Runoff modelling of a small agricultural watershed using satellite data and GIS - A Review

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Abstract: In this study an empirical model was developed and validated for estimating the direct runoff from a small agricultural watershed (Arang) in Chhattisgarh (India) shown in fig. 1. A Geomorphic Information System (GIS) was used to extract most of the parameters of the watershed from various thematic maps including DEM land use, soil texture, watershed and sub-watershed boundary the remote sensing and field data. The Digital Elevation Model (DEM) was prepared using contour map (Survey of India, 1:50000 scale) of the watershed. Various maps including watershed and sub-watershed boundaries, drainage network and soil texture were generated using topographic map and soil resource data in the environment of a Geographical Information System (GIS). The Geometica image processing software was used to extract the topographic features and to delineate watershed and overland flow-paths from the DEM. Land use classification were generated from data of Indian Remote Sensing (IRS 1D) to compute runoff Curve Number (CN). Data extracted from contour map, soil map and satellite imaginary, viz. drainage basin area, basin shape, average slope of the watershed, main stream channel slope, land use, hydrological soil groups and CN were used for developing an empirical model for estimation of surface runoff. Results revealed that the observed runoff values were having good agreement with the runoff values predicted by the empirical model. Student’s t-test resulted that the means of observed and predicted runoff were found to be similar at 95 percent confidence level. Value of coefficient of determination ($r^2$) were found to be 0.827 in case of empirical model indicated that the predicted runoff values for each selected rainfall events were close to the observed values.

Key words: Morphological parameters, Runoff modelling, Runoff measurement, geomorphological parameters, Watershed parameters etc.

Introduction

The average annual rainfall of India is about 1200 mm and 80 per cent of these occur only in monsoon season i.e. from June to September. The amount of rainfall annually received through four different types of weather phenomena southwest monsoon (74%), northeast monsoon (3%), pre-monsoon (13%), and post-monsoon (10%). The distribution of rainfall varies with time and space, the analysis of rainfall become more important for soil conservation point of view. Every hydrologic design is different because the factors that affect the design vary with space and time. It is thus necessary to make measurements of factors that affect the design. Factors such as size, slope, soil type and land use/cover in the watershed, as well as the amount of storage and vegetation within the channel are of importance. Given such factors as input to a hydrologic design, the accuracy with which the measurements of these factors are made should be determined. The drainage area, length of longest watercourses and equivalent main stream slope are the most significant variables for prediction of runoff. A watershed is generally considered as an area from which runoff resulting from precipitation, flows past a single point known as the outlet into either a stream or ocean. In the watershed management activity, assessment and inventorying can be considered as essential pre-requisite. Geographical Information System (GIS) has become and effective tools in planning and integrated development of watershed as Remote Sensing (RS) derived information can be integrated with the conventional data base. In most cases the quantity and type of information necessary to arrive at a decision may be so large that it may become difficult task the divers data systems can be fed into consistent map format. Using suitable software specific integration and analysis of these data can be performed to derive useful output in the form of maps or statistical data. Various types of information related to watershed management like contour, soil, and land use/cover hygrogeomophology can be digitized and converted to raster format and utilized for runoff modelling. It has the potential of performing watershed delineation through techniques such as digital elevation modelling, Rainfall-runoff process modelling hydrologic soil cover complex analysis and runoff depth analysis for identifying potential watershed for rainwater harvesting and its suitability for constructing water harvesting structure and planning over large areas. Thus remote sensing and GIS enable to arrive at natural resource management solutions by adopting a holistic approach. The compilation input data, which are required by the geo-morphological
parameters based models are often cumbersome. The tediousness and time consuming nature of extraction of watershed parameters can be eliminated by means of Remote Sensing Technology (RST) and Geographical Information System (GIS) in addition to obtaining high accuracy. GIS is computer based tools that analyse and manage spatial data. The Digital Elevation Model (DEM) can be used successfully to extract several watershed parameters. A deliberately simplified construct of nature erected for the purpose of understanding a phenomenon (Batchelor, 1994). A watershed hydrology model is an assemblage of component models corresponding to different components of hydrologic cycle (Singh, 1995). Models used to assess impact of human activities (such as change in land use/land cover, tillage practices and installing soil conservation measures) on water quality are generally referred as water quality models.

