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Sensitivity of Initial Abstraction Coefficient on Prediction of Rainfall-Runoff for Various Land Cover Classes of 'Ton Watershed' Using Remote Sensing & GIS Based 'Rinspe' Model

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ABSTRACT

Rainfall, Runoff, Infiltration are most important parameters in water balance equation of any hydrological problems. Among these parameters the real prediction of surface runoff is the crucial task. Many hydrologic models are available to estimate surface runoff from precipitation data. The development of a GIS based model that would make it possible to assess the surface runoff accurately and efficiently. On the basis of this requirement a model called 'Runoff, Infiltration and Nonpoint Source Pollution Estimation' (RINSPE) was developed for estimating runoff, infiltration and nonpoint source pollution in the Ton river catchment based on the different land cover type distribution within the catchment. The Curve Number method for estimating direct runoff from rainstorms is now widely used in engineering design, post-event appraisals, and environmental impact estimation. In the present investigation the Initial Abstraction coefficient in the Curve Number method considered with 2 different scenarios by assuming 'λ' value as 0.2 for general conditions and 0.3 for Indian conditions to run RINSPE model. The results reveal that the surface runoff of 860.79 mm occurred with a loss of 62.93 mm in the form of infiltration for scenarios: 1. The most occupied area in the Ton watershed is forest which is having a runoff of 656 mm with 124mm infiltration and a very slight variation in prediction of runoff and infiltration for scenario: 2 for the same land cover classes. In the present study the results reveals that 'λ' value is 0.2 of I_a gave minute higher runoff values than 'λ' value with 0.3. This experimental investigation makes sure that, higher the initial abstraction lowers the runoff and vice versa.

Keywords: RINSPE, Initial Abstarction, precipitation, Runoff, Soil texture, Initial Loss

I. INTRODUCTION

Runoff is what occurs when rain is not absorbed by the ground on which it falls and so then flows downhill. The most important factor in determining the quantity of runoff that will result from a given storm event is the percent imperviousness of the land cover. Other factors include soil infiltration properties, topography, vegetative cover, and prevailing site conditions [11]. Oceans make up 71% of the Earth's surface and the solar radiation received here powers the global evaporation process. In fact, 86% of the Earth's evaporation occurs over the oceans, while only 14% occurs over land. Of the total amount of water evaporated into the atmosphere, precipitation returns only 79% to the oceans and 21% to the land. Surface runoff sends 7% of the land based precipitation back to the ocean to balance the processes of evaporation and precipitation [6]. The rate of runoff flow depends on the ratio of rainfall intensity to the infiltration rate. If the infiltration rate is relatively low, such as when a soil is crusted or compacted, and the rainfall intensity is high, then the runoff rate will also be high. Infiltration is the initial process of water entering the soil at the ground surface from precipitation or anthropogenic sources, which plays a major role in runoff [12]. Infiltration is a direct loss that governs the volume and rate of runoff, and thus it controls the shape of the runoff hydrograph [10]. Infiltration depends on the type of land use, soil type (texture class), vegetative cover, porosity and hydraulic conductivity, degree of soil saturation, soil stratification, drainage conditions, depth to water table, and intensity and volume of rainfall. The amount of rainwater that runs off during / immediately after a rainfall event depends heavily on the amount of rainfall, ‘initial abstraction’, and the type and condition of ground it lands on.

Development of a GIS based runoff model is a challenging task because of the complexities involved in the urban set up. However attempts were made in Birmingham, UK to develop GIS models for estimating direct or precipitation recharge, indirect recharge through seepage from surface water bodies, indirect recharge through mains leaks and indirect recharge through sewer leaks in a city on a regional scale [7],[8] and the same approach was used in the development of this model as applied to the Western Cape’s Kuils-Eerste river catchment in South Africa.

In this project, GIS based model namely ‘Runoff Infiltration and Nonpoint Source Pollution Estimation’ (RINSPE) for estimating runoff and infiltration from various land use/ land cover types was developed for an urbanised and agricultural catchment. The model was developed taking into consideration that the model needed to be sophisticated enough to account for the routing of all precipitation in the form of surface runoff, infiltration and pollution loading. In order to estimate these parameters, some suitable method for estimating the areal distribution of rainfall losses through infiltration and runoff had to be chosen first in designing the model [9].

