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Application of GIS in Investigating the Influence of Rainfall-Runoff on Landslides

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Abstract -*Water cycle involves many different processes among which Surface runoff is one of them. Surface runoff is the primary agent of soil erosion. Soil erosion is affected by various factors such as the topography, soil type and the land utilization of the region. Landslides can occur which may be because of heavy rainfall, stream erosion, changes in ground water etc. In the past few years, multiple landslides occurred in Kodagu district of Karnataka, which are assumed to be linked with heavy rainfall. This study involves delineating and investigating the potential landslide prone region in Kodagu district of Karnataka with the help of SWAT model (utilizing QSWAT interface developed for QGIS). The study is conducted in the potential landslide prone region around Mukkodlu, Hattihole, Kandankolli, Makkanduru and Hebbettageri covering a total area of 352.88 km.sq. Using QGIS, which is a free and open-source cross-platform desktop geographic information system application that supports viewing, editing, and analysis of geospatial data and QSWAT interface; the varying SCS-CN (Soil Conservation Service Curve Number) is found out for the years 1985-1995, 1995-2005 and 2005-2015.*

Key Words: GIS, SWAT, Rainfall-Runoff, Watershed Delineation, Curve Number

1. INTRODUCTION

A watershed is an area of high ground that divides two or more river systems and drains all the streams and rainfall into common pourpoints such as the outflow of a reservoir, bay, or to a stream channel [1]. Watershed delineation is a fundamental task serving for multidomain studies, such as hydrological modeling, geomorphic mapping, soil erosion assessment, and water resource management. With the modern advancements in satellite imagery and the ease of distributing and accessing, the digital elevation models (*DEMs*) multiple methods have been developed in various researches that enables extracting the drainage networks and watershed boundaries automatically.

The accuracy of the final delineated watershed depends heavily on the resolution of the digital elevation models (*DEMs*) which varies based on the type of satellite and methodology used to generate the map also on the effectiveness of the methods used to delineate the watershed. A DEM can be rendered either as a raster (dot matrix data structure that represents a generally rectangular grid of pixels also known as height map) or as a vector (defined in terms of points on a Cartesian plane, which are connected by lines and curves to form polygons and other shapes). The vector dataset is also known as a primary (*measured*) DEM, whereas the Raster DEM is known as a secondary (*computed*) DEM. The DEM is obtained through various imaging techniques such as lidar, photogrammetry, IfSAR or InSAR, land surveying, etc. Remote sensing techniques are used for building DEMs also; land surveying can be used for the same [2].

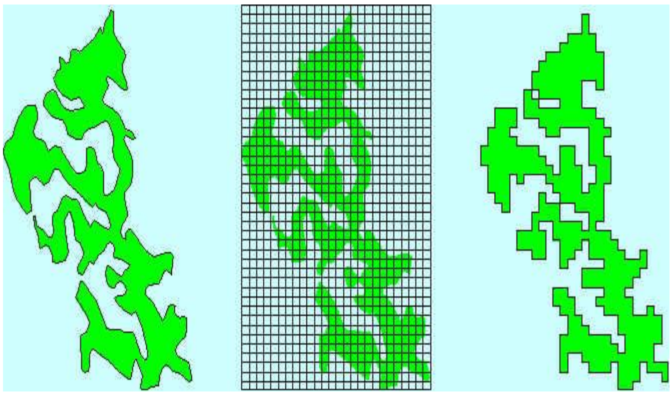

Fig -1: Vector Image (left) vs Raster Image (right)

A free DEM of the whole world called GTOPO30 (30 arcsecond resolution, 1 km along the equator) is available, but its quality is variable and in some areas it is very poor and is applicable for use in the study of the region. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument of the Terra satellite provides a better-quality DEM that is freely available for 99% of the world with elevation resolution of 30m. The Shuttle Radar Topography Mission (SRTM) data was only available for United States while rest of the globe had access to only 3 arc-second resolution maps with about 90 meters along equator. SRTM elevation data is obtained by using RADAR, which in most of the cases does not detect the ground surface, but instead it detects the elevation of the first reflected surface, especially treetops.

