Storm Water Flood Management in the Coastal City- A Case study

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NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAVAN
ROORKEE
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Abstract

Urban flooding is significantly different from rural flooding as urbanisation leads to developed catchments which increases the flood peaks from 1.8 to 8 times and flood volumes by up to 6 times. Consequently, flooding occurs very quickly due to faster flow times, sometimes in a matter of minutes. Urban areas are centres of economic activities with vital infrastructure which needs to be protected 24x7. Therefore, management of urban flooding has to be accorded top priority. Kakinada Municipal Corporation (KMC) is part of a Special Economic Zone and a proposed 'Petroleum, Chemical and Petrochemical Investment Region (PCPIR)'. It is a hub for all the deep-sea exploratory activity in the region due to its deep-water seaport and its proximity to the gas fields. The Ministry of Housing and Urban Affairs, Government of India selected the KMC as "Smart City".

DEM and sub-catchments have been generated using 0.5 m contours of the smart city with the help of field verification/existing drainage/road network. It is found that the existing storm water drainage network has not followed the natural drainage system. The land use/cover of the study area for the period 2016 2022 and 2023 has been prepared using the Sentinel-2 (10m x 10m resolution) satellite data. The major land use found to be water body, barren land, mangroves, plantation, urban, and road. The 2024 monsoon water levels of the drains in the study area have been measured at five different locations (Three temple centre, Dairy form centre, Doodt factory, Kakinada port station and Subbya gari street culvert). The Strom Water Management Model (SWMM) model has been calibrated and evaluated with the observed water level data. The model evaluated parameters and their values are Correlation Coefficient (R) 0.871 to 0.971, Coefficient of Determination (R^2) 0.758 to 0.944, Root Mean Square Error (RMSE) 0.383 to 0.490 and Nash-Sutcliffe Efficiency (NSE) 0.865 to 0.949 respectively. Short interval rainfall data (15 minutes) for the period 2007 - 2023 collected from the hydro-meteorological observation station (Deltaic Regional Centre, Kakinada) have been used to developed the IDF curves for various return periods. 2-year flood storm has been simulated using the calibrated model and found that the exiting storm drainage network is not adequate and also identified the flooding locations. The above analysis shows that to mitigate urban flood in the Kakinada Smart city (KMC) with the limitation of topographical conditions, it is necessary to expand the width of the storm drains. As per the urban storm water drain norms (Ministry of Housing and Urban Affairs) says that the smart city should be adequate enough to withstand the 5-year design storm. Therefore, the model has been simulated for the 5-year design storm and found that modified drainage network is adequate. The climate change is also considered to find the impact of precipitation and discharge in the study area.

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INTRODUCTION

The rapid development of urbanization and climate changes along with poor drainage systems lead to flooding in urban areas in many cities around the globe. When there was a change from natural water-absorbing surfaces, it gave way to concrete and asphalt. Hence, stormwater runoff is increasing, which overwhelms the inadequate and often ill-designed drainage systems. Climate change is making the situation worse with more and more heavy rainfall that causes flash floods. In addition, rising sea levels and extreme weather heighten the risks mainly in the coastal cities. Besides, globalization and rapid population growth have also created high pressure on stormwater management, while unregulated changes of land use, such as deforestation and encroachment into the floodplains, have further decreased the natural capacity of land to drain. There are a lot of severe consequences: transport disruption, loss of property, economic losses, and health risks caused by the diseases caused by water. To address the problems, sustainable flood prevention measures should focus on green infrastructure, improving drainage systems, permeable pavements, and early warning systems. To decrease the negative impacts of urban floods on vulnerable communities, cooperation between the government, urban planners, and communities is needed in applying resilient and adaptive solutions.

The city of Kakinada, a fast-developing coastal city in Andhra Pradesh, has made tremendous progress in infrastructure, technology, and population growth with the onset of industrial growth and migration. Even though its development seems to be quite progressive, the lack of adequate planning and long-term vision for Kakinada was a hindrance. The encroachment of natural drainage channels, lack of stormwater outlets, and the disturbing of the usual flow of water have resulted in frequent flooding and urban flooding due to the heavy downpours. Floods in the past have destroyed life and property in Kakinada in massive scale. Recent rains with shorter durations and intense rainfall have caused wide-spread inundation, further revealing the vulnerability of the city. One of the worst monsoons Kakinada has experienced since the turn of the century, with more than 20 cm of rainfall in a day, occurred in 2021, inundating low-lying areas and snarling traffic on the city's streets. Extremely high rainfall, coupled with very poor drainage systems and rapid urbanization, has made flooding a recurrent phenomenon; there is an urgent need to provide better stormwater management solutions. Drainage canals, major and minor, are clogged with silt and encroachments and, therefore, cannot take excess rainwater into them.

Flood modeling is a crucial process for providing insight into urban flooding and predicting flood occurrence. This is used to inform flood management decisions and prioritize urban development and planning in communities. Flood modeling as a basis, essentially simulates rainfall-runoff processes after rainfall (runoff) and drainage system functionality when flushed with runoff (flooding). Flood modeling is normally accomplished through hydrological models (rainfall-runoff) and hydraulic models (drainage system functionality). The Storm Water Management Model (SWMM) is one of the most widely-used modeling tools for flood modeling and was developed by the U.S. Environmental Protection Agency (EPA). SWMM is a dynamic rainfall-runoff simulation model that can be used for the evaluation of drain systems, accounting for surface runoff, infiltration, and sewer systems when used in urban settings. SWMM is a viable and practical tool to assess flood hazards, design more efficient drainage infrastructure, and assess the effects of land use on stormwater. By utilizing real-time rainfall data, as well as simulated precipitation, SWMM allows planners and engineers to optimize drainage networks, identify flood-prone areas, and consider mitigation efforts (e.g., retention ponds, green infrastructure, etc.) for expressed hazards (e.g. stormwater network). SWMM's ability to model extreme rainfall events is an especially practical tool for urban areas experiencing flooding, and better prepares planners and engineers for future flood risks.

The present study was undertaken in the area of Kakinada Smart City, Andhra Pradesh, India. The study focuses on the methodology applied for improving the stormwater drainage network, proposing necessary modifications, and providing recommendations to the Kakinada Municipal Corporation (KMC). The existing drainage system was simulated using rainfall-runoff software to visualize the network, identify deficiencies, and redesign it to mitigate urban flooding in the study area. The study was carried out with the following objectives:

1. Development of IDF curves (using 15-minute rainfall data) and simulation of storm water flood or various return periods of rainfall in the Kakinada Smart city using EPA SWMM model.
2. Evaluation of urban storm water network and development of flood map using spatial technology.
3. Development of flood management strategies and mitigation measures.

LITERATURE REVIEW

Urban stormwater management in coastal cities is challenging while the necessity for this has increased with rapid urbanization, climate change, and global sea level rise. The expansion of impervious surfaces reduces natural infiltration, leading to higher runoff and flood risk. Effective drainage requires hydrological models, spatial analysis, and adaptation strategies for flood reduction. Advanced tools such as GIS, remote sensing, and stormwater models-such as SWMM-support assessments to improve flood resilience. As the impacts of climate change intensify extreme weather patterns, including long-term projections in urban water planning is essential. Pushback to any development by floodplain layers represents a further difficulty which must be overcome.

2.1 Stormwater Management Techniques

Nazari et al. (2023) have said to introduce a complete framework that integrates SUSTAIN (System for Urban Stormwater Treatment and Analysis Integration) with SWMM (Storm Water Management Model) through Multi-Criteria Decision Making (MCDM) for optimizing the application of Low Impact Development (LID) in urban stormwater systems. This method permits evaluating certain hydrological performances and economic feasibility with respect to options of LID. This study demonstrated that the integration approach successfully identifies cost-effective LID solutions which substantially reduce urban runoff and enhance water quality.

Nazari, et al. (2021) spotted LID optimizations through the coupling of SWMM and SUSTAIN models. Based on the combined modeling, the researchers applied a whole modeling approach to a case study in Tehran, Iran: Out of the six scenarios—the green roof, rain barrels, bioretention cells, porous pavements, vegetated swales, and dry ponds—these researchers assessed for LID scenarios. The results showed that certain LID combinations could lead to a reduction in runoff volume of as much as 72%: that is, efficient integrated modeling offered a basis for building sustainable urban stormwater management strategies.

Rujner et al. (2022) presented an analytical case study with a wide perspective on the implementation of green infrastructure into a commercial plaza built without direct connected impervious surfaces. Research showed that such designs could definitely reduce surface runoff significantly, while at the same time enhancing stormwater infiltrations, and was underlined by the significant role played by green infrastructures in sustainable urban drainage systems. The case study demonstrated that if impervious surfaces are disconnected and green infrastructure elements, such as vegetated swales and permeable pavements, are incorporated, effective stormwater management can be carried out at source-control levels so that the burden on municipal drainage systems can be reduced.

Chang et al. (2018) comprehensively covered global policies promoting Low Impact Development (LID) for urban stormwater management. They explored various formal policies on LID and assessed their influence on the adoption of sustainable stormwater practices in different countries. Their conclusions implied that adequate policy support, public awareness, and incentives to developers and municipalities to integrate green infrastructure into urban planning were necessary for the successful implementation of LID practices.

Yang et al. (2017) evaluated optimized bioretention cell designs to manage the quantity and quality of stormwater runoff. Their goal was to determine the optimal surface area and contributing drainage area ratios of bioretention cells to maximize pollutant removal and runoff reduction. Studies concluded that bioretention cells of proper size work very well in both attenuating peak flows and improving overall water quality and are thus key functional building blocks of urban stormwater management systems.