**Objective:** Determine the various morphological parameters and develop an event based empirical model for estimation of surface runoff from the small agricultural watershed.

**Concept and Classification of Models** The hydrologic and water quality models together provide the basis for improved understanding of hydrological processes and for assessing the impact of human activities on environment and agricultural production. A general classification of models is Physical model and Abstract model. Physical model are Analog, Iconic and Scaled while Abstract model are Theoretical model and Empirical model. Theoretical model are further classified as Deterministic and In deterministic. Following the classical review of models by Chow et al. (1988), the theoretical models can be further divided into in deterministic and deterministic models. Deterministic models define the physical system in such a way that the occurrence of a given set of events leads to an unequal-identifiable outcome. Deterministic models can be further subdivided into lumped or distributed models, depending on the treatment of space. Alumped, deterministic model represents the physical system as spatially homogeneous units and neglects the spatial variability of inputs with the system. Distributed models, on the other hand, assume that the physical system is made of uniform and discrete sub units, each characterized by a homogeneous set of input parameters.

**Application of Remote Sensing and GIS** -
Yifang et al. (1995) tested operationa methodologies for improving agricultural crop identification using airborne synthetic aperture radar (SAR) data and generated mean texture features based on grey- level co-occurrence matrix (GLCM) by using EASI-PACE.

Bingner et al. (1996) predicted the relative trends of runoff on a daily and annual basis from multiple sub-watershed, except for completely wooded sub-watershed which simulating the effects on runoff from temporal and spatial variability of the watershed characteristics.

Ghosh et al. (1996) used GIS for land use/land cover change analysis in a mountainous terrain. They carried out the integration of remote sensing data with other spatial /non-spatial data using ARC/INFO GIS. Sustainability assessment of land where agricultural extension occurred between 1963 and 1993 was made using GIS software package. Expansion of agricultural land was found to be a maximum in 2200-2400 m elevation zone and 20-30 percent slope. When topographic expansion was considered, expansion was maximum on southeast and west facing slopes.

Shantakumar et al. (1997) applied the remote sensing technique for analysis of land use pattern. Comparative analysis and comprehensive evaluation of two period data i.e. aerial photographs of 1960 and remote sensing data of 1994 of Kunda catchment have revealed different type of changes in land use, extent of changes and their spatial distribution. The study has demonstrated and highlighted the potential of remote sensing techniques for monitoring the changes in land use efficiency and economically. It also allows updating of information more accurately, and at faster pace with real time data without much cost.

Jaiswal et al. (1999) studied land use/land cover changes over a period of 30 years using remote sensing techniques in part of Gohparu Block, Madhya Pradesh, India by visual interpretation of two period remotely sensed data. The analysis revealed that synergistic use of SOI toposheets and remote sensing data can be conveniently used to detect the changes in land use/land cover.

Sudhakar et al. (1999) also carried out classification in Jalpaiguri Wildlife Sanctuary in the same Jalpaiguri District by three different techniques viz., Maximum Likelihood. Neural Networks and Contextual to analyze the performance of these techniques in correctly classifying the land use/land cover using IRS-1 B LISS-II data of December, 1994. The classification accuracy was evaluated and it was observed that the neural network classifier would work better in heterogeneous forestlands and the contextual classifier would work better in homogeneous forestlands whereas the maximum likelihood would be the best in both the conditions. More than 85 percent accuracy in classifying forest categories and more than 90 percent accuracy in case of other land use/land cover were achieved.

Tripathi et al. (2001) was also used EASI-PACE software for land use/land cover classification and generation of DEM, which were used as input to model for estimation of sediment yield form a small watershed.

Dwivedi (1993) concluded that remotely sensed data, especially those acquired from space borne platforms hold promise for reconnaissance level mapping of soil resources and degraded land of a watershed in a timely cost effective manner. He attempted to present an overview of the capabilities of satellite data for deriving information on soil resources and degraded land under Indian conditions.

