Determination of Potential Runoff Coefficient and Depth Value for a Usual Flood Area Using Geographical Information System

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Abstract: The runoff coefficient is a hydrologic measure that determines the drainage area's storm water runoff capacity based on soil type, soil moisture, and land use. The potential runoff coefficient (PRC) was calculated using a Geographic Information System (GIS) and data from the Kalutara district in Sri Lanka. The runoff depth is going to be computed using the predetermined PRC. Eleven classes, involving four classes of pervious surfaces and seven classes of impervious surfaces, were used to categorize the land use map. The digital elevation model (DEM) with a resolution of 30 meters was used to create the slope map. The soil texture map was produced using the soil map of Sri Lanka's wet zone. The PRC map was then created by combining that previously mentioned three maps, the soil, land use, and slope maps into a single map using GIS software. Using the raster calculator tool in Arc GIS, the average annual rainfall surplus and the runoff coefficient per pixel were used to determine the annual depth of the runoff. The kriging interpolation technique was used to interpolate the rainfall in this study area. PRC's value ranged from 0.13 to 1.0. The range of runoff depth values was 31.0 mm to 479.2 mm. The findings could be applied to the identification of floodplains, the selection of water harvesting sites, and the improvement of water resources management initiatives.

Keywords: Runoff Depth, Potential Runoff Coefficient (PRC), Digital Elevation Model (DEM), Geographical Information System (GIS).

I. INTRODUCTION

In several areas of Sri Lanka, rain is a common occurrence that produces runoff. Several factors of the land's surface, including topography, soil composition, and land use, will have a significant impact on the amounts of runoff throughout the rainfall process. Today, due to urban growth, forest lands and grass-lands are converted to commercial, residential or industrial lands. This process indicate a conversion of permeable surfaces to impermeable surfaces like, concrete, asphalt, building roofs, and compacted areas. The increase in built-up surfaces are contributes to an increase in flooding and flash flooding frequently. Because it reduced infiltration and reduction of flow resistance.

Flooding has been one of the most costly disasters in Sri Lanka. Riverine and urban floods are the most common in urban and suburban areas of the country, especially in Kalutara and its surrounding urban areas. Reduction in open areas and increase in more paved areas due to rapid urbanization has resulted in faster surface runoff. Identification of flood risk areas with the aim of management of this area is very necessary. In this study, an investigation has been carried out to determined run-off coefficients for Kalutara district. This is the main objective of research.

The runoff coefficient is the ratio of runoff volume to rainfall volume of catchment. It was determine the runoff coefficient under varying land use, slope, soil type, rainfall intensity and soil moisture condition (Liu and De Smedit, 2004). The potential runoff coefficient is lower in permeable, well-vegetated areas and higher in places with heavy runoff and little infiltration. Areas that experience flash flooding may have a high runoff coefficient (C) value (Assessment and Board, 2011).

Another objective of this research is determining runoff depth. The potential water supply during runoff is determined using runoff depth. Determine the runoff depth as a guide when mapping possible locations for rainwater harvesting

(RWH) for various uses. By collecting rainwater in one location and transferring it to another, RWH's primary function is to enhance the quantity of water that is available.

The district of Kalutara in Sri Lanka is the study area taken into consideration in this study. Because of the significant differences in its topography and climate, Kalutara district was chosen as the subject area for this case study. And also Kalutara district is considered as a rapid urbanization area in Sri Lanka. So most of the area of the Kalutara district get flood hazards frequently and affect both humans and infrastructure (Gunawardena, 2015). Therefore, controlling the flood frequencies within the research region requires the creation of a Potential Runoff Coefficient (PRC) map and a Runoff Depth map.