Palanisamy et al. (2015) investigated LID retrofitting of existing concrete canals in urban areas. The study showed that features such as vegetated swales and permeable liners help improve the ecological function of urban waterways and enhance stormwater management. The study showed that these conventional concrete channels could be transformed into green infrastructure corridors benefiting urban catchments with respect to hydrological performance and a boost to biodiversity.

2.2 Urbanization and Land Use Changes

A comprehensive study examining the effect of urbanization on stormwater management in Tbilisi and its regions was done by Gadrani et al. (2018). The researchers used remote sensing along with Geographic Information Systems (GIS) to assess land use and land cover changes over many decades. These scholars discovered that urban expansion led to a sizeable increase in impervious surfaces, lower infiltration rates, and increased surface runoff. Findings point to the need for modern tools and valid empirical assessment methods for the real hydrological effect of urban growth.

Wang et al (2023); This study is intended to conduct a bibliometric analysis of the literature on optimization for urban stormwater management, focusing on the period from 2004 to 2023 and glimpse into the ways the field is responding to challenges like climate change and urbanization. The study is based on research and analysis performed by CiteSpace on publication trends, authorship characteristics and geographical distribution, and changes in keywords and occurrences of citations. The results indicate a notable shift towards practices of stormwater management that embrace sustainability and resilience, emphasizing the integration of green infrastructure and nature-based solutions into urban planning.

Barsha et al. (2021), In this study, the researchers, making use of PCSWMM, developed a calibrated stormwater management model to simulate the effects of both historical and projected changes associated with land use, as also climate scenarios, on urban runoff. It was shown that urbanization, in conjunction with climate change, tends to increase the volume of runoff alongside increasing flood risks. Additionally, this study looked into the effectiveness of such low-impact development practices like rain gardens and rain barrels, which could help alleviate the adverse effects of increased surface runoff and provide for a sustainable type of urban water management.

Rentachintala et al. (2022), The present review attempts to explore different aspects of urban stormwater management such as Low Impact Development, Best Management Practices, Sustainable Urban Drainage Systems, and Sponge City Program. It identifies various knowledge gaps to be filled in the future research and contributes to real-time governance to offer reuse options to support ongoing stormwater management in urban areas. The review converges on the dedication to integrate climate change concerns and adaptive strategies toward developing sustainable, resilient urban water systems.

Xu et al. (2024) Proposed a multi-objective optimization framework that integrates hydrological analysis with earthwork cost assessments to inform terrain modification in urban planning. It aims to reduce flood hazards via the improvement of terrains from a consideration of the hydrological benefits and the economic costs. The study demonstrated an application of that framework within Høje Taastrup, Denmark, providing an aid for urban planners in their quest to balance flood mitigation efforts with their financial feasibility in view of urbanization.

2.3 Climate Change and Future Projections

Kumar et al. (2022), utilizing future projected rainfall data and consequently calibrated hydraulic models, this study examines urban flooding in Delhi, India, as influenced by climate change with two urban watersheds. As its main focus, the research is conducted under regional climate models projecting new patterns of precipitation in the coming future. The findings clearly show the urge in frequency and intensity urban floods will increase due to climate change, establishing the necessity of further planes in the design of stormwater drains and planning in the cities towards future risks of flooding.

Vishwakarma. et al. (2023) evaluated the sustainability of stormwater drainage systems in six Indian cities in India applying eleven indices such as the Natural Drainage System Index, Drainage Coverage Index, and Water Logging Index. Their decade-long comparison (2010–2020) showed that Tier I cities performed poorly, with issues like loss of natural drainage, low permeability, and frequent waterlogging, whereas Tier II cities fared relatively better. The solution is to enhance the capacity of the current drainage system and implement sustainable urban drainage practices to reverse the trend of increasing rainfall intensity due to climate change.

Chowdhury et al. (2024); The research examines the potential impact of climate change on flood risks in the Narmada Basin, India. Scientists gathered and adjusted 30 years of rainfall data (2026–2055) from General Circulation Models (GCMs). Researchers developed Intensity-Duration-Frequency (IDF) curves for future conditions using Gumbel's extreme value distribution on Representative Concentration Pathways (RCP) 4.5 and RCP 8.5. The research employed the Hydrologic Engineering Centre's River Analysis System (HEC-RAS) 2D model for flood mapping and risk, indicating a reduction in flooded areas by 17–18% under RCP 4.5 and 12–14% under RCP 8.5.

Taysi et al. (2022); This study takes into account the updating of IDF curves to represent future climate conditions by decomposing GCM rainfall data. The authors constructed future IDF curves for different times (5 minutes to 24 hours) and return periods (2 to 100 years) using the Gumbel method. The authors compared the new and existing curves using historical rainfall data, showing considerable differences that validate the need for the inclusion of climate change projections in city stormwater system planning and management.

Kourtis et al. (2022); The paper analyzes the revising of IDF curves for Toronto to reflect climate change impacts. The study made use of GCM climate projections, which were downscaled to enhance resolution in space and time. The revising IDF curves show that under future conditions, there will be more frequent and intense heavy rainfall events, and that current city drainage facilities are not adequate to meet future climate conditions. The results suggest revised IDF curves are to be integrated into city and infrastructure planning in order to aid in future flood hazard mitigation.

2.4 Flood Mitigation Strategies

Ma et al. (2024) analyzed a hybrid urban flood prevention approach in Seoul's Dorim River basin in South Korea. The research emphasized the use of structural countermeasures like stormwater detention basins, enhanced drainage facilities, and urban flood storage facilities. The researchers used hydrological and hydraulic simulation to calculate the performance of the measures in mitigating urban runoff and the risk of urban floods. The research concluded that stormwater basins reduced peak flow rates by a significant margin, though their performance was optimized with the addition of real-time flood monitoring and the enhancement of drainage systems. The research suggested that urban flood management should adopt climate change resilience measures in the future, such as the enhancement of drainage facilities to accommodate high intensities of rainfall.

Dawson et al. (2011) evaluated non-structural flood risk management measures in the Thames Estuary, UK, based on a comparison of their effectiveness against a set of socio-economic and climate change assumptions. The study found early warnings, community adjustment, and planning policy measures as means of minimizing flood risk. The characteristics of future floods were projected using climate simulations to compare the effectiveness of different adaptation strategies. From the findings, policies prohibiting new development in flood areas proved highly effective in minimizing flood risk exposure in the long term. Non-structural effectiveness was, however, emphasized in the study as requiring effective governing frameworks and civil engagement.

Montz et al. (2002) provided a complete picture of flash flood mitigation measures with special focus on non-structural approaches such as early warning systems, real-time flood monitoring, and educational campaigns. The study took into account past flash floods in the United States and assessed the efficacy of response systems. It stressed the importance of efficient and timely flood warnings in reducing casualties and economic losses. The authors suggested the application of meteorological forecasting along with community-based flood preparedness programs to increase awareness and accelerate emergency response. The study also identified social factors, such as risk perception and local knowledge, as the determinants of successful flood mitigation policies.

STUDY AREA

Kakinada, situated in the East Godavari district of Andhra Pradesh, is historically and culturally important. Kakinada was a Dutch settlement in the 1700s, but became part of British India, at which point it was known as "Cocanada". Kakinada grew into an important trade center because of its location on the coast and its involvement in sea trade. It eventually became an industrial and commercial city with a good port. Kakinada is about 30.99 sq km, and serves as the headquarters for the district as shown in Figure 1. It is located at latitudes 16.93° N and 17.10° N and longitudes 82.18° E and 82.27° E. Kakinada has low elevation with average elevation of 2 meters above sea level. Kakinada is governed by Kakinada Urban Development Authority (KUDA), an organization that facilitates urban planning and development.

Kakinada(KMC) has a tropical wet and dry climate with hot summers and moderate winters. The city receives an annual average of about 1100 mm of rainfall mostly during the southwest monsoon season from June to September. As Kakinada is near the Bay of Bengal and hydrological boundary limits as shown in Figure 2, it is susceptible to cyclonic storms and heavy rainfall that can cause waterlogging in low-lying areas and flooding whenever an extreme weather system occurs. Kakinada is experiencing increasing urbanization as a consequence of climate change, which worsens the environmental problems in the area, meaning that flood management and even improvement of existing drainage systems are becoming essential for communities in urban and low-lying areas to deal with flooding. As Kakinada continues to urbanize, the city is upgrading drainage infrastructure to address these risks while ensuring development does not compromise environmental resiliency.

Tourism is a key industry in Kakinada's economy, welcoming visitors to its various natural and cultural attractions. Hope Island, a tiny island located off the coast, serves as a natural barrier to Kakinada against tidal surges and cyclones. Coringa Wildlife Sanctuary is among the largest mangrove forests in India, accommodating various flora and fauna, especially rare birds and saltwater crocodiles. The sanctuary serves as a critical ecological zone and offers a major draw for nature lovers. Uppada Beach has golden sands and calming surroundings, attracting both tourists and residents to enjoy the beach and its surroundings. Other notable attractions include Draksharama Temple, an ancient Hindu shrine dedicated to Lord Shiva and Kakinada Port, which has great views of the coastline. The robust food culture, especially famous seafood and Andhra style, attracts visitors from all over India.

In recent years, Kakinada has undergone significant shifts in land use as a result of urbanization and industrialization. The area originally contained agricultural, fisheries, and mangrove forest land uses to mostly a densely populated area with increasing residential, commercial, and industrial uses and diminishing green space and agricultural uses. The establishment of two key projects (Kakinada Special Economic Zone (KSEZ) and Petroleum, Chemicals and Petrochemicals Investment Region (PCPIR)) has contributed to industrial activities but have also raised air, water, and land pollution issues; impact on mangroves as habitat; and encroachments into wetlands and water bodies have impacted drainage patterns encouraging sustainability for long-term growth of the city. There are some emerging directions toward re-establishing green policies like bringing back mangroves and adopting green urban plans.