In addition to the obtaining of DEM data in high quality, various improved methods of acquiring stream networks and watershed boundaries have been proposed through various researches. Watershed delineation method based on the classical algorithm of D8 flow routing is the most widely used method at present. D8 flow routing algorithm has been used in various commercial software's including ArcGIS and QSWAT. The D8 flow routing algorithm requires the filling of the local pits or sinks which is performed by algorithms like "fill sinks by wang & liu". This filling procedure is the main drawback of D8 flow routing algorithm as it removes true landscape depressions. The filling of sinks method is still used widely to ensure the accurate watershed delineation. After obtaining the filled DEMs, the flow direction can be calculated. In the D8 algorithm, each cell can deliver eight possible flow directions to adjacent cells based on the maximum gradient. The accumulated flow is collected as a raster data containing information of the number of cells flowing into down slope cells. Once the output raster of accumulated flow is generated, the watershed and sub-watershed outlets can be defined, and the watershed can be finally delineated [3].

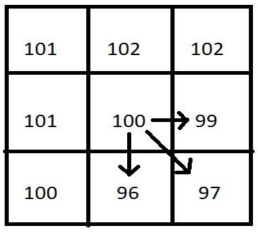

Fig -2: D8 flow routing

The watershed delineation of the study area is achieved with the help of QGIS, which is a free and open-source cross-platform desktop geographic information system application that supports viewing, editing, and analysis of geospatial data. QGIS has functions for using both raster and vector layers. Vector data contains point, line or polygon features. QGIS supports the usage of raster images of various well-known formats and enables geo referencing of the images. QGIS also supports the usage of shapefiles, geodatabases, dxf and other formats, and services such as Web Map Service and Web feature Service for obtaining data from external sources.

Impact of land use and land coverage, soil type etc. on complex watersheds can be quantified using SWAT (Soil & Water Assessment Tool) which is a river basin scale model. The USDA Agricultural Research Service situated at the Blackland Research & Extension Center in Temple, Texas, USA actively supports SWAT. The SWAT model consists of the following components: surface runoff, weather data, percolation, flow, evapotranspiration, land use and land coverage, soil type etc. SWAT model is widely adopted and is under progressive development. The QSWAT interface available for QGIS enables the use of SWAT model for the study region.

This study aims to investigate the impact of changes in land use and rainfall on the occurrence of landslides in the Kodagu district of Karnataka. Compare the results generated by simulating various scenarios for the intervals 1985-1995, 1995-2005 and 2005-2015. Also, put forth necessary suggestions and solutions to mitigate landslides in the Study Region.

2. Study area and dataset

2.1 Study area

Kodagu (also knows as Coorg) is located on the eastern slopes of Western Ghats surrounded by Dakshina kannada district to the northwest, Mysore district to the east, Hassan district to the north, Kannur district of Kerala to the southwest, Kasargod district of Kerala in the west, and Wayanad district of Kerala to the south. The lowest elevation in this district is 50 meters situated at makutta and the highest peak of 1750 meters of Tadiandamol.

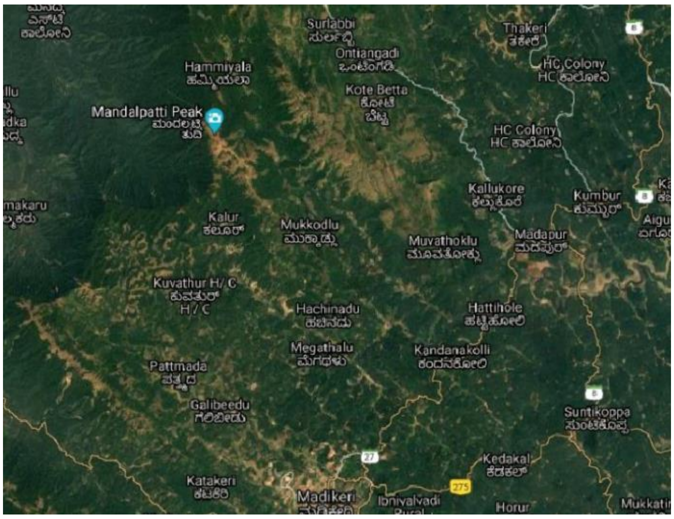

Fig -3: Satellite Image of Study Area

Summer begins in late February and continues until June with the onset of winter starting from October, which is preceded by monsoons beginning in July and continuing until September. The study area includes the potential landslide prone region around Mukkodlu, Hattihole, Kandankolli, Makkanduru and Hebbettageri with a total area of 35288.24 hectares.

