

Assessment of Flood Potential Ranking of Subwatersheds: Adayar Watershed a Case Study

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ABSTRACT: Flooding may be caused due to a combination of heavy rain, blockage in the channel, development along the stream channel and urbanization in the upstream of the watershed. The assessment of the extent of flooding in a watershed is essential for its sustainable development. The flow contribution to the river from upstream areas outside the city limits are generally neglected in the downstream flood management. The present study focuses on the Adayar watershed, Chennai. It emphasizes on identification and prioritization of flood source area by coupling Unit Flood Response (UFR) technique and HEC-HMS, considering the spatial distribution of the rainfall. The results indicate that Manimangalam sub-watershed ranks first in production of peak discharge. As a flood mitigation strategy, recharge zones are identified in order to reduce the severity of flooding. The outcome of the study would help in formulating policy guidelines and intervention strategies.

KEYWORDS: Unit Flood Response (UFR) technique, spatial distribution, Adayar watershed

Highlights (i) Unit Flood Response (UFR) technique accounting spatial variability is applied to Adayar watershed and flood source areas are identified and the measures to reduce the flood hazard are proposed;

(ii) A generalized Intensity-Duration-Frequency Equation is fitted based on Sahadevan's (1980) results for Meenambakkam rain gauge station and can be used to determine the intensity of rainfall for a given return period and time of concentration for south Chennai.

I. INTRODUCTION

Chennai is a coastal city, where the two rivers, namely Adayar and Cooum, flow through. The Chennai Metropolitan Area (CMA) can broadly be divided into three parts. The northern part lies above the Cooum River, middle region is between Cooum and Adayar Rivers and the southern portion is below Adayar River. Due to encroachment along the banks of these rivers and non-enforcement of the laws pertaining to protection of water bodies and fragmentation of responsibilities amongst the agencies, the effect of flooding tends to be severe. Developmental activities along stream channels can reduce the capacity of the channel to convey water and can raise the level of flow. This results in flooding due to heavy rains, with the water overflowing and inundating surrounding habitations.

The Adayar River originates at an elevation of about 40 m above Mean Sea Level (MSL) at Guduvanchery reserve forest. This river serves as a surplus course for the irrigation tanks (water bodies) on the upstream. The flood plain of Adayar River is stressed due to unplanned development and encroachment. The change in the land use and land cover (LULC) pattern due to rapid urbanization adversely affects the hydrological processes in the catchment, leading to a deteriorating water environment. Several Government agencies like Tamil Nadu Public Works Department (PWD), Corporation of Chennai, Tamil Nadu Slum Clearance Board (TNSCB), Chennai Metropolitan Water Supply and Sewerage Board (CMWSSB), Tamil Nadu Pollution Control Board (TNPCB) and Chennai Metropolitan Development Authority (CMDA) have attempted in the rehabilitation and management of river. These agencies have focused mainly on the technical/structural interventions in the system such as clearing of sand bar, dredging the sludge, constructing check dams and lining the river banks to improve the flow in the river. Despite the

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many efforts taken by them, the situation does not seem to improve. This may be due to fragmented approach by the community and professionals, who tend to give high priority to developmental projects with no overview of the watershed or social and institutional aspects of the problem. For formulating any flood management strategy, it is necessary to identify areas having high flood hazard potential. This study focuses on identifying the flood source area and a measure to reduce the effect of flooding on downstream.

II. STUDY AREA DESCRIPTION

According to All India Soil and Land Use Survey Organization (AISLUS 1990), the Adayar watershed is codified as '4C2C2'. The letters signify the following:

- | | | |
|--------------------------|---|--|
| 4 Region | – | Rivers draining in to the Bay of Bengal |
| C Basin | – | Between Cauvery and Krishna (Pennar) |
| 2 Catchment | – | Between Pennaiyar to Pennar |
| C Sub catchment | – | Miscellaneous around Chennai |
| 2 Watershed | – | Adayar |
| a, b, c, d Sub-watershed | – | Thirusoolam, Manimangalam, Orathur, Dasarikuppam respectively. |