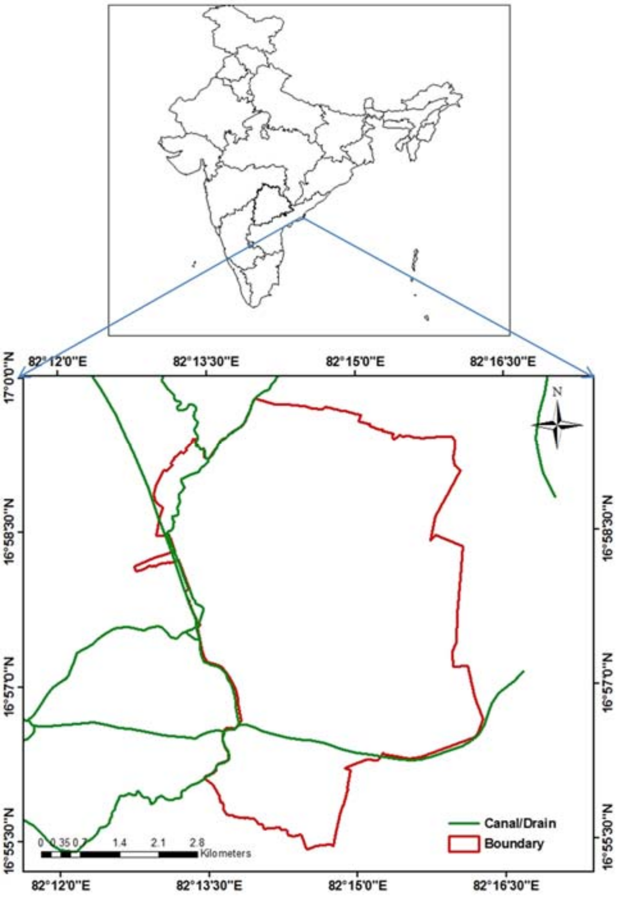


Figure 1. Location of the study area, Kakinada smart city (KMC)

Under the Smart Cities Mission, Kakinada Smart City Corporation Limited (KSCCL) has initiated few projects and these projects focus on improving urban infrastructure including smart traffic systems, digital governance, and improved public transport. Various green initiatives are being promoted for improving the urban environment, such as the installation of solar energy systems, waste recycling programs, and the creation of more green cover to promote an eco-friendly urban environment. Actions are being endeavored to restore water bodies and to strengthen the drainage systems to control urban flooding. Kakinada is taking actions to integrate modern technology with sustainable urban planning in order to become a model Smart City for promoting economic development while preserving its natural ecosystem and historical Heritage.

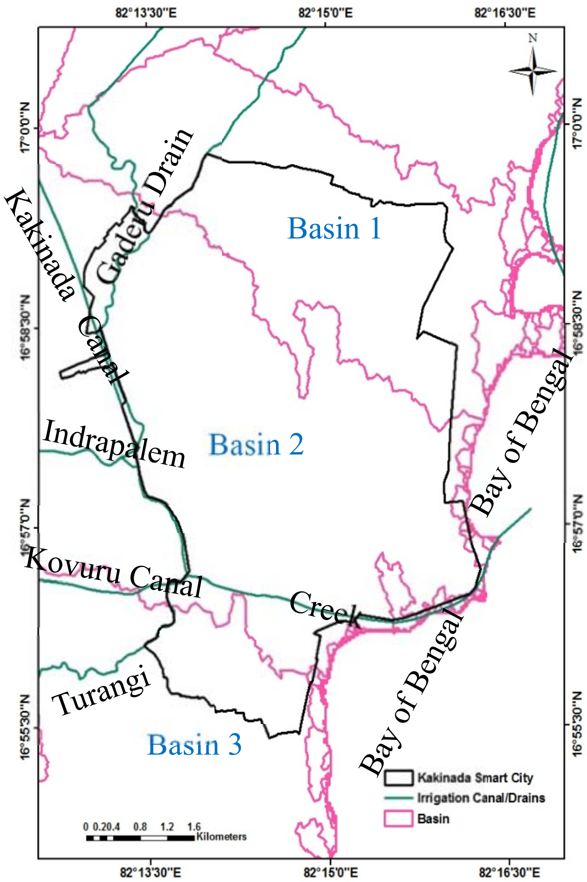


Figure 2. Kakinada Smart City (KMC) watershed boundaries

METHODOLOGY

In this study, we will organize a systematic evaluation of the existing stormwater drainage system in Kakinada Smart City, assess flood risk, and develop proper management strategies to mitigate flooding. The process includes appropriate data collection on local rainfall, land-use patterns, and stormwater drainage systems. The methodology also involves hydrological modeling and hydraulic modeling using stormwater modeling approaches the SWMM model. The process will develop Intensity-Duration-Frequency (IDF) curves and simulate flood scenarios under different rainfall events, and identify deficiencies in the stormwater drainage systems. Based on the results, suggested changes improve flood management in Kakinada. A simplified methodology followed for the study is shown in Figure 3

4.1 Data Collection

Data collection is an essential part of determining the current condition of the stormwater drainage network and flood hazard vulnerability in Kakinada Smart City. Data was collected from varied sources to generate a reliable and validated analysis and modeling for this study. 15 mins Rainfall data were obtained from DRC, NIH, Kakinada for the purpose of creating Intensity-Duration-Frequency (IDF) curves for the purposes of flood modeling. Topographic data and land-use data were also collected, including elevation maps, soil types, and urbanization, from municipal records, satellite imagery, and GIS databases, in order to identify how these, interact with stormwater runoff. The drain network data, including information on existing stormwater pipes, nalas, channels, and outfalls were collected from Kakinada Municipal Corporation (KMC) to assess its conditions and capacity. As well as hydrological and hydraulic data collected, including infiltration rates, runoff coefficients, and surface permeability, for purposes of SWMM modeling and rainfall-runoff modelling. Socio-economic and flood risk data, including post flood event reports, waterlogging issues, and damage reports, were also read to understand the complexity and implications of urban flooding. This collected data set were then processed into hydrological models of simulated floods and drainage improvements.

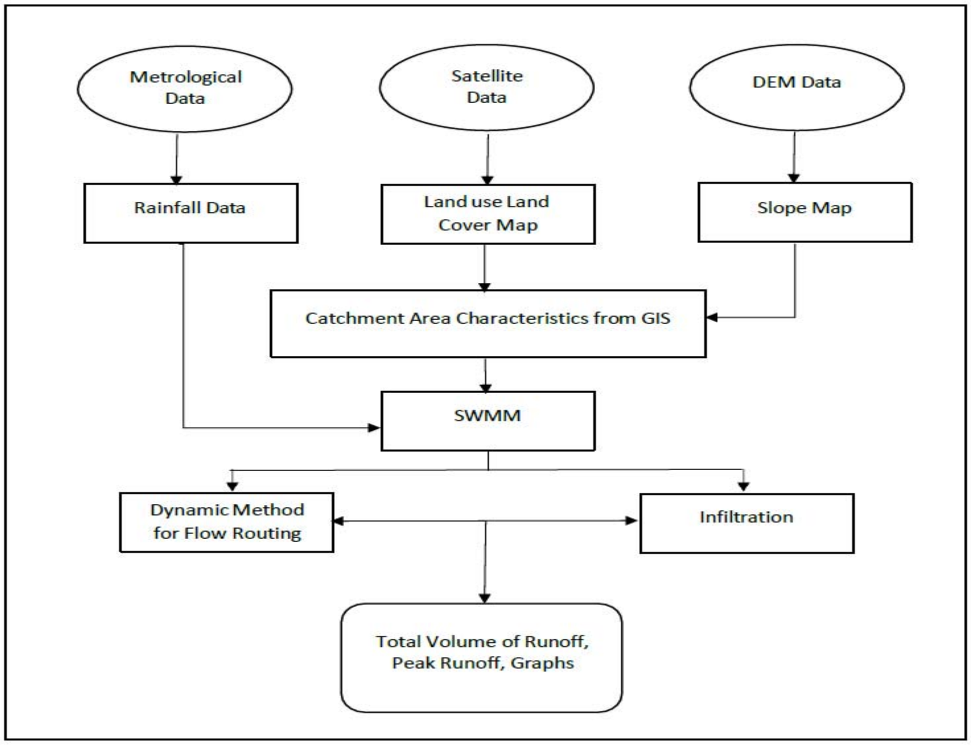


Figure 3. Methodological Framework for the study

4.2 Catchment Delineation

A Digital Terrain Model (DTM) with a 0.5m resolution for the Kakinada Smart City area was accessed through USGS Earth Explorer and the National Remote Sensing Centre (NRSC). Utilizing these Digital Elevation Model (DEMs), the ArcGIS 10.7 hydrology tools were applied to analyze the topography, invert elevation, and flow accumulation to delineate the catchment area. A slope map was produced for flow direction and evaluated runoff characteristics. The drainage network of the catchment was examined in terms of pre-urbanization natural drainage conditions as well as post-urbanization alterations, which included the pre-existing stormwater infrastructure. The urban catchment was also divided into sub-catchments to analyze runoff distribution, design flow rates, and peak discharge at drainage points. This process aided in identifying areas susceptible to flooding, identifying drainage capacity requirements, and estimating peak flow at points of discharge within the drainage network and overall catchment area, implementing a data-driven approach to flood mitigation in Kakinada.

