Spatially Distributed Hydrological Modelling considering Land-use changes using Remote Sensing and GIS

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Abstract:
Distributed hydrological modeling considering spatial variability using remote sensing, and GIS is developed to assess the changes in runoff value due to land use change in a hydrological basin. Kathmandu Valley basin, Nepal, is chosen as a basin of case study**.** In this paper, a spatially distributed model with SCS curve number is developed to assess the runoff changes due to land-use changes. It is found that the average daily monsoon flow is increased by 12% for 9% deforestation and 17% urbanization. Peak flow value in the basin during monsoon season is found increased by 14%. It is found that the percentage change in runoff due to land use change is almost constant for different land use irrespective of the rainfall pattern and time of occurrence. The percentage changes in peak runoff during particular season due to land-use change for the given time interval are found equal regardless of storm events. The relationship developed for the changes in runoff values with respect to change in curve numbers are useful in quantifying the effects due to land-use change. The sensitivity analysis showed that the runoff calculation with distributed approach on estimation of initial abstraction ratio λ is very close to that of observed values. It is found that average value of λ could be taken as 0.25 for forestland, 0.2 for agricultural land, 0.22 for urban and 0.12 for pastureland. In the study area, the peak runoff is found to be increased by 14 % during monsoon season due to deforestation and urbanization. Considering the subbasins, the runoff is found to be increased by 19 % for 13 % increase in curve number. The study clearly demonstrated that the integration of spatial data and application of a distributed model in GIS and Remote-sensing environment provide a powerful tool for assessment of effects due to land-use change.

Introduction

Watersheds may be modelled by a lumped model using basin average input data and producing total basin streamflow. Such a model may produce reasonable result but because of the distributed nature of hydrological properties like soil type, slope and land-use, the model cannot be expected to accurately represent the watershed conditions. For connection of topography, the computer-based methodology known as Geographic Information System (GIS) is quite good to cover the link between the topographic, land-use and other information related to geographical location. It is applied to a hydrologic system to assess the impact due to land-use change. Remote sensing technique because of its capability of synoptic viewing and repetitive coverage provides useful information on land-use dynamics. With the development of GIS, the hydrological catchment models have been more physically based and distributed considering spatial heterogeneity. The purpose of this study is to develop a spatially distributed hydrological model using remote sensing and GIS, which can be used to assess the runoff changes due to land-use changes.

Earlier Works

The SCS-CN method is the most popular method for computing of surface runoff for rainfall event. This approach involves the use of simple empirical formula and readily available tables and curves. It is only one method, which can incorporate the land-use for computation of runoff from rainfall. SCS-CN method provides a rapid means for estimating runoff change due to land-use change. The SCS-CN 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 (The Task Committee, ASCE, 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). Purwanto and Donker (1991) proposed semi-distributed hydrologic modeling using SCS-CN method and assessed the effect of land-use change for hypothetical cases of reforestation and deforestation conditions. When hypothetical case of 5% reforestation or deforestation conditions considered, the peak flow was reduced by 14 % for reforestation and increased by 12 % for deforestation case for hydrologic soil group C when compared to normal land-use. Kite and Kouwen (1992) developed a lumped hydrologic model for computing rainfall-runoff and snowmelt processes separately from different land cover classes. They found that using a semi-distributed model result in better goodness of fit than the lumped basin approach. Schumann (1993) developed a conceptual semi-distributed hydrological model using GIS for a limited consideration of spatial heterogeneity described by area distribution function of the hydrological characteristics and successfully applied for estimation of model parameters.

Warwick and Haness (1994) used *Arc/Info* to determine hydrologic parameters directly for HEC-1 hydrologic model while separate line coverage defining the runoff routing are created manually. Suwanwelarkamtorm (1994) derived semi-distributed hydrologic modeling using GIS for the management of watersheds and assessed the effect of land-use change using integrated approach with HEC-1 and ILWIS. The ability of the model to simulate future and past flood hydrographs based on hypothetical future and past land-use conditions were demonstrated. The results of the simulation runs show that when the forest area is reduced, more runoff will occur in every sub-catchment and also at the outlet.

