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COMPREHENSIVE ASSESSMENT OF URBAN SURFACE RUNOFF MANAGEMENT USING THE SWAT MODEL AND GIS: A CASE STUDY OF VILLUPURAM MUNICIPALITY

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Abstract: Urban surface runoff management refers to the strategies and practices used to control and manage the flow of rainwater, reduce urban flooding, enhance groundwater recharge, disaster risk management, and urban sustainability. This study focuses on improving water management practices and reducing flooding risks in urban areas by optimizing the management of surface runoff using the SWAT (Soil and Water Assessment Tool) model with Geographic Information Systems (GIS). The primary objective is to analyze water management practices and water bodies in Villupuram Municipality, evaluate surface runoff under varying urban and environmental conditions, and identify areas prone to waterlogging and urban flooding, Villupuram Municipality has a population of 141,162 in the 2011 census and covers an area of 33.13 square kilometers, divided into 42 wards. While it has historically been viewed as having low vulnerability to natural disasters, recent severe flooding incidents have highlighted significant issues in its water management strategies. The municipality's transportation infrastructure, including the Chennai-Trichy highway and the railway system, Housing, agriculture, and physical infrastructures has suffered due to unexpected flooding, emphasizing the urgent need for effective surface runoff and water management strategies to bolster resilience and sustainability. By utilizing the SWAT model alongside GIS, surface runoff can be simulated, and spatial patterns can be visualized, offering essential insights for urban planners and decision-makers to develop effective mitigation strategies. Ultimately, this research aims to enhance the resilience of Villupuram Municipality's infrastructure and promote community sustainability by tackling the challenges associated with surface runoff and improving water management practices.

Keywords: Urban resilience; urban surface runoff; SWAT model; flooding risks; waterlogging; disaster risk management.

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INTRODUCTION

Urban surface runoff is a pressing issue in rapidly urbanizing municipalities, particularly in regions prone to extreme weather events. Villupuram Municipality has experienced recurrent flooding due to inadequate surface runoff management, exacerbated by unplanned urban expansion and poor drainage infrastructure. The study area is Viluppuram Municipality, which serves as the administrative hub of Villupuram district. It spans 33.13 km², is made up of 42 wards, and has a population of 141,162. The aim is to optimize urban surface runoff management using the Soil and Water Assessment Tool (SWAT) model integrated with Geographic Information System (GIS) to enhance water management practices and mitigate flooding risks in urban areas. The objectives of this study are:

- Examining water management practices and water bodies in Villupuram Municipality
- Analysing surface runoff behaviour under varying urban and environmental conditions,
- Identifying areas susceptible to waterlogging and urban flooding,
- Analysing the topography of Villupuram Municipality, Understanding land use patterns and their impact on runoff,
- Applying the SWAT model and GIS to simulate surface runoff and visualize spatial patterns for further recommendations.

Background

In the background study, the urban flood risk assessment conducted in SWAT, Pakistan, highlights the integration of various data sources—such as topographic maps, land use/land cover information, rainfall data, and infrastructure details—using AHP and geospatial techniques to develop a comprehensive flood risk assessment model (Waseem *et al*., 2023). Existing drainage systems are inadequate to manage future flooding risks due to slight changes in rainfall intensity predicted by climate models (Bibi *et al*., 2023). The importance of implementing effective flood management strategies to mitigate the impact of flooding on the region's infrastructure and natural ecosystems (Osei *et al*., 2021). Urbanization increased the demand for flood regulation in floodplains, while land use changes decreased the basin's capacity to provide these services (Mori *et al*., 2021). land use practices significantly impact runoff and sediment yields in the Jemma Subbasin. (Zewde *et al*., 2023). understand the valley's topography, drainage patterns, and landforms, which are crucial for water resource management, land use planning, and environmental conservation in the region (Ahmad *et al*., 2024). The SWAT model predicts future trends in water balance components and river discharges under current land use practices (Desta *et al*., 2017). The basin was divided into several HRUs based on land use, soil type, and slope (Panhalkar *et al*., 2014). The methodology was developed for assessing flood regulating services and Key factors influencing flood regulation dynamics (Mori *et al*., 2021). The examination of the relationship between LULC changes and surface runoff generation (Kim *et al*., 2016). The execution of appropriate remedial measures to mitigate potential flash floods (Nasir *et al*., 2020). The influence of rainfall on runoff by considering rainfall records (suwannachai *et al*., 2024). The residential cover significantly influences surface runoff in urban areas. Higher residential cover leads to increased surface runoff due to reduced infiltration and increased impervious surfaces (Xu *et al*., 2020).