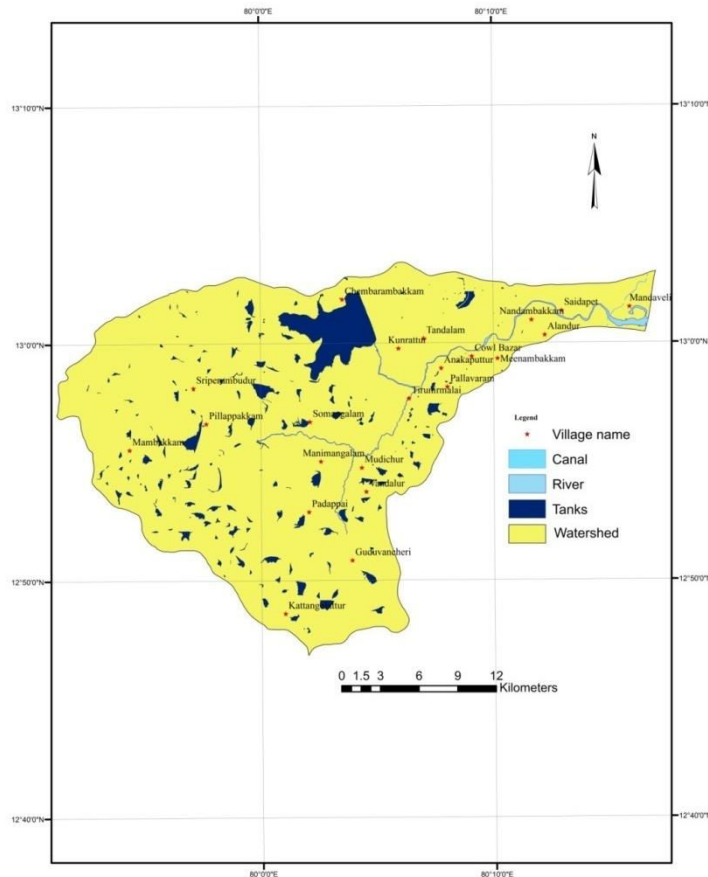


Figure 1 Index map of Adayar watershed

The study area extends between the North Latitudes 12°47'6'' N and 13°3'22''N and East Longitudes 80° 17'1''E and 79°52'36''E with an area of about 705 km². The area falls in 57 P/131, 57 O/ 161, 66 C/4, 66 C/8, 66 D/1 and D/5

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Survey of India Toposheets. This watershed forms part of blocks like Chenglepet, Saidapet, Sriperumbudur and Chennai city. The watershed comprises of about 113 villages and 7 reserve forest. Figure 1 shows the index map of the watershed.

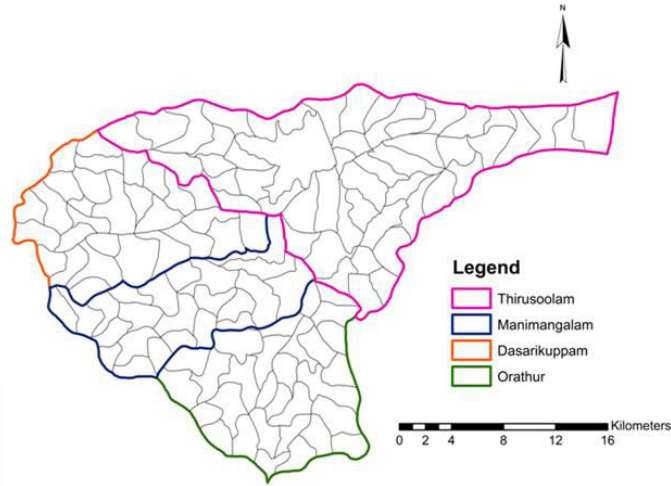


Figure 2 Sub and Micro watersheds of the Adayar watershed

Based on Shuttle Radar Topography Mission (SRTM), Digital Elevation Model (DEM) and stream flow data, the watershed was delineated into four sub-watersheds. Figure 2 presents the sub- and micro-watersheds of the Adayar watershed.

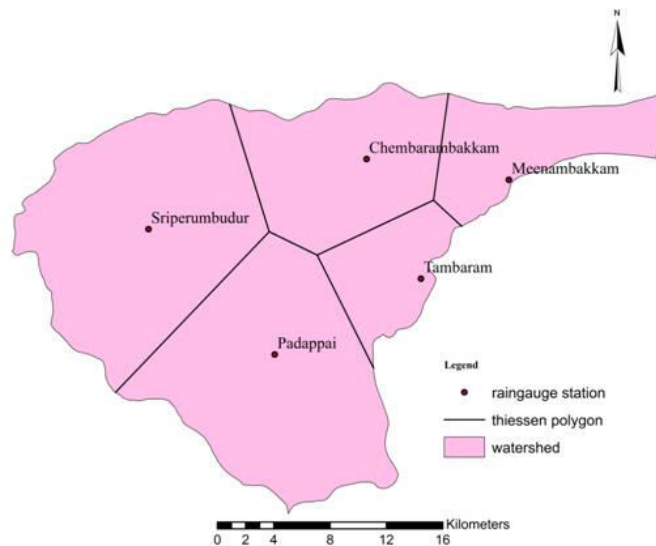


Figure 3 Location of rain gauges in the study area

There are five rain gauge stations located in the study area as shown in figure 3.

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III. MATERIALS AND METHODS

As the hydrological and meteorological data are not extensive, it is difficult to simulate the runoff yield through common hydrological methods. Moreover, the parameters and structure of traditional hydrological models are not adaptable to data from remote sensing (Lu 1990). Therefore, a hydrological model based on remote sensing (HEC-GeoHMS) (USACE 2003) was used to develop the basin model and the HEC-HMS (USACE 2000) was used to simulate the runoff response of an area to a given amount and distribution of precipitation over a defined period of time. The main components of HEC-HMS are basin model, meteorologic model and control specifications. Basin model gives the physical description of the watershed. The basin file created by HEC-GeoHMS was imported as the basin model for the new project.