4.3 Land Use/Land Cover Mapping

Land Use Land Cover (LULC) analysis was performed in the study area of Kakinada Smart City to investigate the association of urban growth with stormwater drainage performance. For mapping purpose, satellite imagery from the Survey of India (SOI), Sentinel data was used. Different land cover categories were classified using supervised classifications and by selecting specific training points for those categories. Analysis was focused on quantifying pervious and impervious surfaces specifically, in order to assess urbanization extent and impacts on surrounding natural drainage channels, water bodies, and vegetative covers. As a method for checking classification accuracies, Kappa Coefficient and accuracy assessment techniques were performed for credible indications of change in land use or land cover over time.

Table 1 Details of Land Use Land Cover (LULC) Plots Generated

S. No	Source	Resolution	Year
1.	Sentinel	10m	2016
2.	Sentinel	10m	2020
3.	Sentinel	10m	2023

Using the maximum likelihood classification (MLC) method, the study area was categorized into six LULC classes: water bodies, barren land, dense vegetation, vegetation, urban areas, and roads. A detailed description of these categories is provided in Table 2. The LULC plots and soil maps were further used to calculate the curve number for each sub-catchment, which is essential for hydrological modeling and flood risk assessment.

Table 2 Description on various Land use/ Land cover categories

LULC classes	Description
Water Bodies	Rivers, lakes, reservoirs, swamps, and ponds.
Barren Land	Areas with no vegetation, including exposed soil, rocks, and open land.
Dense Vegetation	Forested areas with high canopy density and minimal human disturbance.
Vegetation	Grasslands, shrubs, and agricultural lands with moderate greenery.
Urban Areas	Residential, commercial, industrial, and built-up areas covered with infrastructure.
Roads	Highways, streets, sidewalks, and paved road networks.

4.4 Intensity-Duration-Frequency Analysis

The design storm analysis anticipated in this study utilized historical data for rainfall that has occurred over 18 years (2007-2024). Hourly rainfall data was acquired from the India Meteorological Department (IMD), and the data were further employed to extract maximum hourly peak values for varying durations (1-day duration to 24-day duration) on any given day. To create IDF curves, Gumbel's Extreme Value Distribution (EV) was used to establish the rainfall intensities with return periods of 2, 5, 10, 25, 50, and 100 years.

A hyetograph, which is a representation of rainfall temporal distribution based on IDF curves, was generated through the Alternating Block Method (ABM). The total rainfall duration (T) was divided into Δt intervals, and rainfall intensities for Δt, 2 Δt, 3 Δt, … were determined from the IDF curve. Cumulative rainfall depths were derived by multiplying rainfall intensities by their corresponding durations. The peak rainfall intensity was placed in the middle of the hyetograph, and the remaining intensities were alternated around the peak to demonstrate the temporal pattern during the storm event. This hyetograph was then used to input rainfall-runoff simulation within the study.

The weight average areal precipitation was computed using the Thiessen Polygon Method. This is a graphical / cartographic method in which weights are assigned to each monitoring stations according to the size of the area they cover which includes the whole study site. The Thiessen polygon network allow for a spatially representative rainfall distribution to account for a more accurate runoff input in the stormwater models. All calculated rainfall intensity values were then incorporated into the Storm Water Management Model (SWMM) as a time-series data input to model stormwater runoff and analyze flooding risk in Kakinada Smart City.

4.5 SCS-Curve Number Method

The Curve Number (CN) method, created by the Soil Conservation Service (SCS), is often used to estimate direct runoff from a rainfall event, and is utilized as part of hydrological models (e.g., HEC-HMS (Hydrologic Engineering Center's Hydrologic Modeling System)). The CN method relates land cover, soil type, and antecedent moisture condition to runoff potential. The foundation of the CN method is the curve number, an un-dimensioned parameter that ranges from 0 to 100, where larger values indicate greater potential for runoff. The loss method begins with calculating the initial abstraction (I_a), which combines losses prior to the initiation of runoff, including infiltration and surface storage. The equation for the potential maximum retention (S) is defined as:

$$S = \frac{1000}{CN} - 10$$

The runoff (Q) is then calculated using the equation:

$$Q = \frac{(P - I_a)^2}{P - I_a + S}$$

Where P is the total precipitation and I_a is approximated as 20% of S (i.e., I_a=0.2 S). This method is particularly useful for its simplicity and ease of application in modeling the hydrological response of watersheds with varying land use and soil types.

4.6 Flow routing using Hydrologic-Hydraulic Model

Flow routing refers to the assignment of flow hydrographs at a point in the watershed based upon an upstream hydrograph. Flow routing can be categorized into two different types, Lumped (Hydrologic) Routing, which assumes no spatial variability and evaluates flow as a function of time, or Distributed (Hydraulic) Routing, which evaluates flow as a function of both time and space and takes spatial variability into account along the drainage system. In the following study, distributed hydraulic routing was conducted using St. Venant equations that achieve a higher level of accuracy in flood modeling. These equations are:

Continuity Equation:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

Momentum Equation:

$$\frac{\partial Q}{\partial t} + \frac{\partial (\frac{Q^2}{A})}{\partial x} + gA\left(\frac{\partial h}{\partial x} - S_o\right) + gAS_f = 0$$

where:

x = longitudinal distance along the channel (m)

t= time (s)

A = cross-sectional area of flow (m^2)

Q = flow rate (m^3/s)

H = water surface elevation (m)

S_o = bottom slope of the channel

S_f = friction slope

g = gravitational acceleration (m/s^2)

The momentum equation can be solved using different flow routing methods:

1. Kinematic wave (balances gravity and friction forces).
2. Diffusion wave (considers pressure variations but ignores inertial effects).
3. Dynamic wave (accounts for inertial, gravity, pressure, and friction forces).

In this study, dynamic wave routing was chosen over kinematic wave modeling because it effectively captures backwater effects, flow reversals, and rapid variations in stormwater flow, ensuring more accurate flood prediction for Kakinada Smart City.

4.6.1 Storm Water Management Model (SWMM)

The model was set up for the years 2016, 2020 and 2023 and simulated for the single rainfall event of 16th October 2024 to compare the change in runoff depth, peak discharge, runoff coefficient, and percentage imperviousness. The area, percentage slope, percentage imperviousness, curve number, drainage dimensions, and rainfall as time series were given as input parameters for the respective years. The runoff coefficient is an important factor in runoff simulation, where it is dependent on percentage imperviousness and the amount of infiltration. A greater percentage imperviousness has a greater runoff coefficient leading to lower infiltration. The model was also simulated for the year 2020 for different design storms for the existing drainage network with the return periods of 2, 5, 10, 25, 50, and 100 years. The model was also set up for the natural drainage system to identify flooding nodes and conduits, so that they could be redesigned for the design storms with the return periods 2 years and 5 years respectively.

RESULTS AND DISCUSSIONS

The urban hydrological analysis was conducted through thematic mapping, the development of intensity-duration-frequency (IDF) curves, and flood modeling. Based on model simulations for 2-year and 5-year design storms, necessary modifications to the drainage network were proposed. This chapter presents and discusses the results obtained from the methodology described in the previous chapter.

5.1 GIS Mapping

The Digital Elevation Model (DEM) for the study area is shown in Figure 4, the maximum and minimum elevations are +5.4 m and +0.53 respectively. The percentage slope of the study area ranging from 0 to 22.5 and was classified into five classes according to the steepness of the terrain (Figure 5). The natural drainage network, sub-catchment and existing drainage network are shown in Figure 6, 7 and 8 respectively. Natural drainage network is defined as the interconnected network watercourse and channels that naturally transport water from higher elevation to lower elevation whereas existing drainage network refers to a designed system of interconnected channels and conduits that has been established subsequent to human settlement or urbanization.

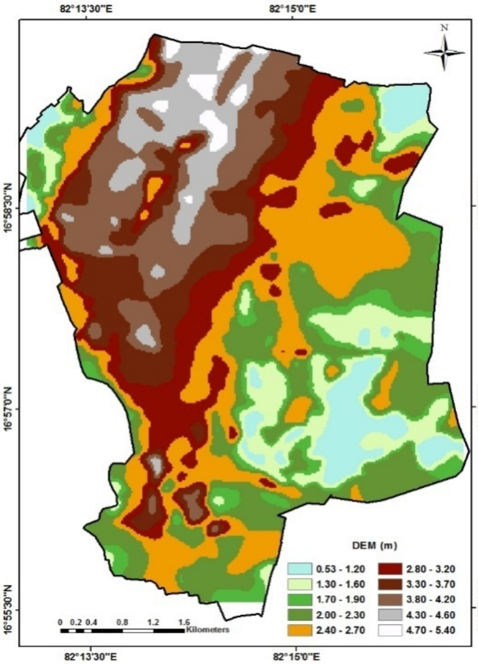


Figure 4. Elevation map of the study area

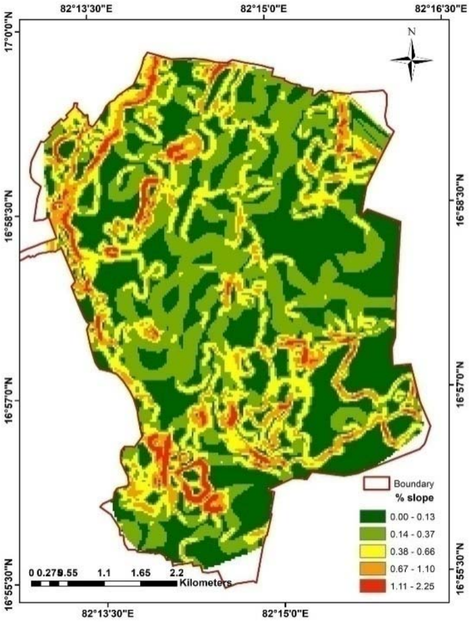


Figure 5. Slope map of the study area

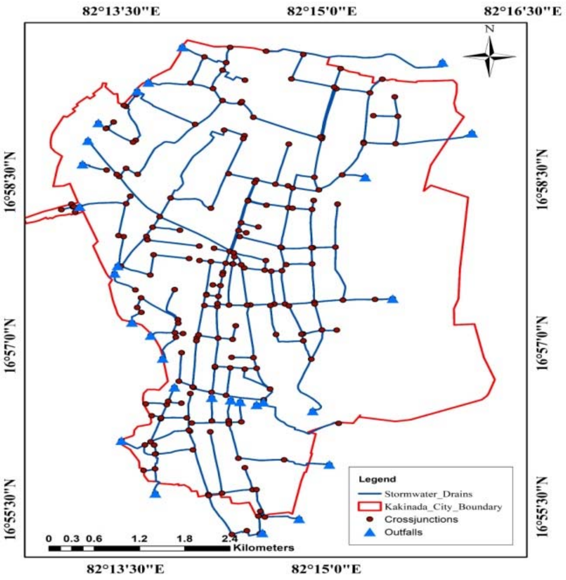


Figure 6. Existing drainage network in the study area.