Villupuram Municipality, the administrative hub of Villupuram district, which was established in 1919, located approximately 11.9398° N and 79.4924° E (**Fig. 1)** has seen considerable growth, evolving from an II Grade to a Selection Grade Municipality. It spans 33.13 square kilometers and consists of 42 wards, with a population of 141,162 (2011 Census). While the area was traditionally viewed as less vulnerable to natural disasters, the recent severe flooding during Cyclone Fengal in 2024 exposed weaknesses in the drainage and runoff systems.

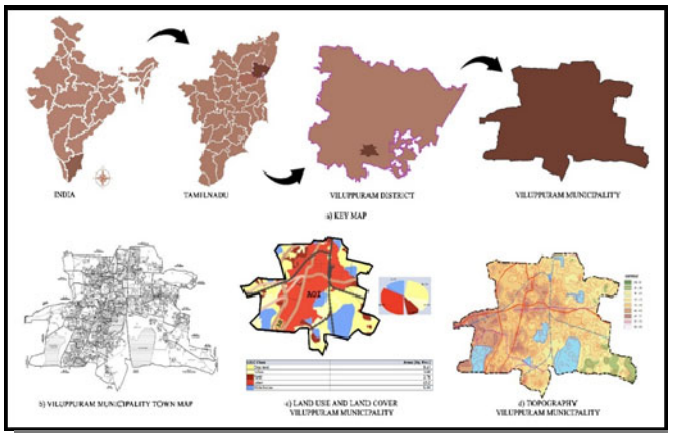


Fig. 1 (a) Keymap, (b) Viluppuram municipality town map, (c) land use and land cover, and (d) topography source: Viluppuram Municipality Town map

Materials and Methods

A comprehensive literature review and case study analysis were conducted using both national and international journals. Villupuram Municipality was chosen due to the effects of Cyclone Fengal in 2024. Secondary data was gathered from Viluppuram Municipality, while primary data was collected through field surveys and sampling to assess the current conditions in the area. The study utilizes the SWAT to

effectively simulate and improve the management of urban surface runoff. The methodology includes several key steps, such as data collection, preprocessing, model setup, and scenario analysis (**Fig. 2**). The input datasets consist of land use/land cover (LULC) maps, soil characteristics, and climate data.