Patil et al. (2008) conducted a study has done work in this field using GIS based interface selected sites. Kosi River is selected as the study case by us as it has been in limelight due to its very uncertain behavior. It changes its path time to time thus cause many people to migrate.

**Hydrogeomorphology Mapping** -
Agrawal and Mishra (1992) made an attempt to delineate different hydro geomorphological units in and around the immediate environs of Jhansi city in Uttar Pradesh State of India with a view to find a correlation between the well yields and hydrogeomorphologic units and the bore well yields with overlapping yields at the margin.
Geeta and Anisa Rao et al. (1993) prepared multi-thematic maps viz., hydro geomorphology and ground water irrigated areas using the satellite data of IRS LISS-I and Land sat TM in pennar river basin in Ananatpur District of Andhra Pradesh State of India. The status of ground water development village wise has been arrived and artificial recharge structures were recommended on the upstream side of ground water irrigated areas so as to utilize the additional recharge to the wells in the downstream areas.

Rao et al. (1997) carried out geological, hydrogeological and geomorphological studies to evaluate the hydro geomorphologic conditions of Niva river basin, Chittor District in Andhra Pradesh State of India. Visual interpretation of Land sat 5, FCC data with adequately ground truth was carried out. Groundwater potential of geo-morphological units i.e. denudational hill, residual hill, pediment, pediplain and valley fill was also discussed in the study.

Murthy and Rao (1999) carried out hydro-geomorphological mapping in Varaha River Basin (VRB) in Andhra Pradesh State of India to develop relationship between groundwater condition and geomorphology of the area by visual interpretation of IRS-1A data. The hydro geomorphological interpretation was found to be helpful in knowing the nature and water potentiality of different landforms.

**Application of Models**

This approach involves the use of simple empirical formula and readily available tables and curves for estimation of runoff and sediment loss. SCS-CN is only one method, which can incorporate the land-use for computation of runoff from rainfall. This method provides a rapid means for estimating runoff change due to land-use change. The method continues to be most satisfactory when used for different types of hydrologic problems that were designed to solve evaluating the effects of land-use changes (Task Committee, 1985). The GIS and SCS-CN method were combined to the model rainfall-runoff relations and the watershed parameters were estimated while computation of other parameters required significant user interaction. (White, 1988; and Bhaskar et al., 1992).

Rajeev Kumar et al. (1999) analyzed the land use and land cover changes in the mid-western part of Gohparu Block, Shahdol district, Madhya Pradesh over a period of 30 years (1967-1996). The loss of vegetation cover was estimated to be 22% and 14% of the land.

Pandit and Srinivasan (2000) conceived and developed a package VARUN (Value Added Rainfall-Runoff Analysis) for rainfall-runoff analysis using SCS-CN method. Package primarily uses themes like land and use cover, hydrologic soil groups, rainfall etc for analysis.

Brath et al. (2001) showed the efficiency and strength of this type of model when applied to catchments with limited data availability, especially in comparison with lumped approaches. The basin is divided in square cells and for each of these the effective rainfall or runoff production is computed by the Curve Number (CN) method of the Soil Conservation Service. The runoff is then propagated to the basin outlet (the triggering site) along the flow path and the channel network derived from the digital elevation model (DEM) on the basis of the topographic gradient and in the case of channel network also by the contributing area.

Shrivastava (2002) had carried out the distribution modelling using Soil and Water Assessment Tool (SWAT) model. It was tested on daily and monthly basis for estimating surface runoff and sediment yield from a small watershed (Chhokeranala, research farm of IGKV, Raipur) using satellite data and GIS techniques. The watershed and micro-watershed boundaries, drainage network, land use/cover and soil texture maps were generated using GIS.
Supervised classification method was used for the land use/cover classification. Several model input parameters for the said watershed were determined using GIS technique and image processing software.