II. METHODOLOGY

➤ Study Area

Kalutara district is situated in south west of Sri Lanka and has an area of 1598 square kilometers. It is bounded by Colombo District from north, Ratnapura District from east, Galle District from south, and by Indian Ocean from west. It is usually (very) warm, humid and rainy all year round.
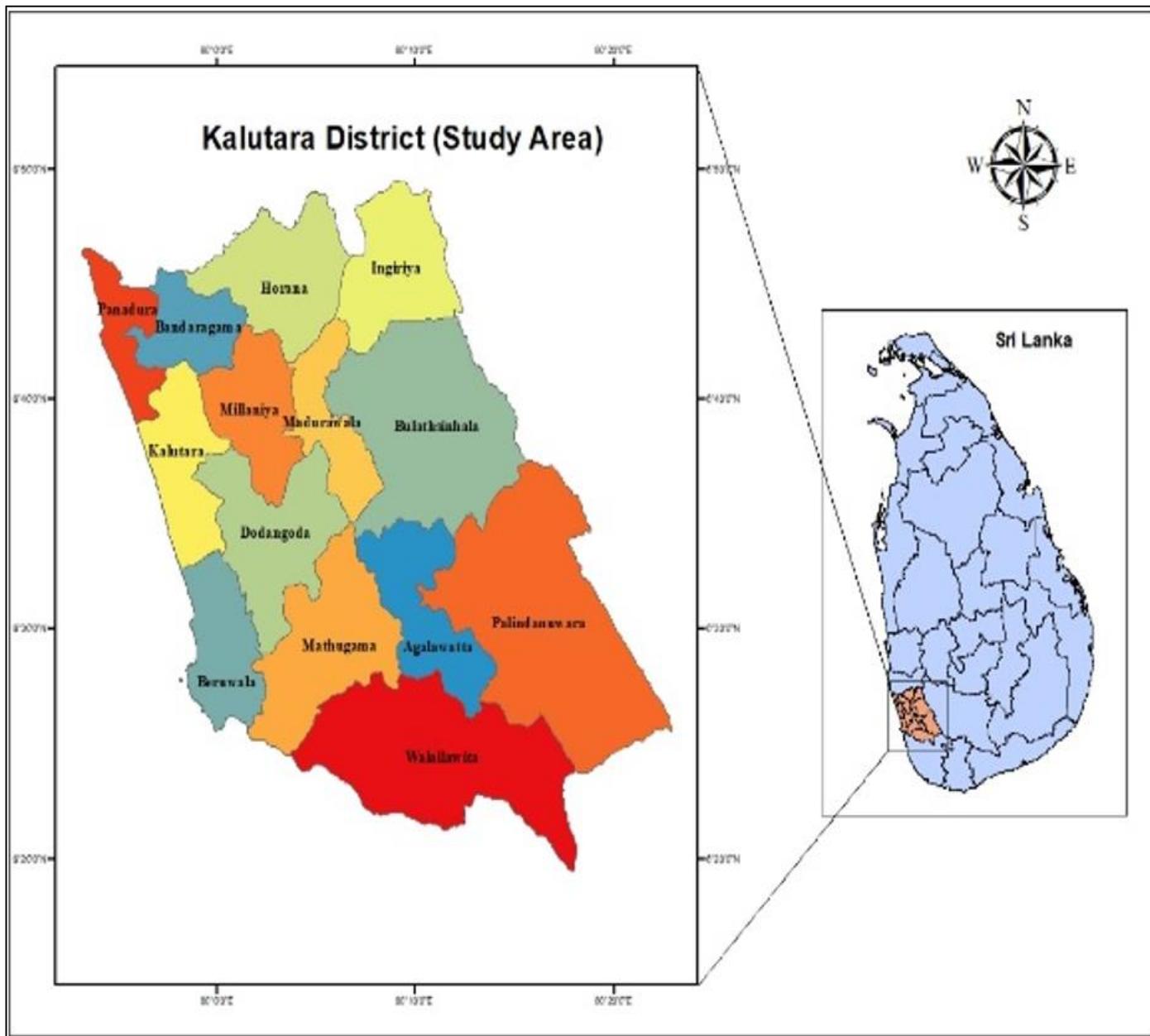

Fig 1 Study Area

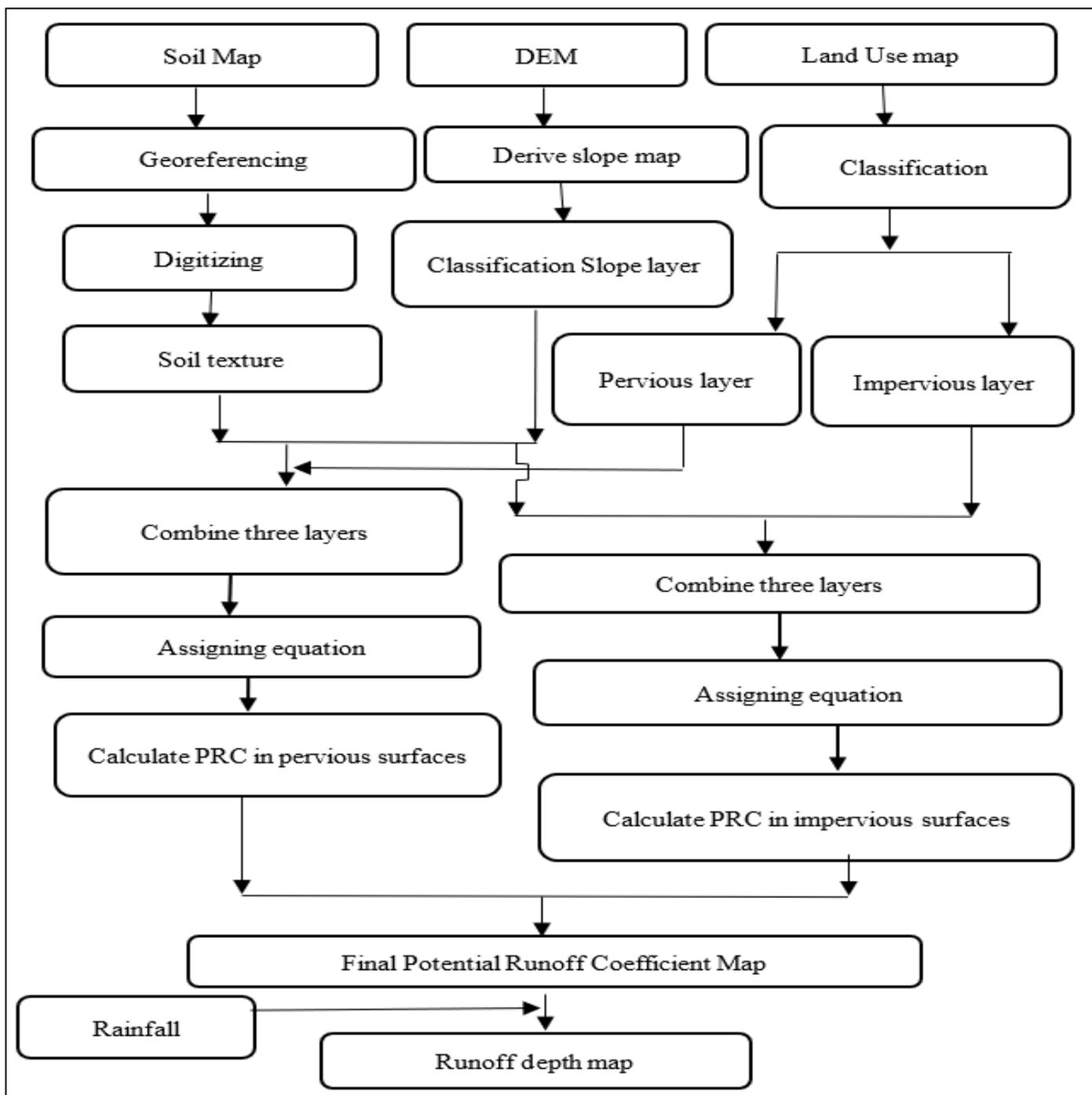### ➤ Factors Identification and Data Acquisition