2.2 Study data

DEMs play a key role in watershed delineation. Various techniques have been proposed and elevation data's have been recorded using the same with varying resolutions. The resolution of a DEM greatly influences the accuracy of delineating the watershed. For the delineation of the selected region DEMs where obtained that were generated under SRTM (Shuttle Radar Topography Mission).

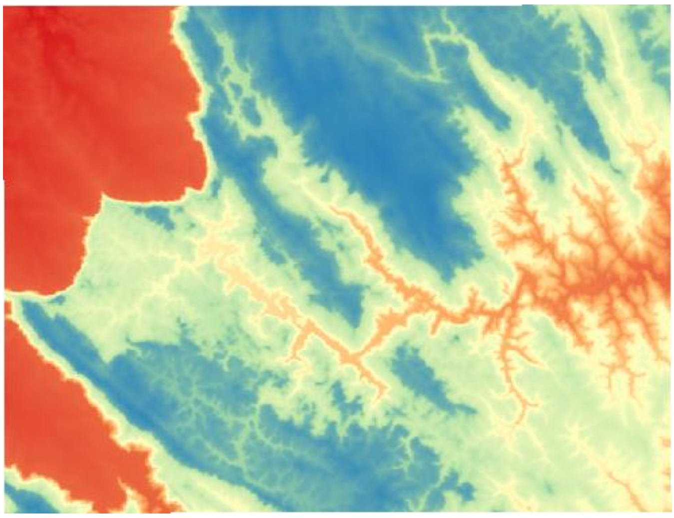

Fig -4: DEM of the study area

SRTM data of regions outside of United States were previously available for public release with an accuracy of 3 arc second or about 90 meters at the equator. Later in time SRTM data with an accuracy of 1 arc second or about 30 meters at the equator was released [4].

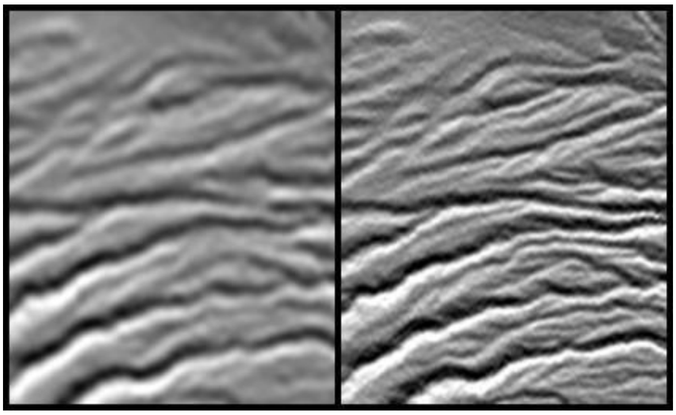

Fig -5: 3 arc second (left) vs 1 arc second (right)

SWAT model requires Soil map and Land Use Land Cover (LULC) map for calculating runoff and determining SCS-Curve Number. Soil map for the study area is obtained from Food and Agricultural Organization of the United Nations portal. The HWSD (Harmonized World Soil Database) is a raster database with an accuracy of 30 arc second with over 15000 different soil-mapping units [5].