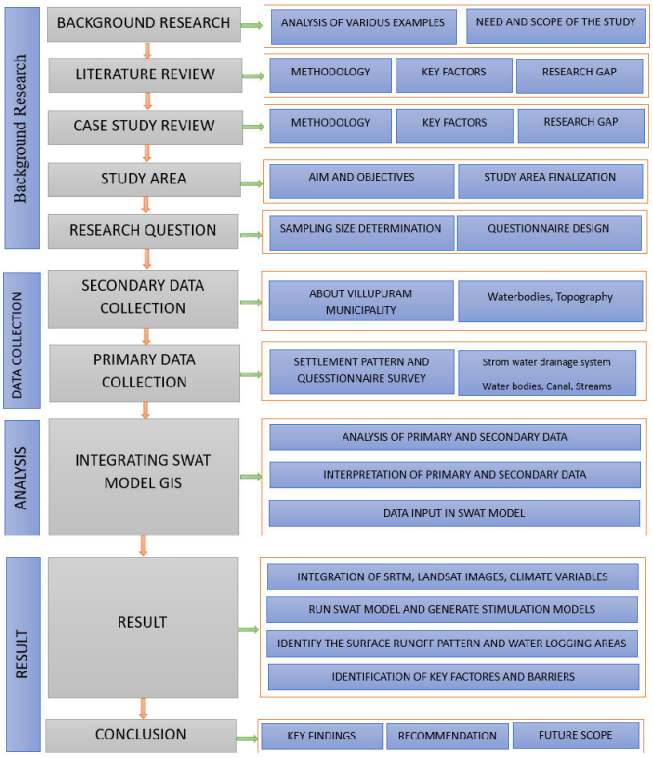


Fig. 2 Methodology

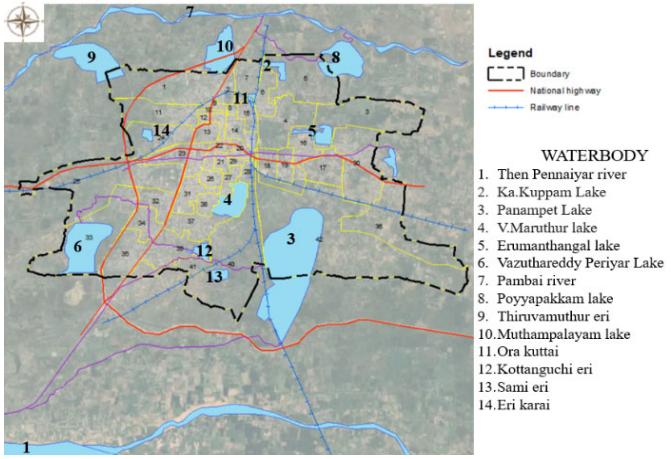


Fig. 3 Waterbody map of viluppuram municipality

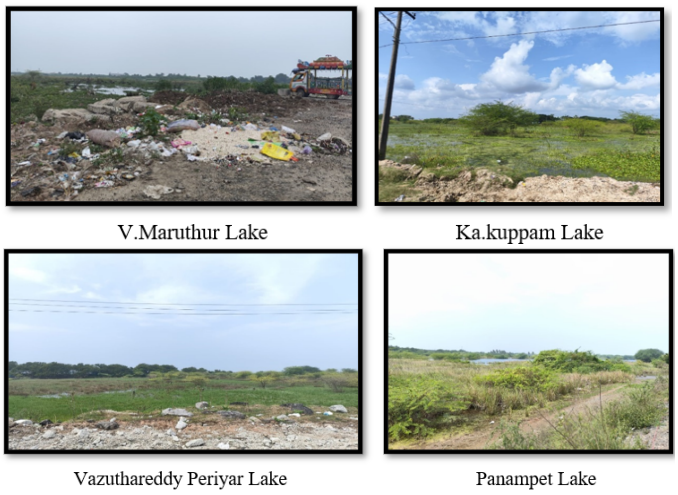


Fig. 4 Major water bodies

Data Collection

Data is collected from the municipal office and the disaster management office to obtain crucial information, such as rainfall patterns from 2008 to 2024, soil maps, and land use maps. This information serves as the basis for analyzing surface runoff patterns and creating effective water management strategies.

Viluppuram Municipality is home to several waterbodies with diverse topography, primarily drawing its water from the Then Pennaiyar River and Panampet Lake. During heavy rains or cyclonic events, Panampet Lake often overflows, causing flooding in various residential wards, especially wards 29, 32, 33, 34, 37, 38, 40, 41, and 42. Ward 34, is particularly hard hit.

Water bodies

The Villupuram municipal region has 14 major waterbodies (**Figs. 3–4**), including V. Maruthur Lake (Figure 1) in Ward 38 as a major water body, which overflows during heavy rains, affecting Wards 28, 29, and 38. Ward 29, with 4,075 residents, suffers significant flooding, causing water to enter homes and taking over a week to drain.

The overflow issues from unwanted plant growth and waste disposal affect Ward 7&4 while flooding from the Fengal cyclone 2024 impacted several other wards, causing significant damage. V. Maruthur Lake is located in Ward 38 on KK Road. The lake lacks a proper embankment, and the growth of unwanted plants and waste disposal causes overflow, affecting Wards 28, 29, and 38. Ward 29, with a population of 4,075, is the most affected. Flooding causes water to enter homes, taking more than a week to drain. Ka.kuppam Lake is located in Ward 4 The growth of unwanted plants and waste disposal in the lake causes overflow, affecting Wards 3, 4, and 7. Ward 7, with a population of 5271. Flooding causes water to enter homes, taking more than a week to drain.

Canal

The Koliyanur Canal affects several wards (**Figs. 5–6**), especially Ward 21 with 4,371 residents, while the Panampet Canal caused significant flooding in Ward 34 Pandiyan Nagar, where water overflowed into homes, damaging property, and vehicles, and took over two weeks to recede.