In this study, the computational elements of ‘Hydrological Similar Units’ (Ott et al, 1991) are considered in distributed hydrological modeling with accurate mapping of land-use at micro level using remote sensing and GIS. In this paper, the focus is on spatially distributed modelling using remote sensing and GIS, considering physiographic heterogeneity in terms of topography, soil, and land-use. The model will assess the hydrological change due to land-use change, which is most essential study for 21st century with the problem of rapidly growing urbanization, or land-use changes.

System for Study

The system considered for the study is Kathmandu Valley basin. The valley is a roughly circular bowl shaped intramontane basin, of 651 km^2 and lies between 27^0 32' N to 27^0 49' N and 85^0 11' E to 85^0 32' E. Bagmati river is the main river originates from north hill and flows towards south-west and forms a typical centripetal drainage system. It passes through Chovar gorge, which is the only outlet of the basin. The maximum and minimum temperatures are 35^0C and -2.5^0C respectively. The rainfall occurs about 80% of the total annual rainfall during the months of June to September. The average annual rainfall in the basin is 1600 mm.

The land use map for the year 1978 is derived from topomaps using Arc/Info. Digital images for 1984 (Landsat TM), 1990 (Landsat TM) and 1996 (Landsat TM) are used to derive the land use maps by digital image process. Maps are projected in Modified Universal Transverse Macerator (UTM) with spheroid system of Everest 1830 on scale factor of 0.999 at Central Meridian. Visual image interpretation of satellite data is carried out using an interpretation key generated through field survey and verifications. The ground checks are made for confirming the land use units. The spatial database containing information on land use, soil type, topography, hydraulic characteristics and meteorological information is created. The hydrological soil group (HSG) map is derived from the soil map whereas subabsin boundary map is derived from the drainage map. There are 14 subbasins delineated. The Thiessen Polygon map is derived using available rain gauge stations. In the study area, the forest (mountainous) area is about 30% of the total basin area having slop range from 20 to 30%, and remaining area (70%) is having average slope of 0 to 4%. The daily and monthly rainfall record of 9 raingauge stations for period 1965 to 1996 are used. The daily data for five stream gauging stations, namely Chovar, Gaurighat, Buddhanilkantha, Sundarijal and Tika Bhairab are collected. Some missing records are filled in considering the correlation structure with other stations. The correlation coefficients are found in between 0.87 and 0.97.

Methodology

The method for evaluating the hydrological change due to land-use changes can be implemented by integrating remote sensing, GIS and HEC-1. The widely accepted, the SCS-CN technique is adapted here to compute the runoff from the several Hydrological Similar Units (HSUs) of the basin for the given rainfall. HSUs are the areas, which have same land-use, same soil type. The runoff from each individual HSUs are then routed and the total runoff resulted from the basin was computed for the given rainfall using HEC-I model.

The derived applicable characteristics from different sources are used to derive the HSU and the hydrological changes due to land-use changes are assessed as described in Fig.1. From satellite image data (LandsatTM), the visual image interpretation is carried out using an interpretation key generated through field survey. The ground checks were made for confirming the land-use units. The spatial information on land-use, soils type, topography, hydraulic characteristics and meteorological information are incorporated. The digital information is kept in different layers. The generated layers are used for overlay analysis and to derive the HSUs, based on its land-use, soil and topography. Appropriate CNs according to standard tables (SCS, 1975) are assigned to each HSUs considering antecedent moisture conditions (AMC). Then the direct runoff values from each HSU are estimated using SCS-CN method for rainfall events. The interflow is taken 5 to 15% of excess soil moisture from soil moisture retention capacity according to slope range of the each HSU (Shrestha, 2002). The runoff values from each HSU including interflow are added to subbasin outlet. Then the total subbasin outlet runoff is routed to outlet of the basin using HEC-1 model. The cumulative runoff value from the basin outlet is compared with observed runoff for that period. Effect of land-use change is evaluated for different periods by quantifying the runoff. In developing the relationship for Q (runoff depth), the SCS (1972) developed the expression as,