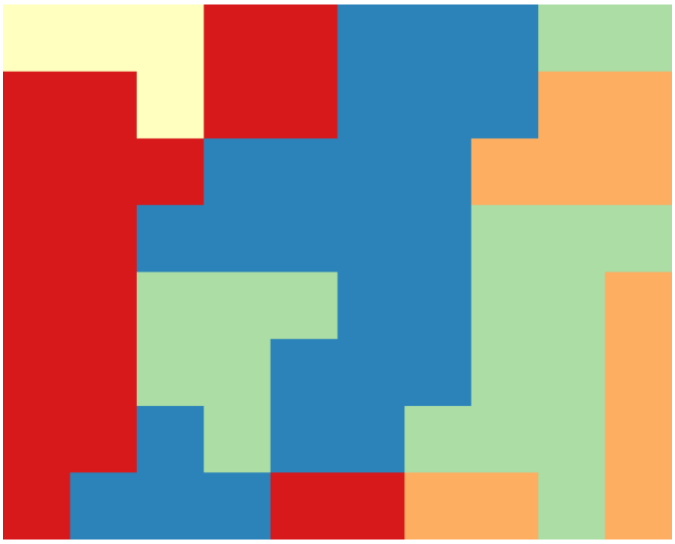

Fig -6: Soil map (with each unique color mapped to different soil type)

LULC maps are also a required input for the execution of the SWAT model. LULC maps classify the land based on different vegetation's and based on the utilization of the land by human beings. For the study region, LULC map is obtained from NASA earth data, ORNL DAAC (Distributed Active Archive Centre for Biogeochemical Dynamics). LULC maps are acquired for the years 1985, 1995 and 2005. Each unique colour in the figure represents different classifications of land.

Fig -7: LULC map 1985

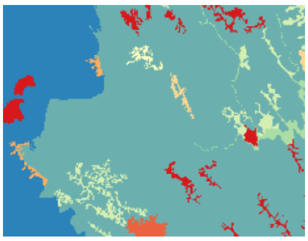

Fig -8: LULC map 1995

Fig -9: LULC map 2005

The obtained LULC maps had a resolution of 100m and were generated using data from Landsat 4 and 5 Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Multispectral (MSS) data, India Remote Sensing satellites (IRS) Resourcesat Linear Imaging Self-Scanning Sensor-1 or III (LISS-I, LISS-III) data, ground truth surveys, and visual interpretation.

Weather data for a period of 36 years is obtained for the study area. The data is recorded by The National Centers for Environmental Prediction (NCEP) for the whole globe high resolution, with atmosphere-ocean-land surface-sea ice system for accurate recording of the weather data.

3. Simulation

Watershed Delineation is an important aspect for the determination of Surface Runoff. In the past, before the development of advanced computer programs; watersheds used to be delineated manually which was time consuming and cumbersome. Nowadays with the availability of powerful computing ability and advanced programs watershed can be delineated quite easily.

The study area was delineated using a geoprocessing software called Quantum GIS (QGIS) version 3.16.7 dubbed Hannover which is a long-term stable release. The delineation process was assisted by the QSWAT interface developed for QGIS. Before the delineation process, DEMs had to be obtained using a plugin for QSWAT called "SRTM Downloader" and stream networks had to be generated.

For accurate generation of stream networks "Fill Sinks (Wang & Liu) "algorithm was applied on the DEM to detect and fill depressions in DEMs. The outputted DEM by the application of this algorithm is depression less enabling accurate Stream generation. The lowest elevation in the study region before the filling function was 147m with highest elevation of 1636m and after filling was 148m and 1636m respectively.

When delineating the watershed, we need stream networks to place outlet points, but the automatically generated stream network can deviate a lot from the original path as seen in a satellite image. This calls for the use of "Burn-In" function, which burns in the accurately produced stream network into DEM.

The processing tool available in QGIS called "Channel Networks and Drainage Basins" which generated stream networks; later saved as an ESRI shape file aids generation of stream network. The generated stream network helps for accurate watershed delineation and enables burn-in method to be adopted.

