Nature Environment and Pollution Technology
An International Quarterly Scientific Journal

p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454

Vol. 20 | No. 5 (Suppl) | pp. 2117-2123 | 2021

Original Research Paper

https://doi.org/10.46488/NEPT.2021.v20i05.029

Open Access Journal

GIS-Based Surface Runoff Modeling Using Empirical Technique For A River Basin In South India

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Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 14-07-2021
Revised: 26-08-2021
Accepted: 03-09-2021

Key Words:
Rainfall runoff
Curve number
GIS
Land use

ABSTRACT

Precipitation is the primary source of fresh water in the world. Surface runoff will happen when the amount of rainfall is greater than the soil's infiltration capacity. In most water resource applications, runoff is the most important hydrological variable. Aside from these rainfall characteristics, there are a number of catchment-specific elements that have a direct impact on runoff amount and volume. This research focuses on estimating surface runoff over the lower Vellar basin, a river basin in the southern part of India, by integrating Soil Conservation Service-Curve Number (SCS-CN) method with GIS. This technique is one of the most common methods used by hydrologists for estimating surface runoff. Curve Number (CN) is an index established by the Natural Resource Conservation Service (NRCS) to denote the potential for stormwater runoff. The nature of the watershed is explored first by creating land use and land cover pattern followed by the preparation of slope, drainage, and location maps. The area taken for this study is the lower Vellar basin situated in the Cuddalore District of Tamil Nadu, India. The curve number is analyzed using the rainfall data of 15 years (2001-2015) and the runoff is being calculated. The watershed pattern of the study area is also explored being analyzed and executed. Preservation of the runoff water is also discussed.

INTRODUCTION

Water is the most important element for all living things; without water, there would be no vegetation on the Earth, no oxygen for animals to breathe, and the world would look very different than it does now. Water is required for human health and the preservation of the environment, and it should be valued and protected as a valuable resource. However, as a result of pollution, clean water is becoming increasingly scarce (Gagan et al. 2016).

The oceans hold around 97 percent of the world's water. Saltwater covers about 1.4 billion cubic kilometers. Freshwater makes up only 3% of the total, and it is found in rivers, glaciers, and lakes. Even though there is abundant fresh water all across the world, there are some areas that are too dry and do not receive enough rain. Water scarcity is a prevalent issue in developing countries due to population expansion. Many areas lack sufficient water because people exhaust it. Water moves in a continuous cycle, never disappearing or ceasing to exist, but shifting from solid to liquid to gas. While some rainwater returns to the atmosphere, the majority of it enters the ground through aquifers.

Runoff is the most significant hydrological factor used in more applications of water resources. Its incidence and amount are based on the features of rainfall occurrence, i.e. the length, intensity and circulation. In addition to these rainfall features, there are numerous catchment-specific variables that directly affect the incidence and quantity of runoff. There are several methods existing for rainfall-runoff modeling. Soil Conservation Services and Curve Number (SCS-CN) techniques offer an empirical relationship to estimate original abstraction and runoff as soil type and land use function. Curve Number (CN) is an index created by the Natural Resource Conservation Service (NRCS) to represent the potential of a drainage region for stormwater runoff (Hailu et al. 2018, Sishah 2021). The U.S. Soil Conservation Service at the Department of Agriculture initially created the SCS-CN technique (Van Dijk 2010, Abon et al. 2011, Steenhuis et al. 1995).

The CN for a watershed is evaluated using a mixture of land use, antecedent soil moisture condition (AMC), and soil. There are four types of hydrologic soils: A, B, C, and D. Group A has a high rate of infiltration, while Group D has a low rate of infiltration. The Soil Conservation Service Curve Number (SCS-CN) method is widely used to forecast direct runoff volume for a specific rainfall event (Mishra & Singh 1999, King & Balogh 2008, Elhakeem & Papanicolaou 2009, Romero et al. 2007).

Recent sophisticated methods such as remote sensing and the Geographic Information System (GIS) are therefore involved in the compilation, storage, and evaluation of spatial and temporal allocation information. These techniques are currently being used to address watershed-related challenges such as watershed planning, growth, and management, with the goal of harnessing all-natural resources for long-term development (Verma et al. 2016, Rawat & Singh 2017, Tiwari et al. 2017). Thus, Geographic Information Systems (GIS) and Remote Sensing is the main tool to provide the foundation for effective water resource management. (Gupta et al. 2004, Frevert & Singh 2002, Siddi Raju et al. 2018, Mahboubeh et al. 2012, Sharma et al. 2008, Ruslin Anwar 2011).

