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Flood Inundation Mapping of Thamiraparani River Basin Using HEC-Geo RAS and SWAT

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Abstract

Extreme events like floods and droughts are of concern for any country in the context of the damage caused to life as well as property. This situation calls for adequate management measures such as flood plain mapping, in order to minimize the extent of damage. ASTER(Advance Space Borne Thermal Emission and Reflection Radiometer) DEM(Digital Elevation Model) along with gridded precipitation, temperature, land use and soils data used for the basin. A distributed hydrologic model, SWAT(Soil and Water Assessment Tool) was used to quantify the land management practices in watershed. Log Pearson Type-III distribution was used to find the flow magnitudes correspond to various recurrence intervals. Flood is a spatial phenomenon, which could be best presented using a geospatial tool like GIS(Geographic Information System). In order to determine the extent of inundation, a 1-D model, HEC-RAS(Hydraulic Engineering Center-River Analysis System) was used. HEC-GeoRAS with Arc GIS was used for creating maps of flood inundation depth and extent. Therefore, this study demonstrated the usefulness of these models as exploratory tools for identifying critical sections of the reach for detailed analysis.

Keywords- Flood Inundation map; Frequency analysis; Hydraulic modeling; Hydrologic model

1. Introduction

Flood is one of the most common hydrologic extremes frequently experienced by any country. The rainfall received in India is not uniformly distributed both in time and space. According to government of India flood statistics, about 4,00,000 km^2 [9] of area is getting inundated due to floods every year. Tamil Nadu has been frequently affected by severe floods and has suffered from many flood disasters in terms of the population affected, frequency, extent of inundation and socio-economic costs. According to Rashtriya Barh Ayog, the area of flooding extent in Tamil Nadu is 4,500 km^2. The state of Tamil Nadu has 17 river basins [6] among which Thamiraparani is the second largest basin. Most of the Thamiraparani catchment area lies in the Western Ghats; hence, the river is benefited by both the South-West and North-East monsoons which make the river perennial. The river is prone to heavy floods, especially during the North-East monsoon season (October to December) and occasionally due to thunderstorms. Due to rapid land use changes, encroachment and sedimentation, the rivers may not be able to carry the excessive runoff resulting from heavy rains of high intensity. As a result the river overflows and water enters the flood plain. Flood water surface elevation information is important to know the depth of the flooding. Accurate water surface elevations can be computed using a hydraulic model. Long-term continuous discharge measurements are available only in few locations across the Indian River basins. Since the current study is agricultural watershed, so the flow values at these locations can be simulated using hydrologic model, SWAT [2] based on landuse practices, crop management, irrigation scheduling and reservoir operation.

Flood frequency analysis is carried out for the flow values obtained from SWAT to calculate the flow magnitudes of several recurrence intervals (2 year, 5 year, 10 year, 25 year, 50 year and 100 year) using a statistical technique known as Log-Pearson type-III distribution [13]. In order to map the level of flood inundation at different downstream reaches, water surface profiles are needed at several places along the river reach. But they are available at very limited places along with stream gauges. Hence, to fill this gap, a hydraulic model such as HEC-RAS is often used to compute the flow depth at various locations along the river reach. GIS is used to extract the geometric information from the digital elevation data for input into a hydraulic model, and then used to map the current spatial extent of flood waters using a mapping software. Flood inundation mapping is one of the vital components in developing flood mitigation measures especially non structural measures. Flood inundation extent and depth can be found by using a mapping tool called HEC-GeoRAS [8] and [12]. Water surface elevations greater than the terrain elevation are included in the inundation depth grid.

2. Study Area and Data Used

The Thamiraparani River originates in the Western Ghat Mountains and flows southeastward 120 kilometers to Gulf of Mannar [7] The basin lies between 8°26'45" N and 9°12'00"N latitude and 77°09'00"E and 78°08'30"E longitude, shown in Figure 1. The basin receives an annual rainfall of about 1,100 mm during the Southwest monsoon (June-September) and the Northeast monsoons (October-December) put togther. Irrigation occupies 48% of the land use in the basin and utilizes 90% of the water available in the basin. According to geomorphologcal classification of Thamiraparani region the Study area has geomorphology of low elevation and this region is also called as floodplain region [18]. The major crop is paddy which occupies almost 60.7% of the gross cropped area and is a major consumer of the irrigation water supply [14].

The datasets used in the current study include the following:

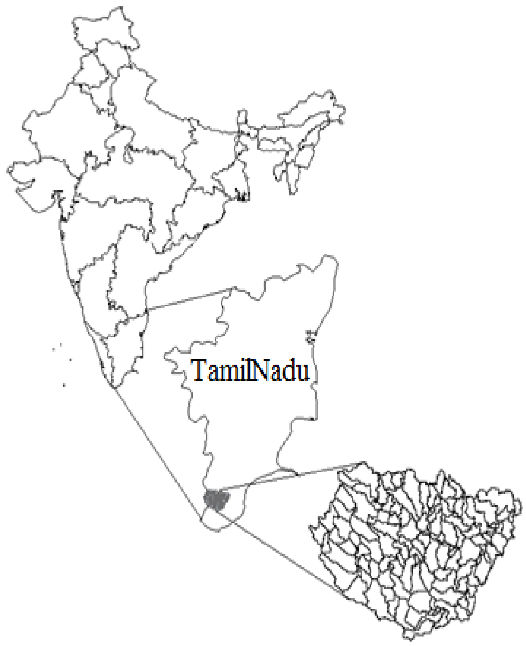

Figure 1. Location of Thamiraparani River Basin in TamilNadu (India)

- ASTER DEM of 30m resolution
- Land use data based on LANDSAT imagery [17].
- Soils data obtained from the Tamil Nadu agricultural university.
- High resolution (0.5° × 0.5°) daily gridded rainfall data (1971-2005) developed by India Meteorological Department (IMD) [15].
- 1°X1° daily temperature data from IMD (1969 to 2007) [21].