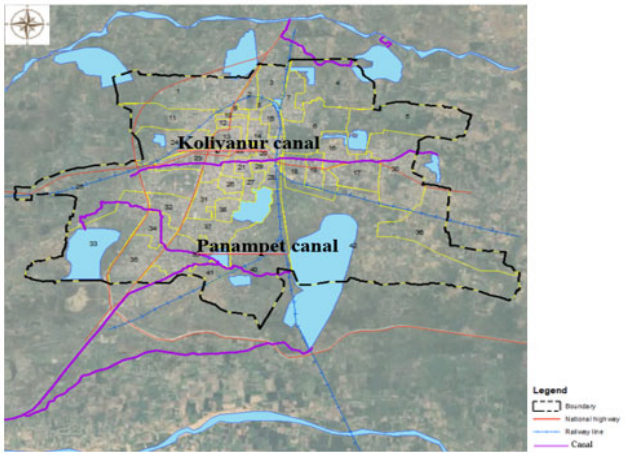


Fig. 5. Canal map of Viluppuram Municipality

Fig. 6 Canal

The Koliyanur canal in Villupuram has faced issues due to insufficient capacity and waste disposal, causing overflow and Panampet canal flooding in neighborhoods like Salamedu and Pandiyan Nagar. Despite ongoing desilting efforts, the 2024 floods severely impacted Wards 17, 18, 19, 21, and 29, particularly affecting Ward 21.

The rainfall pattern is crucial in the SWAT model as it affects the quantity, intensity, and timing of surface runoff. The Low-Pressure area over the Bay of Bengal from 27th October – to 4th November 2021 caused heavy rainfall in Villupuram (**Table 1**) and in 2024 the fengal cyclone caused heavy rainfall.

Findings

Flood Risk Zones

The flood risk zones are identified in Vilupuram municipality (**Fig. 7**) and **Fig. 8** shows During the Fengal cyclone 2024, the overflow of the canal caused flooding due to the disposal of waste in waterbodies affected wards 32, 33, 34, 35, 37, and 39 due to overtopping of water bodies, canal and disposal of waste.

Waterlogging locations

The waterlogging zones in Villupuram municipality are identified (Fig. 9) and Waterlogging occurred near the canal and around water bodies due to the growth of unwanted plants and the disposal of waste, which caused the canal to overflow. Improper waste disposal has clogged the canal, affecting its flow (table 3). The clogged canal has exacerbated the flooding situation. Due to insufficient canal capacity in areas like Salamedu and Pandiyan Nagar, water has overflowed.

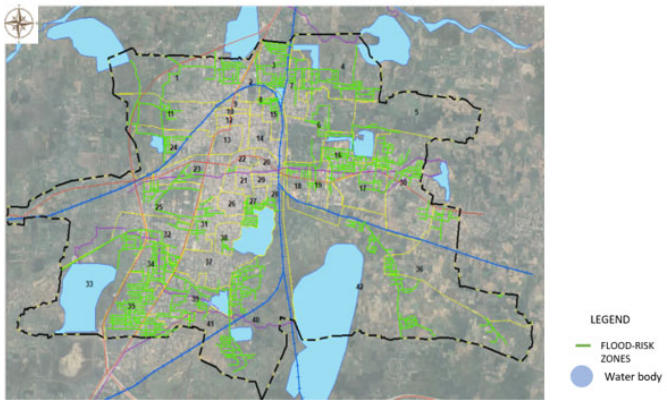
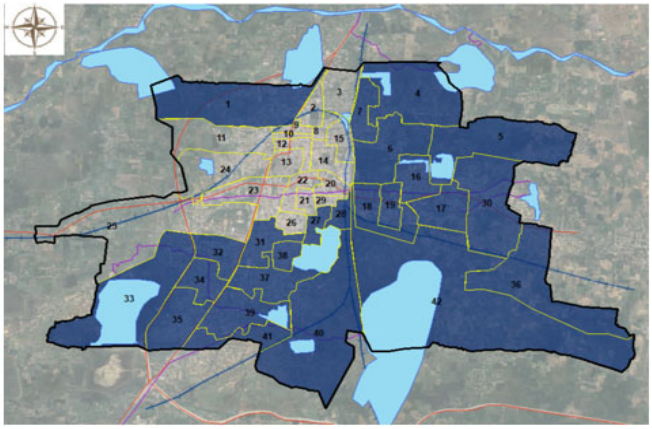
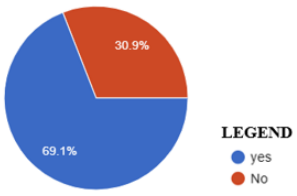