Fig 2 Methodology Workflow

Three different factors were considered in the study to determine the Runoff Coefficient. They were land use, slope, and soil texture. Additionally, rainfall data were used to calculating runoff depth.

The methodology used to determine the PRC for the study area using GIS is shown in the flow chart in Fig. 2.

- *Land Use:*
  Land use is one of the factors for calculating PRC. The land use data for Kalutara district were collected from the Land Use Policy Planning department in Colombo. There were many different categories at first, but they were further divided into eleven subcategories, which included four pervious surfaces and seven impermeable surfaces. Commercial and industrial areas, mixed urban or built-up land, residential areas, open water, rock areas, wetlands, and transportation and communication utilities were all classified as impervious surfaces. Pervious surfaces categorized as forest, grass, bare soil and crop.

- *Slope:*
  A digital elevation model (DEM) from the United States Geological Survey (USGS) Earth Explorer was used to generate terrain slope at a spatial resolution of 30 m. A preliminary analysis of the DEM was performed to fill in the

low areas or "sinks" that are considered to be errors so that modeled runoff would flow smoothly across the land's surface. The filled output map was used to create the slope for the study area. The slope map created for the study area represent an impression of the steepness of the terrain. The percent slope was classified into four classes.

- *Soil:*

The soil map used in the analysis were obtained using book (R.B.Mapa, S.Somasiri, 1999). The soil map was georeferencing and all the soil textures were digitized by using ArcMap. There are five soil textures clay, sandy, loamy sandy, sandy clay loam, and silty clay loam. And also undifferentiated soils were in some areas. Undifferentiated soil areas were not taken to the analysis. Because these soils are not having exact soil textures.

- *Rainfall:*

The rainfall data for the Kalutara district were collected to find the runoff depth using the runoff coefficients. The data were acquired from Meteorological department of Colombo. There are fourteen rainfall stations.

➢ *Calculation of Potential Runoff Coefficient*

Methodology was carried out using runoff coefficient table and related equations. The table was standard table for determining runoff coefficient (Liu and De Smedt, 2004).

Table 1 and table 2 were used to calculate PRC. There are two different parameters in the equation of runoff

coefficient determination (pervious surfaces). Such as C_0 (when the slope is near zero related PRC value) and S_0, (slope constant). C_0 values were taken from using following table 1 and S_0 values were taken from table 2.

The potential runoff coefficient is prepared for various land use type, slope and soil texture type combinations. To simply the table 1, the original land use classes are reclassified into five classes as forest, bare soil, impervious area and grass, crop.

➢ *Equation of Determining PRC for Pervious Surfaces*

A simple linear relationship between PRC and surface slope was used to determine the PRC on the basis of a continuous slope. Zero impervious percent was assumed for land use categories in bare soil, crop, grass land, and forest land. Equation 1 was used to determine the PRC for pervious surfaces.

Which can be described as where C is the potential runoff coefficient for a surface slope S (%).

$$C = C0 + (1 - C0)\,\frac{S}{S+S0} \tag{1}$$

C_0 is the potential runoff coefficient for a near zero slope corresponding to the values listed on the first row of each land use class in Table 1

S_0 (%) is a slope constant for different land use and soil type combinations, as listed in Table 2

Table 1 Slope Constant S0 for Determining Potential Runoff Coefficient

Land use	Slope (%)	Sand	Loamy sand	Sandy loam	Loam	Silt loam	Silt	Sandy clay loam	Clay loam	Silty clay loam	Sandy clay	Silty clay	Clay
Forest	<0.5	0.03	0.07	0.10	0.13	0.17	0.20	0.23	0.27	0.30	0.33	0.37	0.40
	0.5-5	0.07	0.11	0.14	0.17	0.21	0.24	0.27	0.31	0.34	0.37	0.41	0.44
	5-10	0.13	0.17	0.20	0.23	0.27	0.30	0.33	0.37	0.40	0.43	0.47	0.50
	>10	0.25	0.29	0.32	0.35	0.39	0.42	0.45	0.49	0.52	0.55	0.59	0.62
Grass	<0.5	0.13	0.17	0.20	0.23	0.27	0.30	0.33	0.37	0.40	0.43	0.47	0.50
	0.5-5	0.17	0.21	0.24	0.27	0.31	0.34	0.37	0.41	0.44	0.47	0.51	0.54
	5-10	0.23	0.27	0.30	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60
	>10	0.35	0.39	0.42	0.45	0.49	0.52	0.55	0.59	0.62	0.65	0.69	0.72
Crop	<0.5	0.23	0.27	0.30	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60
	0.5-5	0.27	0.31	0.34	0.37	0.41	0.44	0.47	0.51	0.54	0.57	0.61	0.64
	5-10	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60	0.63	0.67	0.70
	>10	0.45	0.49	0.52	0.55	0.59	0.62	0.65	0.69	0.72	0.75	0.79	0.82
Bare soil	<0.5	0.33	0.37	0.40	0.43	0.47	0.50	0.53	0.57	0.60	0.63	0.67	0.70
	0.5-5	0.37	0.41	0.44	0.47	0.51	0.54	0.57	0.61	0.64	0.67	0.71	0.74
	5-10	0.43	0.47	0.50	0.53	0.57	0.60	0.63	0.67	0.70	0.73	0.77	0.80
	>10	0.55	0.59	0.62	0.65	0.69	0.72	0.75	0.79	0.82	0.85	0.89	0.92
IMP		1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Source: Wet Spa Extension, A GIS-Based Hydrologic Model for Flood Prediction and Watershed Management 2004