3. Methodology

SWAT is a complex physically based distributed parameter hydrologic model developed by the United States Department of Agriculture (USDA), which operates on a daily time step [3] and [4]. In SWAT surface runoff is estimated using the SCS curve number procedures [20] from the daily rainfall data. Based on the annual maxima of discharge predicted by SWAT at different reach segments, flood frequency analysis was carried out to predict the flood magnitudes of various recurrence intervals. Log-Pearson Type III distribution is often the preferred statistical technique for flood frequency analysis [19]. The flow values for different recurrence intervals from this technique is given as input into a hydraulic model, HEC-RAS to estimate the water surface profiles. Flood inundation map is generated using HEC GeoRAS by comparing water surface TIN (Triangulated Irregular Network) with DEM, to compute the water surface elevation in the channel and flood plain. The overall modeling sequence is shown in figure 2.

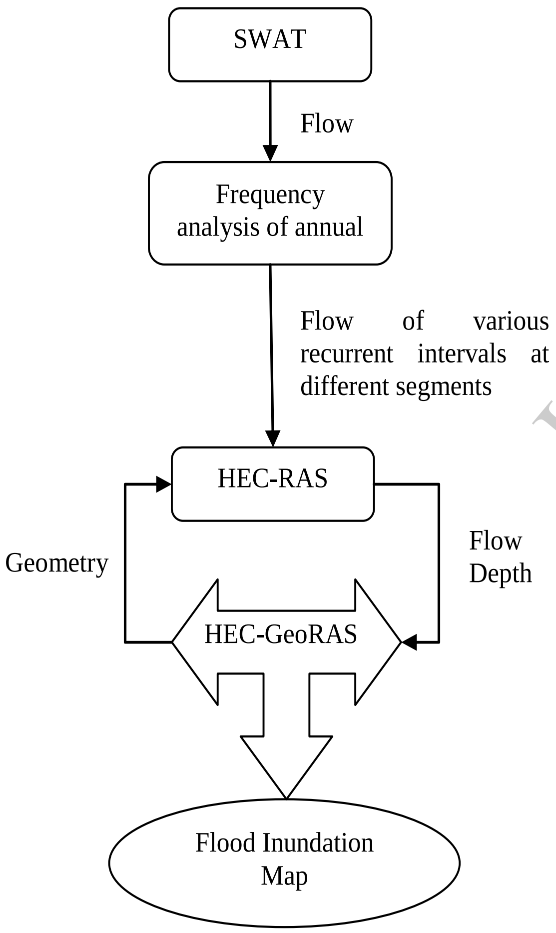

Figure 2. Overall Methodology

4. SWAT Model Setup

Hydrologic modeling was carried out by using a distributed hydrological model SWAT. The data required to setup SWAT include topography, land use, soil, weather and land management practices. Accordingly, the ArcGIS SWAT model setup involves five major processes: 1) Watershed delineation 2) Landuse and Soil setup 3) Hydrologic Response Unit (HRU) definition 4) Weather data and 5) Land management information.

Watershed delineation is the process of identifying the natural drainage pattern in the river basin for delineating the streams, demarking the contributing watershed area and subdividing a large river basin into small subunits called sub basins. ASTER DEM at 30m resolution as shown in figure 3.1 is used to perform watershed delineation.

For identifying the actual stream network in the river basin, the images from Google earth (around 700) were georeferenced and mosaiced in ArcGIS software. From these mosaiced images, the actual stream network was manually digitized in the vector format. Using ArcSWAT, the digitized vector stream network was burnt into the DEM thus forcing delineated stream network to follow the actual stream network as visible in the Google Earth imagery. The manually added outlet points for this delineation was based on eight stream gauges (PWD) and six reservoirs present in the watershed. Based on these manually added outlets and the natural topography, the watershed was divided into 139 sub basins as shown in Figure 3.2.

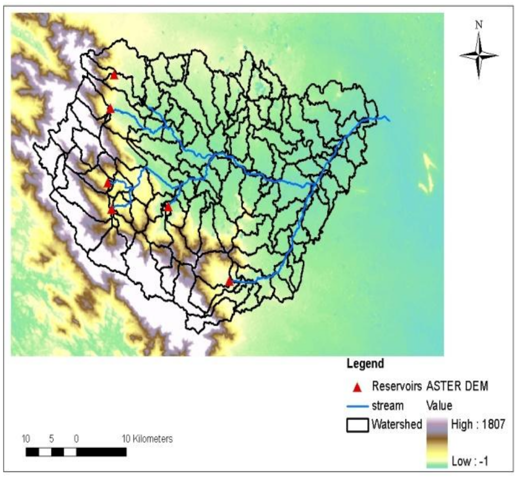

Figure 3.1. Digital Elevation Model

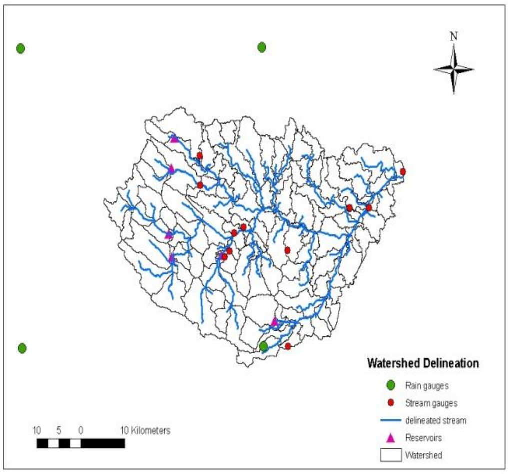

Figure 3.2. Watershed Delineation

The landuse data for the Thamiraparani study area was developed by [18] using image classification techniques on landsat 2006 imagery. The accuracy of the image classification based on field survey is about 93%, shown in figure 4.1. The GIS data on soils were obtained from the Soil and Crop Science Department, Tamil Nadu Agricultural University (TNAU) [16]. The soils in the watershed are equally distributed between hydrologic groups as shown in figure 4.2.