Notwithstanding this, there are other possible models that can be adopted and include the following: i) the rational method, ii) SCS CN method, iii) Horton’s model for infiltration capacity, and iv) Green-Ampt infiltration model etc [5]. After considering various available methods for infiltration and runoff estimation, the United States Department of Agriculture, Soil Conservation Service (SCS, now known as the Natural Resources Conservation Service, or NRCS) Runoff Curve Number (CN) method was chosen.

A. Study Area

The study area is located in the western part of Doon valley, Dehradun district and Uttarakhand state in India. The sub-watershed ‘Ton Watershed’, which is a Sub-basin in ‘Asan’ watershed, is selected to run the RINSPE model. The Ton watershed is upper part of Asan River, which is called as Ton river in earlier days of the local people [2]. The Asan river is tributary of Yamuna River. Geographical location of the study area covers a total of approximately 150 km^2 and lies between 77^{o}45’33” and 77^{o}57’46”and 30^{o}24’39” and 30^{o}29’05” as shown in Fig.1. The study area having large area under hilly tract. The climate is humid to sub-tropical varying from valley to the high mountain ranges of Himalayas. During rainy season 1625 mm rainfall is observed in the year. The area has a favourable climate for the growth of abundant vegetation due to reasonably good rainfall & elevation Dense & moderate mixed forest, shrubs, agriculture crops. Soils of the study area are found to be derived from alluvium parent material. These were observed, well to excessively drain with low to medium permeability and having texture sandy loam to clay loam with low to medium productivity.

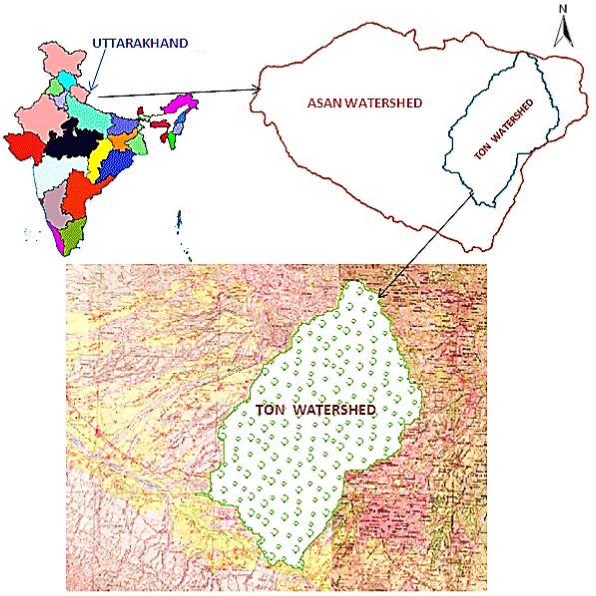

Figure 1: Location Map of Ton Watershed

B. Data Required

GIS based runoff and infiltration estimation using the NRCS Curve Number method normally requires the spatial inputs such as land use / land cover map, soil type/hydrologic soil group map, rainfall distribution map and values of initial abstraction or initial losses for each type of land use / land cover with attributes of specific group types and group codes. The preparation of each map is described in detail as fallows.

i. Preparation of Land Use/Land Cover Map:

A Landsat TM satellite image acquired on 14 Nov 2004 was downloaded from website to prepare land cover classes grid map. There are 7 basic classes are identified under 'supervised classification' with ground truth data in Ton watershed as shown in Fig.2. The basic classes are Agricultural crops, Fallow, Forest, Scrubland, Settlements, Dry river bed, water and Tea gardens. The highest land cover class of 94.27 km^2 area covered under forest land. The lowest area of 0.01 km^2 covered under water body. Agricultural crops covered an area of 2.89 km^2, fallow land covered 6.27 km^2 area, settlements covered an area of 3.78 km^2 and scrub, dry river bed, and Tea Gardens covered 35.54, 4.70, 2.68 km^2 area respectively.

