUH based Clark model, HEC-1 package and Nash model for the various rainfall-runoff events (Approach-III)

Methods	Error functions for DSRO hydrographs					
	EFF	AAE	RMSE	AEV	PEP	PETP
Event 1						
GIUH	78.38	44.91	58.08	145.72	-12.27	22.22
HEC-1	96.43	19.41	26.21	154.40	-0.55	11.11
NASH	87.46	37.75	46.67	160.44	-5.49	22.22
Event 2						
GIUH	38.54	79.18	113.23	191.61	0.88	66.67
HEC-1	60.39	63.08	93.22	199.63	14.39	50.00
NASH	28.98	90.28	123.46	204.10	10.13	66.67
Event 3						
GIUH	91.45	64.62	76.19	378.23	4.78	-18.18
HEC-1	67.38	118.53	149.47	397.35	23.12	-23.27
NASH	85.89	83.51	98.90	404.15	18.23	-9.09
Event 4						
GIUH	86.40	77.63	103.62	333.52	-11.52	0
HEC-1	91.98	66.68	82.20	355.10	0.70	-11.11
NASH	96.43	37.18	37.01	365.14	-6.18	0
Event 5						
GIUH	93.21	6.88	8.08	39.74	-13.81	12.50
HEC-1	64.78	15.40	18.47	41.64	0.09	0
NASH	85.72	9.38	11.82	42.85	-7.68	12.50
Event 6						
GIUH	94.25	33.42	39.76	206.31	1.77	-10.00
HEC-1	58.18	89.17	107.52	215.50	18.18	-30.00
NASH	86.94	46.50	60.38	218.36	9.52	-10.00
Event 7						
GIUH	93.97	26.55	33.54	168.33	-0.34	11.11
HEC-1	79.88	53.02	61.61	176.98	15.72	0
NASH	94.96	26.07	31.31	181.64	6.43	11.11
Event 8						
GIUH	77.32	44.0	53.07	148.28	-3.75	-15.38
HEC-1	25.97	84.22	96.40	154.43	8.29	-30.77
NASH	63.55	58.17	68.02	160.41	10.40	-23.08
Event 9						
GIUH	78.45	54.91	68.43	164.45	-8.78	-10.00
HEC-1	21.19	104.94	131.45	170.16	5.92	-30.00
NASH	56.18	71.84	98.35	173.26	-1.85	-10.00
Event 10						
GIUH	48.41	29.69	40.67	83.76	5.01	28.57
HEC-1	79.19	19.62	26.18	90.29	22.01	14.29
NASH	55.68	30.47	38.63	93.12	11.40	28.57

7.5 Sensitivity Analysis of the Velocity Parameter of the GIUH based Clark Model

In order to study the effect of variation in the velocity parameter of the GIUH model, on the DSRO hydrographs, peak and time to peak of the DSRO hydrographs the sensitivity analysis has been carried out by varying the adopted velocity of 2.5 m/sec to 2.0 m/sec, 2.25 m/sec, 2.75 m/sec and 3.00 m/sec. The parameters of the GIUH based Clark model and the parameters of 1-hour unit hydrograph derived by the GIUH based Clark model for different velocities are given in Table 20. The peak values of the DSRO hydrographs for the various sensitivity runs are shown in Fig. 20 through Fig. 29. From these figures, it is observed that, in general, as the velocity increases the peak of the DSRO hydrographs increases.

Table 20: Variation of parameters of the GIUH based Clark model and the parameters of 1-hour Unit Hydrograph derived by the GIUH based Clark model for different velocities

Parameters	**Velocity (m/s)**				
	2.00	**2.25**	**2.50**	**2.75**	**3.00**
Parameters of the GIUH based Clark model					
T_c (hour)	11.41	10.15	9.13	8.30	7.61
R (hour)	10.56	9.38	8.45	7.68	7.05
Parameters of 1-hour Unit Hydrograph derived by the GIUH based Clark model					
Q_p (cumec)	20.82	23.22	25.84	28.30	30.43
T_p (hour)	11.0	10.0	9	8	7
Q_p*T_p (cumec-hour)	229.02	232.2	232.56	226.4	213.01