Table 2 Potential Runoff Coefficient for Different Land Use, Soil Type and Slope

Land use	Sand	Loamy sand	Sandy loam	Loam	Silt loam	Silt	Sandy clay loam	Clay loam	Silty clay loam	Sandy clay	Silty clay	Clay
Forest	0.680	0.650	0.620	0.590	0.560	0.530	0.500	0.470	0.440	0.410	0.380	0.350
Grass	0.580	0.551	0.522	0.493	0.464	0.435	0.405	0.376	0.347	0.318	0.289	0.260

Crop	0.500	0.471	0.442	0.413	0.384	0.355	0.325	0.296	0.267	0.238	0.209	0.180
Bare soil	0.420	0.393	0.365	0.338	0.311	0.284	0.256	0.229	0.202	0.175	0.147	0.120

Source: Wet Spa Extension, A GIS-Based Hydrologic Model for Flood Prediction and Watershed Management 2004

➢ *Equation of Determining PRC for Impervious Surfaces*

Then Potential Runoff Coefficient was determined for impervious areas (i.e. urban areas). Due to the grid size, cells may not be 100% impervious in reality. In the remaining area is assumed to be pervious and covered by grass. So, the potential runoff coefficient for urban areas was determined using following Equation 2 (Liu and De Smedt, 2004).

$$C_u = IMP + (1 - IMP) Cgrass \qquad (2)$$

Where,

C_{grass} is potential runoff coefficient for grass grid

IMP is the proportion of impervious area. This was taken from table 3 (Liu and De Smedt, 2004).

C_{grass} values were taken from table 1.

C_u is potential runoff coefficient for urban grid

All the created layers were combined separately as described in flow chart. There were two combined output, impervious and pervious. The two fields (IMP, C_{grass}) were added to the attribute table of combined output (impervious layer). Then PRC for impervious areas was determined using equation 2. As next step the two fields (C_0, S_0) were added to the attribute table of combined output (pervious layer). Then PRC for pervious areas was determined using equation 1. Finally, these two maps were combined and get the final PRC map.

Table 3 Impervious Percentages Associated with Selected Land use Classes

No	Land use description	Impervious percent (%)
1	Residential area	30
2	Commercial and industrial area	70
3	Mixed urban or built-up land	50
4	Transportation and communication utilities	100
5	Streams, Canals, lakes and reservoirs	100
6	Forest wetland	100
7	Bare exposed rock	100

Runoff depth map was prepared, the rainfall map and PRC map multiplied (cell-by cell) by using the raster calculator tool.

III. RESULTS AND DISCUSSION

➢ *Soil Textures in the Study Area*

There were no large spatial differences in soil textures throughout the study area, with basically five different soil textures and undifferentiated soil textures. As noticed results, 72.19 % of the area is sandy clay loam, which has a slow infiltration rate. In addition, 12.12 % from the study area is silty clay loam and 0.75% is clay, which have very slow infiltration rate. 1.26 % of the total area is loam sandy and 3.3% is sandy, which have a high infiltration rate. 10.38 % of the area is belonging to undifferentiated soils class. Area of this class is not taken to the analysis. Because those areas including mixture of several soil textures.

➢ *Land Use in the Study Area*

The land use map that used for analysis contain the eleven main land use types for impervious land use surfaces and pervious land use surfaces.

Pervious surfaces in the study area where forest and crop land represent the biggest ratio of the area which is 40.61 %, and 12.30 % of the total area. Grass land, and bare land represent lowest ratio of the area. 33.78% of the total area is shows the Impervious surfaces. The residential area represent

biggest ratio of the area which is 28.06% total of the area. And also this result is clear, 1/3 of the total area represents the impervious surfaces. Due to the 30-m grid size, urban cells (impervious) may not be 100 % impervious in reality. So, in the calculations, PRC for these areas were calculated by adding the impervious percentage with a grass runoff coefficient multiplied by the remaining area.

➢ *Slope in the Study Area*

Slope map was classified into four classes with the ranges; 0–0.5 %, 0.5–5 %, 5–10 %, and >10 %.

59.38% of the total area of the district have slope greater than 10%, which means the biggest area was covered with high slope. The coastal area is covered belong to the slope category less than 5%. Due to increasing slope, PRC was also increase. When PRC is increasing means those areas having high runoff. Therefore, the Kalutara district was affected flood hazard frequently.