MATERIALS AND METHODS

Study Area

The Vellar River is situated in the Cuddalore district which lies in the coastal belt of Tamil Nadu. It is one of the many ephemeral rivers in the area; it runs from west to east and blends with the sea south of Porto-Novo. The lower Vellar sub basin comprises the Perumal Eri (lake) watershed and is connected by the Bay of Bengal to the east. The parts of the lower Vellar watershed (Study area) comprise the catchment and command areas of Perumal 'Eri' extended up to the Bay of Bengal in the East. Cuddalore is the district headquarters, which is well connected by both rail and roadways. The study area (lower Vellar watershed) is bounded to the north by the Ponnaiyar watershed, to the south by the Vellar watershed, and to the east by the Bay of Bengal. The pilot study area (lower Vellar watershed) lies between north latitudes 11° 30' 10' and 11° 42' 16" and east longitudes 79°30'00" and 79°46' 6" and is covered by the survey of India toposheet No.58 M/10. The total study area taken is said to be 1784 km^2, and a Google Earth snapshot of the entire study area is shown in Fig.1.

Data Sources

IRS LISS-III data was used for the LULC classification. Land use/land cover classes in the current study region have been identified, and the LULC map is shown in Fig. 2. Daily rainfall data ((2001– 2015) was used in this study, and the data was collected from IMD, Chennai. Soil information was obtained from the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP). The study area's Digital Elevation Model (DEM) and slope and elevation map were obtained from SRTM (Shuttle Radar Terrain Mission) and is shown in Fig. 3 and 4.

Runoff Calculation

The equation of the runoff curve number is:

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

$$Q = 0 \qquad P \leq I_a$$

Where: Q = Actual Direct Runoff (mm), P = Total Rainfall (mm), I = Initial Abstraction, S = Watershed Retention (mm). IA (I) and WR (S) can be related to each other by analyzing rainfall-runoff data for the sub-watersheds. The empirical relation between I and S may be stated as follows:

$$I = 0.2S \qquad ...(2)$$

Therefore, applying Equation 2 on Equation 1

$$Q = \frac{(P-0.2S)^2}{P+0.8S} \quad P \geq 0.2S \qquad ...(3)$$

Retention parameter (S) is dependent upon soils, land use, and slope, and it is defined as-

$$S = 25.4\left(\frac{1000}{CN-10}\right) \qquad ...(4)$$

Where CN is the day's Curve Number, a dimensionless runoff index determined by land use, hydrological soil groups (HSG), and antecedent moisture content (AMC).

The curve number (CN) depends on the permeability of the soil, its usage, and its previous moisture content. The daily retention value adjusted according to water content is calculated by rearranging equation 4 and inserting the retention parameter (explained in detail below) calculated for the soil which is completely saturated.

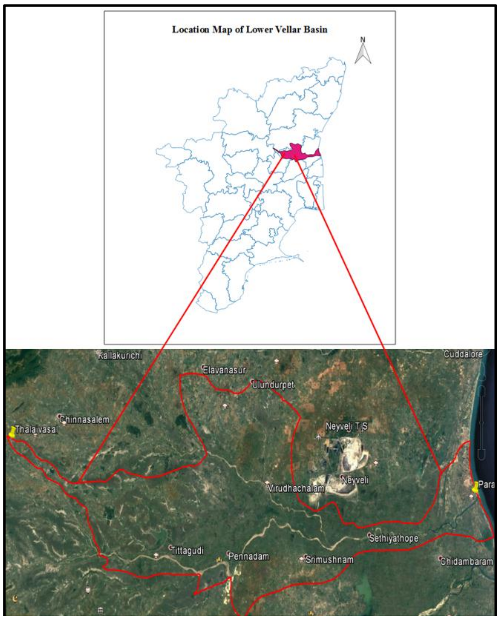

Fig. 1: Study Area-Vellar River Basin

$$S = \left(\frac{25400}{CN}\right) - 254 \qquad \text{...(5)}$$

The curve number (CN) depends on the permeability of the soil, its usage, and its previous moisture content. The equation for the derivation of CN is:

$$CN = \frac{\sum(P1A1+P2A2+\cdots+PnAn)}{\sum A} \qquad \text{...(6)}$$

This equation calculates CN values based on land use and land cover classes and hydrological soil groups, where a 5% slope is under consideration.