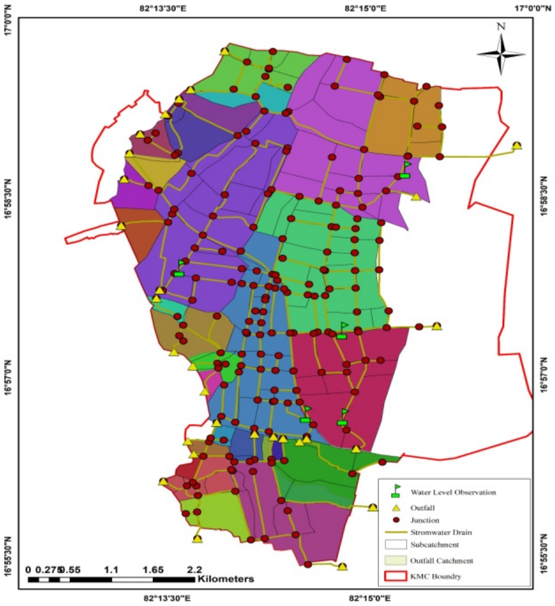


Figure 7. Delineation sub-catchment in the study area

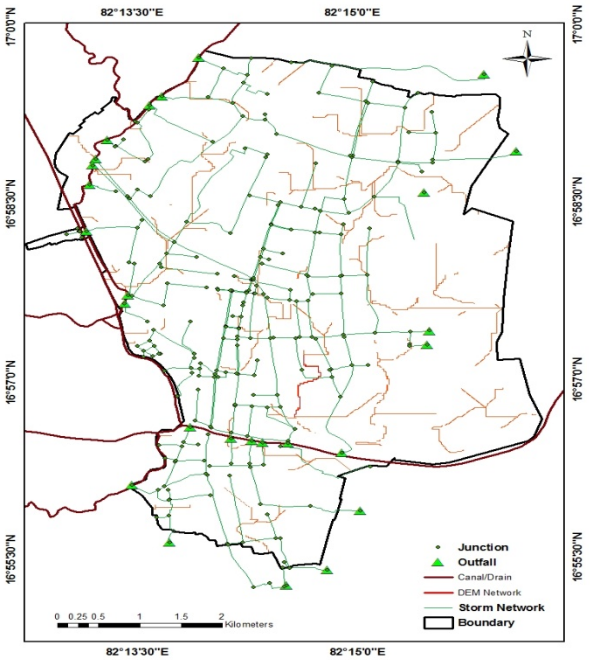


Figure 8. Existing storm drainage network comparison with natural drainage system in the study area

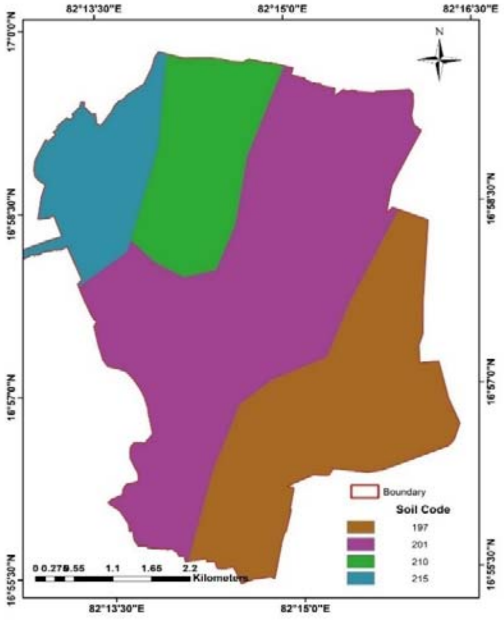


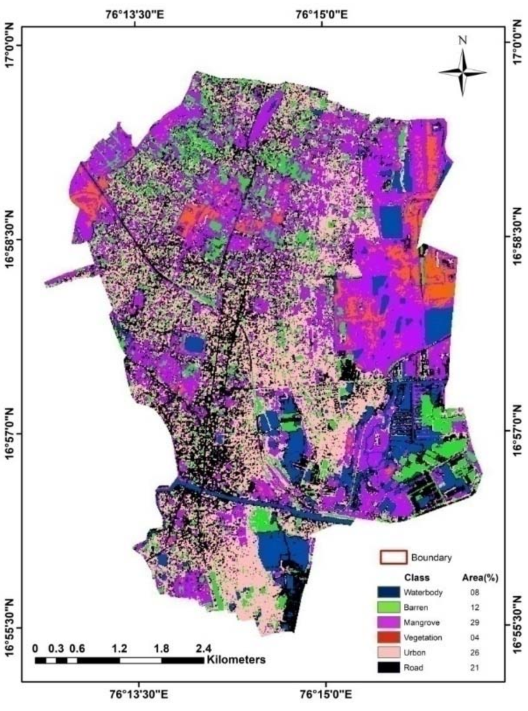
Figure 9. NBBS soil type map of the study area

The study area was divided into 29 catchments, further subdivided into 163 sub-catchments based on the natural drainage network. The soil classification map was prepared using available datasets, identifying different Alluvial soil types represented by codes 197, 201, 210, and 215 (Figure 9).

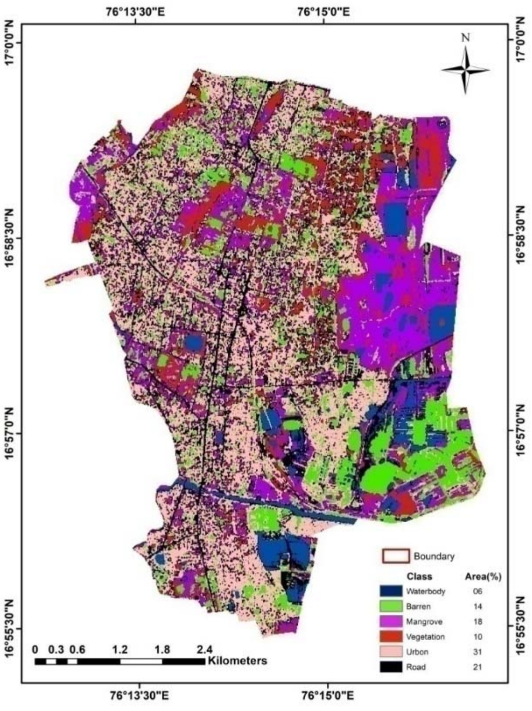
5.2 Land Use/Land Cover (LULC) Mapping

The LULC distribution for the study area is shown in Figures 10 and 11. The classification was performed using the maximum likelihood method, categorizing the land into six primary classes: (i) Barren land, (ii) Built-up area, (iii) Roads, (iv) Mangroves, (v) Vegetation, and (vi) Water body. However, for the years 2016, 2020, and 2023, only six categories built-up area, barren land, vegetation, water body, and roads—were considered due to variations in resolution and data availability. The analysis reveals a noticeable expansion of built-up areas and roads over time, while mangrove cover and vegetation have declined.

2016



2020



2023

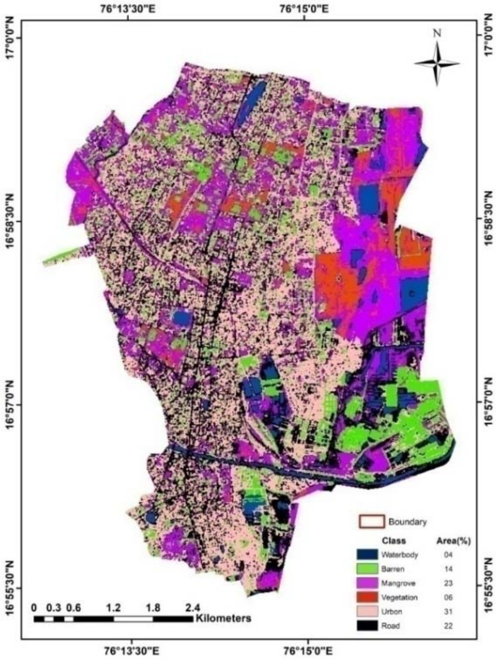


Figure 10. LU/LC mapping throughout the period of study (2016, 2020 & 2023).