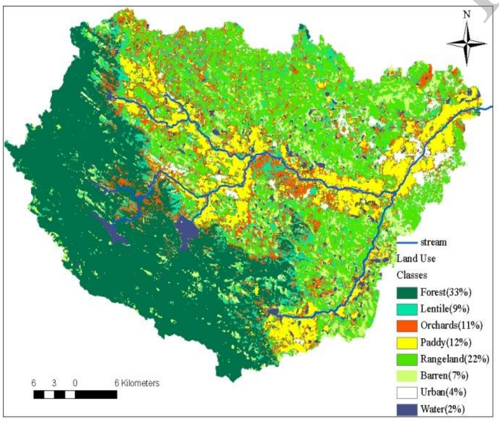

Figure 4.1. Land Use

Based on the unique land use and soil type combination, the sub basins were further subdivided into HRU's (Hydrologic Response Unit) for hydrologic simulation.

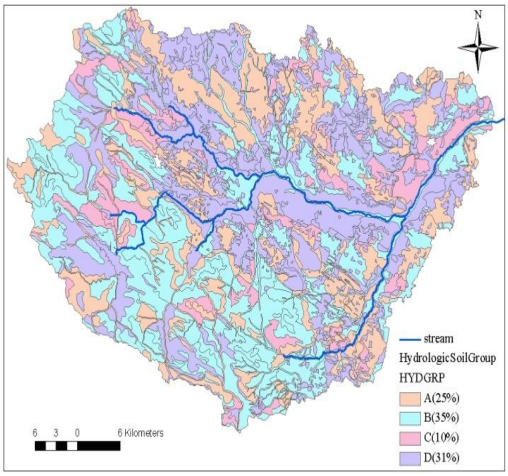

Figure 4.2. Soil Classification

Based on the unique land use and soil type combination, the sub basins were further subdivided into HRU's (Hydrologic Response Unit) for hydrologic simulation. HRU represent a patch of land within the sub basin with similar land use and soil. 2,022 HRUs were identified based on the threshold criteria for simulation. The simulated flows were summed at HRU level to sub watershed level and then routed through the stream system using hydrologic routing (variable-storage method).

SWAT needs daily rainfall, maximum and minimum temperature, solar radiation, relative humidity and wind speed etc. for hydrologic simulation. The high resolution gridded precipitation data viz., 0.5º×0.5º, maximum and minimum temperature developed by the India Meteorological Department (IMD) and the solar radiation, relative humidity and wind speed data developed by [23] is used as weather database for this model. Four rain gauge stations are falling in the study area is shown in figure 5.1. These four stations daily rainfall values are used to generate flow values.

Quality controlled rainfall data from more than 6,000 rain gauge stations all over India for the period 1971-2005 [16]. Daily rainfall data for the four grid points within the study area were used for hydrologic simulation. The monthly average rainfall values for each grid points are shown in Figure 5.2.

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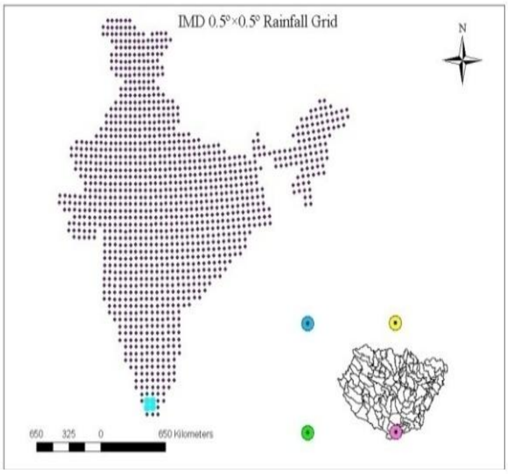

Figure 5.1. Locations of IMD Rain gauge Data Considered for SWAT Model

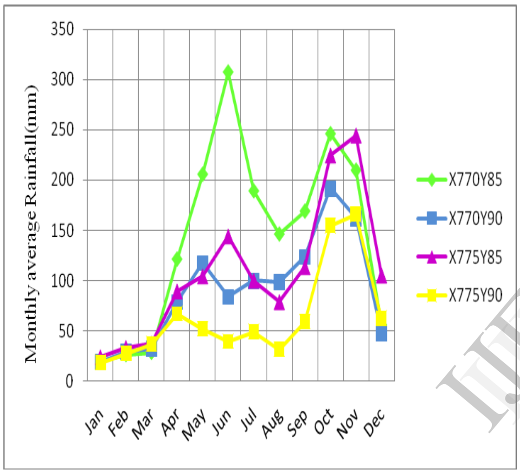

Figure 5.2. Showing Monthly Average of Rainfall Variations of Four Stations

Considering the limited rainfall data of IMD stations over study region, suitability of another resource of satellite data namely Tropical Rainfall Measuring Mission (TRMM) which is a joint mission of NASA and Japan Aerospace Exploration Agency (JAXA) designed to monitor and study tropical rain fall. This IMD annual average rainfall data is compared with TRMM (Tropical Rainfall Measuring Mission) 15 years annual average rainfall data and presented in the Table No:1.

The difference may be attributed to differences in rain fall monitoring technology and duration of data which are in acceptable level for this hydrological modeling.

Table 1. Comparison of IMD Data with TRMM Data

X-Longitude Y-Lattitude	IMD Annual Average Rainfall (mm)	TRMM Annual Average Rainfall (mm)	Difference (%)
X775Y90	795	1236	38.6
X775Y85	1295	1175	9.27
X770Y90	1050	1979	46.9
X770Y85	1782	1785	0.16

For accurate hydrologic simulation, land management information such as crop type, general crop plan and irrigation (quantity and schedule) is important. In the current study, it is noticed that flooding in the downstream reaches is significantly influenced by the reservoirs located upstream. The flood releases and storage in reservoirs depend on the status of reservoir storage during the flood event and the quantity of water released for irrigation during the cropping season respectively. Hence, it is important to realistically simulate irrigation from the reservoirs so that the releases from the reservoir during floods could be reasonably predicted.