The present equation calculates CN for AMC 2. Variability in CN consequences related to moisture conditions of the soil, precipitation duration and intensity, total precipitation, cover density, temperature, and growth stage. These sources of variableness are collectively named as Antecedent Runoff Condition (ARC). The ARC is classified into three classes: CN2 for normal conditions, CN1 for arid conditions, and CN3 for humid conditions. CN1 and CN3 can be calculated with the following mathematical equations.

$$CN1 = \frac{4.2\ CN2}{10-0.058\ CN2} \qquad \text{...(7)}$$

$$CN3 = \frac{23\ CN2}{10+0.13\ CN2} \qquad \text{...(8)}$$

$$S = \left(\frac{25400}{CN1}\right) - 254 \quad AMC \leq 13 \qquad \text{...(8)}$$

$$S = \left(\frac{25400}{CN3}\right) - 254 \quad AMC > 28 \qquad \text{...(9)}$$

$$S = \left(\frac{25400}{CN2}\right) - 254 \quad 28 < AMC > 13 \qquad \text{...(10)}$$

Either CN1/CN2/CN3 is used for the calculation of Watershed Retention (S) using Equation 5 based on the AMC values.

The run-off relationship was calculated using a number of retention criteria. The initial abstraction, Ia, may be regarded as the borderline between the size of the storm that creates runoff and the size of the storm that creates no runoff. Retention at its highest level, S, is dependent upon the soil cover compound and, in principle, must not differ from one storm to the next. It is greater than the initial abstraction, so Ia + S gives the maximum potential loss. The difference between rainfall and runoff (P – Q) is used to calculate the loss. When equation (9) is substituted for Q, the result is

$$Loss = P - Q = P - \frac{(P-I_a)^2}{(P-I_a)+S} \qquad \text{... (11)}$$

Following the multiplication of both terms on the right-hand side by: $1 = \frac{(P-I_a)+S}{(P-I_a)+S}$

With certain manipulation this becomes:

$$Loss = \frac{\left((S+I_a)-\left(\frac{I_a^2}{P}\right)\right)}{\left(1-\left(\frac{I_a}{P}\right)+\left(\frac{S}{P}\right)\right)} \qquad \text{...(12)}$$

The terms in the denominator with P in the denominator approach zero as P approaches large, where large is defined as P being significantly greater than the maximum possible retention (S).

$$Loss = S+I_a \qquad \text{...(13)}$$

The parameter F is the storm's true retention, which is higher than the early abstraction. That is, the total actual retention is equal to the sum of the initial abstraction and the actual retention (Ia + F).

Model Calculation

Let the Rainfall for five days be 40.9, 60.4, 70.2, 0, and 30.8. The rainfall on the 6th day is 25.5.

AMC (Antecedent Moisture Content) for day 6 can be calculated using the following formula (weighted average)

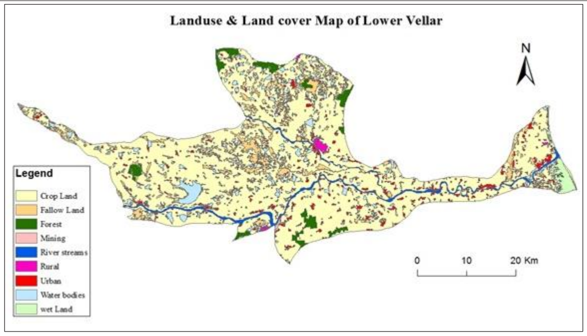

Fig. 2: Land use and Land cover classification of the Vellar

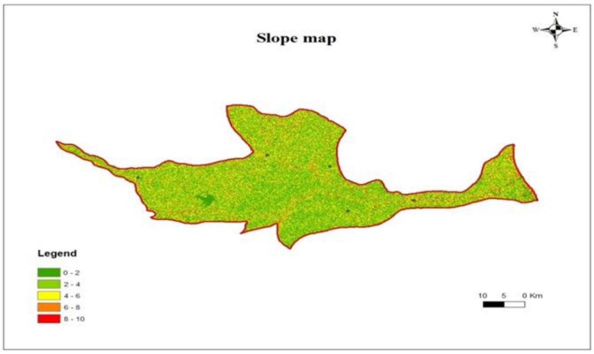

Fig. 3: Lower Vellar basin Slope map

AMC = (0.9*R1) + ((0.9) ^2*R2) +….+ ((0.9)^n*Rn)