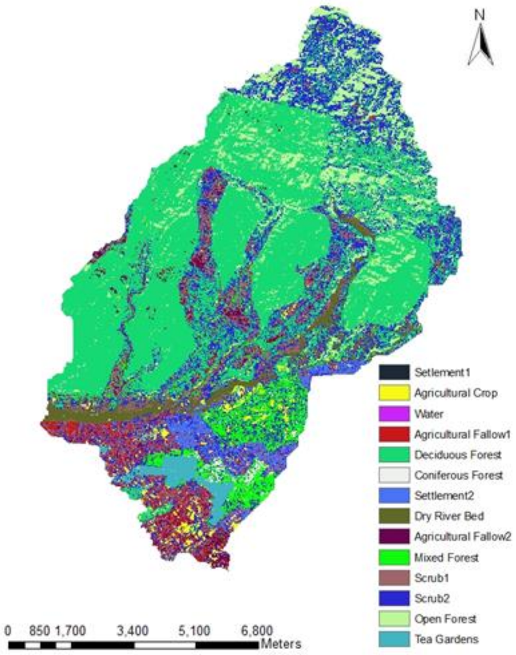

Figure 2: Land use –Land Cover Classification of Ton Watershed

ii. Preparation of Hydrologic Soil Group (HSG) map

Soil data gathered from textural properties of soils covered in the Ton watershed. The hydrologic soil groups (HSG) were derived from the Land Type data by reclassifying the soil textures present in it. Accordingly a soil thematic layer prepared by using soil data available from Ton watershed. A polygonised soil map prepared based on the types of soils covered in the catchment as shown in Fig.3. There are 6 verities of soil textural classes are identified from Ton watershed.

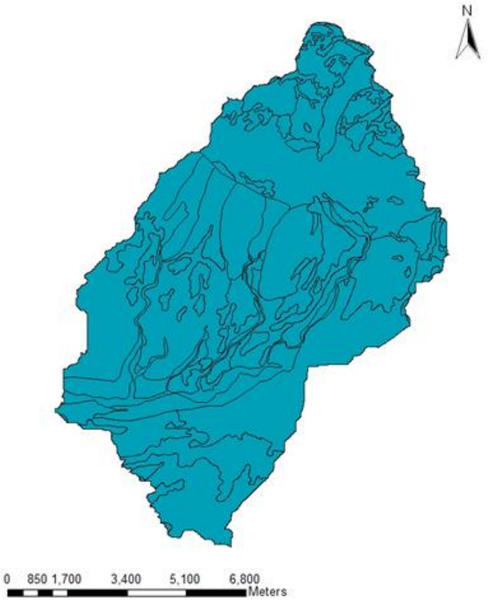

Figure 3: Soil Map of Ton Watershed

These are Loam, Silt Loam, Sandy Loam, Sandy clay Loam, Gravelly clay loam, Loam to Sandy Clay Loam. The higher portion of the catchment covered with Loamy soils and a least area of soils are covered with loam to sandy clay loam. Querying the attribute table and identifying and selecting correct textures (by making a link between the land type units and a corresponding field in the attribute table) from such an attribute table were difficult and time consuming. The soil classes reveal that 38.31% of area covered under HSG of D, and the lowest percent of area of 15.31covered under B type of HSG. The textural classification shows that an area of 90 km^2 covered under loam sands, least area of 8.54 km^2 covered under loam to clay loam type of textural class.

iii. Preparation of Rainfall distribution grid map

Daily rainfall data collected from a Self-recording rain gauge available at Poanta Sahib Village which is covered under Ton watershed for about 30 years from 1980 to 2009. In order to prepare Rainfall grid map, IDW method used from spatial analyst tool available in ArcGIS environment. The rain fall grid map of Ton watershed is shown in Fig.4.