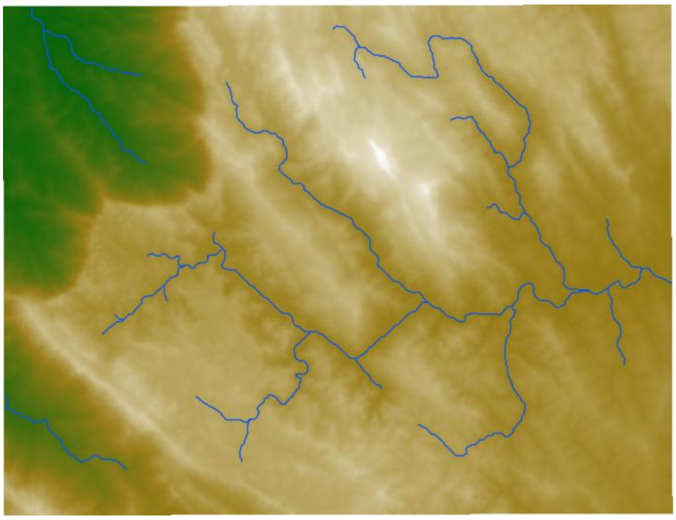

Fig -10: Stream Network generated using "Channel Networks and Drainage Basins" function

A watershed has to have an outlet point or pour point for the water to flow out of the basins. These outlet points are placed manually on the stream network and effect the way in which the watershed is delineated. There are 7 outlets chosen for the study area.

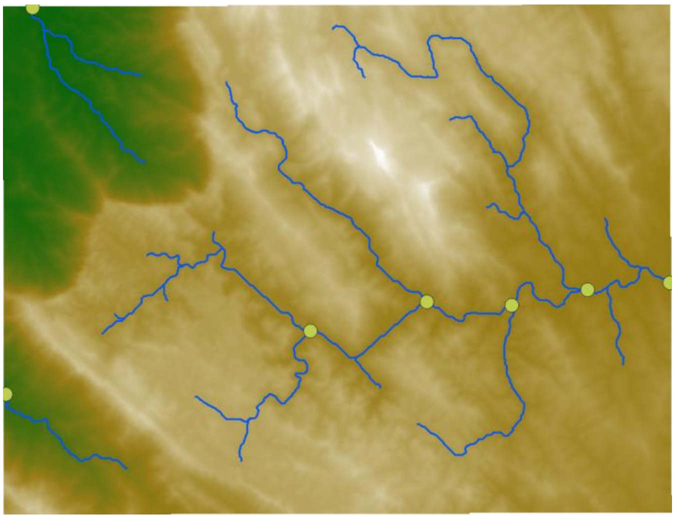

Fig -11: Outlets placed along stream network

At this stage, the watershed can be delineated with all the above data. Delineating the watershed produced 24 sub-basins with a total area of 35,288.24 hectares.

LULC maps were collected for the years 1985-1995, 1995-2005 and 2005-2015, which was imported, to the SWAT model along with Soil map to create Hydrological Response Units (HRUs) [6].

Table -1: Watershed details

Watershed	
Subbasin	Area (in hectares)
1	109.90
2	827.45
3	0.28
4	1071.25
5	0.28
6	179.48
7	1599.44
8	2767.31
9	801.24
10	2966.35
11	917.14
12	834.56
13	990.87
14	995.76
15	2283.59
16	966.88
17	4390.28
18	1373.83
19	895.27
20	2894.74
21	1762.41
22	862.98
23	875.16
24	4921.80

Table -2: Land Use details 1985-1995

Land Use 1985-1995			
Classification Code	Type	Area (Hectares)	Watershed (%)
FODB	DECIDUOUS BROADLEAF FOREST	4835.43	13.70
FOEB	EVERGREEN BROADLEAF FOREST	5489.40	15.56
AGRL	AGRICULTURAL LAND-GENERIC	21936.82	62.16
CRGR	CROPLAND/GRASSLAND MOSAIC	1016.25	2.88
BARR	BARREN	154.29	0.44
FRST	FOREST-MIXED	187.32	0.53
SHRB	SHRUBLAND	902.56	2.56
WATR	WATER	675.01	1.91
URML	RESIDENTIAL-MED/LOW DENSITY	91.17	0.26