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \quad , \text{for } P > I_a \qquad (1)$$

$$Q = 0, \quad \text{for } P \le I_a \qquad (2)$$

Where P = total precipitation, I_a = initial abstraction, S = potential retention. This is valid for P > I_a , that is , after runoff begins and Q = 0 otherwise. To remove the necessity for an independent estimation of initial abstraction, a linear relationship between I_a and S was suggested by SCS (1985) as,

$$I_a = \lambda S \qquad (3)$$

where λ is an initial abstraction ratio. The values of λ varies in the range of 0 and 0.3 have been documented in a number of studies encompassing various geographical locations in the United States and other countries. The value of λ is estimated here in this study through sensitivity analysis. The variable S in mm, which varies with antecedent soil moisture and other variables, can be estimated as;

$$S = \frac{25400}{CN} - 254 \qquad (4)$$

CN values are in a range between 0 to 100, with higher CNs associated with higher runoff potential watershed. To evaluate proper CN values, the soil of the basin are classified into four Hydrologic Soil Groups (HSG) based on their minimum infiltration rate (SCS, 1972). The changes in land-use will be evaluated by accounting the HSU distribution over the entire area for different periods and which in turn, gives the changes in CN over the period considered. The changes in the runoff values are computed using eqns.(1) to (4).

Analysis of Results

From the land-use map, it is found that the urban settlements with highly imperviousness have slope range of 0-2%, residential with average imperviousness (e.g. village) have 2-4%, agricultural land with a slope of 0-4%, pastureland with a slope of 4-20% and forestlands have 21-30% slope. The most of the pasturelands are found inside the forestlands. For different combination of HSG, land-use and slope range, twenty-five types of HSUs are derived. HSU types 1 to 8 are representing forestland, 9 to 16 for built-up land, 17 to 20 for agricultural land and 22 to 25 for pasturelands. HSU type 21 is representing for water bodies. HSU type corresponding to with land-use, slope range and HSG are presented in Table 1. Total numbers of HSUs derived are 1119, 1291, 1375 and 1407 for 1978, 1984, 1990 and 1996 respectively. The minimum delineation of area observed is of 8 m^2.

In the study area, the forest (mountainous) area is about 30 % of the total basin area and remaining area (70%) is having average slope of 0 to 4%. Some subbasins have forest area of less than 3 %. Thus the average orographic influence on the rainfall is assumed to be neglected for estimation of areal rainfall. The available rainfall recording stations are insufficient to prepare isohytel maps. The both rainfall depth and spatial distribution for each sub-basin are taken by Thiessen Polygon method. The daily runoff values are calculated by distributed hydrologic model. The runoff is computed from each HSU separately considering land-use, rainfall and value of λ. The CNs are assigned to all HSUs depending upon daily rainfall according to standard table (SCS, 1972). The sensitivity analysis of λ (initial abstraction ratio) is carried out by two approaches namely distributed approach and single value approach considering premonsoon, monsoon and post monsoon season separately. In distributed approach, the value of λ is considered for each HSU according to seasons, and in single value approach, the represented λ is considered for the basin according to seasons. The Bagmati Subbasin, which is having drainage area of 67 km^2 on the measurement station Gaurighat, is taken for the sensitivity analysis and validated for entire basin with different periods. CN values and areal rainfall are assigned to HSUs. The daily runoff values are computed from each HSUs. The runoff values are summed up to get the runoff at outlet and compared with that of observed values. The performance of the model is evaluated by criteria namely mean square error (MSE), mean percentage error (MPE), mean absolute percentage error (MAPE) and model efficiency R^2 .

