Integrating Geographical Information Systems (GIS) with Hydrological Modelling – Applicability and Limitations

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Abstract- The evolution of Geographic information systems (GIS) facilitated the use digital terrain data for topography based hydrological modelling. The use of spatial data for hydrological modelling emerged from the great capability of GIS tools to store and handle the data associated hydro-morphology of the basin. These models utilize the spatially variable terrain data for converting rainfall into surface runoff. Manual map manipulation has always posed difficulty in analysing and designing large scale water resources projects. Water flows down the hill slope - this clears the importance of terrain modelling in watershed management. Thus the coupling of hydrological model into GIS environment has gained significant interest of scientists and engineers.

Most of the commercial GIS tools are equipped with the capability to handle spatial data for producing better cartographic output. Although the capacity of these tools in analysing geo-spatial data is still limited yet the process of complex watershed analysis is far enhanced by the use of these tools. Many a times the capability of GIS software's for solving the problem in hand is not clearly understood. This poses difficulty in formulating the watershed information system for use in water resources planning and management. This paper describes the attempts made by researchers for integration of GIS and hydraulic modeling for analysis of watersheds.

I. INTRODUCTION

GIS environment was not primarily designed to suit water resources problems. GIS analysis of hydrological model requires significant amount of effort for data handling, calibration and presentation of data in the form of ready to use maps. Integrated GIS environment should act to carry out spatial analysis of input data for hydraulic models, to provide linkage mechanism between models with different spatial representations. It should also perform geo-referencing and post simulation graphics output display and evaluate hydrologic simulation results.

Hydrological models are important aid for water resources analysis, and hence its integration with GIS is extremely valued. Hydrological processes vary both in space and time. Metrological and land use data are inputs for such processes. These processes are also varying as a function of topology and soil types. A Development of Hydraulic model having capability of using GIS data effectively is widely being investigated. The first task of GIS in the context is averaging of slope, soil type and land use. Next the determination of physical and empirical coefficients by comparing map attributes. Overlay of multiple map layer results in parcels. For evapotranspiration and ground water models grid network is used to describe a model descritization unit. Catchment area or sub basin is spatial description unit for watershed models. GIS based solution of water resources problem is obtained in five different steps (1) Digitization of available data (2) performing GIS operations (3) processing data for input to hydraulic model (4) hydraulic simulation (5) post processing of output from hydraulic models. The process for integration of GIS in Hydraulic modeling is outlined below. A sample map of wardha basin is shown in fig. 1. and the delineation process of the basin using GIS tool is explained in the subsections.