For all the simulations, the loss method used is Soil Conservation Service (SCS) Curve Number (CN) method and the baseflow is neglected. Muskingum-Cunge method is used for channel routing and the watershed transform method was SCS Unit Hydrograph (UH). The meteorological model of the HEC-HMS handles the atmospheric conditions over the watershed. In this study, the gauge weight method was used for the meteorological data analysis. It was used for distributing the rain gauge station values over the watershed and the weights of each gauge was found using the inverse squared distance method given in Equation (1).

$$w_i = \frac{\frac{1}{d_i^2}}{\sum_{i=1}^n \frac{1}{d_i^2}} \tag{1}$$

where:

- w_i is weight of i^{th} rain gauge;
- d_i is distance of i^{th} rain gauge to the centroid of the sub basin; and
- n is number of gauges.

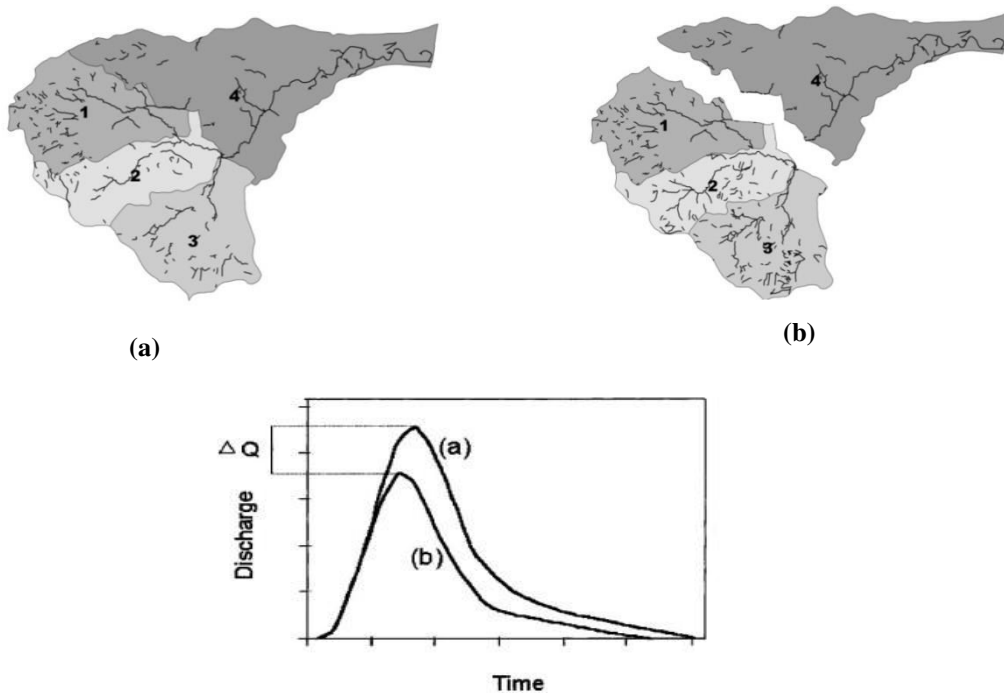


Figure 4 Unit Flood Response Approach
(Source: Saghafian and Khosroshahi 2005)

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The most important task in flood mitigation is the identification of flood source areas. Unit Flood Response (UFR) approach (Saghafian and Khosroshahi 2005) was used to rank the sub-watersheds based on the contribution of the sub-watersheds to the flood generation at downstream areas. According to this technique, the Adayar watershed was subdivided into four sub-watersheds namely Dasarikuppam, Manimangalam, Orathur and Thirusoolam. All data (flow direction, flow accumulation and rainfall data) relevant to the four sub-watersheds were prepared and the flood hydrograph is simulated for 100 year return period in HEC-HMS model. This operation results in the base flood hydrograph. Then, each sub-watershed was turned off one-by-one in successive runs, and the resultant hydrograph at the main outlet were obtained. The changes in flood peak values of the generated hydrographs were compared with the base hydrograph in order to identify the single contribution of each sub-watershed unit on the flood peak at the main outlet. The sub-watershed with the largest decrease on flood peak was given the highest flood rank. Other sub-watersheds were ranked based on their contribution (Saghafian et al 2008). They were prioritized based on two flood indices given in Equations (2) and (3). Figure 4 describes the UFR approach.

$$FI_k = \frac{Q_{o,all} - Q_{o,all-k}}{Q_{o,all}} \times 100 \tag{2}$$

$$fi_k = \frac{Q_{o,all} - Q_{o,all-k}}{A_k} \tag{3}$$

where:

FI_k is (gross) flood index of k^{th} watershed (in percentage);

fi_k is flood index of k^{th} sub-watershed on the basis of unit sub-watershed area ($m^3/s/km^2$);

A_k is area of the k^{th} sub-watershed (km^2);

$Q_{o,all}$ is peak outlet discharge with all sub-watershed units present in the base simulation (m^3/s); and

$Q_{o,all-k}$ is peak outlet discharge with k^{th} sub-watershed removed (m^3/s).