The distributed approach of λ gives better performance compared to single value approach. When considering seasons only, it is found that values of λ as 0.27, 0.2 and 0.17 for premonsoon, monsoon and premonsoon are most fitted values. The average values of λ are found as 0.25 for forest, 0.20 for agricultural, 0.22 for settlement and 0.12 for pastureland irrespective of seasons. Using calibrated values of λ, the daily runoff values are calculated from all subbasins for 1978 and 1990. The daily runoff values from each HSUs under the subbasin are summed up to get runoff at outlet of subbasin and then outlet runoff is routed by Muskingum routing technique to the next hydrograph combination point. The daily runoff values at basin outlet are calculated from daily rainfall for year 1978 and 1990. The values of MSE, MPE, MAPE and R^2 are computed and presented in Table 2.

For this study, the hydrographs are observed from year 1965 to 1981at the outlet of the basin. Due to distinct meteorological characteristics found during premonsoon, monsoon and post monsoon, the baseflow are estimated separately for these three periods by straight-line method. Considering observed and computed different peak runoff values of year 1978, MAPE values are found to be 6.21, 2.61 and 3.32 during premonsoon, monsoon and postmonsoon respectively. Similarly for year 1990, MAPE values are 17.56, 5.73 and 11.10 during premonsoon, monsoon and postmonsoon respectively. The model can compute the runoff close to observed runoff. The model is then used to calculate runoff for other years by the distributed model. The model calculates the daily runoff values for year 1984 and 1996. MSE, MPE, MAPE and R^2 are found acceptable compared with observed runoff values. The comparison of monsoon peak and the total volume of storm with observed are presented in Table 3. The maximum difference between calculated and observed value of peak is 3.7 %, and storm volume difference is 2.2 %.

Percentage area and distribution of each HSU are shown in Fig. 2. In year 1996, the forest area is found increased 9 %, urbanization by 17.2 % and pastureland by 125 % compared to year 1978. Effect of land-use change is evaluated based on hypothesis that when the same rainfall pattern is routed through the different land-use change (different years), the resulting difference in the runoff will indicate the effect of land-use change. In this work, the rainfall values of year 1978 are superimposed on years 1984, 1990 and 1996. The change in land-use has been evaluated in terms of CN for different conditions. The changes in the CN values and the changes in the runoff values are then assessed by the difference in runoff values produced by the same rainfall on different land-use. Comparing between 1978 and 1996, the weighted CN is found to be increased by 7% for AMC I, 6% for AMC II and 4% for AMC III. The daily monsoon streamflow is found to be increased by 11.2% and the peak flow is found increased by 14% for land-use of 1996. In sub-basin level, the most change in CN is observed at Gundu sub-basin (13%) and the corresponding increase in runoff is 19%. By superimposing monsoon storm event of 1978 on land-use of 1984 (LU2), the peak runoff is found to be increased of 4%. Similarly the peak runoff values are found to be increased by 12% from land-use of 1990 (LU3) and 14% from land-use of 1996(LU4). The average percentage change in storm runoff is also found almost same for different years. The peak runoff value is found to be increased by average of 3.8 %, 11.6%, and 13.3% from LU2, LU3 and LU4 respectively compared to that peak runoff values obtained from LU1 in monsoon season as presented in Table 4. Average storm runoff values are found to be increased by 3.6%, 9.3% and 12 % from LU2, LU3, and LU4 compared to that from LU1 in monsoon season. Thus the percentage changes in peak runoff value or average change in storm runoff values are depending upon the land-use change irrespective of storm event and time.