Fig. 20 Comparison of observed and computed DSRO peak values for various velocities for the GIUH based Clark model (Event No. 1)

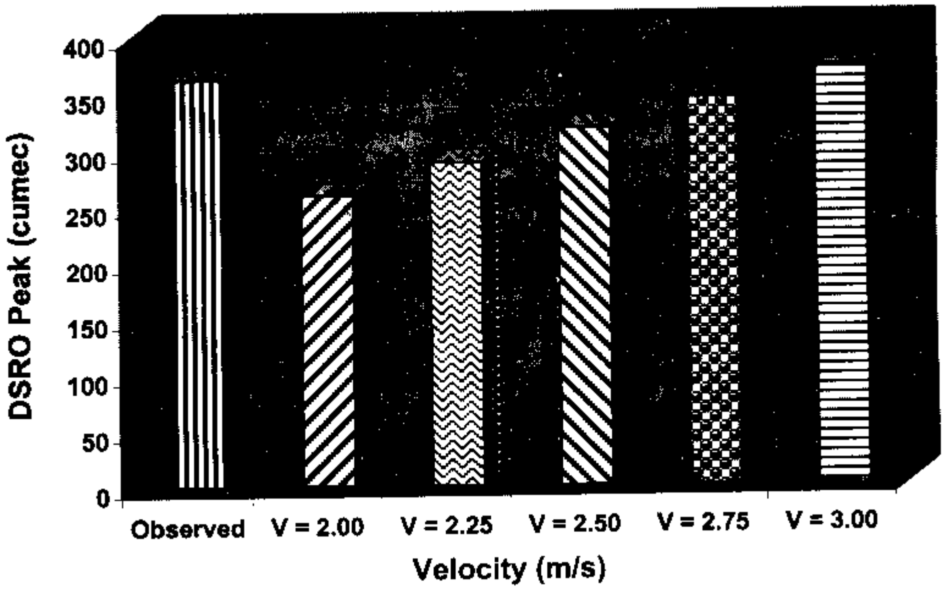


Fig. 21 Comparison of observed and computed DSRO peak values for various velocities for the GIUH based Clark model (Event No. 2)

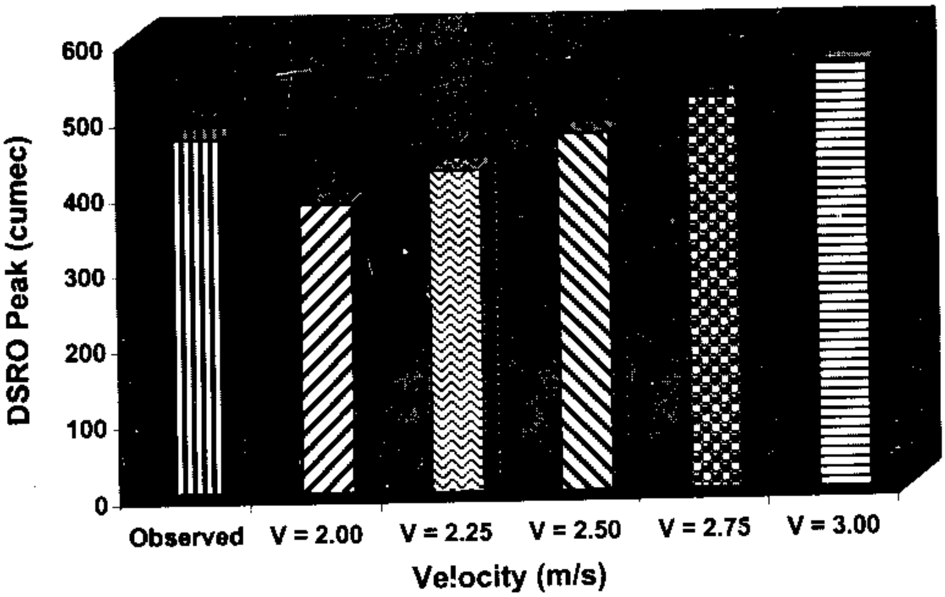


Fig. 22 Comparison of observed and computed DSRO peak values for various velocities for the GIUH based Clark model (Event No. 3)