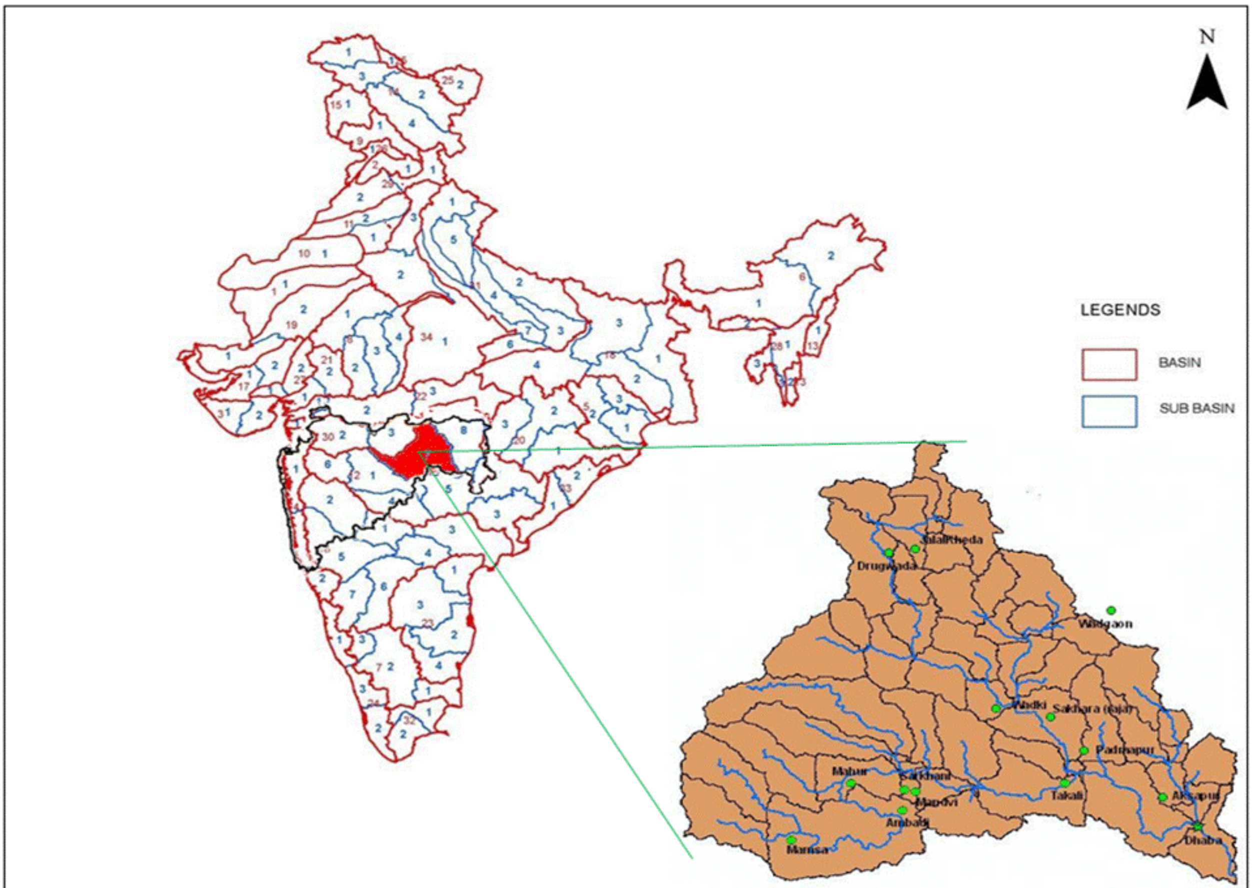

Fig. 1. Sample map showing location of Wardha watershed

II. DATA PROCESSING

GIS software's are equipped with the tools that capture, store and manage data such as vector data (Points, lines and polygons) or Raster data (continuous fields). Tablet digitizing is basic GIS function popular due to low capital cost. Scanning technologies allows capture and processing of map stock using image processing. GIS software's facilitate format conversion from other data sources to GIS. COGO (coordinate geometry) feature is used for storing distances, bearing and curve calculation from field surveys. Field data collection is made easy by Global positioning system (GPS). GPS data can be imported to GIS to provide local information. High resolution spatial databases for urban areas can be developed using photogrammetry. Satellite photogrmmety facilitate mapping of selected areas with resolution less than one meter. GIS software can transform data from one reference frame to another. Attribute entry feature allows capture and management of non spatial data.

Relational database feature of commercial GIS software is useful for data integrity and data consistency. Structured Query language is used for modification of parameters. Quick updating of model parameters is an added advantage for models dependent upon in situ parameters. Apart from parameter data, both qualitative and quantitative data can be integrated using spatial relationships instead of relationships between non existing attributes. GIS software's also facilitate construction and import of Digital elevation models (DEM) and triangulated irregular networks (TIN's). Slope and aspect can be derived from DEMs and TINs using specific functions. Such information is the basis for surface runoff and slope stability models.

A sample digital elevation model obtained by combining the ASTER GDEM tiles for the Wardha basin is shown in Fig.,2. The digital elevation model is then processed for obtaining useful derivatives by performing series of operations like Fill sink, Flow direction, Flow accumulation, catchment polygon processing, drainage line processing, batch watershed delineation etc. The watershed thus delineated is shown in Fig.3.