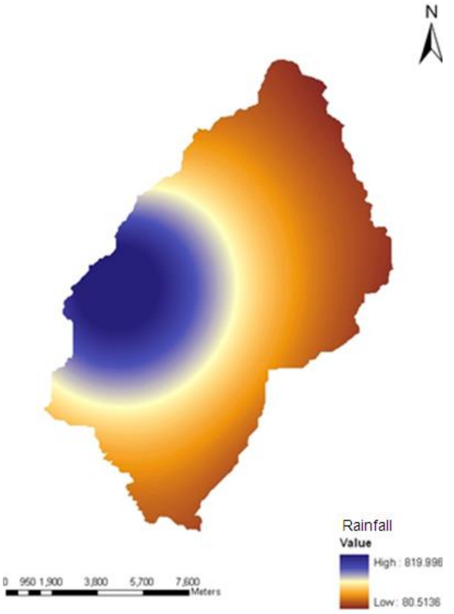

Figure 4: Rainfall Distribution Map of Ton Watershed

iv. Curve Number (CN) and Initial Loss (Ia) Values

The input values of CN and 'Ia' were identified for the different land use / land cover types and HSG combinations through a literature search done on the Internet and from other sources. The CN values of each land class with code values are prepared in excel sheet and converted into Text (tab limited) format to prepare a 'CN' text file. Similarly for Ia values corresponding land cover types are prepared by considering 'λ' value as 0.2 and 0.3 for different text files prepared like CN text file as input files for the application of RINSPE model.

II. METHODS AND MATERIAL

It was decided to use the NRCS Curve Number (CN) method for a quick estimation of runoff and infiltration taking place in the identified study area. It is important to note that surface runoff and infiltration in any location can be estimated through the following equation:

Surface Runoff = Rainfall – Initial abstraction – Infiltration

The NRCS curve number method is an empirical description of infiltration. It combines infiltration with initial losses (interception and detention storage) to estimate the rainfall excess, which would appear as runoff. The model was developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types [11].This model is relatively simple requiring few input parameters, and has been widely applied in the fields of soil physics and hydrology [13]. The method is an empirically based one, and is applicable to the situation in which amounts of rainfall, runoff, and infiltration are of interest [4]. The USDA NRCS curve method predicts direct surface runoff using the following equation:

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)}$$

In which:

Q = Total rainfall excess (runoff) for storm event (mm or inches),

P = Total rainfall for storm event (mm or inches),

Ia = Total initial loss or "initial abstraction" (inches),

S = Potential maximum retention capacity of soil at beginning of storm or maximum amount of water that will be absorbed after runoff begins (inches).

S, also called the retention parameter, is a statistically derived parameter related to the initial soil moisture content or soil moisture deficit [3]. The value of S is determined based on the type of soil and the amount and kind of plants covering the ground (cover types). This is derived through its relationship to the value of the NRCS runoff curve number (CN). A curve number is a numerical description of the impermeability of the land in a watershed. This number varies from 0 (100 % rainfall infiltration) to 100 (0 % infiltration –e.g., road/concrete). The following relation relates the value of S to the curve number.

$$S = \frac{1000}{CN} - 10$$

CN = runoff curve number (0-100, based on the soil and land use information).

CN is determined through several factors. The most important are the hydrologic soil group (HSG), the ground cover type, treatment, hydrologic condition, the antecedent runoff condition (ARC), and whether impervious areas are connected directly to drainage systems, or whether they first discharge to a pervious area before entering the drainage system. Soils are extremely important in determining the runoff curve number. Soils are generally classified into four Hydrological Soil Groups (HSG): A, B, C, and D, according to how well the soil absorbs water after a period of prolonged wetting. The whole methodology illustrated in the form of flow chart as shown in Fig.5