IV. RESULTS AND DISCUSSIONS

4.1 Development of Generalized IDF Equation for South Chennai

The precipitation data recorded by the rain gauge stations help to determine the frequency and the character of the precipitation events in the vicinity of the site. The point rainfall data were used to develop frequency relationships among rainfall depth, intensity and duration. These relations are known as Intensity–Duration–Frequency (IDF) curves and they are used for designing storm water management facilities and floodway reservations (Viessman and Lewis 2007). IDF curves were developed for Meenambakkam rain gauge station for different return periods by Sahadevan (1980). However, in the above study the maximum time of concentration was limited to 480 minutes. But, in the Adayar catchment area, the time of concentration is about 1552 minutes. The curves given by Sahadevan (1980) cannot be directly used in the present study. In the absence of IDF curves for duration greater than 480 minutes, there is a need to extrapolate the IDF curves for the duration of 1552 minutes. Curve fitting was resorted in order to find the relationship between intensity, duration and frequency. Thus, treating Sahadevan’s IDF curve as a base, a generalized Equation was arrived at by exploiting the data. The intensity duration curve for the Meenambakkam rain gauge station is given in Figure 5 and their relationship is given in the Table 1.

Table 1 Relationship between intensity and duration

Sl.No.	Return period (years)	Relationship
1	2	$i = 353.09 t_c^{-0.554}$
2	5	$i = 401.93 t_c^{-0.509}$
3	10	$i = 433.10 t_c^{-0.484}$
4	20	$i = 452.59 t_c^{-0.472}$
5	30	$i = 471.75 t_c^{-0.463}$
6	40	$i = 487.95 t_c^{-0.457}$
7	50	$i = 501.16 t_c^{-0.455}$
8	100	$i = 537.97 t_c^{-0.446}$
9	200	$i = 583.51 t_c^{-0.446}$

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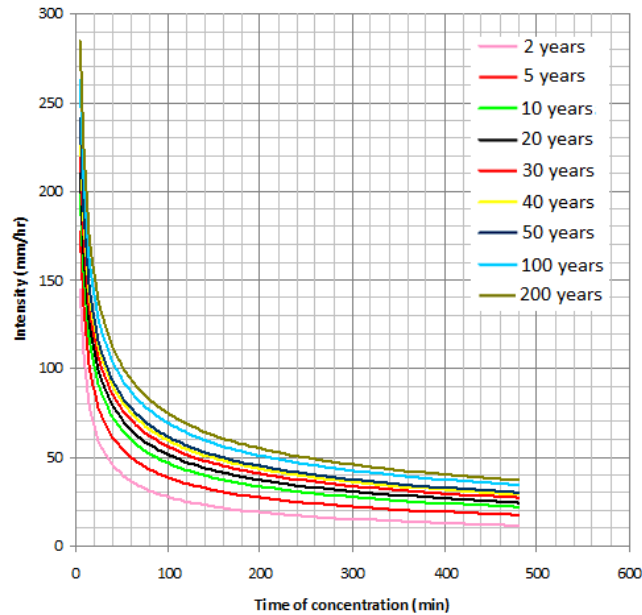


Figure 5 Intensity–Duration–Frequency (IDF) diagram for Meenambakkam rain gauge station

The generalized Equation for the Meenambakkam rain gauge station which gives relationship between intensity – duration – frequency is found to be

$$i = kt_c^{-n} \tag{4}$$

where:

i is intensity of rainfall (mm/hour); and
 t_c is time of concentration (minutes).

$$k = 47.74 \ln(t_r) + 318.02 \tag{5}$$

$$n = 0.551 t_r^{-0.0468} \tag{6}$$

where:

t_r is return period (years)

4.2 Flood Index Results Using UFR Approach

As stated in the previously, HEC-HMS model was used to determine the flood index values corresponding to 2005 land use conditions and a 100 year return period rainfall. The contribution of each sub-watershed to the flood peak at the outlet was quantified using Unit Flood Response (UFR) approach (Saghafian and Khosroshahi 2005) under two conditions (i) with no spatial variation in the distribution of rainfall; and (ii) with spatial variation in the distribution of rainfall. The rainfall values of the five rain gauge stations were spatially distributed over the watershed using inverse square distance method. This forms a basis to rank the sub-watershed in terms of their flood potential. Tables 2 and 3 show the ranking of sub-watersheds in terms of their flood characteristics. A dimensionless flood index fi^* is introduced and is given in Equation (7) as

$$fi^* = \frac{FI}{(A_{all} - A_{all-k}) / A_{all}} \tag{7}$$

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Table 2 Flood index without spatial variability