➢ *PRC Map*

The results shows the runoff coefficient varies with the soil type, land use type and slope condition. The PRC values range from 0.13 to 1 (Fig.3). The impervious surface's PRC value range from 0.39 to 1 and pervious surfaces range from 0.13 to 0.99. The PRC range is high in impervious area than pervious surfaces. So, the urban area is having high PRC values and those areas are most prominent for flooding.

According to the Fig.3 PRCs are lower in close proximity to the coastal areas since slope is lower. So, due to the low PRC coastal boundary is not affecting to the flood hazards. PRC is high for lands covered by bare soils. In open water surfaces, PRC is 1. Furthermore, the high PRC values areas with the surface slope are high. The low lying areas in the district is affecting flood hazard frequently. Bulathsinhala and Palindanuwara are the most flood affected DS division in Kalutara district, PRC map shows, and those areas having highest PRC values. The PRC is not determined for the undifferentiated soil areas, because the lack of soil texture information in those areas. According to the Fig.2, most of the areas in Kalutara district have high PRC values which implies that probability of getting frequent flood hazards is high for this district.
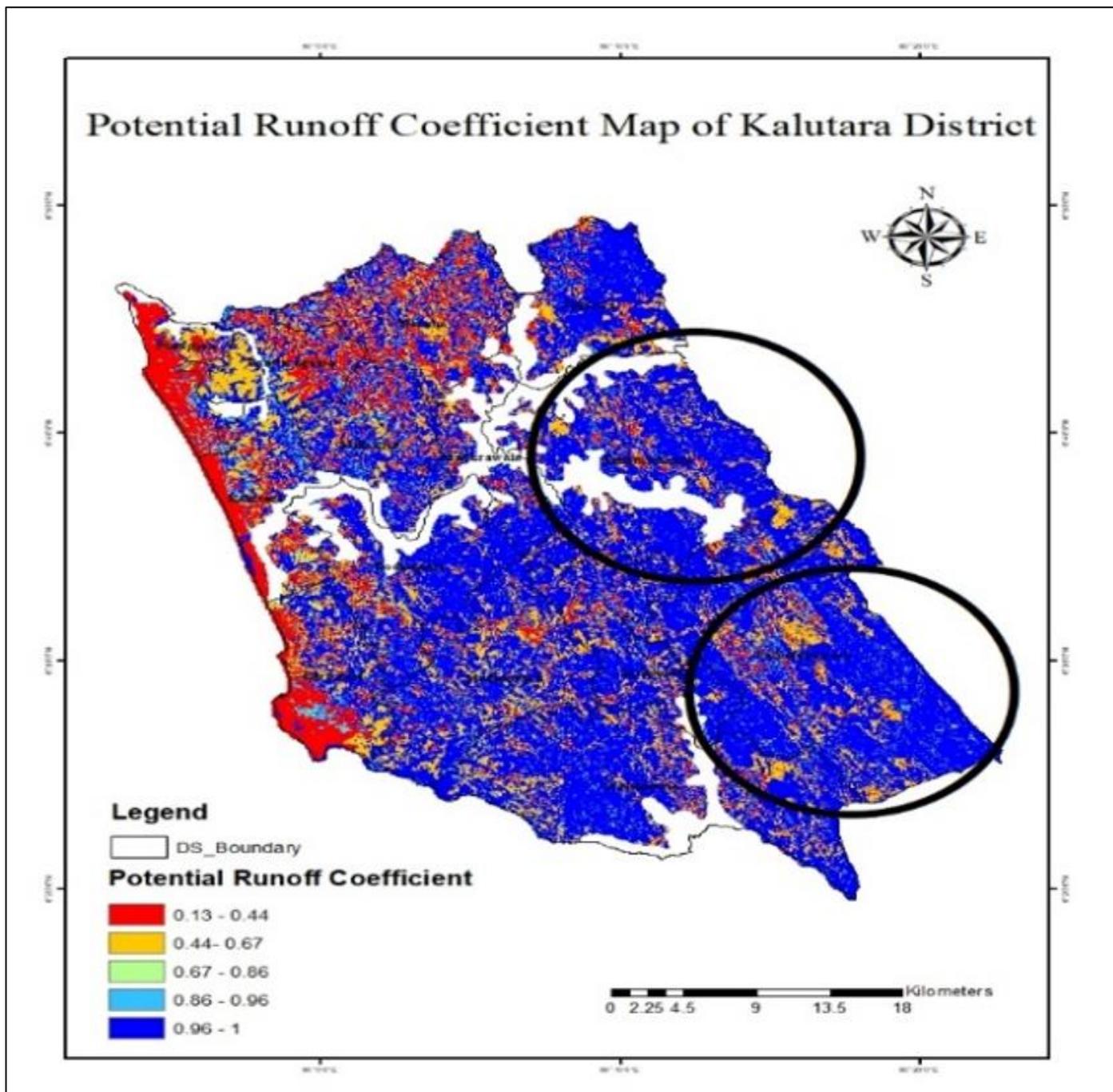