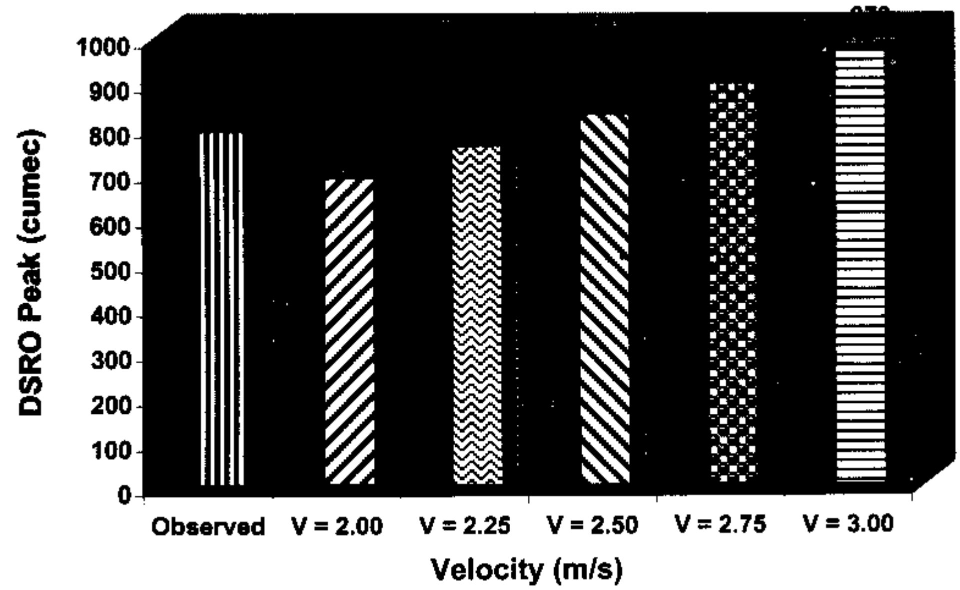


Fig. 23 Comparison of observed and computed DSRO peak values for various velocities for the GIUH based Clark model (Event No. 4)

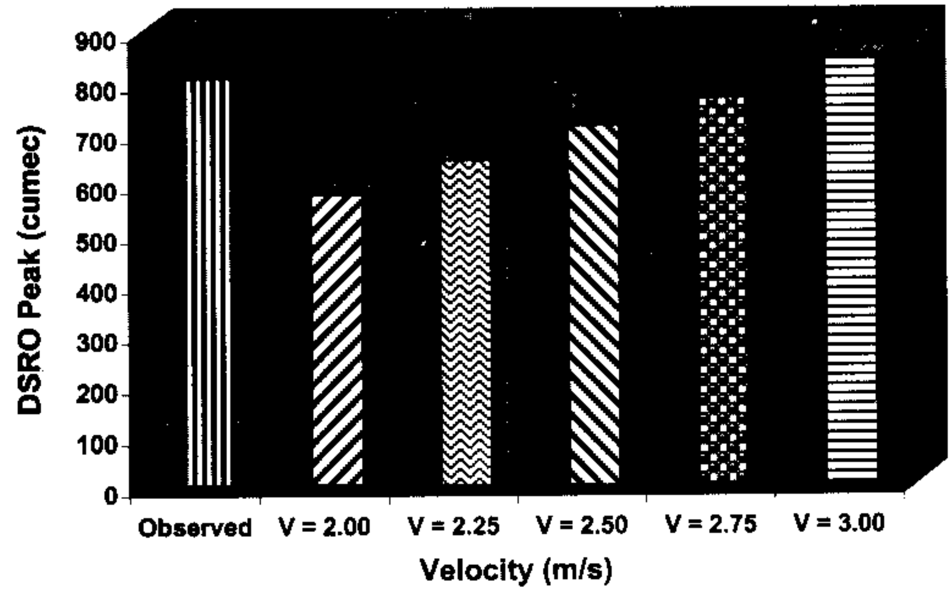


Fig. 24 Comparison of observed and computed DSRO peak values for various velocities for the GIUH based Clark model (Event No. 5)