Sl. No.	Category	Dasarikuppam sub-watershed	Manimangalam sub-watershed	Orathur sub-watershed	Thirusoolam sub-watershed	Adayar watershed
1	Area (km ²)	146.99	112.82	145.44	299.75	705
2	Sub-watershed peak discharge (m ³ /s)	256.4	148.7	302.9	443.5	1151.5
3	Priority based on sub-watershed peak discharge	3	4	2	1	–
4	Priority based on sub-watershed specific peak discharge	2	4	1	3	–
5	Outlet peak discharge without sub-watershed (m ³ /s)	866.9	429.2	489.2	823.9	–
6	Flood index FI (%)	25	63	58	28	–
7	Priority based on FI	4	1	2	3	–
8	Flood index fi (m ³ /s/km ²)	1.94	6.4	4.55	1.09	–
9	Priority based on fi	3	1	2	4	–
10	Dimensionless fi*	0.32	0.75	0.73	0.49	–
11	Priority based on fi*	4	1	2	3	–

Table 3 Flood index with spatial variability

Sl. No.	Category	Dasarikuppam sub-watershed	Manimangalam sub-watershed	Orathur sub-watershed	Thirusoolam sub-watershed	Adayar watershed
1	Area (km ²)	146.99	112.82	145.44	299.75	705
2	Sub-watershed peak discharge (m ³ /s)	269.9	168.5	318.4	483.8	1342.2
3	Priority based on sub-watershed peak discharge	3	4	2	1	–
4	Priority based on sub-watershed specific peak discharge	2	4	1	3	–
5	Outlet peak discharge without sub-watershed (m ³ /s)	1036.9	483.8	552.8	911.4	–
6	Flood index FI (%)	23	64	59	32	–
7	Priority based on FI	4	1	2	3	–
8	Flood index fi (m ³ /s/km ²)	2.08	7.61	5.43	1.44	–
9	Priority based on fi	3	1	2	4	–
10	Dimensionless fi*	0.29	0.81	0.74	0.56	–
11	Priority based on fi*	4	1	2	3	–

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From the Tables 2 and 3, it is obvious that by accounting for the spatial variability of rainfall, better results can be obtained. As seen in Table 3, Thirusoolam sub-watershed generates the largest peak discharge of 483.8 m³/s and Manimangalam sub-watershed produces the smallest peak flow of 168.5 m³/s. Based on the UFR approach, the flood source areas are identified and ranked as in row 7 (peak discharge contributions, FI) and row 9 (per unit sub-watershed area peak-discharge contribution, fi) in the above table. Although Thirusoolam and Manimangalam sub-watersheds hold first and last ranks, respectively in both area and peak discharge, they are in difference with respect to FI, fi and fi* ranks. For example, the rank of Dasarikuppam sub-watershed, which has second largest area, has the third highest peak, and ranks fourth for FI flood index and third for fi flood index. This illustrates that integrated effect of different factors such as spatial distribution of rainfall, physical characteristics of watershed, topology of river network, river routing play an important role in determining the contribution to flood peak at the outlet. The effects of these factors were simulated using hydrologic models.

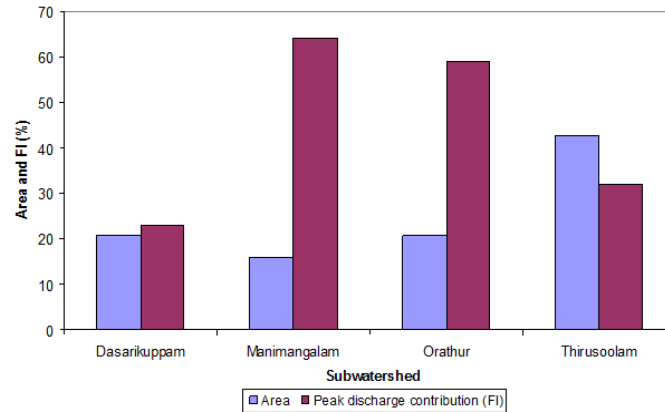


Figure 6 Comparison of area and flood index (FI) for the respective sub-watersheds

Figure 6 compares the flood index FI and the percentage area for each sub-watersheds. The area of Manimangalam sub-watershed (112.82 km²) is 1.28 times less than that of Orathur sub-watershed (145.44 km²) and the ratio of their contributions to the outlet peak discharge stands at 1 to 1.89. These two sub-watersheds ranked first and second, respectively in the flood index, FI and flood contribution per unit area, fi. The flood contribution per unit area, fi is considered an important criterion in determining the location of head water flood – abatement measures (Saghafian and Khosroshahi 2005).

