

A GIS - Remote Sensing compatible rainfall-surface runoff model for regional level planning

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Abstract:

In the broad sense, the term hydrological modeling implies rainfall-runoff modeling, which helps in simulating and forecasting the flow from a catchment and in determining the inflow series for the ungauged catchments. Efforts have been made for the spatial distributed nature of the watershed properties by introducing GIS for spatial discretisation of watershed into interlinked systems of triangles (TIN) and development of a physically based rainfall-surface runoff model for simulating flood hydrographs in a user-friendly interface (GUI). The model is compatible with both the Geographical Information System (GIS) database and the Remote Sensing (RS) data, although interactive option is provided to the user for modifying the database, if necessary. GIS has also been used to describe the various thematic layers such as physiography, Landuse, soil etc. in the present study. Terrain modeling is a pre-requisite to hydrologic simulation of the rainfall-runoff process. Algorithms have been used in the present study to extract watershed features such as overland flow cascades, channel network, confluence points, ridges etc. for a given digital elevation data using Triangulated Irregular Network (TIN). The overland flow is modelled as one-dimensional sheet flow over cascades of overland "flow planes" contributing as lateral inflow to the channels flowing in the valley. Both the overland and channel flows are simulated using the kinematic wave approximation of fluid flow and solved through explicit finite difference routines. The main input to the watershed is taken as the rainfall. The usage of the model for regional level planners is demonstrated for tasks such as determination of waterways for small bridges and culverts, design of spillways of small dams, construction of flood protection levees, agriculture, site planning for micro hydels etc.

Introduction

Physically based models for simulating the dynamics of a system are the ones that are based on physical laws. For given initial and boundary conditions these laws, represented by governing equations, are solved mathematically to obtain the system variables in space and time. In the realm of geohydrology, a number of such models are in use, or have been used. These range from simulation of the entire watershed process to the ones limited to a single aspect of the hydrological cycle process for rainfall-runoff simulation. These models vary in their representation of process dynamics with those solving the "exact" equations to the ones based more on conceptual representation of the processes.

During its initial phases, the physically based models were not developed with the objective of using remotely sensed data or geographic information system (GIS) as the availability of such data was, generally, scarce. With the gradual availability of such data and increased computing power, hydrological models being based on more and more spatially distributed data. However, with time, remotely sensed data and geographic information system data have become almost a necessity for spatially distributed models and such databases are also being made available to the public more conveniently. Even in developing countries, like India, attempt is being made to disseminate geographically distributed data in an electronic format to regional level planners (for example, the Natural Resources Data Management System programme of the Department of Science and Technology, Government of India). It is therefore natural that a need has arisen

to develop computer models that may facilitate local planners in taking a decision by analysing the relevant regional databases and coming up with a desired result. The present model is one such, which can be linked to the spatial physical characteristics of an ungauged watershed, and for a given rainfall generate the possible discharge hydrograph at desired locations within the watershed. A user-friendly interactive interface has also been developed which would help the user in modifying some changes, if necessary, to the database. Effort is on to develop a post-processing screen which would visually display the flood hydrograph at user-selected locations in the catchment. The flood hydrograph, or more importantly the flood peak, is required for hydraulic design of spillways of small dams, for determining the waterways for bridges and culverts, construction of flood protection works, estimation of erosion potential, site planning for micro hydels etc. within a catchment.

In the remaining sections of this paper, a brief description of the model is presented followed by an example showing the application of the model. The paper concludes with brief guidelines regarding the usage of the model in taking decisions on some specific tasks.

Description Of The Model

The requirements for the application of the proposed model to a catchment are an elevation contour map of the area, corresponding land use and soil maps preferably in a digital format, and a guideline for estimating the design storm. The

elevation map, if available in a digital form, is processed by GIS software to create a Triangulated Irregular Network (TIN) form of digital elevation model (DEM). Some care must be taken during its creation (with the use of break line, etc.) such that the obvious drainage and ridgelines are recognized. If a GIS package is not available or if the one available does not have the capability to generate a TIN, the same task may be done manually although it may be quite time consuming and prone to errors.