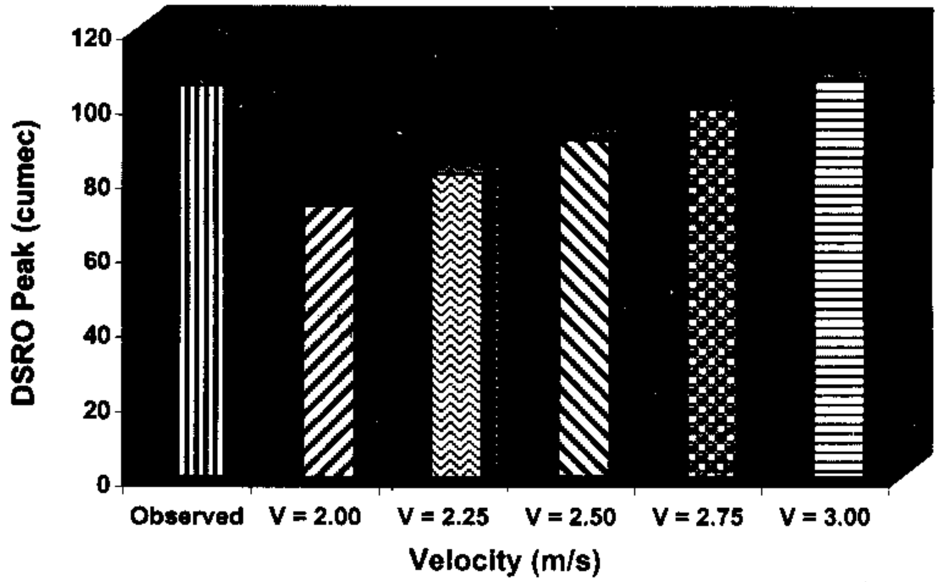


Fig. 25 Comparison of observed and computed DSRO peak values for various velocities for the GIUH based Clark model (Event No. 6)

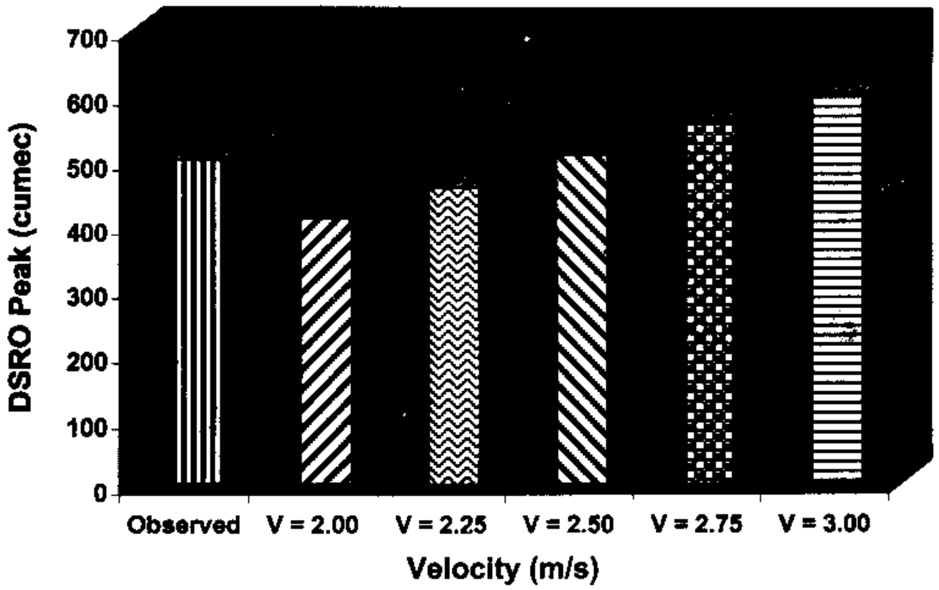


Fig. 26 Comparison of observed and computed DSRO peak values for various velocities for the GIUH based Clark model (Event No. 7)