Tripathi et al. (2003) calibrated a model called Soil and Water Assessment Tool (SWAT) and verified for a small watershed (Nagwan) and used for identification and prioritisation of critical sub-watersheds to make them widely applicable. Tripathi et al. (2004) conducted a study for an adequately tested Soil and Water Assessment Tool (SWAT) model was applied to the runoff and sediment yield of a small agricultural watershed in eastern India using generated rainfall. The capability of the model for generating rainfall was evaluated for a period of 18 years (1981-1998). The watershed and sub-watershed boundaries, drainage networks, slope, soil series and texture maps were generated using a Geographical Information System (GIS). A supervised classification method was used for land-use/cover classification from satellite imageries. Model simulated monthly rainfall for the period of 18 years was compared with observations.

Cox and Madramootoo (2005) studied two small watersheds in St. Lucia, under contrasting land management regimes. These watersheds revealed that the soil losses from an intensively cultivated agricultural watershed were 20 times higher in magnitude than that of a forested watershed both for peak rainfall event and for total duration of analysis. Soil loss from the agricultural watershed was strongly correlated ($R^2=0.85$) to storm 51 energy-intensity (EI30). However, the correlation of soil loss with the EI30 ($R^2=0.71$) was poor for the forest watershed due to the effect of canopy vegetation, which significantly reduced the energy of raindrop impact. Over the study period, cumulative soil losses were 10.0 t/ha for the agricultural site and 0.5 t/ha for the forest site. The largest storm observed during the study period resulted in erosion losses of 4.0 t/ha and 0.2 t/ha from the agricultural and forest sites respectively.

Rajput et al. (2005) quantified twenty-two numbers of geomorphological parameters for each selected watershed. It was found that the geomorphological parameters are correlated among themselves. So these parameters were transformed into the scores of principal components to make them uncorrelated. Then multiple regression models between Sediment Production Rate (SPR) and scores of principal components were developed using principal component regression in Statistical Analysis System (SAS) environment. Finally, these sediment yield models were meaningfully discussed in terms of geo morphological parameters of the watersheds to make them widely applicable.

Mishra et al. (2006) this paper presents a rain duration-dependent procedure based on the popular Soil Conservation Service Curve Number (SCS-CN) methodology for computation of direct surface runoff from long duration rains. Curve numbers are derived from long-term daily rainfall-runoff data, and antecedent moisture condition (AMC) related with antecedent duration. Analysis of data from five Indian (large, in terms of area) watersheds reveals the calculated curve numbers to decrease with the considered duration, showing the existence of a characteristic value of minimum CN or maximum initial abstraction to occur in a watershed for a pre-selected AMC.

Neshat et al. (2007) This paper describes two methods for estimating the rainfall runoff at the Bach Malex watershed in Khuzestan (Iran). One method estimates the rainfall runoff based on soil properties and soil vegetation cover to determine the curve number. Another method uses observations and hydraulic conditions related to flood to estimate the curve number. The HEC-HMS model was calibrated using the rainfall-flood observations. The estimates using the curve number method using the model is compatible with those of the observed curved number.
This study indicated that curve number was the major factor influencing the hydrology while pesticide fate and transport were mainly affected by surface runoff and pesticide application and in the study area. Major factors governing the in-stream loads of organophosphate pesticides are magnitude and timing of surface runoff and pesticide application.

Jadhao et al. (2009) conducted a study for the Soil Conservation Service-Curve Number (SCS-CN) is an empirical model was applied for estimating direct runoff from a small watershed (Arang) in Chhattisgarh (India). Various maps including Digital Elevation Model (DEM), watershed and sub-watershed boundaries, drainage network and soil texture were generated using topographic and soil resource data in the environment of a Geographical Information System (GIS). Supervised classification method was used for land use/cover classification of a satellite image of IRS 1D using daily rainfall data of selected events. Performance of model was evaluated by using several test criterions including graphical, statistical and mathematical. Overall deviation indicated that the model over predicted the daily runoff by 26.6 per cent. On the basis of the study it can be concluded that the SCS-CN model can estimate surface runoff from the Arang watershed marginally well for various daily storm events.