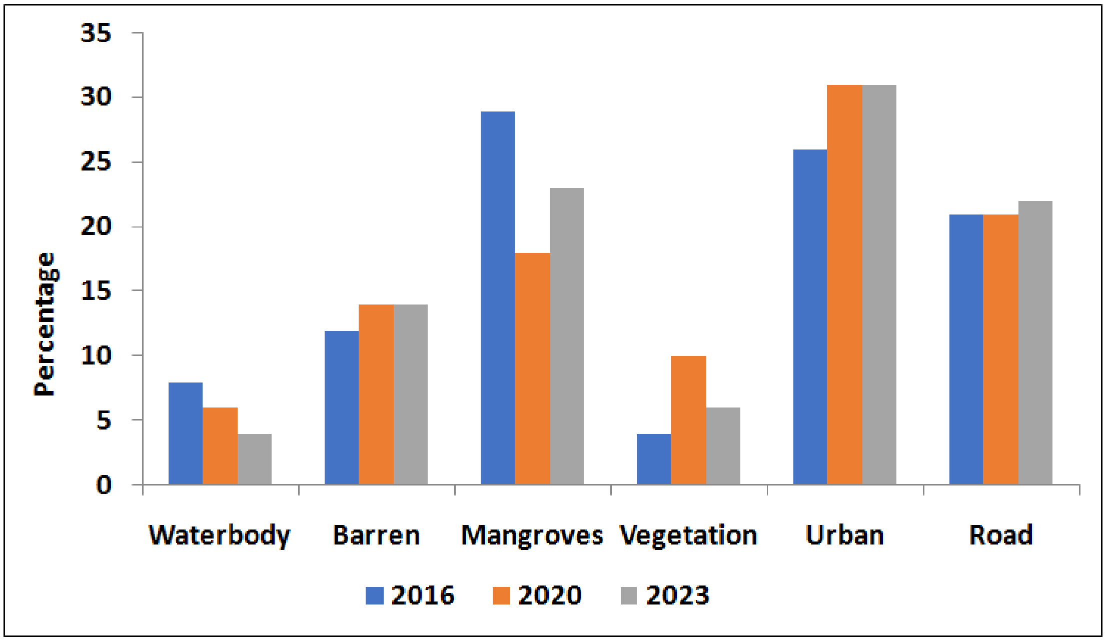


Figure 11. Bar chart distribution of LULC from 2016, 2020 and 2023

The catchments geomorphologic characteristics considered in the SWMM model obtained for each sub-catchment and conduit on the basis of existing drainage network details are given in table 3 respectively.

Table 3 Sub-catchment input characteristics of the study area in SWMM for existing drainage network

S. No	Name of the subcatchment	Area(ha)	Width(m)	%Impervious	%Slope	CN
1	Sub11	48.37	569.73	54.89	0.12	91
2	Sub12	13.45	462.20	47.14	0.13	89
3	Sub13	20.57	627.13	35.33	0.15	87
4	Sub14	9.59	299.69	36.18	0.25	86
5	Sub15	9.66	227.83	23.45	0.25	84
6	Sub16	24.85	769.35	49.60	0.13	89
7	Sub17	8.00	180.18	84.64	0.30	94
8	Sub18	38.00	695.97	53.55	0.14	90
9	Sub19	38.96	296.50	39.22	0.14	89
10	Sub110	38.10	559.47	31.54	0.13	87
11	Sub111	17.32	434.09	56.12	0.18	90
12	Sub112	19.20	294.03	11.92	0.13	85
13	Sub113	19.15	465.94	53.73	0.13	91
14	Sub114	10.69	537.19	76.66	0.13	94
15	Sub115	4.62	500.00	82.86	0.13	94
16	Sub116	10.68	403.02	52.58	2.00	90
17	Sub117	4.81	220.64	68.12	0.15	93
18	Sub118	6.20	274.34	60.18	0.13	93
19	Sub119	13.92	473.47	88.99	0.13	94
20	Sub120	4.18	115.15	80.86	0.08	95
21	Sub121	4.55	140.43	82.53	0.08	95
22	Sub122	11.02	396.40	70.24	0.09	92
23	Sub123	13.21	302.98	43.84	0.13	88
24	Sub124	8.33	548.03	78.42	2.00	94
25	Sub125	5.77	222.78	70.31	0.21	93
26	Sub126	7.53	345.41	48.87	0.16	90
27	Sub127	7.00	614.04	65.46	0.12	91
28	Sub128	9.87	240.15	66.77	0.15	92
29	Sub129	13.37	334.25	59.21	0.31	91
30	Sub130	15.47	295.79	45.00	0.15	89
31	Sub131	13.71	155.27	36.57	0.27	88
32	Sub132	4.36	162.69	58.09	0.12	93
33	Sub133	7.45	227.83	72.17	0.30	92
34	Sub134	6.22	184.02	58.20	0.40	89
35	Sub135	13.62	416.51	62.90	0.15	91

S. No	Name of the subcatchment	Area(ha)	Width(m)	%Impervious	%Slope	CN
36	Sub136	21.55	637.57	34.24	0.40	86
37	Sub137	35.70	347.61	37.32	0.25	89
38	Sub139	23.79	793.00	77.88	0.30	95
39	Sub140	9.10	169.78	60.11	0.25	91
40	Sub141	16.37	500.00	54.95	0.13	92
41	Sub142	19.32	244.87	71.11	0.21	93
42	Sub143	5.00	206.11	49.51	0.25	91
43	Sub144	39.98	626.65	59.16	0.40	91
44	Sub145	23.30	549.53	25.00	0.50	92
45	Sub146	25.33	710.96	68.12	0.32	92
46	Sub147	28.82	811.83	51.83	0.40	89
47	Sub148	21.14	385.06	54.39	0.40	91
48	Sub149	25.97	280.15	21.53	0.49	86
49	Sub150	22.92	353.16	17.55	0.28	85
50	Sub151	18.06	275.30	59.72	0.13	92
51	Sub152	6.61	245.72	67.13	0.30	94
52	Sub153	6.66	350.53	67.02	0.30	91
53	Sub154	4.12	104.04	78.47	0.14	94
54	Sub155	11.46	331.21	70.03	0.12	92
55	Sub156	15.07	369.36	76.77	0.14	93
56	Sub157	12.31	519.41	85.11	0.28	94
57	Sub158	7.66	135.34	90.48	0.13	95
58	Sub159	9.02	222.72	65.44	0.40	93
59	Sub160	9.50	575.76	77.02	0.13	94
60	Sub161	9.46	575.00	65.39	0.13	93
61	Sub162	21.35	532.42	77.60	0.13	94
62	Sub163	16.16	581.29	65.96	0.14	91
63	Sub164	12.75	317.16	92.57	0.14	95
64	Sub165	7.09	176.37	90.97	0.15	95
65	Sub166	6.34	231.39	90.72	0.13	95
66	Sub167	16.18	289.45	79.95	0.13	94
67	Sub168	26.00	675.32	60.95	0.13	91
68	Sub169	22.80	440.15	77.29	0.13	94
69	Sub173	27.36	463.73	87.87	0.31	95
70	Sub174	9.14	154.91	88.33	0.13	95
71	Sub175	14.53	290.60	80.18	0.25	93
72	Sub176	7.88	151.54	93.77	0.14	95
73	Sub177	19.25	307.51	67.44	0.30	95
74	Sub178	21.96	350.80	68.06	0.24	95
75	Sub179	11.23	494.71	62.78	0.25	91
76	Sub180	11.11	337.69	74.55	0.25	93

S. No	Name of the subcatchment	Area(ha)	Width(m)	%Impervious	%Slope	CN
77	Sub181	37.31	614.66	68.60	0.35	93
78	Sub182	5.10	98.27	89.35	0.45	96
79	Sub183	45.48	403.91	79.77	0.35	95
80	Sub184	9.78	150.69	25.51	0.13	86
81	Sub185	17.56	577.63	14.24	0.25	83
82	Sub186	6.35	157.96	32.13	0.15	87
83	Sub187	9.15	150.49	73.36	0.15	93
84	Sub188	23.20	500.00	77.87	0.14	93
85	Sub189	14.66	332.43	55.59	0.45	91
86	Sub190	13.92	400.00	80.62	0.29	94
87	Sub191	8.20	222.83	79.46	0.15	94
88	Sub192	13.19	172.87	69.64	0.14	92
89	Sub193	19.19	251.51	85.16	0.16	95
90	Sub194	15.24	363.72	70.56	0.31	92
91	Sub195	24.95	721.10	57.20	0.14	91
92	Sub196	2.65	129.90	75.85	0.18	96
93	Sub197	5.00	125.31	56.13	0.15	89
94	Sub198	23.84	439.04	70.67	0.16	92
95	Sub199	9.61	204.90	77.19	0.15	94
96	Sub1100	6.94	240.97	91.92	0.18	96
97	Sub1101	3.60	180.90	94.08	0.14	96
98	Sub1102	12.76	562.11	95.01	0.28	96
99	Sub1103	4.46	191.42	87.64	0.20	95
100	Sub1104	5.12	266.67	86.41	0.14	95
101	Sub1105	13.62	446.56	78.21	0.13	94
102	Sub1106	11.95	173.44	84.17	0.13	94
103	Sub1107	9.03	586.36	82.57	0.12	95
104	Sub1108	1.09	91.60	92.66	0.11	95
105	Sub1109	3.62	163.06	73.26	0.13	92
106	Sub1110	1.87	153.28	91.26	0.13	95
107	Sub1111	2.87	133.80	97.18	0.11	97
108	Sub1112	5.45	201.85	92.31	0.13	96
109	Sub1113	2.91	185.35	95.52	0.11	97
110	Sub1114	4.71	253.23	87.13	0.11	95
111	Sub1115	2.95	292.08	78.91	0.12	95
112	Sub1116	3.52	218.63	74.28	0.12	96
113	Sub1117	5.37	308.62	66.85	0.11	92
114	Sub1118	7.04	322.94	87.08	0.12	95
115	Sub1119	12.90	486.79	91.69	0.13	96
116	Sub1120	11.99	255.65	80.53	0.45	94
117	Sub1121	17.46	307.39	79.99	0.15	94