The TIN map is overlaid on the land-use and soil maps, if possible again, through GIS software. Even if done manually, each triangular surface (also called a facet) of the TIN is associated with a corresponding land-use type for which a correlation table would assign an “equivalent overland flow roughness coefficient” required for surface runoff simulation. Similarly, each triangle is associated with a particular soil type which is correlated to a corresponding infiltration rate which, when subtracted from the design rainfall, produces the effective rainfall over the triangular surface.

The “equivalent overland flow roughness coefficient” can be expressed in various forms like the Darcy-Weisbach’s, Chezy’s, or Manning’s. In the present model, the Manning’s coefficient is used. Numerical values of infiltration rates for specific soil types can be had from agricultural handbooks. However, in the absence of field data, an assumed value may be adopted for the entire watershed, which is then later optimized.

The channels require slope, roughness and cross-sectional data, the first of which is obtained from analyzing the TIN model. Roughness data for the channel bed is based on the well documented values as given by any standard literature of channel hydraulics. The cross-sectional areas of the channels, at least for the main streams, have to be obtained from field observations. In the absence of such data, some guidance may be taken from literature on channel morphology.

For a given TIN, the drainage network is identified and numbered by the algorithms used in this model. Typically, the network composes of channel reaches emanating from ridges, which combine at confluences from where further reaches originate in a recursive pattern. The network of reaches at the outlet of catchment is assigned the first confluence number. This is because sometimes two reaches may meet at the outlet point of the catchment. According to the definition adopted for the model, a reach comprises of a number of channel segments and span between a ridge and a confluence or between two confluences.

The effective rainfall over the triangular facets may be assumed to move as an equivalent sheet flow down to the valley below. In the algorithms it is recognized that though the flow is two-dimensional globally, it may be considered one-dimensional if the local axes of each triangle are directed along the triangle’s steepest slope. Accordingly, the triangles are divided into overland flow planes that cascade down from the higher to the lower facet till it meets a channel segment. The shape of the cascade plane is calculated and stored in relation to the connected channel reach/segment identification.

The flow on the overland cascade planes as well as that in the channel reaches is assumed to be modelled by the kinematic wave assumption for simplicity. The flow of each channel segment is treated as inflow to the segment connected just downstream and

the outlet flow of a reach is input as the inflow to the confluence connected to its lower end. The equations are solved by an explicit finite difference scheme.

The model considers only Hortonian flow, that is the flow which occurs when the rainfall exceeds the infiltration rate. Thus, a rainfall input applied to the model routs the net precipitation (after deducting the infiltrated amount) over the watershed surface to generate flow hydrographs at the outlet of the catchment and at various locations within. The discharge and the corresponding water depths are used for taking decisions about the salient features of the different structures, as would be shown in the subsequent section. The selection of the rainfall, however, requires some judgment. The philosophy is a risk-based design, implying that for the structures across a river or a stream a decision has to be taken regarding the worst rainfall event that may be expected to occur within the life of the structure. It is expected that the structure would be able to withstand the resulting flood without any loss of performance. The return period of the design rainfall thus has to be chosen judiciously. Several guidelines exist for selecting the design storm, which mainly depend on the importance of the structure and the risk associated with it. Discussions regarding the usual practice followed in India and foreign countries may be had from the report National Institute of Hydrology. As such, for the Indian context, the Central Water Commission may be referred to. However, since the proposed model is mainly applicable to small catchments, of size around 25 km² to 1500 km², the design of only small water resources projects to be constructed by local authorities are considered. Normally, a design frequency of 1 in 50 years may be found to be sufficient.

The flood estimation using a design storm and a physically based routing model has perhaps never been tried in any Indian catchment. This is partly because other methods are available which, though quite empirical, have been correlated from past many years’ observed data and also because they are less computation intensive than the physically based deterministic models.

It is the intention of this paper to demonstrate the use of a physically based distributed deterministic model for predicting design flood for small water resources structures, as it can be directly linked with GIS and RS data at the local level. Instead of empirical formulae or regression equations, a physically based model should give the decision managers a more realistic picture of the flow parameters within the watershed.