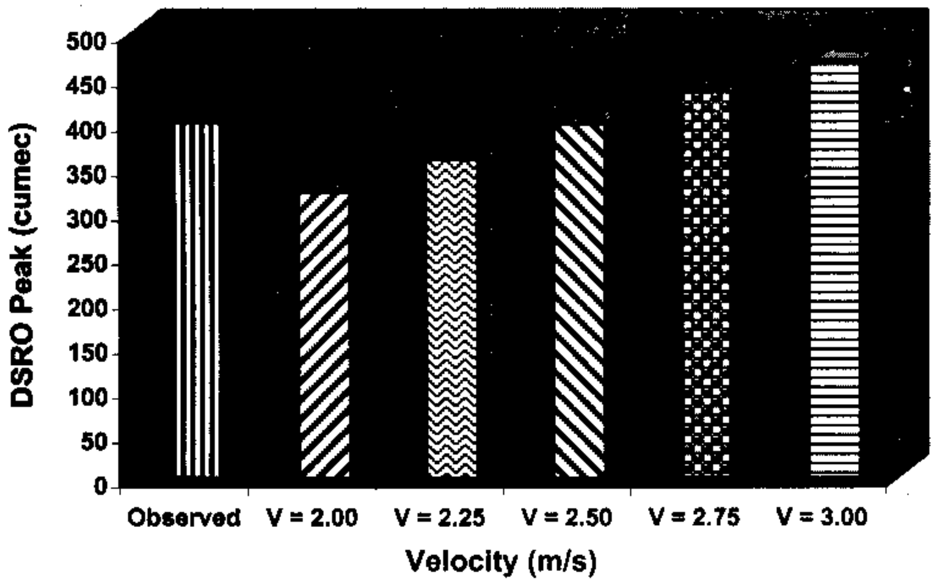


Fig. 27 Comparison of observed and computed DSRO peak values for various velocities for the GIUH based Clark model (Event No. 8)

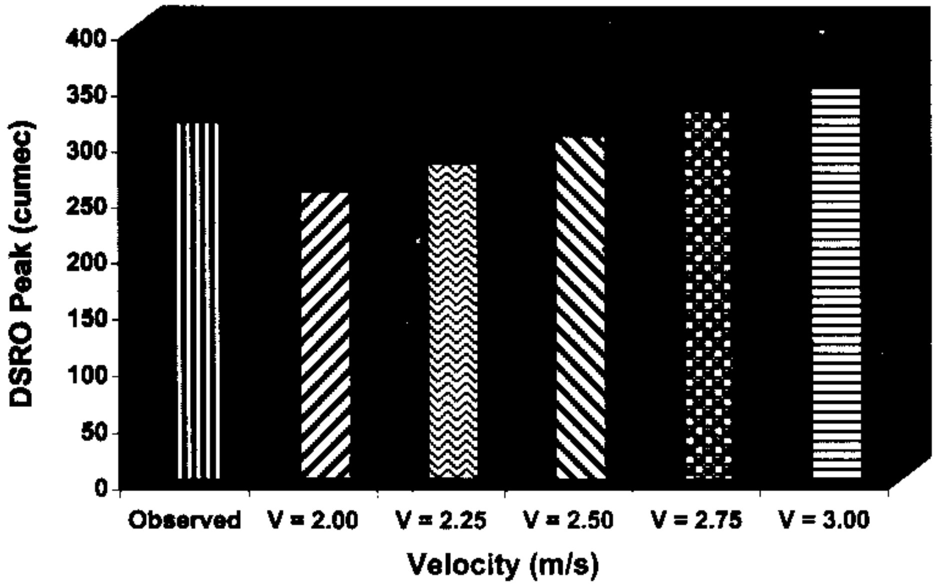


Fig. 28 Comparison of observed and computed DSRO peak values for various velocities for the GIUH based Clark model (Event No. 9)