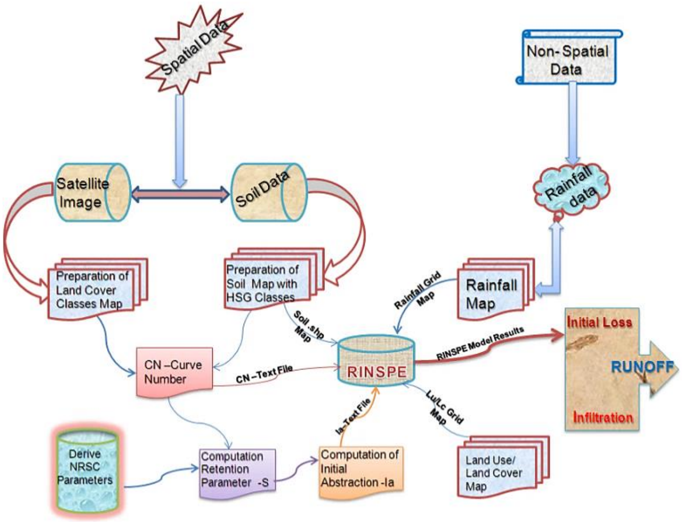

Figure 5: Methodology of RINSPE Model Application

The terms 'initial abstraction or initial surface loss incorporates rainfall loss due to interception, evaporation from surface during rainfall events, depression and detention storages. The value of 'I_a' depends greatly on the cover types (the verity of plants covering the soil or land use), the kind of soil (hydrologic soil groups, hydrologic condition and its treatment) and antecedent soil moisture of the area being studied. For a given drainage basin, the values of 'I_a' are highly variable, but generally are correlated with soil and cover parameters. A major limitation for applying the SCS model lies in that the values of the parameter 'I_a' must be evaluated with field data for each specific site as fallows.

$$Ia = \lambda * S$$

Where

Ia = Initial abstraction

S = Potential maximum retention

λ = a constant

Values of λ: on the basis of extensive measurements in small size catchments SCS (1985) adopted λ=0.2 as standard value [3].

SCS-CN Equation for Indian Conditions: Values of 'λ' varying in the range of $0.1 \leq \lambda \leq 0.4$ have been documented in a number of studies from various geographical locations, which included USA and many other countries. For use in Indian conditions λ = 0.1 and 0.3 subject to certain constraints of soil type and AMC type has been recommended [3].

Based on the available theory regarding 'Ia' in SCS-CN equation the present investigation carried by taking into consideration of 'λ' value. The main tenet of this paper is to run RINSPE model in 2 scenarios by considering 'λ' value as fallows.

Scenario 1: assuming the 'λ' value is 0.2 for general condition

Scenario 2: assuming the 'λ' value as 0.3 for Indian condition

Overview of RINSPE Model

The '**R**unoff, **I**nfiltration and **N**on-point **S**ource **P**ollution **E**stimation' model implemented in ArcView GIS 3.2 platform through Avenue programming and its extension Spatial Analyst was selected for the estimation of runoff and infiltration. RINSPE model was developed as one of the deliverables of a Water Research Commission funded research project on assessment of non-point source pollution in the Kuils-Eerste River catchments of Western Cape [1]. RINPSE is an event-based/annual based model that can estimate runoff & infiltration (using the NRCS CN method) and the pollutant loading from different land cover within a catchment. With this model, using digital elevation data, land use/ land cover type grid data and rainfall data together with attribute tables covering chemical characteristics, surface water runoff and pollutant loading in surface runoff waters was calculated and various maps displaying the distribution of these parameters were generated. The Interface of RINSPE Model for Runoff and Infiltration Estimation is shown in Fig. 6.

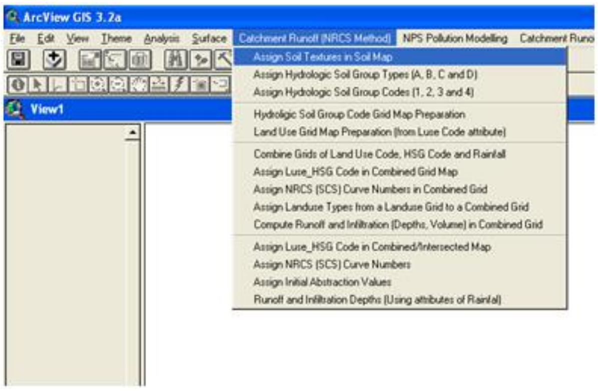

Figure 6: Interface of RINSPE Model for Runoff and Infiltration Estimation.

III. RINSPE MODEL APPLICATION

The major outputs from the model are distribution of surface runoff, infiltration, pollutant concentration and loading distribution, for each chosen pollutant. In this paper pollution parameters are not considered because, the main intention of this paper is to estimate runoff. However, applying the tool in other regions may require the preparation of land use input data in the required format. The RINSPE model has the advantage of its ability to assign more realistic individual initial abstraction/initial loss values for a particular land use / land cover underlain by a certain type of hydrologic soil using a table, thus providing more accurate estimation of runoff and infiltration.