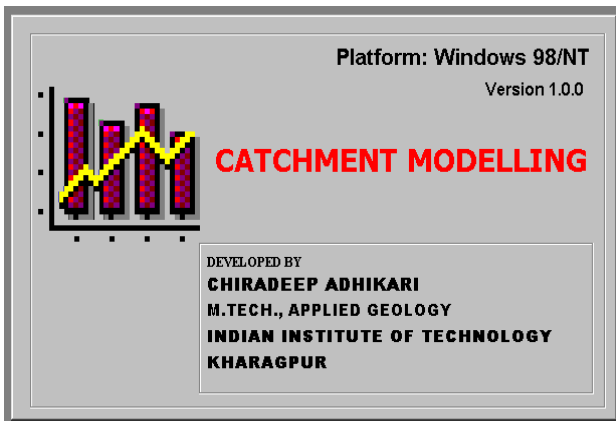
Developing graphical links between arc/ info, microsoft visual basic ver. 6.0 and the catchment model

Currently the major stumbling block to progress in hydrologic modeling is not the ability to generate realistic models to simulate physical processes, or the ability to solve the equations associated with these processes, but it is the time consuming and costly process of considering the spatial variation of model parameters during the modeling process. However spatially explicit data and the ability to manipulate these data are essential for detailed hydrologic modeling.

GIS could offer those capabilities for the efficient integration of spatial variation within hydrologic model. Hydrologic parameters could be generated with in GIS, but the procedures are no sufficiently straight forward to be handled by the non-GIS operators. Many GIS data remain underutilized due to the absence of a bridge between the raw GIS data and the end user.

While the need for integration of GIS with hydrology is understood, an interface system has been developed to improve the link between GIS and hydrologic modeling by integrating GIS software (here Arc/Info) and the model.

The model is a Windows based tool for data entry and data checking and running the overall catchment modeling steps. It is designed to overcome many of the significant hurdles faced by users, particularly the lack of user interface. The proposed model is rather a shell program operating in Microsoft Windows that accepts data input for the delivery of the output. The development environment for catchment model is Visual Basic Professional, version 6.0 operating under Microsoft Windows 98. The model follows the standard Windows single document interface (SDI) format common to many Windows programs and employs standard Windows controls (menus, frames, command buttons, radio buttons etc.) and dialogs, thereby providing the users with a familiar graphical user environment that will require a minimum of training. The GUI so far developed performs input, including import of data generated by Arc/Info GIS software, editing, management and execution of the project files. The GUI automates what was once a tedious manual process. Because Arc/Info and the model are mature and complex software systems, each with its own data structures and operating mechanisms, they were used in minimal or no modifications. Therefore the project comprising of a graphical user interface and an internal database, automates the communication between any GIS software and hydrologic model of advanced capabilities and this will allow hydrologists to fully explore the capabilities of the proposed catchment model and GIS and ultimately contribute to effective water resources management.



MODEL APPLICATION

To demonstrate the application of the proposed model a model catchment has been selected along with assumed digital elevation data of some selected points (Table 1).

6		: Total Number of edges
1	2.0 2.0 200	: Edge number with x, y, z coordinates
2	4.5 3.0 210	
3	4.5 4.5 215	
4	2.5 6.5 212	
5	0.5 6.0 215	
6	2.0 4.0 202	
5		: Total number of triangles
1	1 6 5	: Triangle number with vertices
2	1 2 6	
3	6 2 3	
4	6 3 4	
5	6 4 5	

Table 1. Input table for the triangular network of model catchment

The corresponding TIN for the watershed is shown in Fig.1 and derived watershed features in Fig.2. In order to simulate the flow, the effective rainfall is routed over the overland planes. This is then assumed to flow into the channels as lateral inflow, which is then routed along the respective channel length. For the model catchment in the present case, a constant effective rainfall at a rate of 10mm/hr has been assumed to act over the entire catchment uniformly for duration of 30 minutes. The Manning's roughness coefficients for the overland flow for all the triangular facets taken as 0.1 assuming a forested area. The infiltration rate has been taken as a constant 5mm/hr. These values have been assumed for demonstration purpose only. In actual practice the field data, as available should be used.