Al-Zubi et al. (2010) the study area is located in the Eastern parts of Jordan in semi arid area. The determination of flows has been done by applying the United States Soil Conservation Services (SCS). Curve number approach to the available rainfall data since 1976 till 2006 taking in consideration the Antecedent Moisture Conditions (AMC), the initial abstraction of rainfall and land use. The Curve Number (CN), was calculated from the topographic maps, geologic map and land use map. Therefore, the curve number 80 was found for Wadi Muheiwir catchment area. The calculations of the flood volumes for Wadi Muheiwir catchment area were determined and statistically analyzed by applying Gumble theory (distribution). The calculations and the results for 10, 25, 50,100 and 200 years return period were estimated.

Bhunya et al. (2010) In this paper, an effort has been made to develop a simple conceptual model of sediment yield based on Soil Conservation Service Curve Number (SCS-CN) method, instantaneous unit sediment graph (IUSG) method, and Power law and the performance is tested using real field data of Chaukhutia watershed of Ramganga river catchment (area = 452.25 km2). The proposed model is found to provide realistic estimates of temporal variation of sediment yield as well as total sediment yield during a storm event.

Data Extraction from Dem -

De Vantier and Feldman (1993) reviewed and discussed various approaches including lumped parameters, physically based and hybrid to hydrologic modeling with respect to their geographic data inputs. They summarized past efforts and current trends in using Digital Terrain Model (DTM) and GIS to perform hydrologic analysis. The Digital Terrain Model (DTM) or Digital Elevation Model (DEM) has proven to be a useful and consistent tool for deriving information about the morphology of the land surface.

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Luo et al. (2008) used EASI-PACE software for land use/land cover classification and generation of Digital Elevation Model (DEM). They extracted the watershed parameters from DEM, which were used as input to the SWAT model for estimation of runoff and sediment yield from a small watershed of eastern India. SWAT estimates runoff and sediment yield using SCS-CN method Modified Universal Soil Loss equation (MUSLE) respectively.

Morphometric Analysis -

Bakose and Numan (1990) showed that drainage pattern can be simply and readily identified on aerial photographs or any other remotely sensed image and analyzed quantitatively. The author analyzed the drainage networks by calculating the bifurcation ratios in eleven sample of northern Iraq by using black and white panchromatic aerial photographs.

Nautilyal (1994) conducted morphometric analysis of a drainage basin using aerial photographs in the Khairkuli Basin in Dehradun District, Uttar Pradesh, India. The morphometric parameters were measured and computed manually. It was concluded that Remote Sensing techniques using satellite image and aerial photographs are convenient tools in morphometric analysis of a drainage basin and the photo-interpretation techniques is far less time consuming.

Wang and Yin (1997) conducted a study in twenty basin of west Virginia State in USA to explore the capability of ARC/INFO in generating drainage networks and extracting various basin physiographic parameters. The networks derived from 1:24,000 Digital Elevation Models (DEMs) were compared with the US Geological Survey 1: 100,000 Digital Line Graph (DLG) stream networks with the 1:250,000 DEMs. Basin parameters commonly used in hydrology and geomorphology such as drainage density, stream frequency, stream length, relief ratios, ruggedness number and slopes were examined. The results show that the goodness-of-fit between the parameters based on 1:250,000 DEMs and 1:24,000 DEMs varies amongst different types of parameters and the 1:250,000 DEMs may be used to enhance computing efficiency in drainage basin an characteristics Murli sub-watershed in the Subarnarekha basin using remote sensing GIS techniques. This sub-watershed was further divided into 44 micro-watersheds (with areas less than 10 km2), which were prioritized based on morphometric parameters.

Biswa et al. (2002) have studied the hydro geomorphological characteristic of Murli sub-watershed in the Subarnarekha basin using remote sensing and GIS techniques. This sub- watershed was further divided into 44 micro-watersheds (with areas less than 10 km2), which were prioritized based on morphometric parameters.

Narendra and Rao (2006) used the GIS and image processing techniques to identify the morphological feature and water resources of the Meghadrigedda (Andhra Pradesh) watershed. The morphometric parameters such as linear aspects and aerial aspect of six sub-watersheds of the watershed were computed. Further suitable sites were selected for the water conservation structures.