The input maps of land use / land cover and HSG were processed /converted into grid maps and were combined as one grid map of land use and HSG in the RINSPE model. An input table of Curve Number Values for different LUSE- HSG combinations for Antecedent Moisture Condition (AMC) II and initial abstraction 'Ia' values for different land use / land cover units were prepared. The Curve Number (CN) grid was prepared in RINSPE model by running the programs for combining the HSG grid with the Land Use / Land Cover grid, for assigning the LUSE-HSG codes and finally querying and assigning CN values from the input table prepared for the LUSE-HSG codes. Later the grids of land use, CN and rainfall were combined together and initial abstraction or initial loss values were assigned through a map query done in RINSPE model. The submenu of "Runoff and Infiltration Depth" implements this step and finally calculates runoff and infiltration values. The modeling of runoff and infiltration was done for two scenarios as mentioned in the methodology.

IV. RESULT AND DISCUSSION

The results obtained from this modeling exercise Scenarios 1 are shown in Table 1 and Figures 7 & 8. The results reveals that the volume of annual rainfall lost as initial loss from the catchment is 88.266 ML or 0.0882 GM^3.The initial loss (initial abstraction) predicted for the Scenario-1 in a year using the annual rainfall grid ranges from 415.866–1238.49. The total annual volume of surface runoff (direct runoff) is 104021 ML or 0.104 Gm^3 (because of space constraint not shown in Table:1).

The runoff depths ranges from 106.76-489.64 m^3 as the rainfall received in the Northern part is low, the infiltration and runoff observed are also low in that region. The mean initial loss predicted by the model is 2.9296 mm, mean infiltration is 62.93 mm and the mean surface runoff is 860.79 mm. The summarized depths (mm) of annual rainfall, initial loss, infiltration and runoff based on scenario-1 and their respective percentage values are shown in Table:1. All type of Forest category has got the lowest runoff percentage of 83.94 % of rainfall received whereas the Water Bodies and river bed categories have got maximum runoff percentages (100% and 96.25% of rainfall respectively). The highest infiltrations observed are in the areas covered by forest areas and lower river bed, settlement lands. The majority of the southern parts of the catchment have minimum runoff as shows in Fig: 7.