Table -3: Land Use details 1995-2005

Land Use 1995-2005			
Classification Code	Type	Area (Hectares)	Watershed (%)
AGRL	AGRICULTURAL LAND-GENERIC	26135.44	74.06
FOEB	EVERGREEN BROADLEAF FOREST	6030.14	17.09
CRGR	CROPLAND/GRASSLAND MOSAIC	696.05	1.97
BARR	BARREN	154.29	0.44
FRST	FOREST-MIXED	187.32	0.53
SHRB	SHRUBLAND	142.38	0.40
SPAS	SUMMER PASTURE	1258.66	3.57
WATR	WATER	473.20	1.34
URML	RESIDENTIAL-MED/LOW DENSITY	210.76	0.60

Table -4: Land Use details 2005-2015

Land Use 2005-2015			
Classification Code	Type	Area (Hectares)	Watershed (%)
AGRL	AGRICULTURAL LAND-GENERIC	26067.15	73.87
SHRB	SHRUBLAND	1133.63	3.21
FODB	DECIDUOUS BROADLEAF	4818.91	13.66

	FOREST		
CRGR	CROPLAND/GRASSLAND MOSAIC	1206.99	3.42
BARR	BARREN	161.30	0.46
FRST	FOREST-MIXED	184.37	0.52
WATR	WATER	472.09	1.34
SPAS	SUMMER PASTURE	759.53	2.15
URML	RESIDENTIAL-MED/LOW DENSITY	250.26	0.71
FOEB	EVERGREEN BROADLEAF FOREST	234.02	0.66

Table -5: Soil Use details 1985-1995

Soil Use 1985-1995			
Classification Code	Texture	Area (Hectares)	Watershed (%)
Ne55-2b-3826	SANDY_CLAY_LOAM	26706.08	75.68
Ne53-2ab-3824	SANDY_CLAY_LOAM	8582.16	24.32

Table -6: Soil Use details 1995-2005

Soil Use 1995-2005			
Classification Code	Texture	Area (Hectares)	Watershed (%)
Ne55-2b-3826	SANDY_CLAY_LOAM	26706.08	75.68
Ne53-2ab-3824	SANDY_CLAY_LOAM	8582.16	24.32

Table -7: Soil Use details 2005-2015

Soil Use 2005-2015			
Classification Code	Texture	Area (Hectares)	Watershed (%)
Ne55-2b-3826	SANDY_CLAY_LOAM	26706.08	75.68
Ne53-2ab-3824	SANDY_CLAY_LOAM	8582.16	24.32

Hydrological Response Units are the smallest spatial units, which combine similar soil, land and slopes into smaller lumps based on user-defined thresholds

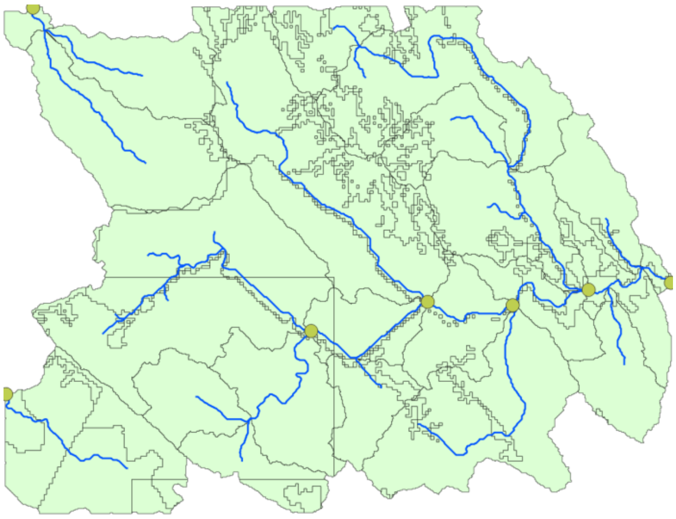

Fig -12: Generated HRUs

Ninety-one HRUs were created in the study area. For further processing, weather data such as precipitation, relative humidity, temperature, wind, and solar radiations were imported into SWAT model. The simulation is split into three-year groups 1985-1995, 1995-2005 and 2005-2015.

During calculation of runoff, antecedent moisture can affect the final result. Antecedent in other words "preceding condition" is the condition of the soil moisture content before the simulation. To eliminate the possibility of inaccuracy in the output results simulations are started 2 years earlier implying simulations processed for years 1983-1995, 1993-2005 and 2003-2015 thus making corrections for the antecedent moisture [7].