Drainage network and watershed delineation: Processes for delineating watershed boundaries and flow paths based on contour networks (Moore and Foster, 1990) and triangular irregular networks (Vieux, 1991; Tachikawa et al., 1994) provide...
reliable results. Many researchers described and presented various algorithms to identify watershed features like channels, ridges and overland flow planes from a digitized elevation location data of discrete points of a catchment (Djokic and Maidment, 1993; Garg and Sen, 1994).

**Stuebe and Johnston (1990)** delineated watershed with the use of GIS and compared with the manually delineated area. The areas of the six watersheds, as determined through manual and GIS method were compared. The difference between the two methods ranged from 0.4 percent to 37.6 percent, with a mean of 13.4 percent. In this study, GIS runoff volume was estimated using Curve Number (CN) method judged against the manual runoff estimates. They concluded that the GIS method is a satisfactory alternative to the manual method for watershed lacking relatively flat terrain.

**Kaur and Dutta** (2002) state that traditional manual delineation of watersheds involves subjectivity in locating the ridgelines, which often leads to a slight change in the actual watershed shape and area. Digital delineation of watershed boundaries avoids this subjectivity and thus gives more accurate shape and size of the delineated watershed.

**Tripathi et al.** (2002) was conducted for the Nagwan watershed of the Damodar Valley Corporation (DVC), Hazaribagh, Bihar, India. Geographical Information System (GIS) was used to extract the hydrological parameters of the watershed from the Remote Sensing and field data. It was found that the model can predict runoff reasonably well and is well suited for the Nagwan watershed. Design of conservation structures can be done and their effects on direct runoff can be evaluated using the model.

**Generation of DEM:** The DEM generated in the environment of a GIS using topographic map of the study watershed. The colored area represents the zone of interpolation between two contour lines. Different colors show different zones of interpolation. The accuracy of results obtained from a DEM depends on the recent topography or contours and resolution. The DEM was prepared by considering 24 m by 24 m resolution which was found to be satisfactory. Previous researchers were also found satisfactory results using the DEM of 30 m by 30 m resolution in their respective studies (Binger, 1996, Tiwari et al., 1997, Tripathi et al., 2002).

**Soil texture map:** Soil texture map of the Arang watershed was prepared using soil resource data through GIS. Areas under different soil texture were found to be 174.62, 520.20, 711.78 and 4043.40 ha for sandy loam (Bhata), sandy clay loam (Matasi), loam (Dorsa), and clay (Kanhar), respectively. Areas covers under each soil texture present in the watershed are given in Table 1.

**Model development:** An empirical model was developed using multiple regression analysis. In this study an empirical model in exponential equation was developed. The following basic assumptions were taken into consideration for development of the empirical model as per Tripathi et al. (2002).

1. Runoff depends directly on watershed characteristics such as, hypsometric integral, bifurcation ratio, circulatory ratio, elongation ratio, relief ratio, relative relief, basin shape factor, ruggedness number, main stream channel slope, and average slope of the watershed.

(2) There would not be major change in land use/land cover for five years in the watershed.

The runoff model in multiplication form can be given as,

\[ R = H_i \times R_s \times R_b \times R_r \times R_a \times S_a \times S_b \times S_c \times S_d \times S_e \times C_N \times R_f \]

Where, various morphological parameters of the Arang watershed such as hypsometric integral (Hsi), bifurcation ratio (Rb), circulatory ratio (Rc), elongation ratio (Rr), relief ratio (Rr), relative relief (Rf), basin shape factor (Sa), ruggedness number (Rk), main stream channel slope (Sb) and average slope of the watershed (Sa), length of overland flow (Lg), SCS runoff curve number(CN), R is the depth of runoff (mm), Rf is the depth of rainfall and m is the exponent of the Eqn.1 were determined using standard formula. Models were sometimes under predicting the runoff as compared to observed runoff. These models were also over predicting the runoff as compared to observed runoff for some of the rainfall events. The empirical model seems to be better than GIUH_CAL model for predicting the runoff for the Arang watershed.

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