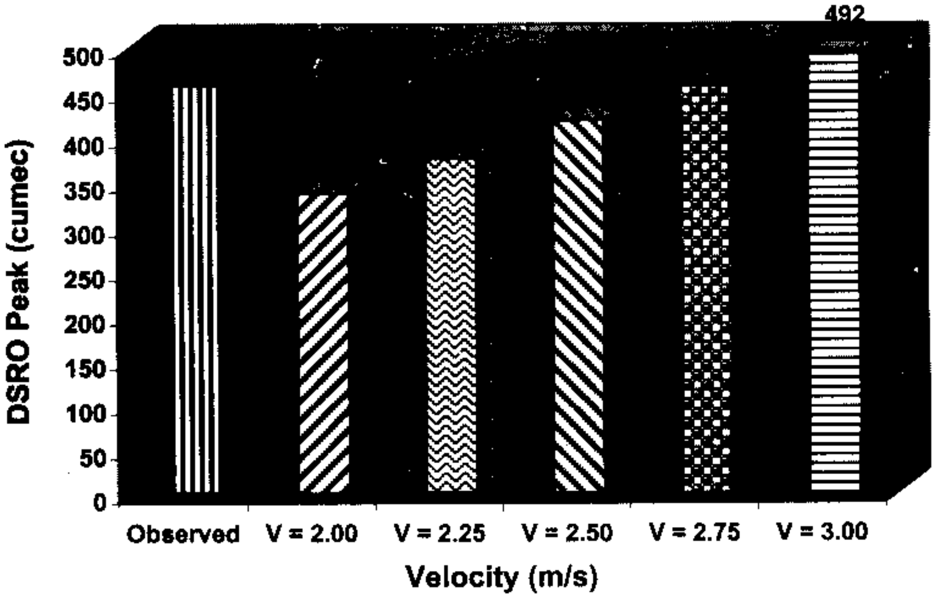
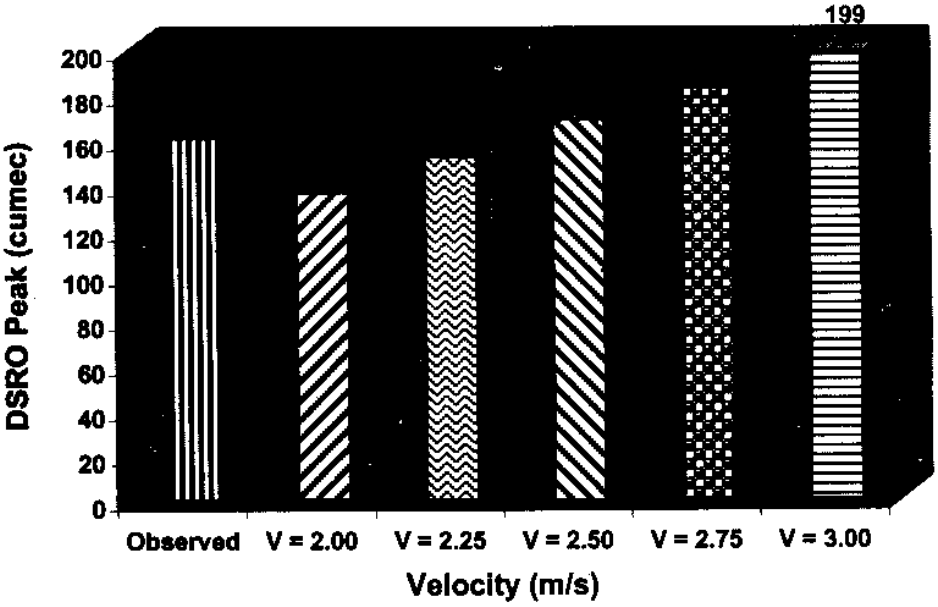


Fig. 29 Comparison of observed and computed DSRO peak values for various velocities for the GIUH based Clark model (Event No. 10)



8.0 CONCLUSIONS

In this study, the DSRO hydrographs have been estimated using the three methods viz. GIUH based Clark model, Clark IUH model option of HEC-1 package and Nash IUH model using three approaches as discussed in Chapter 7 (Section 7.4). The DSRO hydrographs computed for the ten rainfall-runoff events using three methods have been compared employing six 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). Based on this study, the following conclusions are drawn.