Conclusions

The results of the study show that the spatially distributed hydrological model is the best model to assess the hydrological change due to land-use changes. GIS appears to be an efficient tool for presentation of input data as required by the model. The runoff values computed by the model are closely matching during the wet season than dry season. The sensitivity analysis showed that the runoff estimation with distributed approach of λ is very close with observed values. The analysis also shows the distributed λ approach gives better performance when compared to single value approach and traditional SCS-CN method. By single value approach over the seasons, the value of initial abstraction ratio λ as 0.27 for premonsoon, 0.20 for monsoon and 0.17 for post monsoon are best suitable for agricultural mountainous basin. The average λ value of 0.25 is found suitable for forestland, 0.2 for agricultural land, 0.21 for urban settlement, and 0.12 for pastureland.

This study clearly demonstrated that interactive integration of spatial data and application of distributed hydrologic model in GIS environment provides a powerful tool for assessment of effects due to land-use changes. Future change in land-use can also be incorporated in the model once digital database is available and the change in runoff production can be found out. Thus land-use planning and management can be done efficiently. The relationships developed between changes in runoff with respect to change in CNs are very useful to quantify the effect of land-use change. The change in peak runoff values can be estimated for basin having known changes in land-use for known rainfall. It is concluded that the percentage change in runoff due to the land-use change almost constant for different land-use irrespective of the rainfall pattern (different years) and irrespective of time of occurrence (premonsoon, monsoon and postmonsoon).

For the study area, it was found that the peak flow value is increased by 14% for 9.1% deforestation and 17.2 % urbanization. . Considering individual subbasins, the runoff is found most increased by 19 % for 13 % increase in curve number.

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Table 1 Land-use/Land cover, Slope, Hydrological Soil Group (HSG) and Type of HSUs

HSU Type	Slope (%)	HSG	Land-use/Land cover
1	21-30	A	Forest land with good cover
2	"	B	"
3	"	C	"
4	"	D	"
5	"	A	Reserved forest with good cover
6	"	B	"
7	"	C	"
8	"	D	"
9	0-2	A	Urban with Imperviousness (72%)
10	"	B	"
11	"	C	"
12	"	D	"
13	2-4	A	Residential with average imperviousness
14	"	B	"
15	"	C	"
16	"	D	"
17	0-4	A	Agricultural with conservation treatment
18	"	B	"
19	"	C	"
20	"	D	"
21	-	-	Streams and water bodies
22	13-20	A	Contoured pasture land
23	"	B	"
24	"	C	"
25	"	D	"