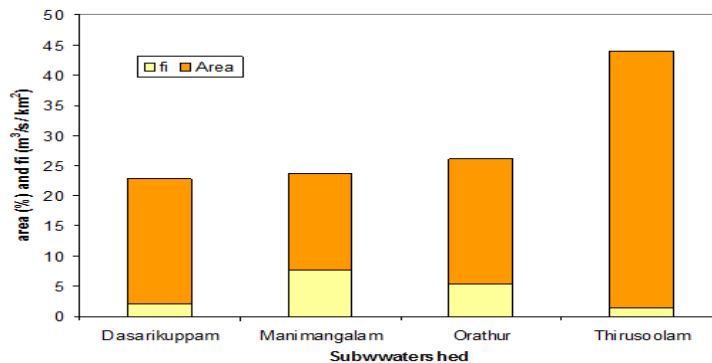


Figure 7 Area (in percent of total area) and outlet peak discharge contributions per unit area (fi) of sub-watersheds

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Figure 7 depicts values of row 9 in Table 3 in a histogram form and shows the relative rankings of sub-watersheds with respect to unit area contribution. According to Table 3 and Figures 6 and 7, it is understood that rankings of flood index, FI and flood contribution per unit area, f_i and dimensionless f_i^* may differ i.e. Thirusoolam watershed ranks 3 in FI and f_i^* but holds rank 4 in f_i . Manimangalam watershed which ranks first in FI, f_i and f_i^* is identified as a flood source area and therefore it should be prioritized for planning flood – abatement measures.

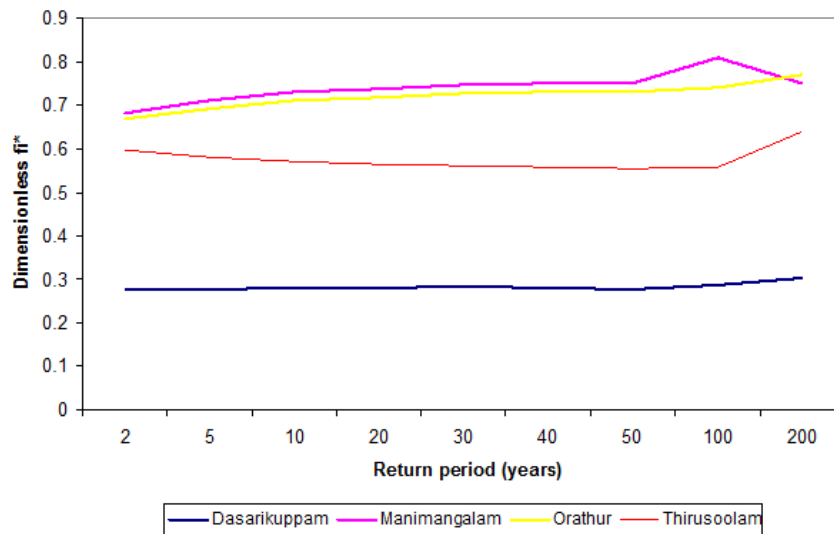


Figure 8 Comparison of f_i^* for different return periods

From Figure 8, it is clear that for higher return periods, rural watershed tends to show a small decrease, urban watershed tends to show a sharp increase and in a mix of rural and urban watershed, it tends to show a small increase in dimensionless flood index. This dimensionless flood index can also be used to prioritize the sub-watersheds.

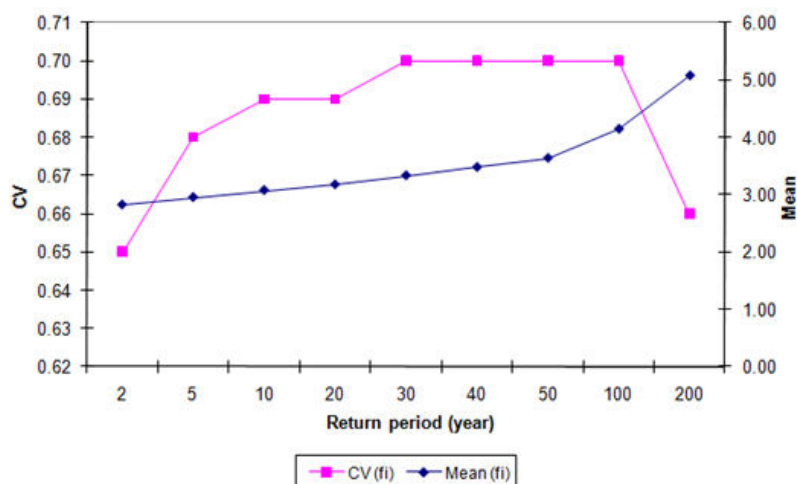


Figure 9 Effect of return period on coefficient of variation and mean of sub-watershed flood index, f_i

Figure 9 presents the effect of return period on coefficient of variation and mean of sub-watershed flood index, f_i . It is seen that the mean of the sub-watershed flood index increases with the return period, whereas, there is no consistent trend in coefficient of variation with respect to the return period. This trend exists due to the flat topography

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of the watershed. The results indicate that the rainfall with higher return period would tend to increase the sub-watershed flood responses in urban areas.