Here, R1, R2, Rn represents rainfall in mm

= (0.9*40.9)+(0.9^2*60.4)+(0.9^3*70.2)+(0.9^4*0)+(0.9^5*30.8) = 142.68

Now, AMC > 28, we consider CN3 (wet) (CN3 = 91.89)

S = (25400/91.89)-254 = 22.42

I = 0.2*22.42 = 4.48

P-I = Daily rainfall – 4.48 = 25.5-4.48= 21.02

$Q = (P\text{-}I)^2/P+0.8*S = 21.02^2/25.5+0.8*22.42 = 10.17$ mm

The runoff of day 6 is **10.17mm**.

RESULTS AND DISCUSSION

Land Use

According to the LULC map of the lower Vellar basin, the majority of the area was classified as fallow land and cropland, implying that there may be more infiltration and consequently lesser runoff. Out of the overall area (1784 km^2), 2 km^2 have been designated as mining areas (Fig. 2), which will manage surface runoff.

Slope Map

The slope is one of the deciding factors in surface runoff. SRTM elevation data acquired from USGS Earth Explorer was used. ArcMap 10.3 is the software used. The slope map findings for the chosen research area are less than 5%. As a result, it is not taken into account. Fig. 3 shows the slope map of the research area.

Elevation Map

The most common type of map used to depict elevation is a topographical map. In Geographic Information Systems (GIS), digital elevation models (DEM) are commonly used to represent the surface (topography) of a location using a raster (grid) dataset of elevations. The color difference in the map depicts the study area's high to low elevation values. The elevation map is created using SRTM elevation data. Fig. 4 shows an elevation map of the research area.

Contour Map

A contour map represents the elevation of the particular area within the elevation lines drawn on it. The contour interval is the difference in height between successive contour lines on a contour map. A two-variable function's contour line is often a curve that connects points where the function has the same value. The presented map's contour interval is 20 m. The study area's western side is sloppier than the lower Vellar basin's east side, and the distance between each contour is higher, implying that the study area is practically plain. Fig. 5 shows the contour map of the research region.

Rainfall and Runoff Kuppanatham

The total rainfall recorded at Kuppanatham is 18191.4 mm, with a runoff of 8787.48 mm. Rainfall and runoff averages 1212.8 mm and 585.83 mm, respectively. In 2015, the largest rainfall was recorded, as well as the highest runoff. In the year 2012, the lowest rainfall was recorded, and the lowest runoff was recorded in the year 2003. This was because of the driest period, which lasted from 2001 to 2003. As a result, the actual amount of rain that fell throughout these years would sweep in. Despite the fact that rainfall was minimal in 2012, the rainfall in 2011 was adequate to recharge the groundwater potential. The runoff in 2012 is higher than in 2003. Data 2 contains the yearly runoff table for station Kuppanatham, while Fig. 6 and Fig. 7 depict the rainfall-runoff distribution and relationship.