Fig. 7 Flood Risk Zones in Viluppuram Municipality

Fig. 8. Waterlogging in Pandian Nagar





Waterlogging	No. of persons
Yes	145
No	65

Fig. 9 Waterlogging locations in Viluppuram municipal region and Percentage of waterlogging questionnaire survey 210 sampling

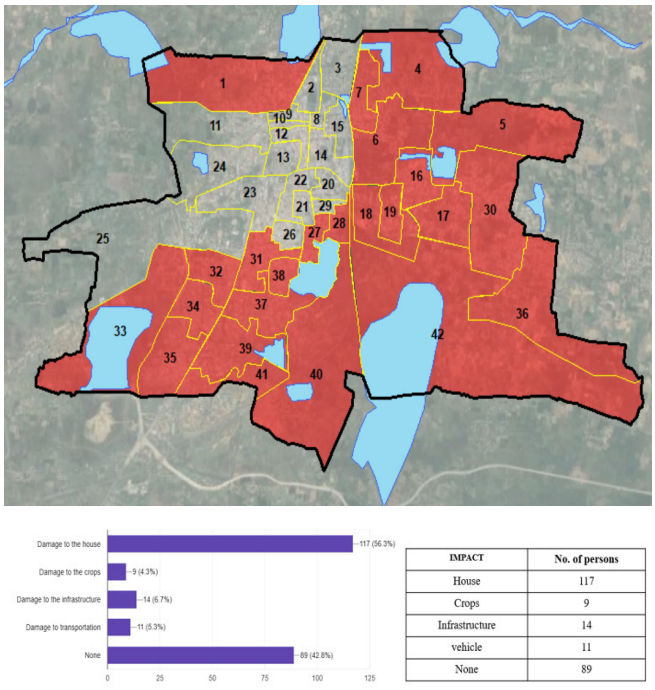
Table 1. Rainfall data of Viluppuram Municipality from 2008 (Source: Viluppuram Municipality)

Month	Normal	2025	2024	2023	2022	2021	2020	2019	2018	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008
January	9 .72	6 .37	122 .04	0 .1	26 .67	74 .45	4 .21	0	0 .33	42 .94	0	3 .72	0	0	0	8 .61	9 .78	2 .67	27 .78
February	8 .63	0	0	0 .25	0 .05	18 .6	0 .52	0	11 .94	0	0	0	14 .44	6 .44	0	15 .28	0	0	47 .94
Winter	18 .35	6 .37	122 .04	0 .35	26 .72	93 .05	4 .83	0	12 .28	42 .94	0	3 .72	14 .44	6 .44	0	23 .89	9 .78	2 .67	75 .72
March	8 .68	0	0	21 .09	2 .38	0	0	0	15 .22	8 .28	0	0	0	19	0	0	0	21 .12	113 .07
April	11 .25	0	0	15 .29	18 .03	2 .29	34 .02	1 .33	0	0	0	90 .16	0	0 .78	1 .11	97 .37	0	0	20
May	27 .25	69 .27	69 .27	106 .43	75 .87	57 .53	17 .43	32 .33	10 .78	45 .2	93 .86	68 .61	116 .55	13 .47	7	10 .33	66 .17	18 .22	76 .39
Summer	47 .18	0	69 .27	144 .81	96 .28	59 .82	51 .45	33 .66	26	54 .48	90 .86	158 .77	116 .56	33 .25	8 .11	107 .7	66 .17	39 .34	209 .46
June	54 .7	87 .51	87 .51	85 .03	65 .57	36 .2	62 .82	29 .33	39 .03	76 .78	44 .94	15 .83	80 .69	27 .85	24 .72	24 .89	108 .81	39 .5	56 .44
July	72 .3	73 .93	73 .93	120 .24	71 .97	173 .44	105 .91	109 .02	25	74 .72	118 .48	75 .54	50 .11	50 .17	87 .55	89 .43	39 .94	57 .33	71 .72
August	106 .36	319 .06	319 .06	122 .03	128 .05	141 .99	50	149 .55	87 .4	194 .52	69 .44	115 .83	179 .35	209 .28	154 .94	115 .61	149 .89	107 .61	95 .06
September	121 .3	59 .39	59 .39	230 .54	88 .44	116 .64	101 .76	219 .77	115 .14	107 .74	67	84 .17	124 .72	123 .22	112 .28	125 .89	168 .61	108	75 .52
S.W. Monsoon	356 .66	0	537 .89	557 .84	355 .03	468 .27	320 .49	507 .67	268 .58	453 .76	299 .86	291 .37	434 .88	410 .52	379 .5	355 .82	467 .25	312 .44	298 .74
October	252 .11	162 .35	162 .35	65 .58	115 .53	288 .26	122 .04	177 .69	167 .33	223 .4	86 .5	78 .67	211 .42	119 .72	354 .87	153 .46	105 .93	65 .18	226 .87
November	317 .8	143 .23	143 .23	255 .25	213 .66	732 .95	277 .15	97 .23	156 .19	179 .96	12 .17	558 .66	129 .9	137 .19	117 .4	310 .5	485 .2	390	432 .71
December	569 .83	569 .83	569 .83	33 .4	111 .6	52 .75	335 .87	99 .46	17 .88	130 .29	74 .29	299 .06	73 .22	88 .17	40 .2	163 .69	203 .61	134 .36	38 .67
N.E. Monsoon	1139 .74	0	875 .41	354 .23	440 .79	1073 .9	708 .06	374 .37	341 .39	532 .65	172 .96	936 .39	414 .54	345 .08	512 .47	627 .65	800 .74	589 .54	698 .25