4.3 Flood Mitigation Measures

Flood mitigation is defined ‘as measures aimed at decreasing or eliminating the impact of floods on society and the environment’ (BTRE Report 2002). Andjelkovic (2001) states that ‘mitigation means planning, programming, setting policies, co-coordinating, facilitating, raising awareness, assisting and strengthening and it does not include insuring, assessing, financing, relieving and rehabilitating’. Mitigation is split into two types: Structural mitigation, which refer to the engineering measures such as construction of levee, check dams, flood gates, diversions and channel improvements etc., Non-structural mitigation, which pertain to knowledge development, public awareness including participatory mechanisms and the provision of information can reduce risk with related impacts.

Structural mitigation measures should be adapted in urban watershed, while in rural watersheds, non-structural mitigation measures are more appropriate. Since, Manimangalam sub-watershed (non-urban watershed) has been prioritized as flood source area, it would be better to make interventions in that sub-watershed. Hence, potential recharge zones were identified in Manimangalam sub-watershed. The concept behind the identification of potential recharge zone in the upstream is to minimize the effect of flooding in the downstream tributaries. In this study, the recharge zones were identified by overlaying the soil map, geology map, geomorphology map and lithology map.

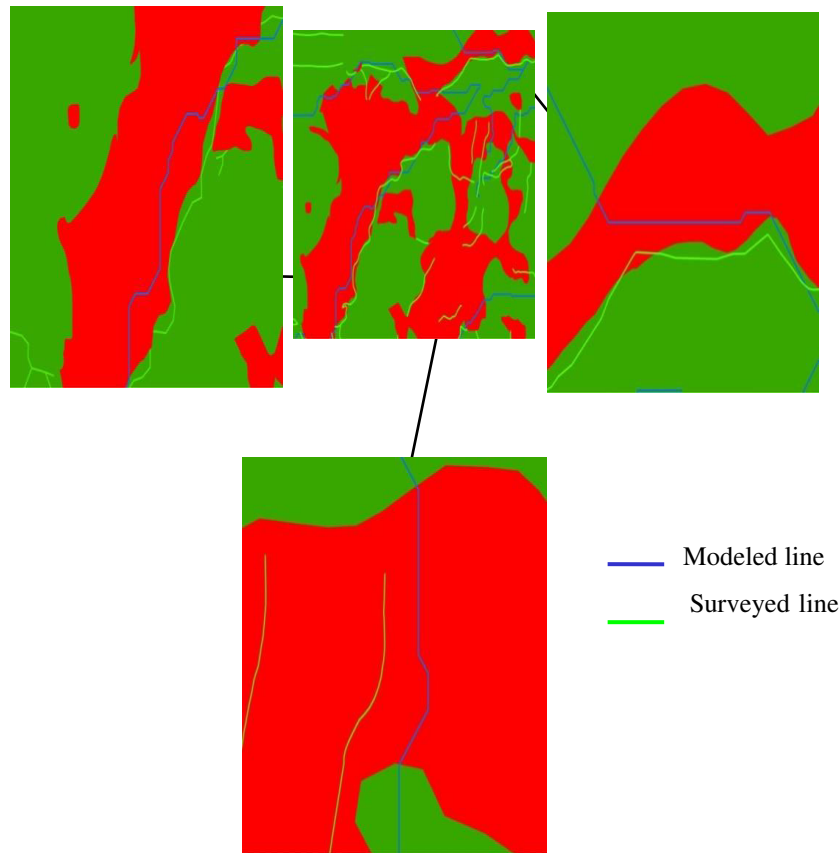


Figure 10 Identification of potential recharge zones

The overlaid map was once again overlaid with modeled stream lines (blue lines) and surveyed streamlines (light green lines) as found in Figure 10. There is a mismatch between surveyed and simulated streamlines.

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Most of the mismatches are found in the Manimangalam sub-watershed, which is identified as flood source area and is located in the upstream end of the Adayar watershed. It is also found that the modeled streamlines extend beyond the surveyed streamlines. Saraf et al 2004 showed that where the ground water recharge is high, the degree of mismatch between the surveyed and the simulated lines are also high and this mismatch can be used to delineate the ground water recharge zones. Combining with soil, lithology, geology and geomorphology information of the study area, the high recharge zones are identified, where there is misfit between the surveyed and simulated stream lines.