The storage and discharge specifications for these six reservoirs were obtained from [15]. The area which reservoir should support for irrigation is calculated by using a thumb rule that one cubic meter of water is needed to irrigate 11,646 ha of paddy crop [7]. Considering this as preliminary information the cropping pattern is simulated in canal and the well irrigated area. Based on the reservoir area for each crop, the sub basins coming under the command of each reservoir were assigned as shown in the figure 6.

Planting, irrigation, and harvesting are the three important agricultural operations simulated by the model. Simulation of irrigation water on crop land can be simulated on the basis of five alternative sources: stream, reservoir, shallow aquifer, deep aquifer and external source. The irrigation source was assigned based on the available water from different sources. Based on the flow available in each reservoir, area to be irrigated and irrigation operations, single cropping and double cropping patterns are assigned. The result from this base simulation (with default parameters) is subsequently used in flood frequency analysis.

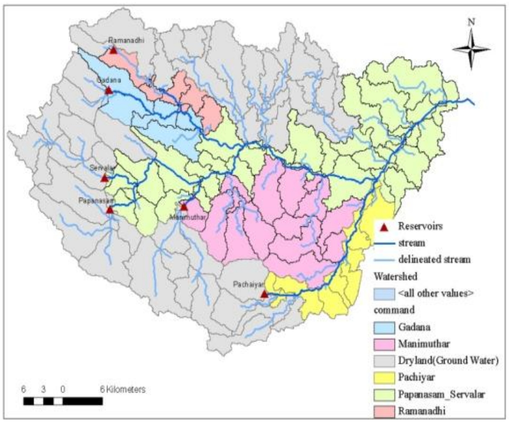

Figure 6. Reservoir Command Area for Irrigation

Among many SWAT parameters, the five critical parameters which affect the runoff volume are ESCO (Soil Evaporation Compensation factor), CN (Curve Number), K_{sat} (Saturated Hydraulic Conductivity), SURLAG (Surface Runoff Lag) and AWHC (Available Water Holding Capacity). As the flow values predicted by SWAT could not be calibrated or validated due to lack of measured data, the flow values simulated by SWAT are taken as primarily data based on default parameter values. Hence, a sensitivity analysis on flood plain mapping is performed on SWAT parameters that would increase the flow to a maximum, another combination of parameters that would reduce the flow to a minimum.

5. HEC-RAS Model Setup

HEC-RAS is designed to calculate water surface profiles for steady or unsteady Gradually Varied Flow (GVF) in natural and manmade channels. Steady state analysis is performed in this study to calculate the water surface profiles using the "standard step method". In this method, water surface profiles are computed by solving energy equation using an iterative procedure.

HEC-GeoRAS is a geographic river analysis system developed using ArcGIS by U.S Army corps of engineers [11] to function as a pre-processor for preparing the input data for HEC-RAS from GIS and a post-processor to map the extent of flood plain. The data needed to perform these computations are separated into geometric data (elevation, river center-line, hydraulic structures etc) and steady flow data (flow values of various recurrence intervals).

The geometric data required by HEC-RAS were digitized from the Google earth imagery. The network was created on a reach by reach basis, starting from the upstream end and working downstream. Only the main Thamiraparani stream segment downstream of the confluence of Pachiyar, having a total length of 18 km (nine reaches), was considered for flood plain modeling. The ASTER DEM has a spatial resolution of 30 m, which is a very coarse resolution for flood inundation mapping. Due to this the comparison is made between the channel profile extracted from DEM with one of the stream gauging station (Manimuthar), available from the state PWD. Figure 7 showed surprisingly a reasonable comparison for the active portion of the channel. However, for many sections along the stream, the active channel portion was not clearly discernable from the profiles extracted from the DEM. Hence, an artificial depression of reasonable dimension has to be burned in to the DEM to accurately represent the active portion of the channel.

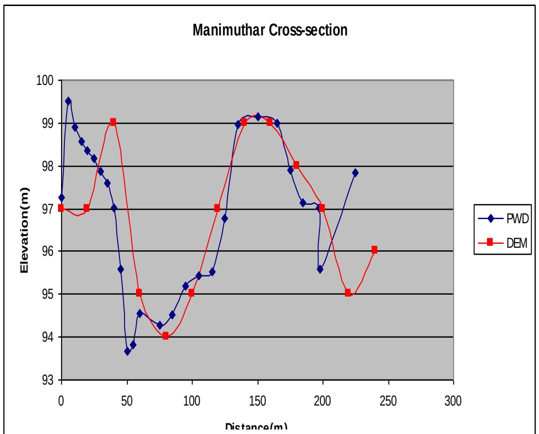

Figure 7. Comparing PWD Cross section with ASTER DEM

Due to the lack of rating curve of flow data, the normal depth condition is assumed as the downstream boundary by assuming the flow below the most downstream section is mostly generally uniform. Many flood plain studies have used normal depth boundary condition at the downstream boundary when the actual water profile or rating curve information is lacking [5], [1] and [22]. Water surface profile predicted by HEC-RAS beyond a threshold limit in the river length from the downstream boundary, the effect would be negligible [10].

In flood inundation modeling, levees play an important role in channelizing the flow, thus preventing the floods from entering the adjacent low lying areas. Being a one dimensional model, HEC-RAS computes the water surface profile based on the deepest portion of the cross section, irrespective of whether it is the main channel or not. Thus the main channel would be forced to fill first before the banks overtop and water spread to other regions of the cross section. Sometimes it is necessary to provide embankments with some elevation to avoid filling the adjacent depressed area. In reality, such depressions cannot actively convey the flood water. Hence, the height of the levee was adjusted until it could carry the maximum flow simulated by the model. This was done only at few cross-sections where there was local depression without discernable connectivity to the main channel. Manning's 'n' is another important parameter in hydraulic flood routing. These values were extracted along each cross sectional cut line from LANDSAT imagery.