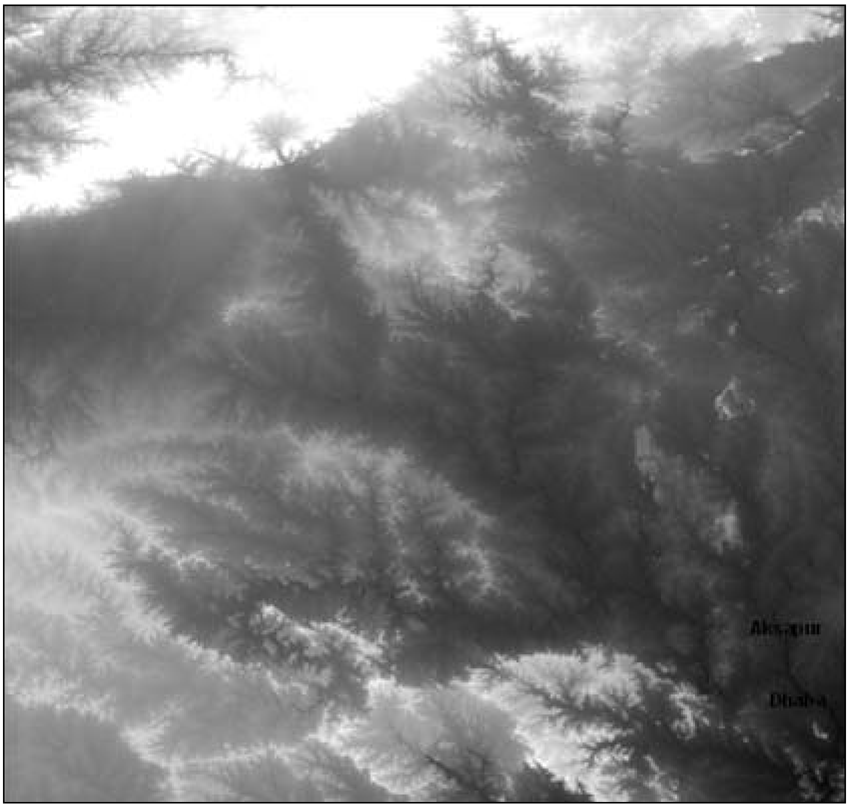

Fig 2. Digital Elevation model

III. MODEL APPLICATION

Spatial operations were performed manually in past. The map based engineering analysis like flood forecasting is greatly benefited with the use of GIS. Functions such as area computation, measurement of flow length and critical path determination are made easy with the use of GIS software's along with the map based modeling for parameter determination.

Drainage structure can be determined with the complimentary software's compatible with GIS. Raster type DEM should be at fine resolution to represent actual topography and accurate determination of watershed area, its river networks and sub watersheds. Filtering of initial data allow determination of slop and aspect of each cell. The outlet cell is then identified, the neighboring cells contributing to that cell are next identified, all the cells constitute a watershed. Next step is to identify river network and sub watersheds corresponding to this river network.

Land use information is obtained from high resolution remote sensing data. Land use classes are grouped into new classes based on their hydrologic response. Mean soil type is determined from soil maps for each cell constituting watershed.