Table 2 MSE, MPE, MAPE and R^2 for year 1978 and 1990

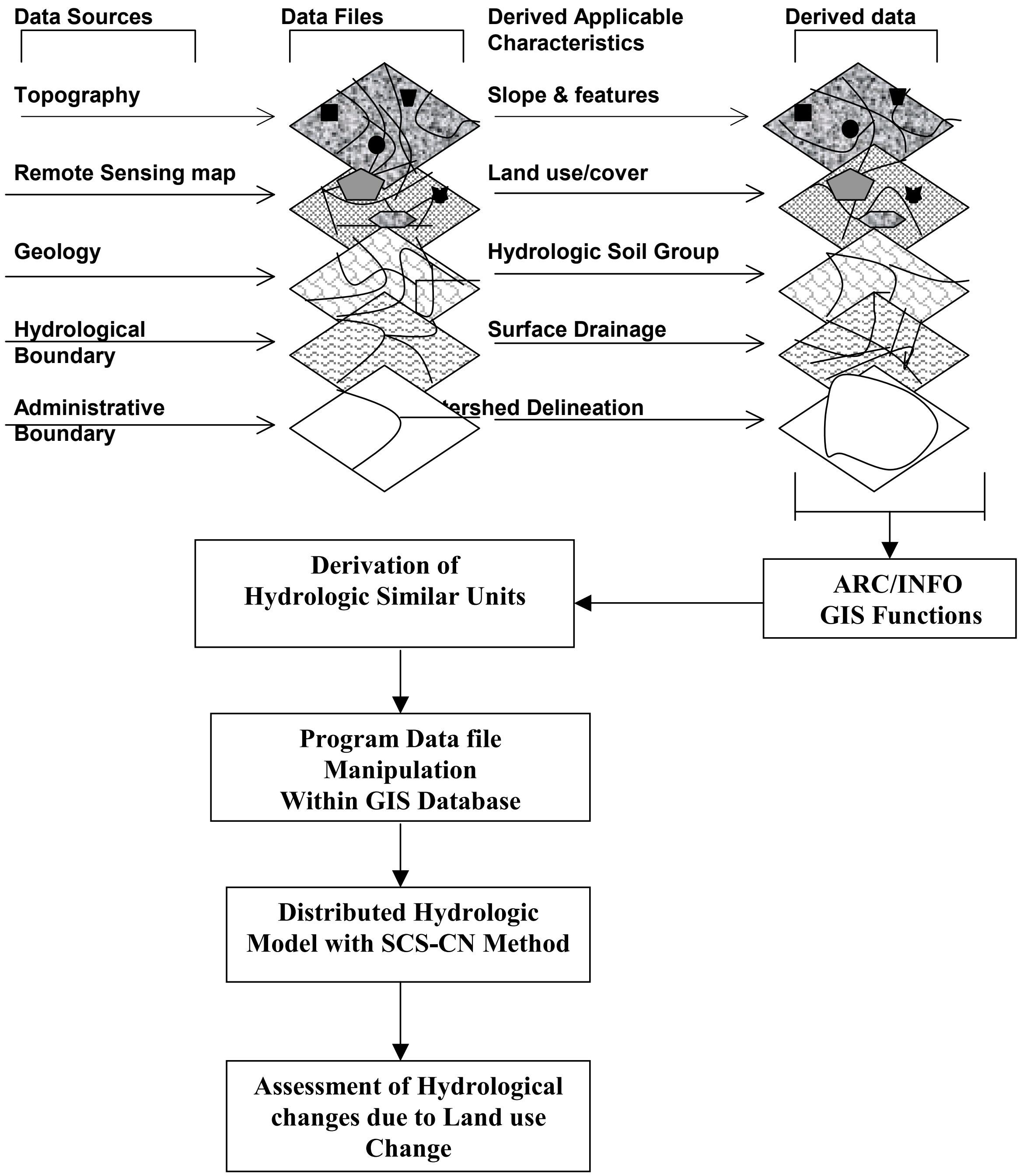
	1978			1990		
	Pre monsoon	Monsoon	Post monsoon	Pre monsoon	Monsoon	Post monsoon
MSE	0.16	5.55	1.04	0.09	8.66	0.51
MPE	-2.67	-1.05	-5.23	3.67	2.71	0.84
MAPE	8.63	5.43	7.77	10.86	7.26	6.00
R^2	0.98	0.98	0.98	0.97	0.97	0.96