6. Results and Discussions

Four scenarios were run with SWAT to study the impact of flow simulation on flood inundation. The scenarios include virgin flow simulation (without any reservoirs) and flow simulation for the current hydrologic condition (with reservoirs). Further, with the present hydrologic setting, to study the effect of model parameters, critical SWAT parameters were changed within a reasonable range. SWAT model is simulated for flows with default model parameters (DEFAULT), parameter combinations that would increase the flow (MAX) and parameter combinations that would decrease the flow (MIN). The cumulative flow plots shown in figure 8, clearly demonstrates that, as expected, the volume of flow and the flow magnitudes predicted without the reservoirs will be higher than with the reservoirs.

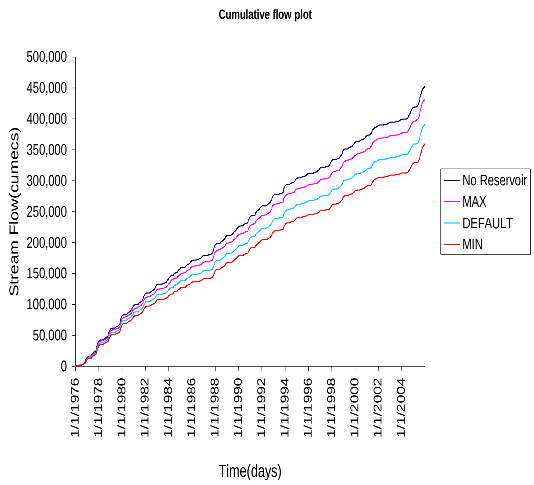

Figure 8. Cumulative Plot of Flow values

Flood frequency analysis is carried out for these four simulations of the daily flow values. The frequency plots for the different SWAT simulations are plotted for upstream Reach 1 and downstream Reach 9 as shown in figure 9.1 and figure 9.2 respectively.

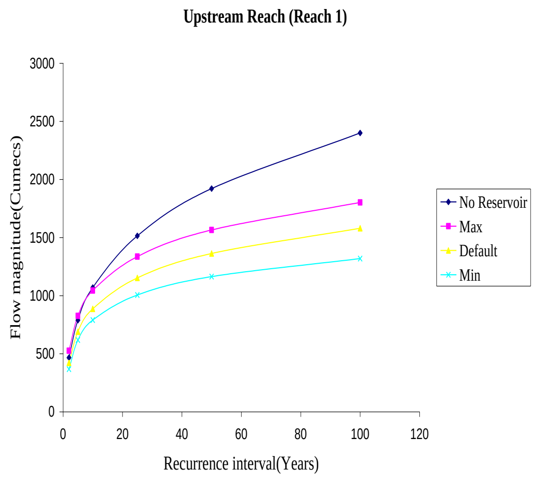

Figure 9.1. Frequency Analysis for the Upstream of the reach

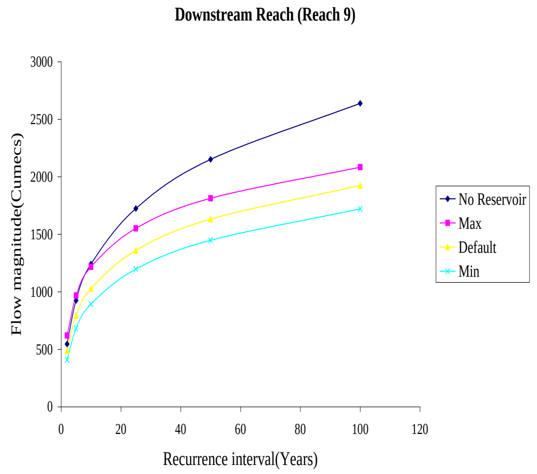

Figure 9.2. Frequency Analysis for the Downstream of the reach

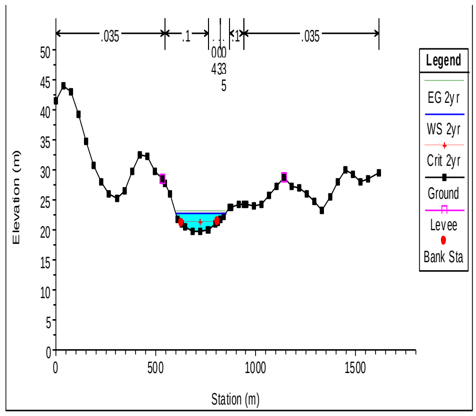

Figure 10.2. Burned DEM with 2 Year Flood Capacity

The coarse resolution of the DEM caused some inconsistencies in getting the cross sectional data of the river. Hence, a stream channel was artificially burned into the DEM based on the channel dimension (depth and width) used by SWAT for hydrologic flow routing. Figure 10.1 shows the cross sectional profile along a cut line before and after burning the stream.

From the figure it can be observed that the artificially burned channel segment is getting filled during a 2-year flood itself. Hence, the burned DEM will not considerably impact the flood inundation map for higher recurrence intervals. The flood inundation map for the 2 year return period with original DEM and with burned DEM with the default simulation was shown in figures 11.1 and 11.2 respectively.