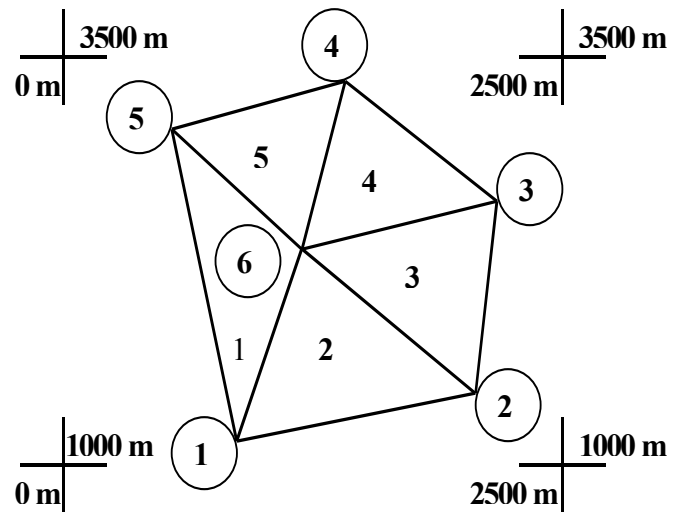


Fig. 1 Triangular Network of model Catchment

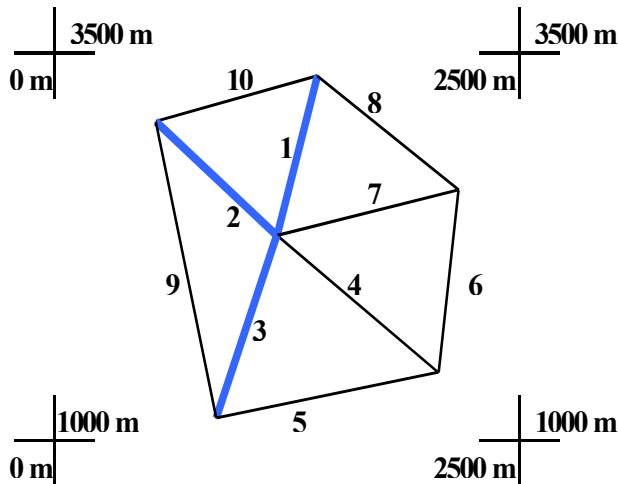


Fig.2. Channel network of model catchment.

The discharge hydrographs at lowest nodes of the branches 1,2,3 of the model catchment have been shown in Fig.3. The time step chosen is in the order of 10 secs.

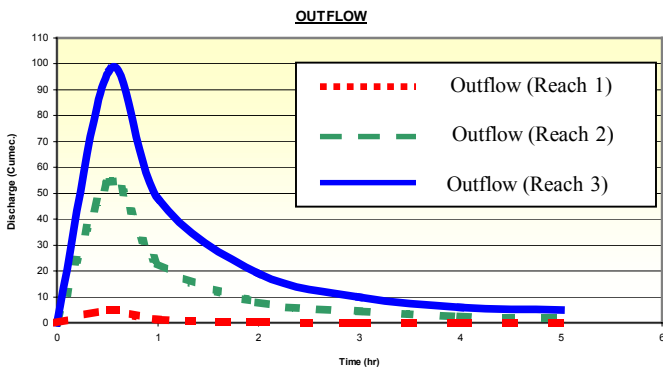


Fig.3. Discharge Hydrographs at selected nodes.

As may be observed from the figures the resulting hydrographs are realistic from physical point of view. The model may therefore be used on any real catchment with the real data. Since this is a spatially distributed model the infiltration rate and flow friction coefficient may vary from one TIN to another in real situation though these have been assumed constant in the proposed model. There is scope for the model to be enhanced by considering these factors. Also methods could be adopted to give time invariant weighting coefficients for the estimation of rainfalls on cascade planes from the temporal rainfall values at different rain gauge stations.