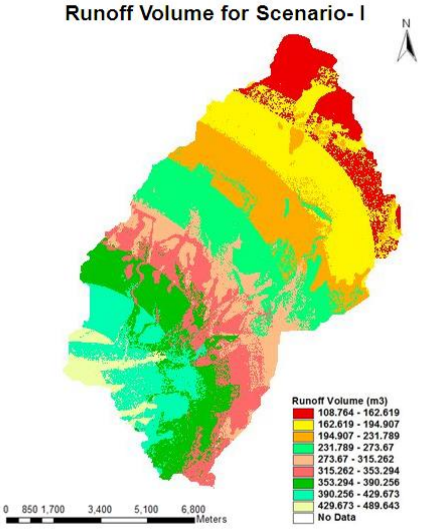
Runoff Volume for Scenario- I

Figure 7: Runoff Volume Depths of RINPSPE Model for Scenario:1

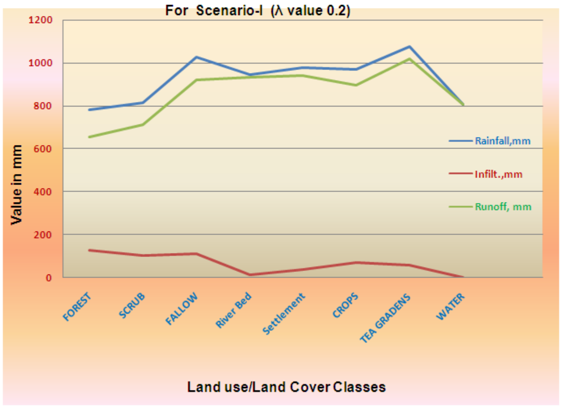

Figure 8: A comparison graph for Scenario: 1

Table 1: RINSPE Model results for scenario 1: λ value as 0.2

Land use/ classes	Area Km2	Rain mm	Ini.Loss mm	Infilt mm	Runoff mm	Ini.Loss %	Infilt %	Runoff %
Forest	95.27	781.77	0.62	124.85	656.29	0.079	15.97	83.94
Scrub	37.54	814.82	0.61	99.75	714.45	0.075	12.24	87.68
Fallow	6.27	1027.39	0.39	107.29	919.7	0.038	10.44	89.51
River Bed	4.70	942.65	0.1	10.93	931.61	0.010	1.16	98.82
Settlement	3.78	977.18	0.2	36.44	940.54	0.020	3.72	96.25
Crops	2.89	967.34	0.4	69.49	897.45	0.041	7.18	92.77
Tea Gardens	2.68	1074.24	0.6	54.67	1018.96	0.055	5.08	94.85
Water	0.01	807.36	0	0	807.36	0.000	0	100
Average		924.09	0.366	62.93	860.79			

Table 2: RINSPE Model results for scenario 2 : λ value as 0.3

Land cover class	Area Km2	Rain mm	Ini.Loss mm	Infilt. mm	Runoff mm	Ini.Loss %	Infilt %	Runoff %
Forest	95.27	781.77	1.68	124.83	655.26	0.215	15.96	83.81
Scrub	37.54	814.82	0.85	99.74	714.22	0.104	12.24	87.65
Fallow	6.27	1027.39	0.59	107.29	919.5	0.057	10.44	89.49
River Bed	4.70	942.65	0.2	10.93	931.51	0.021	1.16	98.81
Settlement	3.78	977.18	0.3	36.44	940.44	0.030	3.72	96.24
Crops	2.89	967.34	0.7	69.49	897.15	0.072	7.18	92.74
Tea Gardens	2.68	1074.2	0.9	54.67	1018.66	0.083	5.09	94.82
Water	0.01	807.36	0	0	807.36	0.000	0	100
Average		924.09	0.653	62.92	860.51			

The results obtained from RINSPE model exercise for Scenarios: 2 are shown in Table : 2 and Figures 9 & 10. The results reveals that volume of annual rainfall lost as initial loss from the catchment is 88.266 ML or 0.0882 Gm^3. The total annual volume of surface runoff (direct runoff) is 104021 ML or 0.104021 Gm^3. There is no much variation in runoff volume between scenario 1&2. The runoff depths ranges from 106.16-479.24 m^3 as the rainfall received in the Northern part is low, the infiltration and runoff observed are also low in that region. The mean initial loss predicted by the model is 2.9296 mm, mean infiltration is 62.93 mm and the mean surface runoff is 860.79 mm.

The summarized depths (mm) of annual rainfall, initial loss, infiltration and runoff based on scenario-2 and their respective percentage values are shown in Table:2. All type of Forest category has got the lowest runoff percentage of 83.81 % of rainfall received whereas the Water Bodies and River bed categories have got maximum runoff percentages (100% and 98.81% of rainfall respectively). The highest infiltrations observed are in the areas covered by forest and low for dry river bed and settlement. Figure 9 shows that majority of the southern parts of the catchment have minimum runoff.

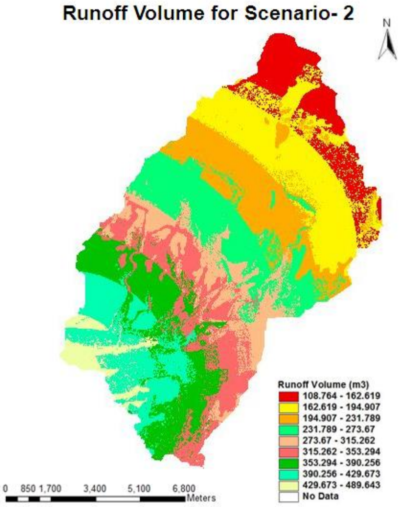

Figure 9: Runoff Volume Depths of RINPSPE Model for Scenario : 2

The comaprision graph between rainfall and predicted values of infiltration and runoff for Scenario:2 from RINPSPE model as shown in Fig. 10. This graph resembles the graph drawn for Scenario:1. The results of runoff depths for fallow land, riverbed, settlements and crop land are at similar trend when compare to forest and tea gardens