Fig 3 Final Potential Runoff Coefficient Map in Kalutara District

➢ *Rainfall*

Rainfall data from fourteen rain gage stations were collected to create rainfall map. Kriging interpolation was used to interpolate the data. The maximum average annual (2018) rainfall is 483.333mm in the study area and minimum rainfall is 235.6mm.
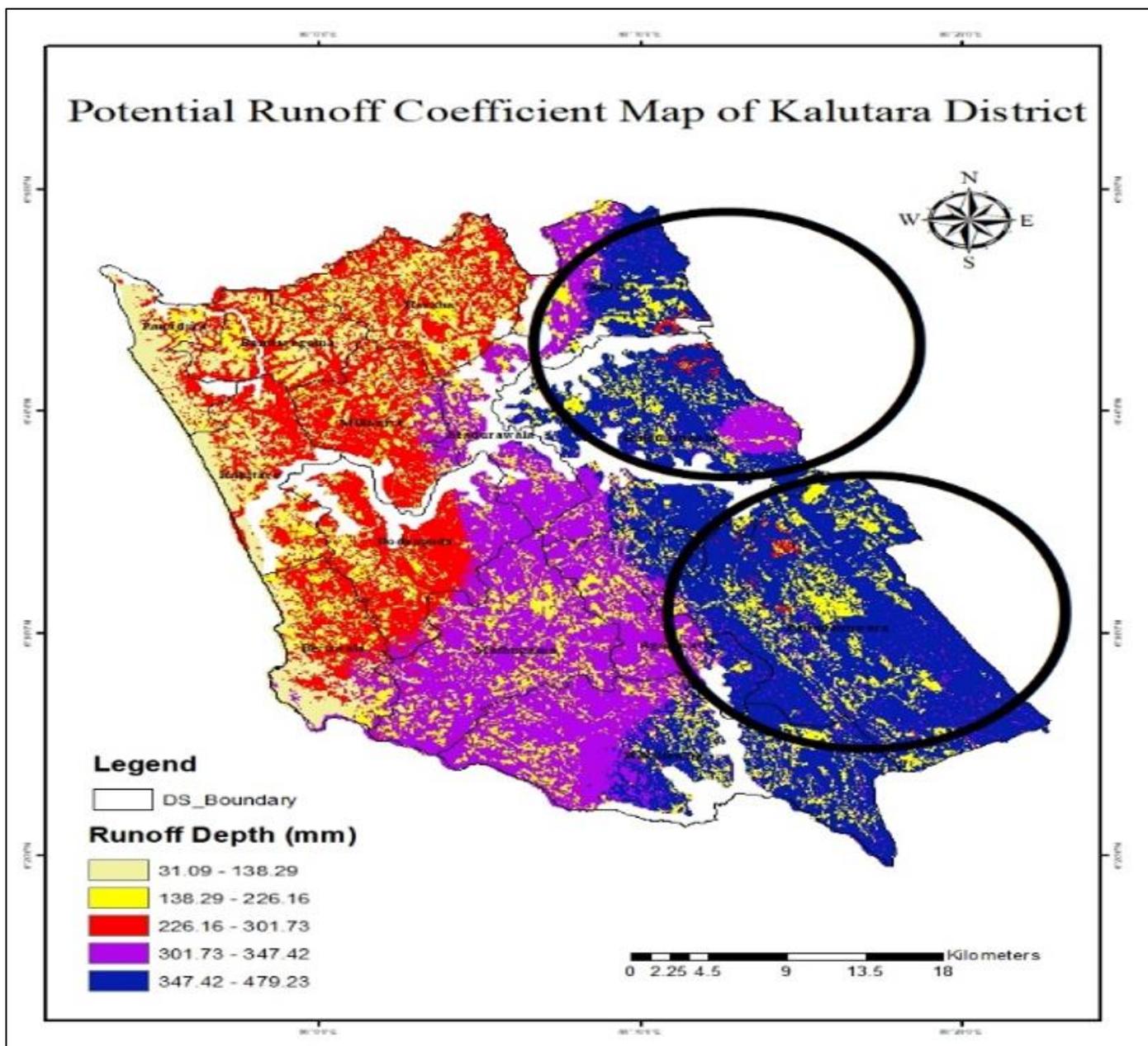
Fig 4 Runoff Depth Map in Kalutara District

➢ *Runoff Depth Map*

Using the raster calculator tool in ArcGIS, which indicates the percentage of rainfall that was converted into runoff, the annual runoff depth was calculated using the annual rainfall surplus and runoff coefficient per pixel. Figure 4 displays the spatial distributions of the modeled annual runoff depth in millimeters. Due to differences in the study area's terrain and environment, rainfall and runoff depth varied from as little as 31 mm to a high of 479 mm, with steep slope areas showing the greatest rainfall and runoff depth. Palindanuwara, Bulathsinhala, and Ingiriya DS divisions are indicated by the greatest runoff depth.

➢ *Validation of Analysis Results*

A model validation was conducted to ensure that the results of the PRC map and runoff depth map were accurate and reliable. Here, the PRC map of Kalutara district result and the existing flood map of Kalu river area were compared. The flood map was partially covered by the total area

The highest PRC values indicate the lowest infiltration rate and high runoff areas. So, those areas are most prominent for flooding.