S. No	Name of the subcatchment	Area(ha)	Width(m)	%Impervious	%Slope	CN
118	Sub1122	7.32	500.00	78.88	0.12	94
119	Sub1123	15.11	197.00	85.25	0.29	95
120	Sub1124	8.61	176.07	76.86	0.30	94
121	Sub1125	8.89	189.96	82.17	0.25	95
122	Sub1126	7.18	318.92	89.74	0.14	96
123	Sub1127	3.86	205.32	59.37	0.13	91
124	Sub1128	8.23	242.77	83.94	0.14	95
125	Sub1129	13.70	213.40	26.66	0.13	86
126	Sub1130	13.92	207.76	21.48	0.20	84
127	Sub1131	18.52	370.10	77.96	0.15	93
128	Sub1132	15.13	302.36	62.33	0.30	90
129	Sub1133	11.02	247.64	33.03	0.45	87
130	Sub1134	54.66	555.49	75.98	0.40	93
131	Sub1135	5.98	439.71	75.46	0.13	93
132	Sub1136	32.42	517.06	80.67	0.45	94
133	Sub1137	10.94	242.04	58.83	0.15	89
134	Sub1138	16.09	166.05	77.80	0.15	95
135	Sub1139	46.14	476.16	73.12	0.30	95
136	Sub1140	8.39	140.77	83.49	0.50	93
137	Sub1141	22.80	181.53	80.67	0.25	96
138	Sub1142	2.74	12.62	87.13	0.35	95
139	Sub1143	5.24	152.33	48.08	0.50	88
140	Sub1144	4.25	117.08	70.14	0.45	92
141	Sub1145	4.67	119.44	57.82	0.45	91
142	Sub1147	11.86	303.32	76.85	0.45	94
143	Sub1148	41.41	892.46	70.19	0.20	92
144	Sub1149	11.84	300.51	91.80	0.13	95
145	Sub1150	11.65	295.69	88.47	0.13	95
146	Sub1151	43.27	413.28	92.34	0.49	95
147	Sub1152	12.76	116.42	92.65	0.20	96
148	Sub1153	5.99	330.94	90.47	0.49	96
149	Sub1154	2.10	116.02	93.84	0.29	96
150	Sub1155	6.01	175.22	73.99	0.15	94
151	Sub1156	11.75	210.95	85.92	0.15	95
152	Sub1157	12.31	245.22	86.04	0.15	95
153	Sub1158	3.60	236.84	95.54	0.15	96
154	Sub1159	2.46	161.84	99.59	0.14	98
155	Sub1160	35.70	725.61	51.61	0.13	89
156	Sub1161	2.90	184.71	61.03	0.12	94
157	Sub1162	4.80	305.73	67.63	0.12	94
158	Sub1163	5.28	183.97	89.85	0.15	95

S. No	Name of the subcatchment	Area(ha)	Width(m)	%Impervious	%Slope	CN
159	Sub1164	7.26	578.29	82.32	0.15	94
160	Sub1165	0.89	95.29	87.91	0.13	95
161	Sub1166	5.45	148.50	80.11	0.13	95
162	Sub1167	2.92	99.68	86.06	0.13	95
163	Sub1168	19.21	314.92	75.56	0.13	93

5.3 Integration of Tidal and Rainfall Data for Flood Modeling

To effectively simulate flood events in coastal settings such as Kakinada, both tidal data and extreme rainfall events must be incorporated into the SWMM model. Tidal data for the simulation period of 17th October, 2024 (Figure.12), along with mean tidal data from June to October 2024 (https://tides4fishing.com/in/andhra-pradesh/Kakinada) (Figure.13), provide critical boundary conditions for drainage outlets influenced by tides. The extreme rainfall event of 16th October, 2024 (Figure 14), which was a major contributor to flooding, is included as a time-series input to represent runoff from that storm and serves as an indicator of drainage efficiency. Integrating these datasets enables a comprehensive assessment of the combined impacts of tidal backwater effects and intense rainfall on urban flooding, thereby supporting improved forecasting, effective flood mitigation, and enhancements to the urban drainage system.

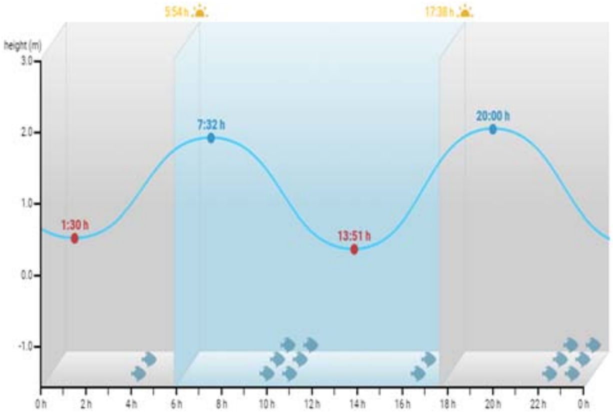


Figure 12. Tidal data on 17th Oct 2024

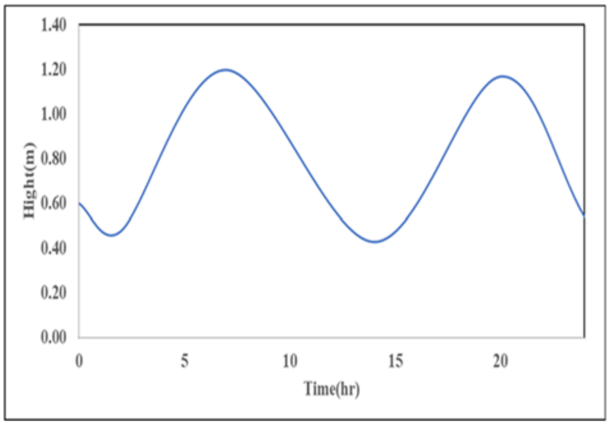
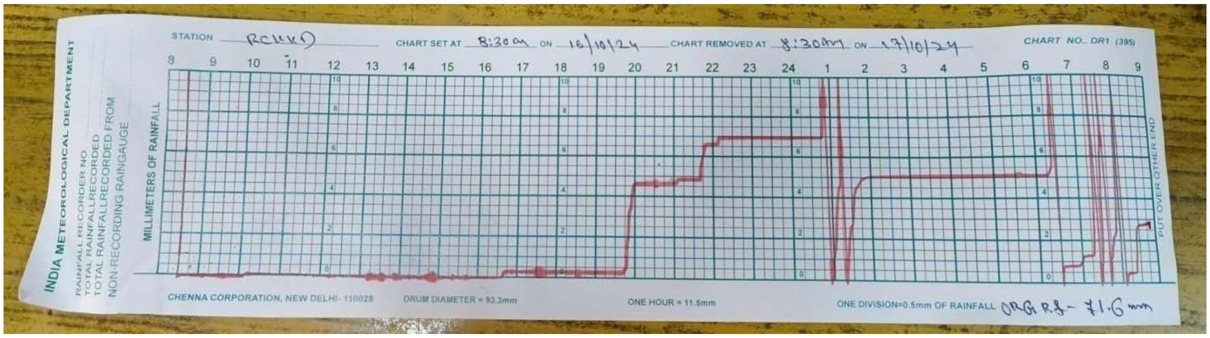


Figure 13. Average Tide (June-Oct 2024)

(https://tides4fishing.com/in/andhra-pradesh/Kakinada)



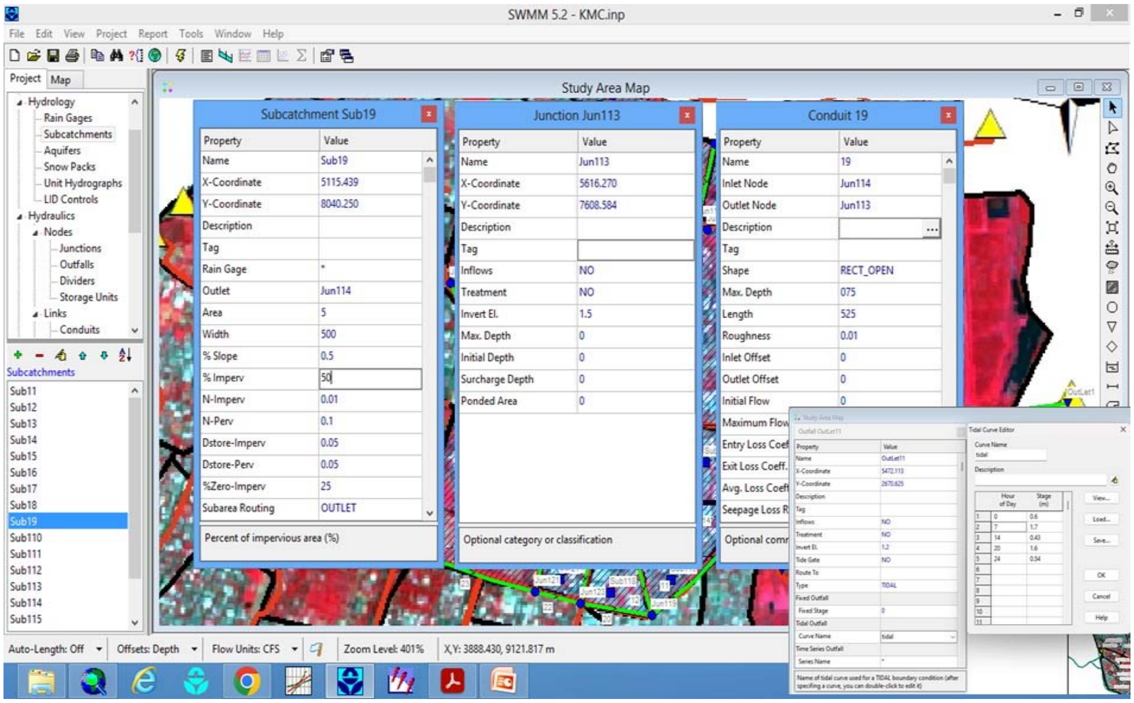
STATION RCUKD CHART SET AT 8:30am ON 16/10/24 CHART REMOVED AT 8:30AM ON 17/10/24 CHART NO.. DR1 (395)