(i) The geomorphological parameters required for derivation of the GIUH based Clark model have been evaluated for the Ajay basin upto Sarath of South Bihar using the GIS package viz. ILWIS. 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) As per approach-I, HEC-1 package provides higher values of efficiency (EFF), lower values of absolute average error (AAE) and root mean square error (RMSE) as compared to the GIUH based Clark model and the Nash model. However, the values of average error in volume (AEV), percentage error in peak (PEP) and percentage error in time to peak (PETP) are lower for the GIUH based Clark model as compared to the HEC-1 package and the Nash model. The better estimates of the DSRO hydrographs for HEC-1 package, as per approach-I, may be attributed to the fact that the parameters of the Clark IUH model of HEC-1 package are derived from a particular rainfall-runoff event and these parameters are used to reproduce the DSRO hydrograph of the same event. To overcome this limitation, comparisons of the DSRO hydrographs have been carried out employing the approaches-II and III.

(iii) As per approach-II, the values of EFF for the GIUH based Clark model are highest and the values of AAE and RMSE are lowest for two out of the five rainfall-runoff events. The values of EFF for HEC-1 package are highest and the values of AAE and RMSE are lowest in case of two events while the values of EFF for Nash IUH model are highest and the values of AAE and RMSE are lowest in case of only one event. It is observed that the values of AEV are lowest for GIUH based Clark model for all the five rainfall-runoff events. It is also seen that the values of PEP are lowest for GIUH based Clark model in two cases. The values of PEP are lowest for HEC-1 package in two cases; whereas, the values of PEP are lowest for Nash IUH model in only one case. Thus, it is observed that as per Approach-II, the GIUH based Clark model provides better DSRO estimates as compared to the HEC-1 package and Nash IUH model.

(iv) As per approach-III, the GIUH based Clark model provides the best DSRO estimates for five rainfall-runoff events, the HEC-1 package provides the best DSRO estimates for three rainfall-runoff events and the Nash model provides the best DSRO estimates for two rainfall-runoff events out of the ten rainfall-runoff events. But when only two methods viz. HEC-1 package and Nash model are compared; then it is seen that the Nash model provides better DSRO estimates for seven rainfall-runoff events as compared to the HEC-1 package; whereas, HEC-1 package provides better DSRO estimates for only three rainfall-runoff events as compared to the Nash model. Thus, it is observed that the GIUH based Clark model which considers the basin under study as ungauged, estimates the DSRO hydrographs more accurately for the Ajay basin of South Bihar upto Sarath gauging site as compared to the HEC-1 package and Nash IUH model. The performance of the HEC-1 package and the Nash model for estimation of the DSRO hydrographs may be considered as comparable.

(v) The parameters of the GIUH based Clark model have been estimated quite accurately by using the geomorphological characteristics of the Ajay basin upto Sarath, instead of the observed rainfall-runoff data, as the basin has been considered as an ungauged basin under the GIUH approach.

(vi) The sensitivity analysis conducted for the velocity parameter of the GIUH model shows that as the velocity increases the peak of the DSRO hydrographs increases. Thus, estimation of the peak velocity is the main issue involved in this methodology. Hence, study may be carried out for improving the methodology described in this report for estimation of the velocity parameter of the GIUH based Clark model. For this purpose, the fact that the velocity is not dependent only on the highest rainfall block but it depends on the pattern of the rainfall distribution of any rainfall event should be taken into consideration.

(vii) The ratio between storage coefficient (R) and the sum of storage coefficient and the time of concentration (T_c), i.e., $R/(T_c + R)$, has a unique value for a catchment. The value of this ratio may be estimated for a catchment and it may be used for employing the conventional Clark model also. In the present study its value has been estimated as 0.481 by the GIUH based Clark model.

(viii) In principle, this methodology provides a different unit hydrograph for each event. This shows that the proposed methodology is capable of simulating the non-linear response to different storm events. However, this capability is limited in the sense that the exact relationship between the rainfall pattern and the expected velocity of flow is very difficult to be ascertained.

(ix) Further study may be carried out to examine the effects of using the velocity-excess rainfall intensity relationships of the nearby gauged catchments over the simulation results of various events of different catchments. Possibility of using a regional velocity-excess rainfall relationship may also be investigated, as this regional relationship and the geormophological characteristics of the ungauged catchments of the region may be used for derivation of unit hydrographs of the ungauged catchments.

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