The runoff coefficient values in the PRC map was compared with flooded areas in the flood map. After, validating those two maps closely matched with the PRC map. As the result of validation, more than 50% was validated with the flood map. The comparison result shows that those maps are almost the same. That gives an indication that the potential runoff coefficient (PRC) map is accurate, which encourages the use of GIS in hydrological modeling and environmental studies. Fig.6 shows the validation result of the Kalu River area in Kalutara district.
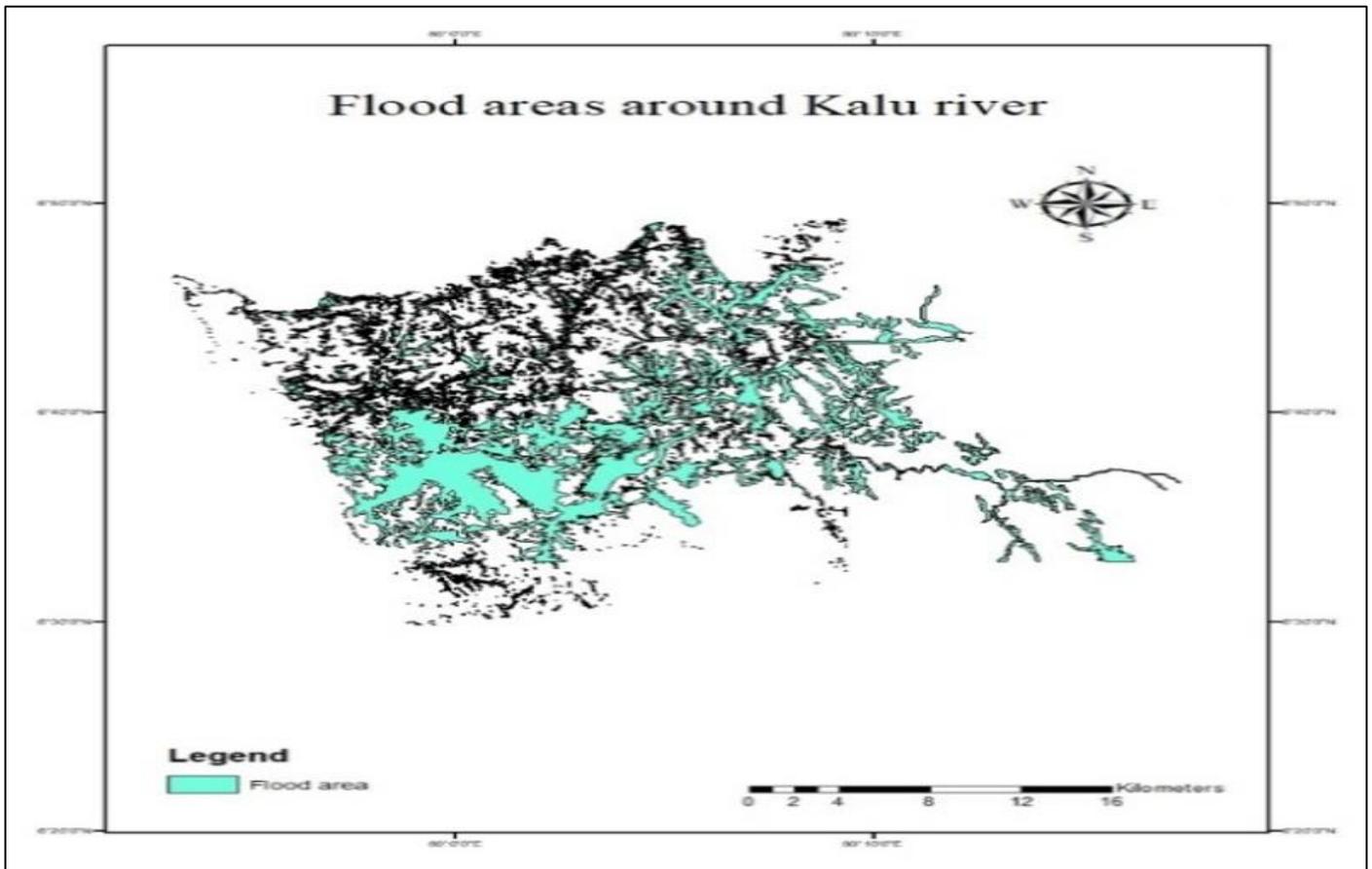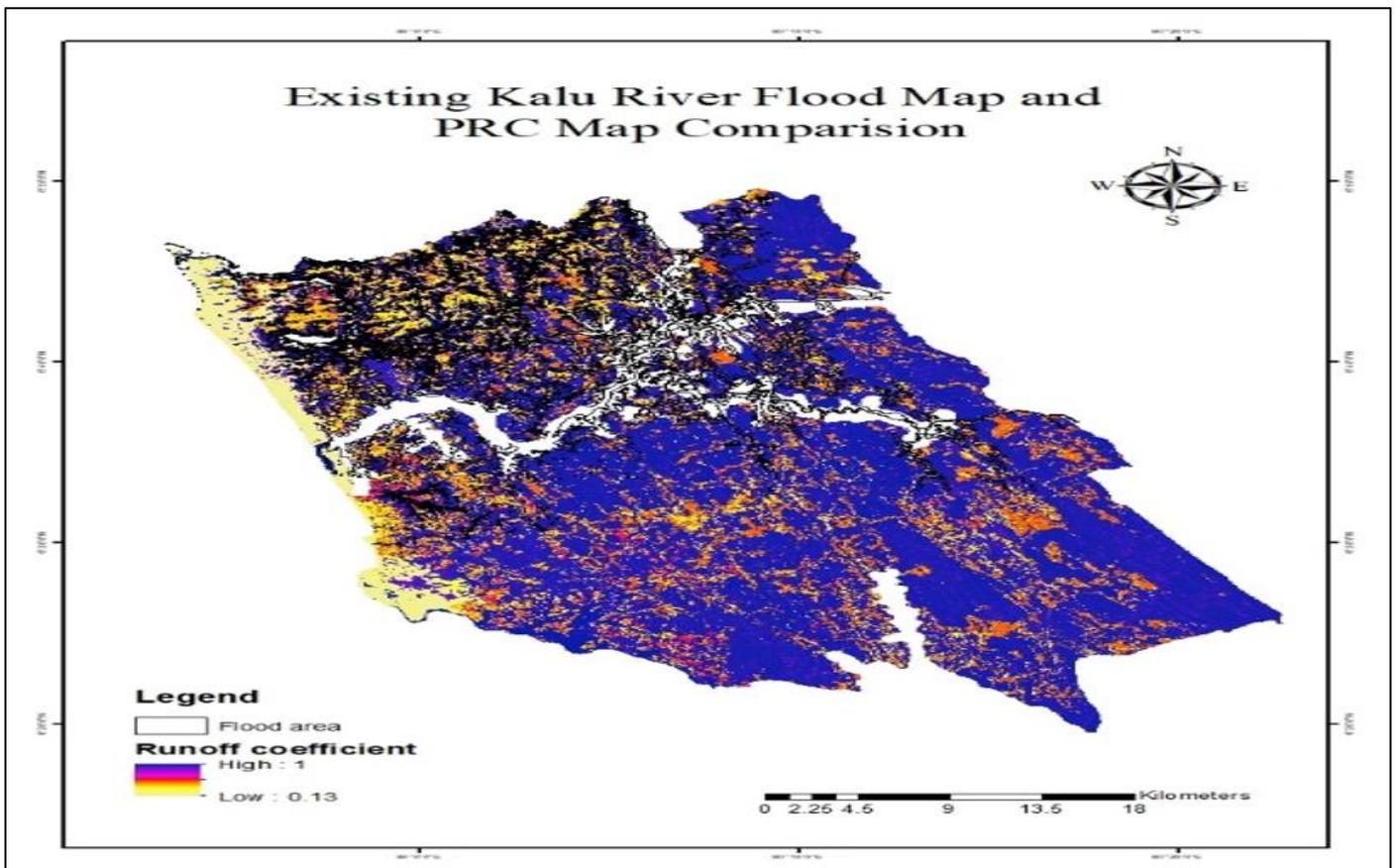
Fig 5 Flood Map Around Kalu River Area