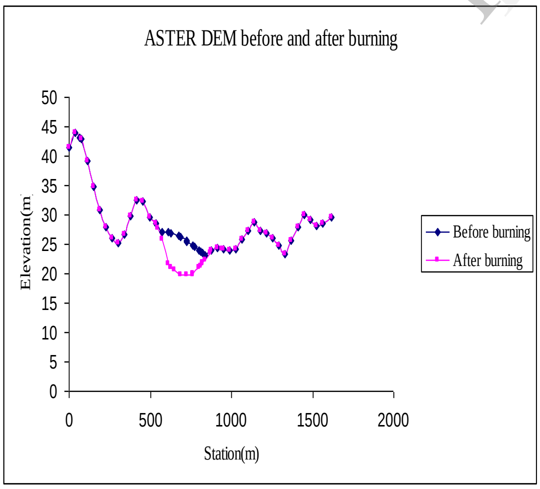

Figure 10.1. DEM Before and After Burning

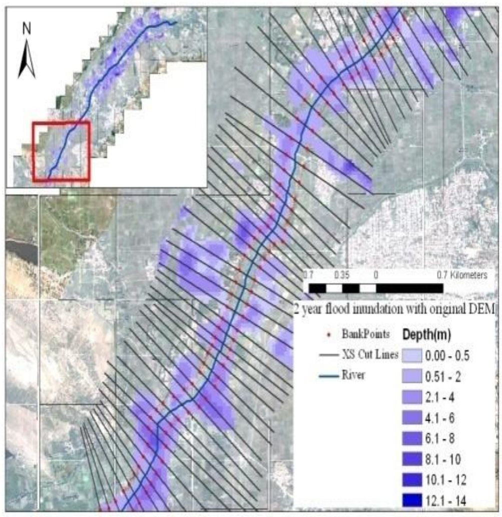

Figure 11.1. Flood Inundation Map of 2 year with Original DEM

A model run of HEC-RAS for DEFAULT scenario for the 2-year flood is plotted for the burned DEM as shown in Figure 10.2.

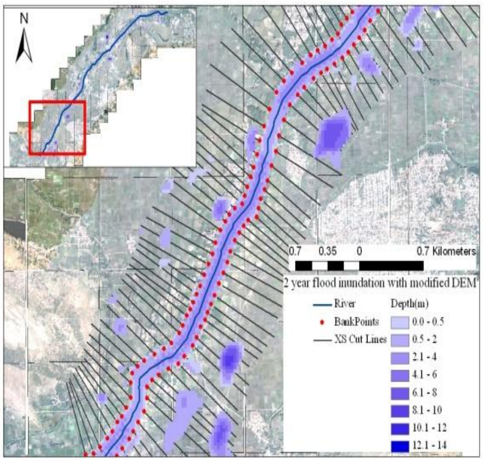

Figure 11.2. Flood Inundation Map of 2 year with Burned DEM

6.1. Artificial Placement of Levees for Flood Inundation Modelling

HEC-RAS being a 1-D model, fills the lower elevated area within channel profile first irrespective of the section is a part of a main channel or sub channel. Considering this as a flow character, correction is applied by defining artificial levees placed on one or either side of the main channel banks as shown in figure 12.1. Otherwise the flood depth, inundation map and extent of flooding will be erroneous. The inundation map after placing the levee for the same section is shown in figure 12.2.

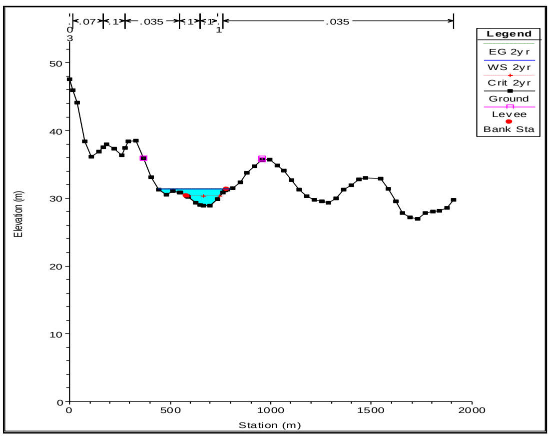

Figure 12.1. Placing an Artificial levee on either side of Main Channel

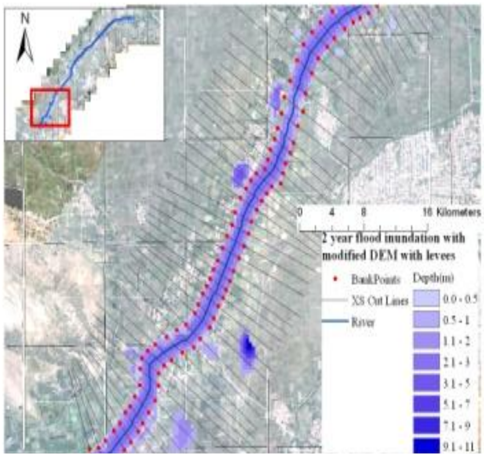

Figure 12.2. Inundation Map of 2 year flood after placing levees on either side

This clearly demonstrates the limitation of the 1-D model and the careful attention needed in determining the active channel section. After several iterative runs of model simulation and inundation mapping, active channel sections were defined by artificially placing the levees on either side of the channel banks.

6.2. Flood Inundation Mapping

Flood inundation mapping was done for the four model scenarios. For illustration purpose the inundation maps of only the DEFAULT scenario of 2 year and 100 year flood for one critical section is shown in figure 13 and figure 14 respectively.

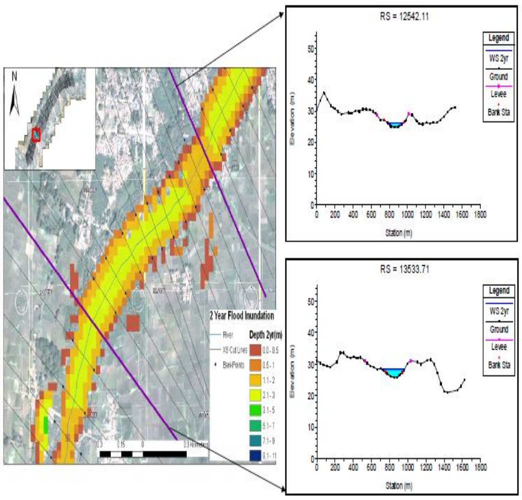

Figure 13. Two year Flood Inundation Map with Water Surface Profiles at two Cross Sections as Part of Thamiraparani River Basin