Rainfall and Runoff Memathur

The total rainfall in Memathur is 17613.6 mm, with an

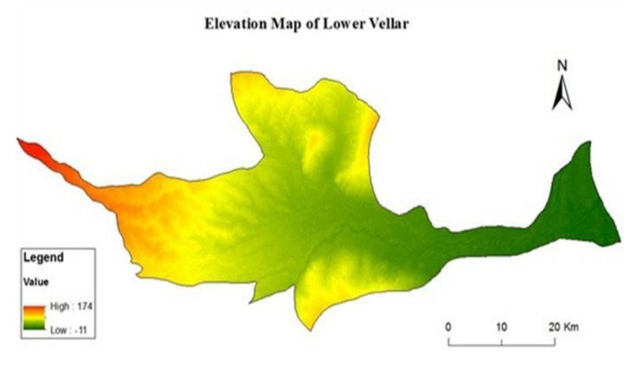

Fig. 4: Elevation Lower Vellar basin

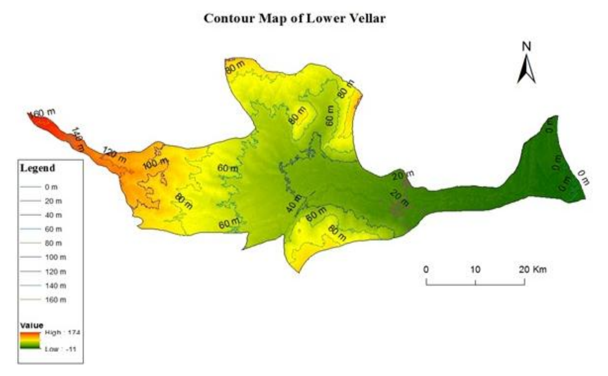

Fig. 5: Contour Lower Vellar basin

equivalent runoff of 8091.09 mm. Rainfall and runoff averages 1174.2 mm and 539.41 mm, respectively.

The year with the high rainfall was 2015, and the year with the highest runoff was 2005. In the year 2012, the lowest rainfall was recorded, as well as the lowest runoff. Because the rainfall in Memathur was higher in all of the years from 2001 to 2005, the year 2005 had the largest runoff (Fig. 8 & 9).

Rainfall and Runoff Sethiyathope

The total rainfall at Sethiyathope is 21150 mm, while the runoff is also 21150 mm. The average rainfall is 1410 mm, while the average runoff is 716.02 mm. In 2005, the largest rainfall was recorded, as well as the highest runoff. The year 2012 saw the lowest rainfall, while 2001 saw the lowest runoff. Table 2 contains the yearly runoff table for station Sethiyathope, as well as graphs depicting the rainfall-runoff relationship and distribution. Fig. 10 and 11 show the graphs depicting the rainfall-runoff relationship and distribution.

Rainfall and Runoff Srimushnam

In Srimushnam, the total rainfall reported is 17510.3 mm, with a runoff of 8531.86 mm. Rainfall and runoff average 1167.4 mm and 568.79 mm, respectively. The maximum rainfall and runoff were both recorded in the year 2003. The lowest rainfall and runoff were both recorded in the year 2012 (Fig. 12 & 13).

Rainfall and Runoff Virudhachalam

The total amount of rainfall in Virudhachalam is 18815.1 mm, with a runoff of 8744.22 mm. The average rainfall is 1254.3 mm, while the average runoff is 582.95 mm. In 2005, the largest rainfall was recorded, as well as the highest runoff. In the year 2014 the lowest rainfall, as well as the lowest runoff has been recorded (Fig. 14 & 15).

Rainfall and Runoff relationship in Lower Vellar basin

In 2005, the lower Velar basin received the most average rainfall (1758.92 mm). In 2012, the lower Vellar basin's average rainfall was at its lowest (750.84 mm). The highest

Table 1: Land Use and Land Cover

S.No	Land Use	Area [km^2]
1	Water bodies	91.5
2	Fallow Land	161.4
3	Forest	49.5
4	Urban	77.5
5	Rural	9
6	Crop Land	1321.8
7	River Stream	47.7
8	Mining	2
9	Wet Land	23.8

Table 2: Rainfall and Runoff in Vellar Basin

	Kuppanatham		Memathur		Seithiyathope		Srimushnam		Virudhchalam	
Year	Rainfall	Runoff	Rainfall	Runoff	Rainfall	Runoff	Rainfall	Runoff	Rainfall	Runoff
2001	867.50	384.13	1186.00	516.16	927.70	309.98	962.80	446.00	989.10	386.62
2002	918.70	411.69	1164.60	582.65	1141.10	594.46	1417.00	835.89	827.80	335.44
2003	895.60	317.71	1200.00	447.80	954.40	315.02	2281.00	1569.95	932.50	330.73
2004	1599.00	938.44	1149.00	550.98	1593.70	898.94	1801.00	1107.68	1503.70	755.39
2005	1660.20	898.94	1576.00	919.93	2021.00	1177.52	1788.50	992.67	1748.90	938.67
2006	897.00	330.11	905.00	335.09	1685.00	886.82	1292.00	596.86	1029.30	362.06
2007	1156.00	618.04	1021.00	469.63	1578.00	935.95	1046.00	417.79	1139.10	596.58
2008	1365.70	607.00	1248.00	533.29	1848.00	1134.72	1252.50	559.72	1511.70	677.10
2009	1150.90	466.48	1245.00	632.20	1388.50	635.56	755.00	282.67	1294.20	538.57
2010	1615.80	784.16	1557.00	750.21	1562.50	787.27	1106.00	482.37	1711.10	872.05
2011	1456.00	805.43	961.00	496.21	1207.00	632.81	853.00	299.01	1374.60	740.76
2012	752.80	325.42	747.00	304.74	832.00	392.89	414.00	119.64	1008.40	475.35
2013	1236.70	601.32	952.00	310.82	1161.70	453.09	650.00	129.19	1224.10	541.18
2014	873.90	343.98	936.00	339.29	1256.80	500.21	832.00	298.54	831.30	306.45
2015	1745.60	954.64	1766.00	902.10	1992.60	1085.03	1059.50	393.88	1689.30	887.27