Model Utility For Practical Applications

The data obtained by running the model (as shown in the last section) may be used effectively by regional authorities for taking

decision on certain water resources projects. These include small structures on the river mainly for the use of the local community. The following paragraphs enumerate a few of them.

Bridges, Culverts, and Aqueducts

Design of cross drainage structures like the above requires, among other data, the linear waterway and the high flood level (HFL) anticipated. Following the Indian practice the design engineers first find estimate the flood discharge corresponding to a given return period at the point of interest in the catchment. By working out the maximum discharge anticipated at a certain location of a river the waterway and HFL may easily be found out provided the cross sectional geometry of the river at that section is known.

Spillways for small dams

For augmenting drinking water to villages or for irrigation and other purposes, the regional authorities may plan small dams within small catchments. Standard hydrology books (Singh 1992, Mutreja, 1986, and others) give the prescribed range of storm frequency that is to be adopted for designing the spillway capacity of dams depending on the structure size and risk hazard. Applying the design storm over the catchment, the peak flood at the point of interest may be obtained which, in turn, is used to decide the width of a spillway bay, number of bays, and other parameters of the spillway.

Levees for flood protection

Quite often the human activity around some low-lying banks of rivers may have to be protected from floods. The general requirement usually is that the embankment/levee constructed along the riverbanks should be able to protect flood occurring with a 50- or 100- year return period (depending on the importance of the structure or the potential hazard). The flood simulation should be run initially assuming no levees (the river cross section being defined according to actual observations taken at certain convenient intervals) and then run for different location (along the riverbank) and heights of the levees. The optimum levee height should be one that is just about 1 to 1.5 metres (as freeboard) above the high flood level at various points along the river.

Predicting erosion potential due to land use change

Quarrying of hill slopes or excavations for laying of a roadway open up bare soil which has the tendency to erode during subsequent rainfall events. This endangers the slope towards landslides apart from the loss of soil that gets eroded on the steeper planes and gets deposited on the flatter reaches of rivers thus reducing their discharge carrying capacity and increasing the potential for flooding. The regional level managers may need to have an estimate of the eroded earth for an altered land use scenario in order to put a limit on the human activity. The proposed model gives the discharge along with the water depths at various nodal points in the catchment. These values could also be used to estimate land erosion after coupling with suitable sediment transport model.

Site planning for micro hydels

A hydraulic turbine is always selected and designed to match the specific conditions under which it has to operate in order to attain a high order of efficiency which is expected in present day installations. Several preliminary data required while selecting different types of water power plants which will ultimately effect the right type of selection of hydraulic turbine and selection of sites mainly depend upon factors like availability of head and discharge, places of power shortage, peak load etc.

Thus the proposed model could assist the regional planners in getting the discharge value at the point of interest which in turn helps in estimation of power available from the discharge as well as selection of turbine to be used in power generation.

Limitations Of The Proposed Model And Scope Of Future Development

Keeping in view the scope of the present study, the following recommendations could be made

- The impact of Landuse change on flood hydrographs could also be investigated with the help of the proposed model
- The model gives discharge along with the water depths at various nodal points in the catchment. These values could also be used to estimate land erosion after coupling with suitable sediment transport models.
- Contributions of the ground water flow to the catchment modeling have not been considered in the proposed model. If this could be included in the model it could be a complete one in the sense of water cycle.
- Method could be proposed to give the time invariant weighting coefficients for the estimation of rainfall on cascade planes from the temporal rainfall values at different rain gauge stations.
- The infiltration rates have been kept constant for different types of soils due to lack of availability of data. If this could be taken into consideration the model would get more accuracy towards the calculation of the discharge amount from the catchment outlet.

Conclusion

A physically based rainfall-runoff model is presented for estimation of flood hydrographs. The model, based on the triangulated irregular network (TIN) digital terrain model is adaptable to GIS (like soil type, etc.) and RS (like land use / land cover etc.) data. The model is simple to run, though some experience is needed during its setting up and calibration stages. It is oriented towards the use of regional level managers for taking a decision on local water resources related projects and some applications of the model has been demonstrated with examples.

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