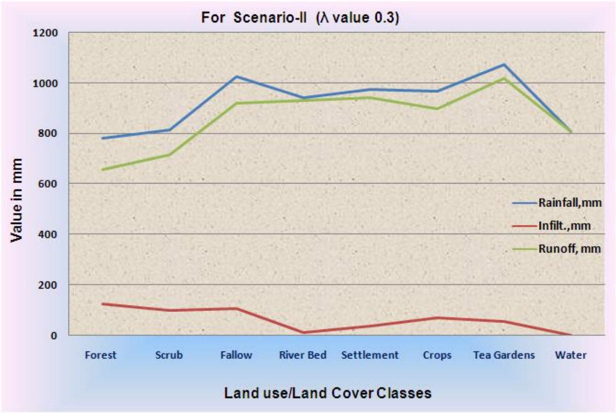

Figure 10: A comparison graph for Scenario: 2

A comparison graph (Fig:11) has been prepared to show the runoff depths obtained from both scenarios of RINSPE model. Visually there is nothing much variation of runoff depths between scenario 1 & 2 for all types of land classes covered in the entire Ton watershed. The graph clearly demonstrated that tea gardens showing highest rainfall along with highest runoff depths. Similarly, the lowest rainfall and the corresponding runoff occurred at forest areas of the watershed.

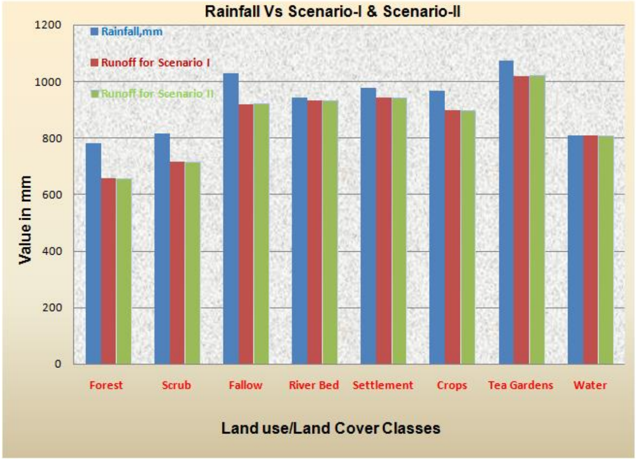

Figure 11: A comparison graph of Runoff-Depths for Scenario 1&2

V. CONCLUSION

RINSPE model could be used successfully to estimate the surface runoff, cumulative infiltration and accumulated runoff in the Ton watershed area, using Land Type data and HSG with SCS-CN method. Results reveal that the distribution of surface runoff and infiltration is fully dependent on the rainfall distribution and the nature of the land use / land cover types underlain by different types of hydrologic soil groups.

With Scenario:1 considering 'λ' value 0.2, the initial loss of the catchment is about 0.04% of the annual rainfall while surface runoff and infiltration are 92.98 %, 6.97 % of the annual rainfall received. With an average annual rainfall of 924.09mm the predicted average initial loss, infiltration and surface runoff is 0.366mm, 62.93mm and 860.79mm respectively. The total annual surface runoff volume predicted by the model for the Ton watershed is 104021.77ML or 10.402 Mm^3 whereas the total volume of cumulative infiltration is 16800.203 ML or 1.680 Mm^3.

With Scenario: 2 of using 'λ' value as 0.3 shows that the initial loss from the catchment is 0.6539 mm, the cumulative infiltration is 62.92mm, whereas the surface runoff is 860.51mm. During such a rainfall event, the total volume of direct runoff predicted by the model is 10391.276 ML or 10.391 Mm^3, whereas the total volume of cumulative infiltration is 1679.749 ML or 1.679 Mm^3

The runoff predicted by the model is just the surface runoff or direct runoff and it does not include the contribution of interflow from the catchment that forms part of surface runoff as return flow or discharge from the groundwater which forms part of the total flow in a river. This study reveals that a slight higher runoff obtained with scenario : 1. The other parameters values are not much sensitive with both the values of 'λ' used in Initial Abstraction (Ia) calculation used for SCS-CN equation in RINSPE Model for both scenarios. This study reveals that Initial Abstraction parameter is sensitive to get higher runoff depths with general condition of Initial Abstraction values, and sensitive to get lower Runoff depths with Indian conditions of Initial abstraction values.

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