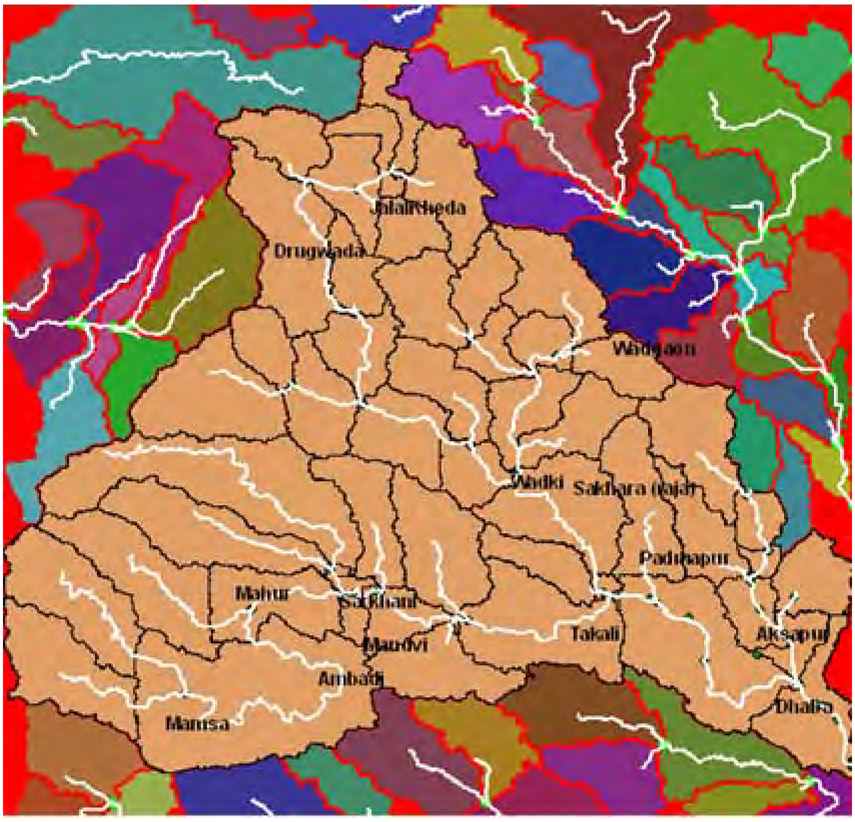

Fig.3. Watershed Delineation Using GIS

IV. INTERPRETATION OF RESULTS

Conducting spatial queries on GIS database is essential function for error checking and reviewing. Pointing operation returns data about particular feature and it depends upon topological integrity of the spatial database. Various search commands such as “show attributes”, “show Records”, “find”, “Browse”, “generate reports” and compute are used. Relational database keys link files with different attributes. A relational join combines two or more tables useful for data analysis and reporting. User can accomplish classification and generalization using the set of commands mentioned above. Reclass command resolve spatial data into patterns that we can understand. Combining number of classes to more detailed class is called generalization. Relation between map themes, coverage’s or layers is deduced from Principal-component analysis. Conditions at area surrounding a given location are analyzed by neighborhood operation. Proximity assigns areas of proximity to features. Buffer operations are conducted to find features within specific distances of other features. Elevation data filters are applied to find slope, aspect and other terrain characteristics.

GIS has great capability of presenting analysis results in map form. The reasonableness of the predictions can be accessed through visualization of model results. Critical area requiring in depth analysis can be identified. Visualizations supplemented by spatial queries of model results help in determining relation between input parameters and model results.