3. Simulation Results

SWAT model provided various output including Surface runoff, SCS-Curve Number, Lateral Flow etc. [8]. The precipitation pattern can be observed to change with the varying seasons. Since precipitation effects the quantity of the runoff, we can observe a similar pattern of crests appearing in the chart of runoff data exactly at the location of crest in chart of precipitation data [9].

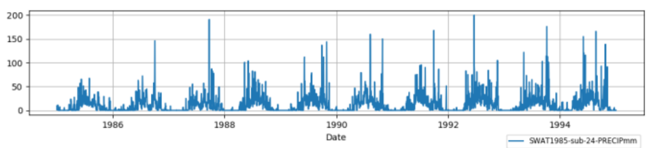

Chart -1: Precipitation 1985-1995

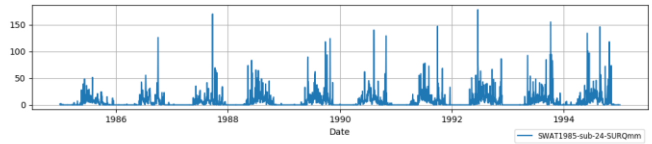

Chart -2: Surface Runoff 1985-1995

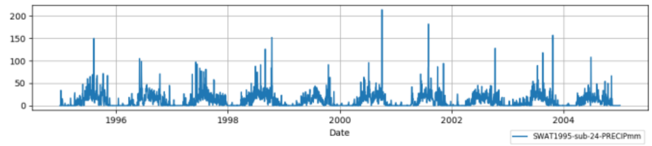

Chart -3: Precipitation 1995-2005

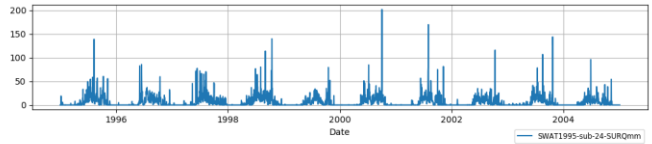

Chart -4: Surface Runoff 1995-2005

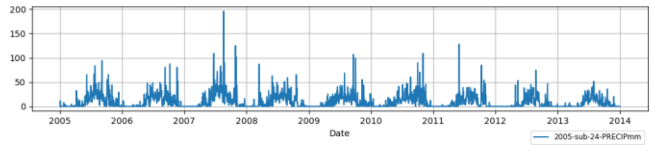

Chart -5: Precipitation 2005-2015

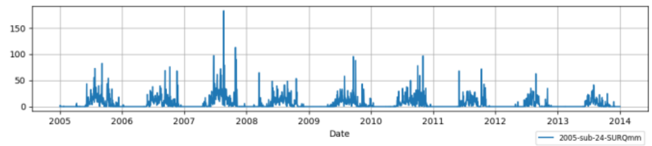

Chart -6: Surface Runoff 2005-2015

Excess Surface Runoff can cause erosion of soil leading to weakening and causing landslides in slopes. Precipitation alone cannot provide a clear idea of surface runoff potential as can be observed from the chart below.

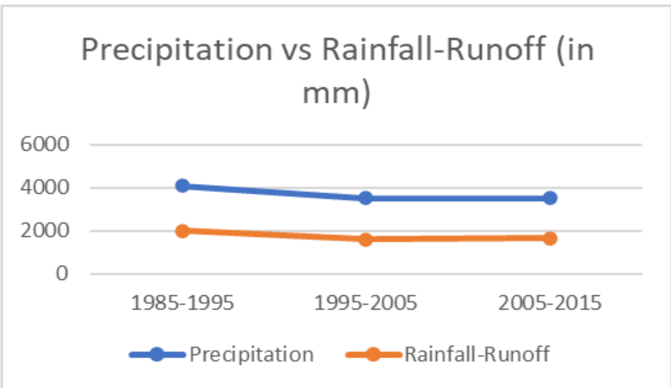

Chart -7: Precipitation vs Rainfall-Runoff (in mm)

An observable pattern in runoff potential is observed by considering Soil Conservation Service-Curve Number. This is an empirical parameter providing an insight and predicting direct runoff or infiltration from excess rainfall.