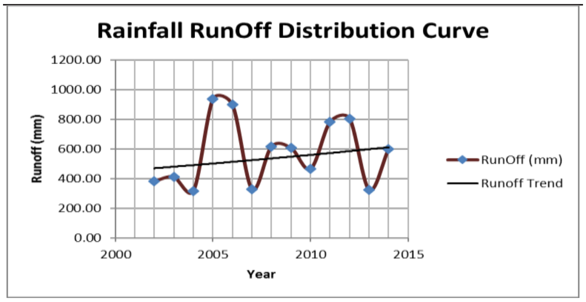

Fig. 6: Trend line of runoff Kuppanatham.

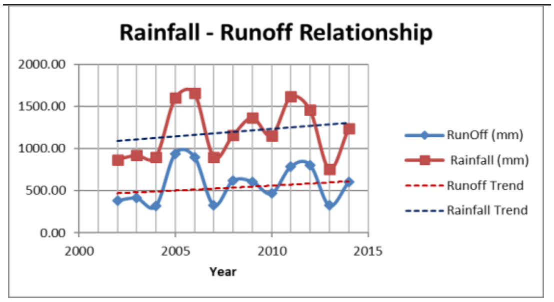

Fig.7: Positive correlation between rainfall and runoff in Kuppanatham.

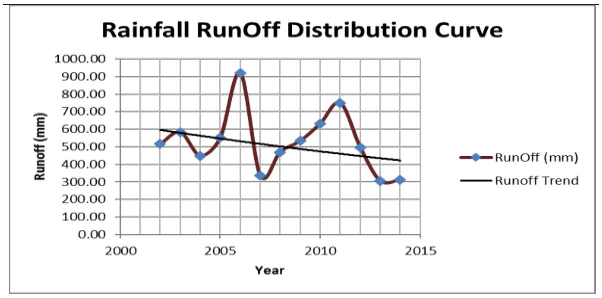

Fig. 8: Trend line of runoff decreased over years in Memathur.

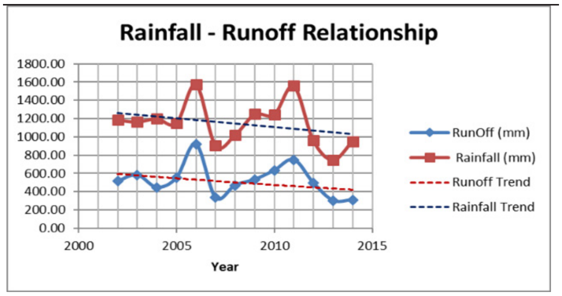

Fig. 9: Positive correlation between rainfall and runoff Memathur.

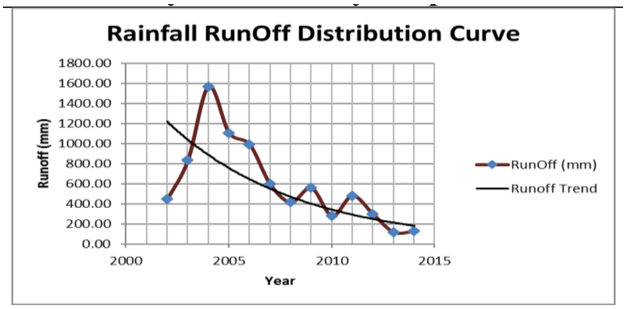

Fig. 10: Trend line of runoff increased over years in Sethiyathope.