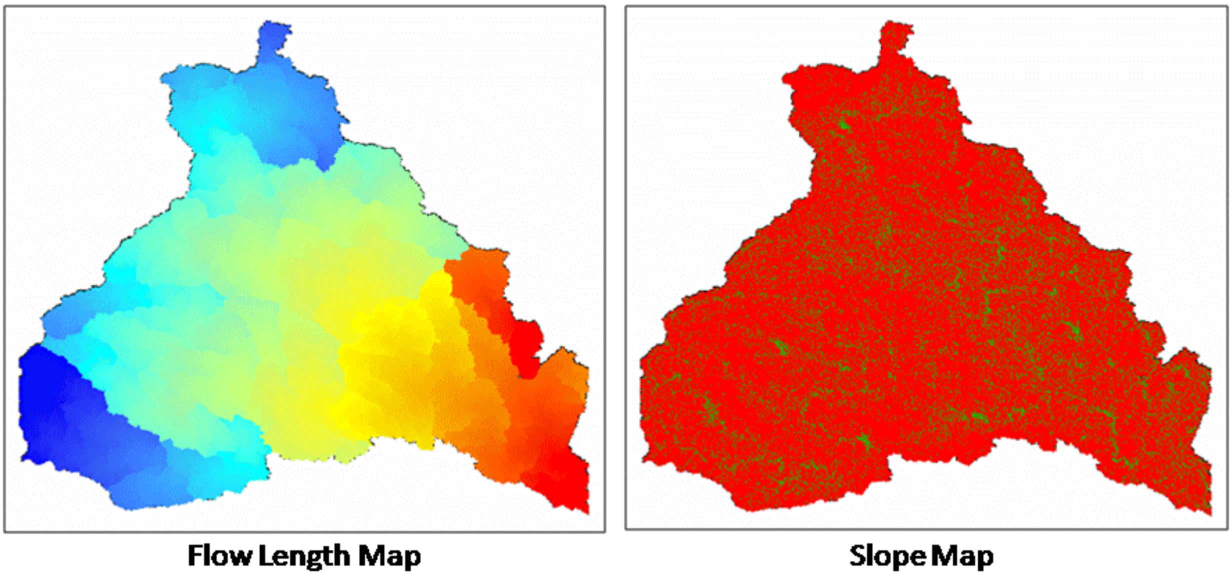

Fig. 4. : DEM derivatives – Flow length map and slope map

V. INTEGRATED HYDRAULIC MODELS

1. Storm Water Pollution

Nonpoint pollution processes are stochastic in nature. The data requirement of such processes is large, this perhaps make such modeling difficult. The pollutant loading is estimated by using data on land use, local rainfall, drainage and local and national water quality in such models. Three spatial layers namely land use; sub basins and catchment are required for GIS implementation of the model. Basins and land uses producing most polluted runoff can be determined using the GIS software's like ARC/INFO. In ARC/INFO the empirical model can be applied using calculation functions. This is done by associating the land use with rainfall and runoff coefficients as spatial data layer attributes. With all relevant attributes the three data layers are overlain.

2. Sediment Transport

This model is composed of set of simple equations for chemical, runoff and erosion. Drainage area and slope are two main spatial parameters. This group response unit concept based model is less data intensive than gird based models, and thus its execution in GIS is easier and efficient for large areas. Drainage boundaries are delineated on topography maps and digitized using GIS. Soil groups are represented by polygons and are digitized at the same scale. Imported rainfall data is interpolated by creating Theissen polygons in GIS to account for spatial distribution. Land use is classified using imaging software from remotely sensed data. Homogeneous computational units are identified manually. The data coverage's are overlain and spatial parameters are calculated. The technique is very efficient for determining the effects of slope, land use and soil type on the runoff and sediment yield.

3. Solid Waste collection

A significant part of the total expenditure of municipal solid waste management program is spent on collection of wastes. Optimization of the collection process has great potential for savings. Distribution of collection crew and vehicles is an important part of waste management process of municipal waste. The prediction of demand for waste disposal is depending upon several economic, social and environmental parameters. Effective routing and scheduling strategies with GIS could be crucial for efficient waste management practice.

4. Distributed Rainfall Runoff

Distributed hydrology is very much dependant on DEMs and radar rainfall maps. Development of distributed hydrological modeling tools involves spatial data handling. Such models operates on cell basis and accepts inputs from raster Geographic information system. The DEM model is used to generate drainage paths in proper hydrological order. The amount of soil erosion can be computed by making use of cell based structure of the model. The actual coding for distributed model implementation in GIS may be little difficult and may lead to the construction of an alternative means. Fig.5. Shows a typical hydrograph obtained by using GIS derivative and uncoupled hydrologic model.