Flood impact zones

The Flood-affected areas in Villupuram Municipality (**Fig. 10**) include Wards 40, 36, 41, and 42 (agricultural zones), Wards 34, 35, 39, and 37 (Panampet Canal overflow), and Wards 18, 19, 17, 1, 27, 28, and 36 due to overtopping of lakes and canal which affects the water flow during heavy rains in Viluppuram municipality.

During the Fengal Cyclone 2024, flooding caused significant harm to residents It was identified (Table 4) that water entered homes and took at least one to two weeks to drain in wards 34,35,40,39. And also affects the agriculture zone in wards 41&42.



IMPACT	No. of persons
House	117
Crops	9
Infrastructure	14
vehicle	11
None	89

Fig. 10 Flood Impact Locations in Viluppuram Municipality and damages Caused by Flooding

Swat Model

Soil and Water Assessment Tool (SWAT) model effectively estimated annual runoff in Villupuram Municipality (**Fig. 11**), particularly in regions prone to flash floods. By analyzing surface runoff patterns based on land use and environmental factors, the model accounted for variables such as rainfall intensity, soil moisture, land cover, and topography. The Vilupuram municipal region, with its moderate topography and surrounding water bodies, faces significant challenges due to inadequate stormwater drainage systems, leading to water stagnation. The digital elevation model (DEM) map for Villupuram provides a visual representation of the terrain elevation in the area. The map uses a color gradient to indicate elevation values, with red representing higher elevations and green representing lower elevations. The legend shows that elevation values range from a low of 28 to a high of 60. The southeast of Villupuram is a low-lying area, whereas the western region, including wards 32, 33, 34, and 35, has

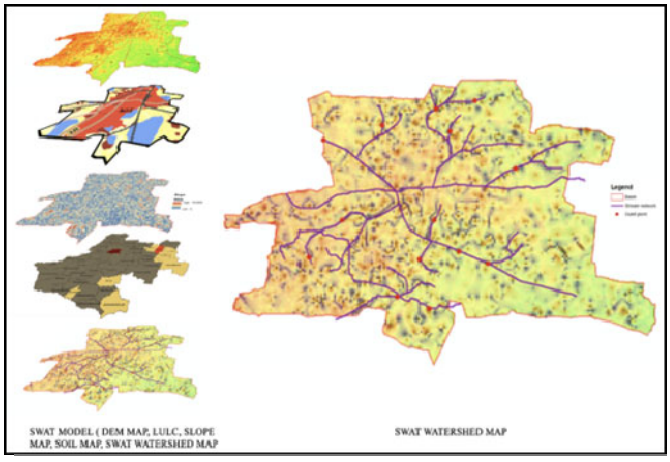


Fig. 11 SWAT model (DEM Map, LULC, Slope Map, Soil Map, SWAT Watershed Map)

a higher elevation. However, wards 34 and 35 are significantly impacted by waterlogging due to the drainage system.