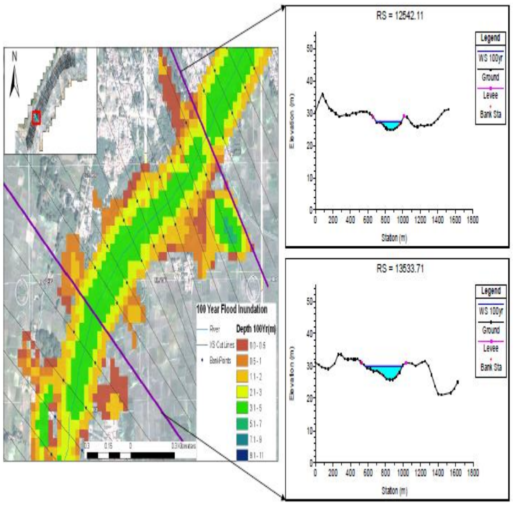

Figure 14. 100 Year Flood Inundation Map with Water Surface Profiles at Two Cross Sections as Part of Thamiraparani River Basin

The inundation maps of the DEFAULT scenario of 5 year, 10 year, 25 year and 50 year flood for one of the critical section is shown in figures 15, 16, 17 and 18 respectively.

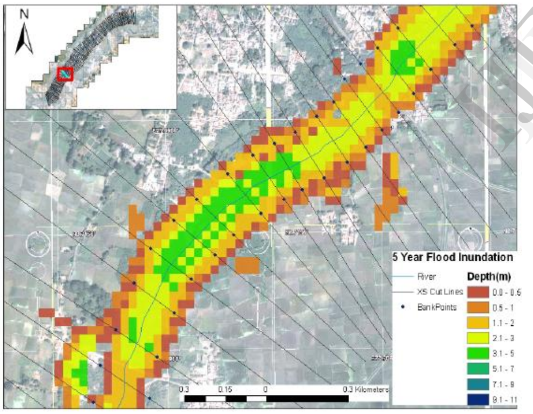

Figure 15. Five Year Flood Inundation Map

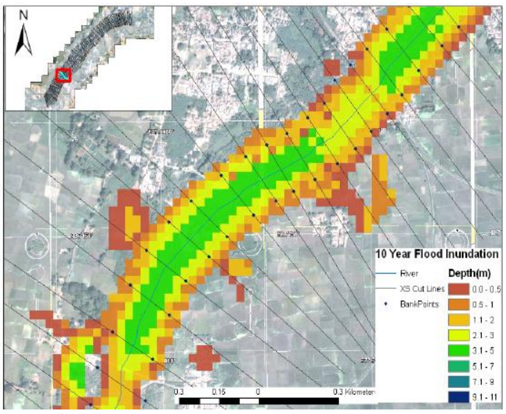

Figure 16. Ten Year Flood Inundation Map

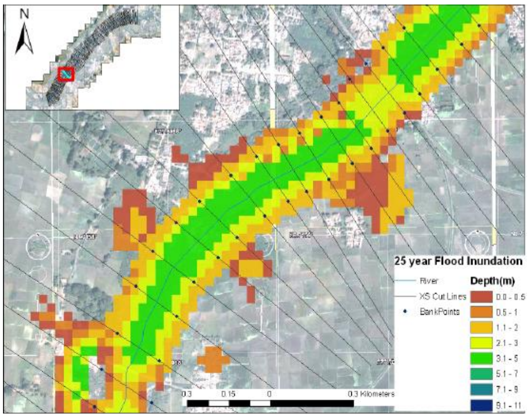

Figure 17. 25 Year Flood Inundation Map

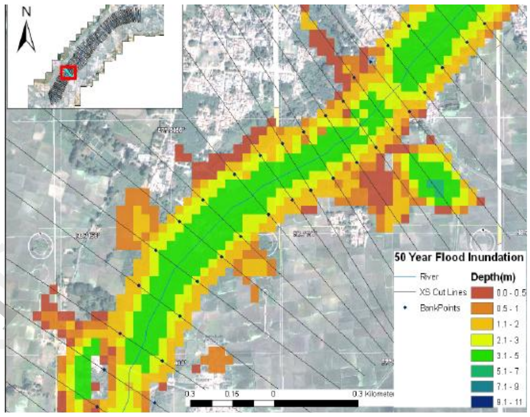

Figure 18. 50 Year Flood Inundation Map

As can be observed from these figures, flood depth and extent is continuously increasing with frequency interval.

For long term planning and management studies flood damage analysis needs to be conducted for various recurrence intervals. This could give an idea of the worst case scenario and the emergency measures which needs to be adopted under such conditions. The frequency curve shown in figure 19 is used to represent the distribution of future flood events and the expected value of damage is computed by the summation of probability weighted estimates of damage

In this case the inundated area (in sq.km) is used as a measure of damage instead of damage in terms of money value. This relationship is developed for one cross section located at the upstream side of the modelling segment.

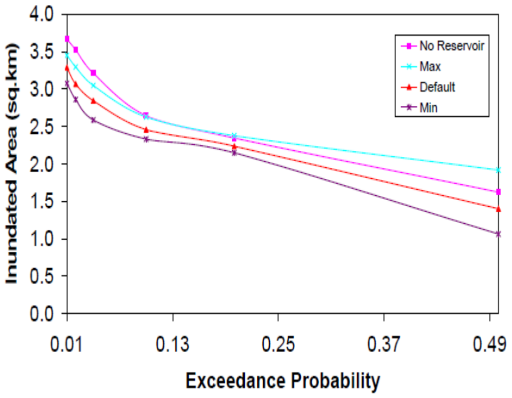

Figure 19. Damage-Frequency analysis

From the figure 19, it can be noticed that the inundated area in the presence of reservoir (SWAT parameters which contributes maximum flow) is more, compared with the absence of reservoir for lesser return periods. This is because, if the reservoir is not present in the catchment area, then the submerged area for downstream region will be less compared with the upstream region due to improper channelization. If reservoirs present in the upstream side of the catchment area, the flow will be well distributed with reservoirs, so the chance will be more for accumulation of entire flow at the downstream region. Since the inundated area is plotted for the downstream part, the above justification is valid. The difference in the extent of inundated area is small due to the coarse resolution (30 m) of DEM.