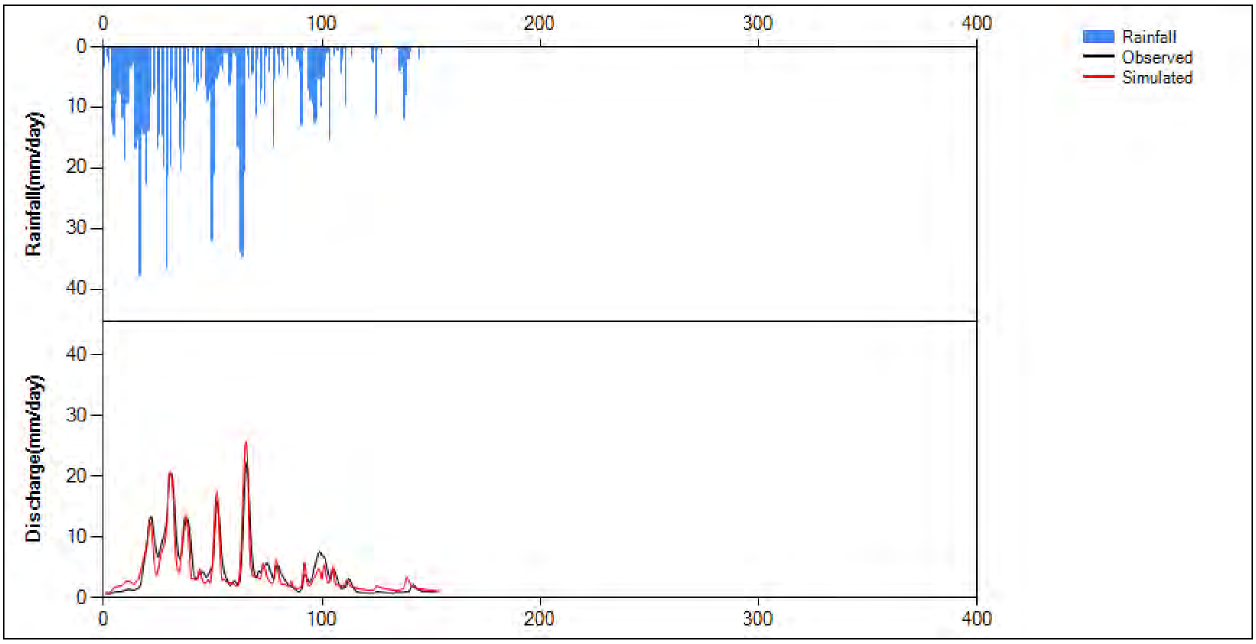

Fig. 5. Sample hydrograph obtained using GIS based hydrologic modeling tool

5. Estimation of Flood Damage

Flooding causes great economic loss and human hardship, thus estimation of damages associated with floods is important for developing flood control policies for the future. The analysis involves understanding of flood interaction with spatial domain. Several hydraulic models have been developed to quantify the factors associated with floods such as velocity, sediment deposition and water elevations. Input parameters for economic analysis are derived from prediction of potential damages. Flood prone areas can be delineated on the maps based on the results from such modeling. Estimation of annual damages is carried out in four steps (1) hydrologic frequency analysis (2) hazard assessment (3) hazard exposure analysis and (4) damage assessment. Recurrence interval or probability of exceeding rainfall is predicted based on historical data. Design flows are also based on the parameters like extreme events or simulated runoff calculated using hydraulic models. Hazard assessment comprises estimation of tangible and intangible damages caused by a flood. Tangible damages are measured in terms of monetary units, where as intangible damages include loss of damage of historical site or adverse health caused by exposure to flood water. Extent and severity of damages is estimated by carrying out exposure analysis. The magnitude and distribution of loss due to flooding is dependent upon hydraulic, land use and human factors. The hydraulic factors included in the study are depth of flooding, the rate at which water level rises, spread of flood wave, flood duration and sediment load. Impact of exposure in terms of cost for restoring affected area is estimated by damage assessment. Correlation method is applied taking depth of flooding as major determinant in estimating total damage function.