This number provides information about the approximate Quantity of direct runoff during precipitation in the particular region [10].

The Curve Number ranges from 30 to 100 where lower number implies low runoff potential and higher numbers indicate high runoff potential. In the study area, an increasing pattern of curve number is observed which implies that the Runoff potential is increasing which can be seen in the chart below.

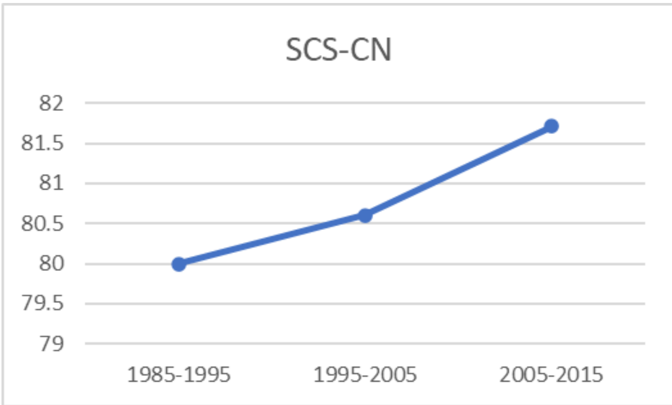

Chart -8: SCS-Curve Number

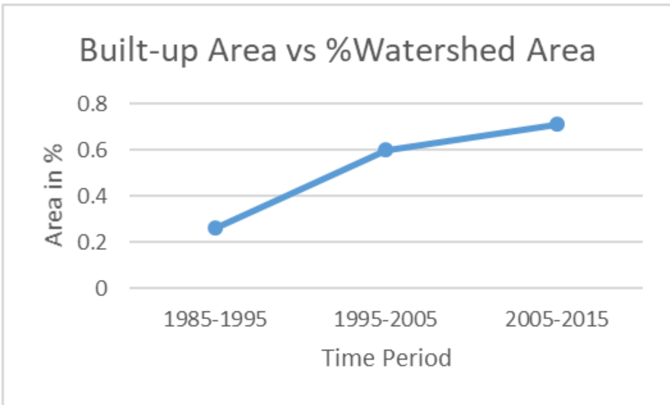

Chart -9: Built-up Area vs %Watershed Area

More number of landslides were recorded in the study area in the past few years. Several studies also have shown the impact of Surface runoff on slope stability. The increasing runoff potential may be one of the reasons for the increasing number of landslides especially in the monsoon seasons [11].

4. CONCLUSIONS

Advancements in GIS technology has helped for faster processing and accurate delineation of watersheds. Modern mapping methods with increased resolution helps capture more accurate data hence contributing to better accuracy.

Landslides even though it seems to be less dangerous has caused multiple deaths if not property damage. They have potential to change the entire landscape. The topology of the region, soil composition and vegetation and land use in the region can impact and aid in occurrence of landslides [12].

Kodagu district receives heavy rainfall in the monsoons. In the past, occurrence of landslides in the district were rare but in the past few years, there has been records of multiple landslide related incidents. In the study period of 30 years, not much change has occurred in the soil composition but change can be observed in how the land is utilized and distribution of various vegetation. We can observe and increase in the Built-up area in the study region. In the year 1985-1995, Built up region occupied an area of only 0.26% of the watershed, which in the later period of 1995-2005 increased to 0.60% and later to 0.71% in the period of 2005-2015. This increase in the Built-up area along with changes in vegetation can increase the quantity of runoff during the time of precipitation, which can be observed in the SCS-CN chart.

Urbanization may be one of the reasons for increased Surface Runoff. Changes in the type of vegetation can also be a reason for increased runoff as the type of vegetation largely depends on the weather in the region and land utilization by human beings.

The study region has high elevations with sharp slopes, which by themselves are a landslide hazard but when combined with increased surface runoff, can trigger the multiple landslides in the region. Possible solutions include growing vegetation's that has been proven to reduce soil erosion and hold the soil together as well as limiting urbanization in landslide prone region.

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