The urban area represents the largest portion at 33.57%, while the rural area makes up about 8.07%. Water bodies within the municipal limits account for roughly 18.9%, cropland covers around 29.46%, and 10% of fallow land. The slope map for Villupuram provides a visual representation of the slope values. The map uses a color gradient to indicate slope values, with blue representing low slopes and red representing high slopes. The legend indicates that slope values range from 0 (low) to 16.6303 (high). Alluvial soil can significantly influence changes in slope and terrain level height. This type of soil is deposited by rivers and streams and is rich in nutrients, silt, and clay. The deposition and erosion processes associated with alluvial soil can alter the landscape over time, leading to variations in elevation. The Villupuram municipality experiences significant variations in slopes, resulting in uneven terrain. These drastic changes in slope can pose challenges for infrastructure development, water drainage, and land use planning. This analysis helped identify critical flood-prone areas and guided the determination of optimal culvert sizes to enhance water conveyance and reduce flooding risks. However, the model's accuracy depended on data quality and did not account for human activities such as construction or future climate change scenarios.

The watershed delineation map in the SWAT model for Viluppuram municipality shows the boundaries of the watershed area, stream networks, and various points of the Outlet. allows for the identification of flood risk zones and areas prone to waterlogging, especially as a result of canal narrowing. The outlet points on a watershed delineation map are often referred to as "outlets," "pour points," or "drainage points." These are the points where water exits the watershed and moves to another area, such as a river, or lake. The direction of water flow from the northwest to the southeast can have several important implications for the Viluppuram municipality. This model also helps in determining the flow direction of important canals, like the Panampet Canal, which runs from Vazuthureddy Lake to Panampet Lake, and the Koliyanur Canal, which flows in a similar west-to-east direction, affected by different topographic levels.

Result

Flood risk simulation maps for the Vilupuram municipal region can help visualize and assess the impact of rising water levels. These maps show areas that are likely to be affected by flooding, based on various scenarios of water level rise. A flood risk map buffer (**Fig. 12**) is an

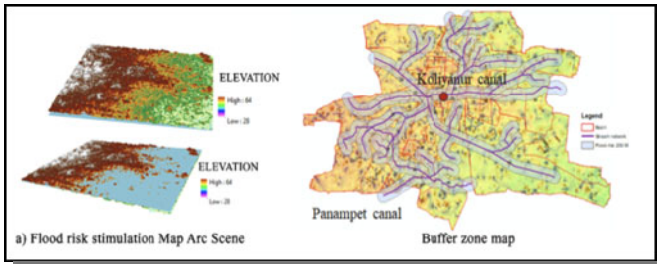


Fig. 12 Flood risk stimulation map and Flood risk Buffer zone Map

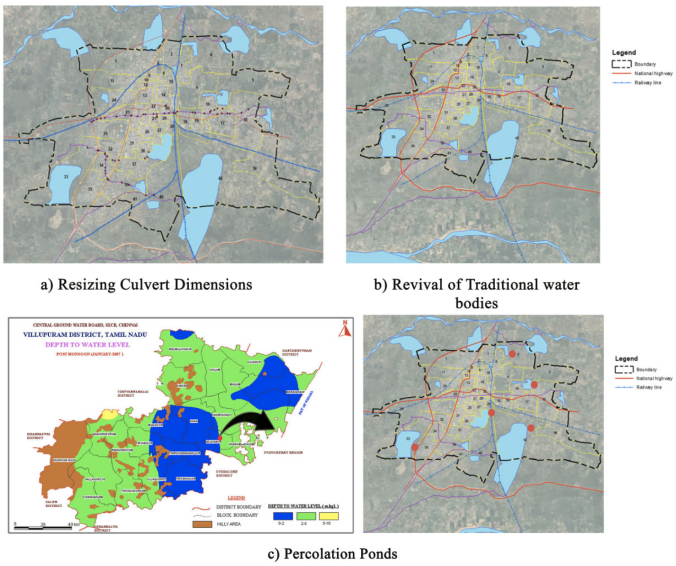


Fig. 13 (a) Resizing culvert dimensions, (b) revival of traditional water bodies, and (c) percolation ponds. Source: Groundwater table map Viluppuram District.

area surrounding a stream, river, or water body that is identified as being at risk of flooding. Highlighted in light blue, this area represents the buffer zone within 200 meters of the stream network that is at risk of flooding.