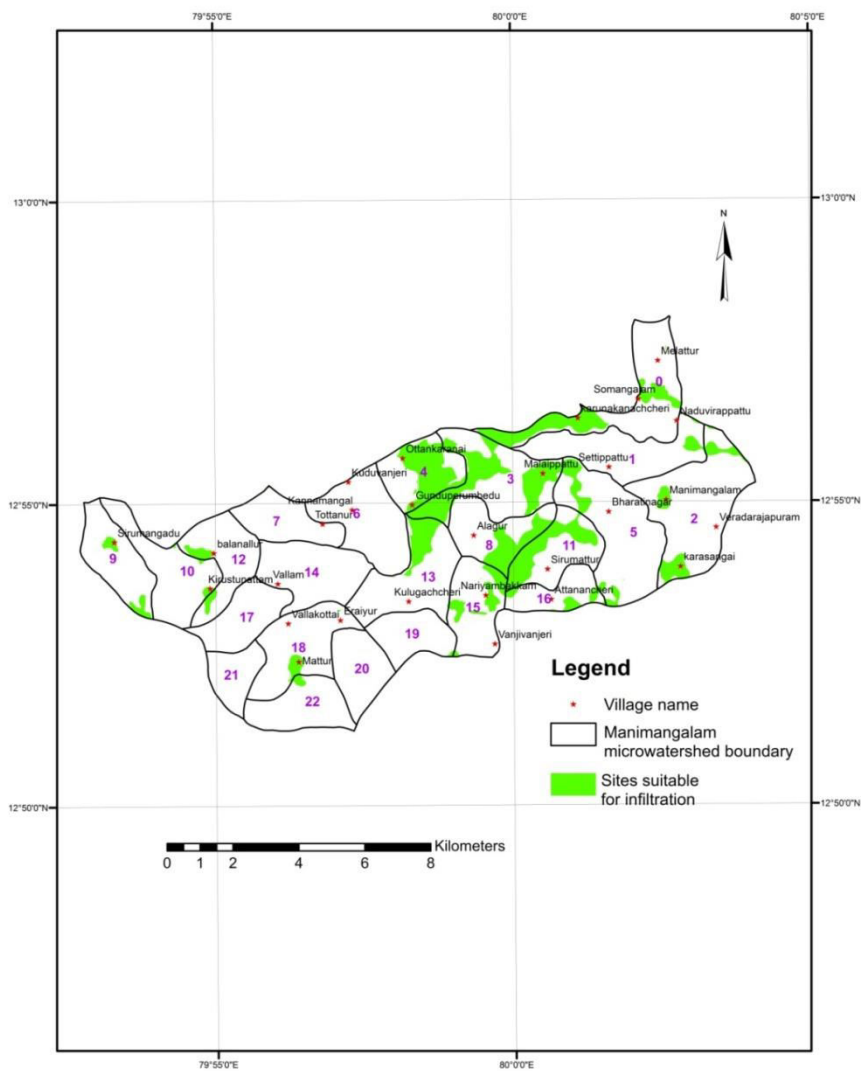


Figure 11 Sites suitable for recharge zones

From the Figure 11, it is seen that some portions of micro-watersheds 0, 3, 4, 8 and 11 are the locations suitable to be recharge zones in Manimangalam sub-watershed.

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V. CONCLUSIONS AND RECOMMENDATIONS

Identifying flood source areas in the watershed is considered to be important in order to reduce the impact of floods. In this study, the flood source area (watershed) was identified by coupling UFR technique developed by Saghafian (2005) and HEC-HMS in the Adayar watershed. The following are the salient conclusions drawn from the present study:

- (i) An equation is derived for the Intensity-Duration-Frequency curves of Sahadevan (1980). This can be used to determine the intensity for a given time of concentration and return period for South Chennai.
- (ii) Contribution of each of the sub-watersheds to the runoff process is calculated using Unit Flood Response (UFR) method. Thus, the flood potential of a particular sub-watershed is quantified and its priority is determined based on its contribution of flood peak discharge at the outlet. UFR approach was used to identify flood source area. Results indicate that Manimangalam sub-watershed of Adayar watershed ranks first in production of peak discharge compared to other sub-watersheds due to high slope and low infiltration. As a flood mitigation strategy, if the flood at source area is managed, then the severity of flooding in the downstream areas can be reduced. Hence, recharge zones are also identified in Manimangalam sub-watershed in order to mitigate the floods.

Urbanization tends to increase peak discharge, reduce infiltration and increase the runoff volume. Due to increasing population and encroachments, the channels have lost their ability to carry flood water. Therefore, efforts should be made to prevent the destruction of the channels. Human settlements must not be allowed in the flood prone areas. Existing storm water drains and water bodies must be maintained properly. On the whole, the encroachment seen on the river banks, sewage disposal and solid waste dumping in the river must be prohibited to reduce flood vulnerability. The Government should clearly delineate the responsibility and obligation of each management sector and it should consider the entire watershed and not the river alone within city limits for any intervention. The effect of flooding on downstream can be minimized if the potential recharge zones identified in Manimangalam sub-watershed is utilized to recharge the aquifers. Further studies are required in developing 'iso-flood severity map' which would help to identify and prioritize flood source area at desired scale.

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