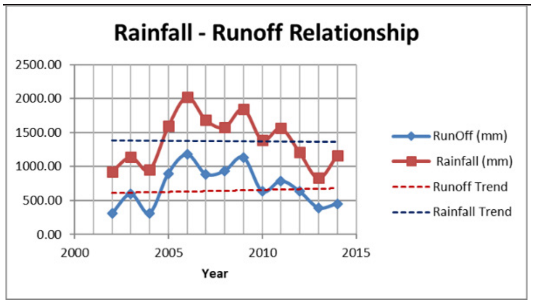

Fig. 11: Positive correlation between rainfall and runoff in Sethiyathope.

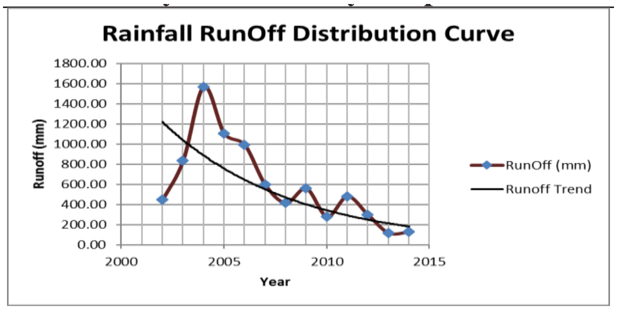

Fig. 12: Trend line of runoff tremendously decreased over years in Srimushnam.

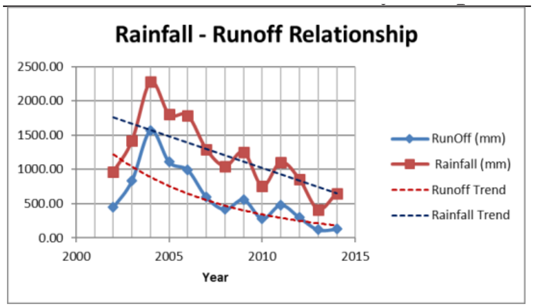

Fig. 13: Positive correlation between rainfall and runoff in Srimushnam.

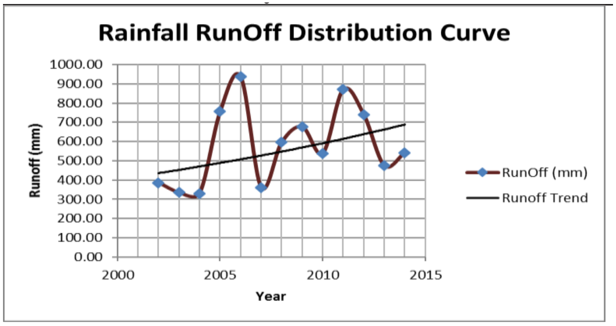

Fig. 14: The trend line of runoff increased over years in Virudhachalam

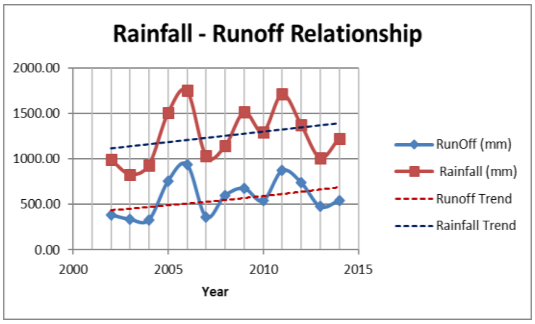

Fig. 15: Positive correlation between rainfall and runoff in Virudhachalam.

rainfall and runoff at Sethiyathope were both recorded at the same rainfall station. In Srimushnam, the Memathur rainfall station received the least rainfall and had the least drainage. In 2005, the lower Vellar basin's average runoff was at its highest (985.5445 mm). In 2012, the lower Velar basin's average rainfall was at its lowest (323.6096 mm).

CONCLUSION

This study mainly focuses on the estimation of losses due to surface runoff, which is favorably based on the soil infiltration characteristics and the continuation of rainfall occurrences. Knowledge of runoff from individual rainfall is required to evaluate the runoff behavior of a catchment area, as well as a sign of both the runoff-peaks that the water harvesting scheme's structure must be able to withstand the elements, as well as the required capacity for temporary surface runoff storage, such as a micro catchment system, the size of an infiltration pit. The watershed as a whole receives a good amount of rainfall. But, when compared to runoff, recharge is relatively low, as the terrain is comprised of crystalline rocks. By building agricultural ponds at suitable locations, this runoff potential can be used for artificial recharge. Additionally, buildings such as check dams are being built to store water. It will be useful for drinking water as well as agricultural applications during the hot summer days.

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