6.3. Using Flood Inundation Map to Design Levee Placement

Construction of levees and embankments form a major component of any Flood management measure. The location of levees is important to avoid random filling of channels which would inturn lead to unreasonable estimates of inundation extent. The location of the levees was identified so as to force the flow to be first filled in main channel and then fill the surrounding channel. The cross sections with levees and without levees were observed and the change in inundation extent was studied which showed that accurate location of levees is highly critical in controlling the inundation and lessens the extent of damage. This becomes important in the case of sensitive locations like townships, electric poles, railway lines etc adjacent to the channel where levees should be provided inorder to prevent the place from getting inundated. Figure 20 and figure 21 show a typical cross section where the location of levee really matters in deciding the area of inundation.

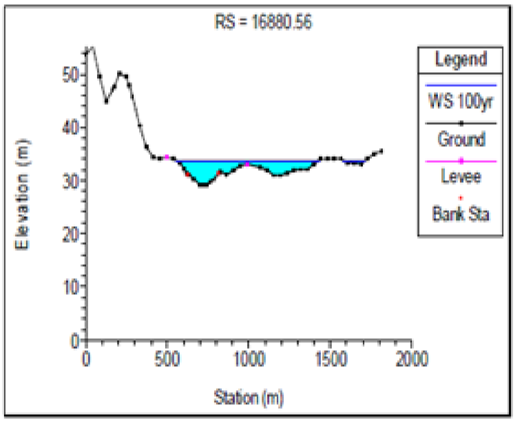

Figure 20. Cross Section in the Absence of Levee

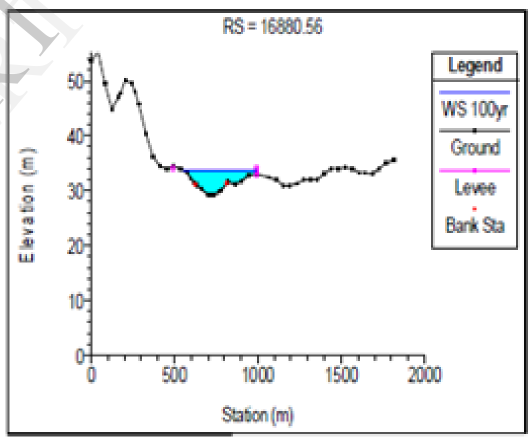

Figure 21. Cross Section in the Presence of Levee

These are the few cross sections locates at upstream side of the modelling segment. Corresponding flood inundation map for the 100 year recurrence interval in the absence and presence of levees is shown in the figure 22 and 23 respectively.

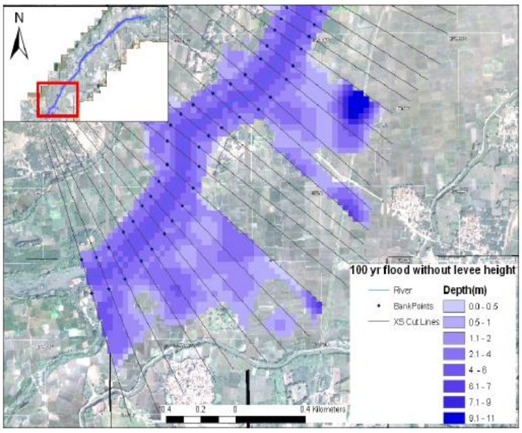

Figure 22. 100 Year Flood Inundation Maps in the Absence of Levees

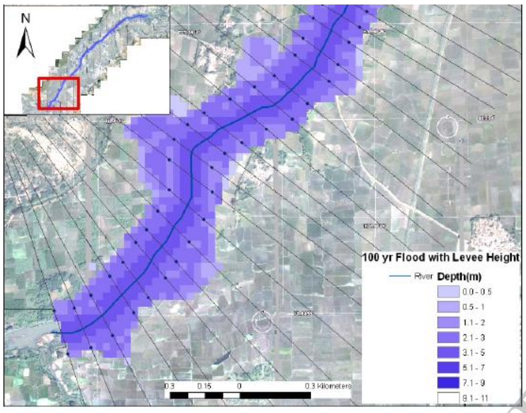

Figure 23. 100 Year Flood Inundation Maps in the Presence of Levees

The above figures 22 and 23 shows the effect of levees in controlling the flood. In the absence of levee, the flooded area spreads to a larger extent compared to the one with levees. In order to lessen the inundation extent, the appropriate levee height in the modelling reach is 1 to 3m. Thus location of levees at required position becomes critical in flood management planning works.

7. Conclusion

With the increasing availability of GIS data, the combination of SWAT, HEC-RAS and GIS models provides a method for modelling and visualizing the spatial distribution of the catchment response for a given storm event in terms of flood inundation area. It is confirmed that, TRMM data may also be applied for such hydrological studies data in the absence of ground based rain gauge data. The hydrologic analysis from this study shows that SWAT model could be used to get a reasonable estimate of the hydrology with minimal calibration. The results of the model could be further improved if dense network of weather stations are available along with a good network of stream gauge data.

High resolution digital elevation model or detailed channel cross section is not available for this study. In spite of this, the study demonstrates that ASTER DEM of 30 m resolution with artificially burned streams could be used for exploratory flood plain study of large watersheds. HEC-RAS being a 1-D model, careful attention should be placed to define the active channel section for modelling the flood depth by placing artificial levees on the channel banks. Future studies could focus on how this limitation could be overcome with the model.

In spite of limitations due to not calibration the model, a simple sensitivity analysis of parameters was done to give an envelop of flood inundation area for various recurrence intervals. This envelop of flood inundation area for the same recurrence interval indicate the uncertainty due to hydrologic model parameters in flood plain mapping.

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