Resizing Culvert (**Fig. 13a**) Implementing stricter waste disposal regulations and improving waste collection, especially near water bodies, are crucial steps to prevent flooding. Additionally, resizing the dimensions of culverts to adequately handle water flow to the canal is essential. Revival of traditional water bodies (**Fig. 13b**) to Restore and maintain traditional water bodies like Lakes, and ponds. Desilt and deepen existing lakes to increase storage capacity Clear encroachments and improve inlet/outlet structures. The rainfall intensity is the main factor of groundwater recharge. In hard rock areas, the presence of groundwater is confined to top-weathered. The depth of water level in the Viluppuram municipal area ranges from 2 to 5 m. Percolation Ponds (**Fig. 13c**) is to Construct small percolation ponds in natural drainage paths and urban outskirts. Identify low-lying areas and seasonal streams for construction. Use local materials like stones and gravel to build cost-effective structures.

Table. 5. Proposal for surface runoff in Viluppuram municipal area

	2025–2030	2025–2035	2025–2040
STAGE 1	**WASTE MANAGEMENT:** • Implement stricter waste disposal regulations and improve waste collection especially near water bodies and canals to prevent clogging and overflow. • Conduct regular clean-up drives near lakes canals and drainage systems.	**IMPROVE DRAINAGE INFRASTRUCTURE:** • Expand and maintain the stormwater drainage system to cover critical areas ensuring proper integration and capacity to handle heavy rainfall. • Clear encroachments and desilt existing drains to improve water flow.	• Construct large-scale retention ponds and embankments to manage excess water during heavy rainfall.
STAGE 2	**INTEGRATED WATER MANAGEMENT:** • Implement rainwater harvesting systems in public buildings and residential areas to reduce surface runoff.	**LAND USE PLANNING:** • Regulate land use to prevent encroachments on floodplains and ensure sustainable development. • Develop zoning regulations to restrict construction in high-risk flood zones.	**DEVELOPMENT OF A MASTER PLAN:** • Create a comprehensive master plan for Villupuram Municipality that includes detailed flood risk assessments drainage system improvements and land use regulations. • Incorporate future climate change scenarios into urban planning to ensure long-term resilience against extreme weather events.
STAGE 3	**FLOOD RISK STIMULATION & MITIGATION** • Develop flood risk maps and buffer zones around water bodies to identify and protect vulnerable areas and improve culvert designs in flood-prone areas.	**REVIVAL OF TRADITIONAL WATER BODIES:** • Restore and protect natural water bodies and wetlands to enhance their capacity to absorb excess water.	

DISCUSSION

The study addresses the ongoing problem of urban flooding in Villupuram Municipality, which stems from insufficient drainage systems, poor waste management, and unchecked vegetation growth in water bodies. Areas particularly vulnerable to flooding, such as Pandiyan Nagar, Trichy Trunk Road, Panampet Lake, Maruthur Lake, and Ka. Kuppam Lake experienced significant impacts from heavy rainfall and cyclonic events like Cyclone Fengal. The SWAT (Soil and Water Assessment Tool) model, combined with GIS, was utilized to evaluate urban surface runoff, highlighting critical areas of concern. The study emphasizes the urgent need for desilting water channels, reinforcing embankments, and enhancing waste management practices to reduce future flooding risks. It also stresses the importance of aligning urban planning with sustainable drainage solutions.

CONCLUSION

The study addresses the ongoing challenge of urban flooding in Villupuram Municipality, which is primarily caused by insufficient drainage systems, poor waste management, and unchecked vegetation growth in water bodies. Areas particularly vulnerable to flooding, such as Pandiyan Nagar, Trichy Trunk Road, Panampet Lake, Maruthur Lake, and Ka. Kuppam Lake, has experienced significant impacts from heavy rainfall and cyclonic events like Cyclone Fengal. The SWAT (Soil and Water Assessment Tool) model, along with GIS, was utilized to evaluate urban surface runoff and identify critical areas of concern. There is a research gap regarding the need for long-term hydrological data to enhance understanding and prediction of changes in water balance components. The study emphasizes the urgent need for desilting water channels, reinforcing embankments, and improving waste management

practices to reduce future flooding risks. It also highlights the importance of integrating urban planning with sustainable drainage solutions. Recommendations include desilting channels, building retention ponds, and adopting green infrastructure. This study serves as a foundation for policymakers and urban planners to implement targeted interventions that enhance the municipality's flood preparedness and response strategies.

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