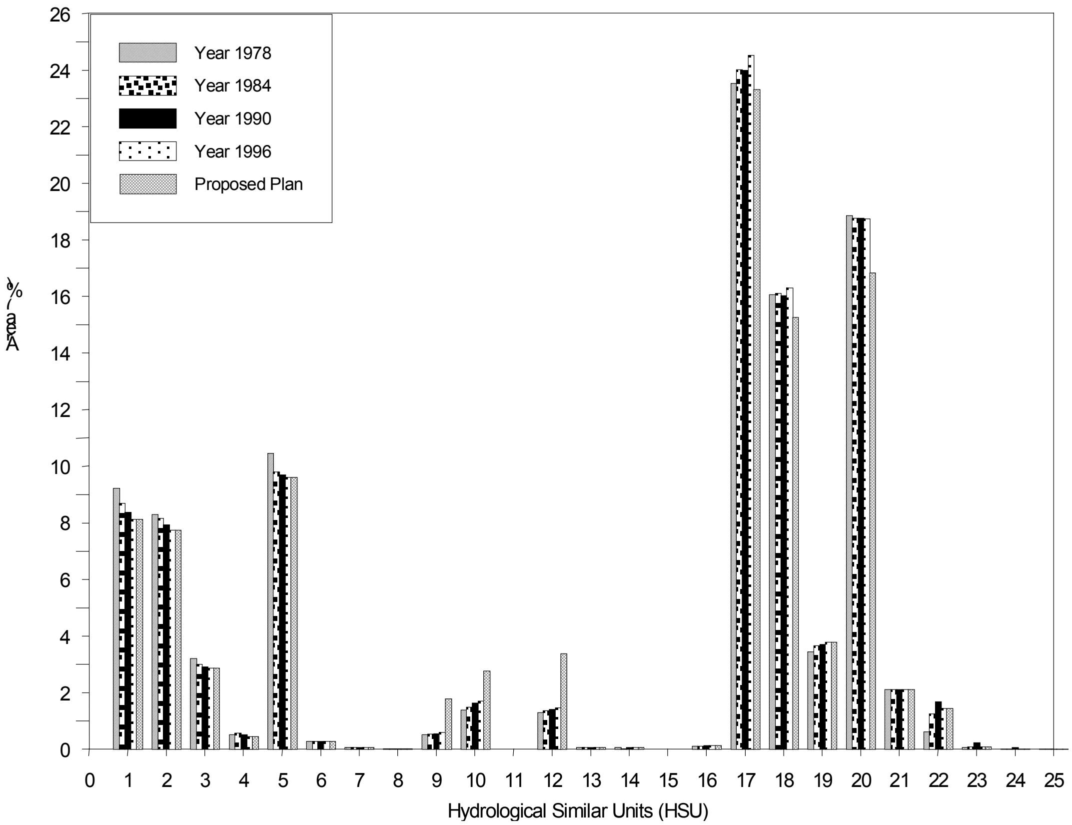
Table 3. Comparison of monsoon peak (m^3/s) and total volume of the storm (Mm^3)

Year	1978			1984			1990			1996		
	Obs.	Cal.	% diff	Obs.	Cal.	% diff	Obs.	Cal.	% diff	Obs	Cal.	% diff
Peak	230	233.1	1.4	195.5	201.2	2.9	123.3	127.9	3.7	251	254	1.2
Storm Volume	36.1	36.9	2.2	43.4	44.1	1.7	48.7	48.3	0.8	65.6	64.9	1.1

Table 4 Percentage change in peak runoff and storm runoff from different storm events during monsoon season of different years

Year	% Change in peak runoff values						Average %change in storm runoff					
	L1-2	L1-3	L1-4	L2-3	L2-4	L3-4	L1-2	L1-3	L1-4	L2-3	L2-4	L3-4
1978	3.9	11.6	13.3	7.4	9.1	1.5	4.0	9.6	12.0	5.4	7.8	2.3
1984	3.8	11.7	13.2	7.5	9.0	1.4	3.6	9.1	12.1	5.7	8.0	2.2
1990	3.8	11.6	13.3	7.6	9.1	1.6	3.8	9.4	12.2	5.6	7.9	2.3
1996	3.8	11.5	13.3	7.4	9.1	1.6	3.3	9.1	11.7	5.5	8.1	2.4


Data Sources
Data Files
Derived Applicable Characteristics
Derived data
Topography
Slope & features
Remote Sensing map
Land use/cover
Geology
Hydrologic Soil Group
Hydrological Boundary
Surface Drainage
Administrative Boundary
ershed Delineation
Derivation of Hydrologic Similar Units
ARC/INFO GIS Functions
Program Data file Manipulation Within GIS Database
Distributed Hydrologic Model with SCS-CN Method
Assessment of Hydrological changes due to Land use Change


Year 1978
Year 1984
Year 1990
Year 1996
Proposed Plan
Area, %
Hydrological Similar Units (HSU)
0 2 4 6 8 10 12 14 16 18 20 22 24 26
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25