Fig 6 Comparison of Existing Flood Map and PRC Map in Kalu River Area

IV. CONCLUSION

Determination of runoff coefficient is highly important for flood control channel construction and possible flood zone hazard delineation. A high runoff coefficient (C) value may indicate flash flooding areas. The large spatial variability in runoff coefficient, which ranges from 0.13 to 1. In the study area, impermeable surfaces including concrete, asphalt, and building roofs have relatively high run-off coefficients. Residential areas still maintained considerable amounts of green space and home gardens, thus their run-off coefficients were not very high. The flood situation areas may indicate high runoff coefficients. As the runoff coefficient could not be determined in some areas (undifferentiated soils) due to lack of soil texture data.

The PRC map of the current study can provide a guideline for finding flood occurrences areas in the Kalutara district. Bulathsinhala, Palindanuwara DS divisions were affected flood frequently. The PRC map (Fig. 3) shows, those areas having high runoff coefficients.

In this study runoff depth is variate from 31mm to 479mm. Runoff depth is a factor of runoff harvesting suitability site analysis. From investigating final runoff depth map most of the areas having high runoff depth values. Bulathsinhala, Palindanuwara and Ingiriya DS divisions were having high runoff depth values (Fig.4 is shows those areas having high runoff depth values).

All the data was obtained from various sources. Therefore, the result of the study also depends on the accuracy of the considered datasets. This method can be used to determine runoff coefficient and runoff depth for any location. In addition, it can be utilized for flood prediction, rainwater harvesting site suitability analysis, and better storm water management purposes. This work can help estimate runoff at places where observed runoff records are not available.

RECOMMENDATIONS AND FUTURE WORK

Many areas of the Kalutara district, as well as those of developing countries like Sri Lanka, lack the historical data and comprehensive runoff information necessary for hydrological study. This study may be able to offer a better flood management program in such situations. The described technique has many advantages, such as being cost-effective, having fewer input data, and being a simple and time saving technique. Because this method used only three input data (soil texture, DEM and land use) and used one GIS software to perform all procedure steps. All needed calculations were done within the GIS environment using the raster calculator tool. The estimation process can be efficient, faster, and easily performed for any region. Based on the results and analysis of the runoff coefficient value of research area, there are a few suggestions for future studies. In this study land use map was directly taken from the classified map, because the research study area is relatively large and field survey was a very difficult task in the current time period. This study is mainly based on the land use type of the study area. Therefore, a field survey with supervised classification is recommended for future study. If the study area is relatively small, the land-use changes are so dynamic, that images with the better spatial and temporal resolution are recommended. Finer resolution data will significantly improve the classification accuracy. Soil texture information used in this study was taken from the wet zone of the soils book Sri Lanka and which was in 1999. The soil texture information can be change in the current situation. So, the field survey is recommended for future study to find the soil texture of the area. Using exact soil texture information will improve the accuracy of the final output. The SRTM DEM was used for creating slope map, which was 30m resolution. If the study area is relatively large 30m resolution is better enough for the accuracy of the final output. But, if the study area is small, for the future study images with the better spatial and temporal resolution are recommended. In the future, this study could be improved upon by figuring out the runoff coefficient for the entirety of Sri Lanka. This will make it easier for the water management to give farmers helpful information on the availability of water. As a result, farmers may plan the timing of their agricultural activities, the age and type of crops to be grown, and the size of the cropping area for a given crop season.

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