6. SEWER SYSTEM DESIGN

Sever Network design involve spatially dependant decisions due to requirement of gravity flow and Right of way considerations. The spatial analysis capacity of GIS and sewer design program combined together form integrated sever system design procedure. The program uses user specified manholes locations for sever network generation. The GIS has been effectively used to analyze topography, street network and surface features for locating pump stations and to find path for force main. Minimum human intervention is required for complete design of sewer networks.

7. Erosion Prediction and Control

The Universal Soil loss equation (USLE) uses data concerning soil, land use, rainfall intensity and topographic properties. GIS methodology can be easily applied using TINs and Kinematic wave equation. The kinematic wave and erosion potential predicted by USLE can be used together to determine suspended sediment load. Thus erosion and water quality predictions are linked. Erosion potential prediction using GIS is widely applied GIS operation.

8. Water Quality Prediction and Control

Air and water carry contaminants. Flowing water is assumed to be a potential transporter of contaminants. The movement of water causes dispersion of contaminants. Knowledge of magnitude and temporal distribution of flow is necessary for accurate prediction of the movement. The prediction of movement of contaminants is known as non point pollution. Non point pollution is most amenable to GIS.

Physical storm water management model requires urban water managers to acquire, maintain and utilize spatial data. GIS serve this purpose in terms of preparing, storing, updating, analyzing and displaying these data. The impact of storm water management strategies is analyzed through preprocessing by GIS. Urban runoff model is utilized for calculation of discharge, and post processing and display through GIS.

The objective of storm water management program is to prevent adverse impacts of excessive rates and volumes of storm water runoff. The input for storm water quality model is provided by GIS, and then storm water quality predictions are made. The results of water quality are then linked to GIS for post processing.

9. Ground Water flow modelling

Numerical models used in ground water flow studies represent heterogeneous hydrological parameters and boundary conditions. The task of assembling data, assigning parameters for model cells and checking errors is time consuming. The ground water problem solution by numerical method is based on grid, and generally there is no consideration of model sensitivity to discretization. Visualization of model results is time consuming and often simulations performed for calibration are limited.

GIS facilitate development, calibration and verification of ground water models as well as display of results. GIS have capability to interchange data layers and perform spatial operation on ground water flow data. Many of the data compilation and management operations can be automated with the use of GIS in ground water flow modeling. Grid design and spatial statistics capabilities of GIS can reduce the modeling effort and aid reliability assessment. Visual display capability of GIS can perform calibration, verification and production of final results.

VI. Conclusion

In last decade the computation power of desktop computer is increased dramatically. The availability of spatial data to large extent has made it easy to represent and visualize watershed characteristics in distributed manner and investigate hydrologic data based on a distributed approach. Increasing radar and satellite data is great source of data sets of watershed characteristics. Use of GIS in watershed analysis is beneficial in terms of improved accuracy, easier map storage, flexibility and greater efficiency. Modules that exchange data with GIS and allow pre and post processing are becoming popular.

Physically based model such as the Geo-morphological instantaneous unit hydrograph (GUIH) is preferred for simulation of watershed runoff. One such hydrologic model that uses such a procedure is called the watershed hydrology simulation (WAHS) model. GIS is capable of storing such a big volume of data required for hydrologic modeling. When modeling watershed runoff with SCS curve number method, overlying capability of GIS is very useful in determining parameters like composite SCS curve number.

Integration of surface water, Evapotranspiration and ground water model has been made easy by the discretization referencing feature of GIS. Hydrologic impacts associated with land use changes can now be modeled and evaluated in hours using digital data and GIS. GIS based watershed physical parameters are accurate due to small size of sub-basins; this capability reduces model calibration time and cost of modeling. GIS provides re-gridding capabilities for reliability assessment and model sensitivity analysis this feature is particularly useful for integration of GIS and ground water model.

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