ORG R.f – 71.6 mm

Figure 14. Rainfall data on 16th Oct 2024

5.4 Model setup and Evolution

The SWMM model was developed to simulate the hydrologic and hydraulic behavior of the study area, incorporating both tidal influences and extreme precipitation events. The model was structured by discretizing the area into sub-catchments, nodes, conduits, and storage units to represent the drainage network. Precipitation from the 16th October, 2024, storm was used as an hourly time-series input to evaluate runoff response, while tidal parameters from 17th October, 2024, along with mean tidal values from June to October 2024, were applied as boundary conditions for tidal-influenced outfalls. Model inputs included node and outfall characteristics such as invert elevations and conduit profiles, which were derived from Google Earth Pro. Sub-catchment areas, slopes, and imperviousness were estimated using detailed land-use data in ArcGIS. To ensure hydraulic accuracy, conduit offsets were adjusted to establish a continuous water level profile, eliminating unrealistic discontinuities and maintaining hydrologic consistency throughout the drainage system. These integrated parameters allowed the SWMM model to effectively analyse flood response and evaluate the efficiency of the drainage network in the study area. The SWMM model setup and the water elevation profile of the study area are shown in Figure 15 and 16 respectively.



Subcatchment Sub19

Property	Value
Name	Sub19
X-Coordinate	5115.439
Y-Coordinate	8040.250
Description	
Tag	
Rain Gage	*
Outlet	Jun114
Area	5
Width	500
% Slope	0.5
% Imperv	50
N-Imperv	0.01
N-Perv	0.1
Dstore-Imperv	0.05
Dstore-Perv	0.05
%Zero-Imperv	25
Subarea Routing	OUTLET

Percent of impervious area (%)

Junction Jun113

Property	Value
Name	Jun113
X-Coordinate	5616.270
Y-Coordinate	7608.584
Description	
Tag	
Inflows	NO
Treatment	NO
Invert El.	1.5
Max. Depth	0
Initial Depth	0
Surcharge Depth	0
Ponded Area	0

Optional category or classification

Conduit 19

Property	Value
Name	19
Inlet Node	Jun114
Outlet Node	Jun113
Description	
Tag	
Shape	RECT_OPEN
Max. Depth	075
Length	525
Roughness	0.01
Inlet Offset	0
Outlet Offset	0
Initial Flow	0
Maximum Flow	
Entry Loss Coef	
Exit Loss Coeff.	
Avg. Loss Coeff	
Seepage Loss R	

Optional comm

Study Area Map

Outfall OutLet11

Property	Value
Name	OutLet11
X-Coordinate	5472.113
Y-Coordinate	2670.625
Description	
Tag	
Inflows	NO
Treatment	NO
Invert El.	1.2
Tide Gate	NO
Route To	
Type	TIDAL
Fixed Outfall	
Fixed Stage	0
Tidal Outfall	
Curve Name	tidal
Time Series Outfall	
Series Name	*

Name of tidal curve used for a TIDAL boundary condition (after specifying a curve, you can double-click to edit it)

Tidal Curve Editor

Curve Name: tidal

Description:

	Hour of Day	Stage (m)
1	0	0.6
2	7	1.7
3	14	0.43
4	20	1.6
5	24	0.54
6		
7		
8		
9		
10		
11		

Figure 15. SWMM Model setup

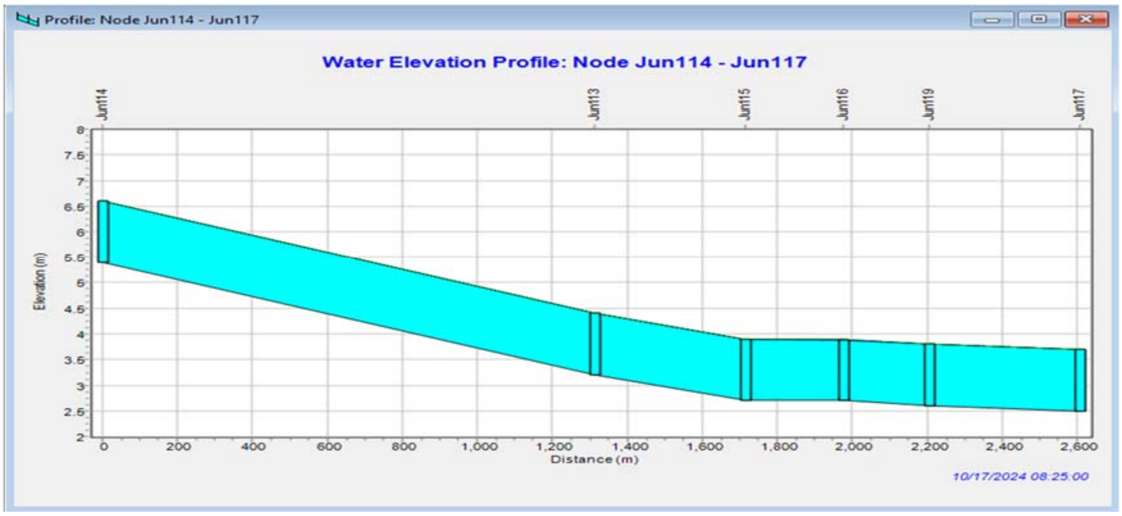


Figure 16. Water Elevation Profile

5.5 Model Calibration

In order to ensure the accuracy and reliability of the SWMM model, calibration was done by comparing simulated water levels to observed water levels at five key locations as shown in Table 4: Three Temple, Dairy Farm Centre, Doodh Factory, KKD Port Station Back Side and Subbaya Gari Street Culvert. Calibration involved tweaking significant model parameters such as

Manning's roughness coefficient, infiltration rates, and conduit losses, in order to replicate the observed values as closely as possible to the simulated values. Calibration was a critical step in modifying the model to reflect, as closely as possible, the hydrologic and hydraulic characteristics of the study area. The performance assessment was based on four statistics are Correlation Coefficient (R), Coefficient of Determination (R^2), Root Mean Square Error (RMSE), and Nash-Sutcliffe Efficiency (NSE). Based on the calibration it can be determined that all sites were in strong agreement between observed and simulated water levels scattered plot shown in Figure 17. Five observation locations statics indices as shown in table 5. Correlation Coefficient (R) 0.871 to 0.971, Coefficient of Determination (R^2) 0.758 to 0.944, Root Mean Square Error (RMSE) 0.383 to 0.490, and Nash-Sutcliffe Efficiency (NSE) 0.865 to 0.949 respectively for five observation locations. These findings confirm that the SWMM model effectively reproduces the hydrologic and hydraulic behaviour of the study area, demonstrating its reliability for flood prediction, forecasting, and supporting flood mitigation planning in Kakinada..

Table 4 Comparison of Observed and Simulated Water Levels (in meters) at Different Locations

S.no	Date	Rainfall (mm)	Water Level (m) Location									
			Three Temple		Dairy Form Centre		Doodth Factory		KKD Port Station Back Side		Subbya Gari Street Culvert	
			Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated	Observed	Simulated
1	16.06.24	42.50	0.70	1.00	1.00	1.50	0.67	1.05	0.70	1.05	1.05	1.41
2	22.06.24	59.00	0.70	1.20	1.20	1.75	1.00	1.20	0.74	1.20	1.20	2.10
3	23.06.24	28.50	0.40	0.66	0.40	0.80	0.54	0.71	0.30	0.67	0.50	0.80
4	29.06.24	29.50	0.41	0.68	0.50	0.85	0.57	0.73	0.40	0.69	0.43	0.82
5	02.08.24	23.80	0.38	0.64	0.48	0.74	0.42	0.65	0.30	0.67	0.35	0.72
6	07.08.24	61.00	0.68	1.20	1.20	1.75	0.78	1.20	0.78	1.20	1.42	2.30
7	22.08.24	25.50	0.36	0.65	0.48	0.76	0.38	0.68	0.32	0.68	0.35	0.74
8	30.08.24	36.20	0.42	0.72	0.86	1.05	0.45	0.72	0.38	0.88	0.50	0.87
9	31.08.24	49.40	0.52	1.20	1.20	1.75	1.05	1.20	1.20	1.20	1.10	1.45
10	24.09.24	27.20	0.39	0.64	0.52	0.80	0.42	0.69	0.38	0.71	0.37	0.78
11	27.09.24	41.00	0.68	0.98	1.02	1.50	0.70	1.10	0.60	0.97	0.98	1.40
12	15.10.24	38.60	0.67	0.97	0.70	1.30	0.68	0.95	0.62	0.98	0.79	1.15
13	17.10.24	72.80	0.74	1.20	1.20	1.75	0.83	1.20	1.00	1.20	2.13	2.50

Table 5. Calibrated statistical parameters at five key locations in the Kakinada Smart City.

Location	**R**	**R^2**	**RMSE**	**NSE**
Three Temple	0.871	0.758	0.383	0.865
Dairy Form Centre	0.971	0.944	0.447	0.949
Doodth Factory	0.918	0.843	0.290	0.879
KKD Port Station Bank Side	0.906	0.820	0.358	0.866
Subbaya Gari Street Culvert	0.956	0.915	0.490	0.930

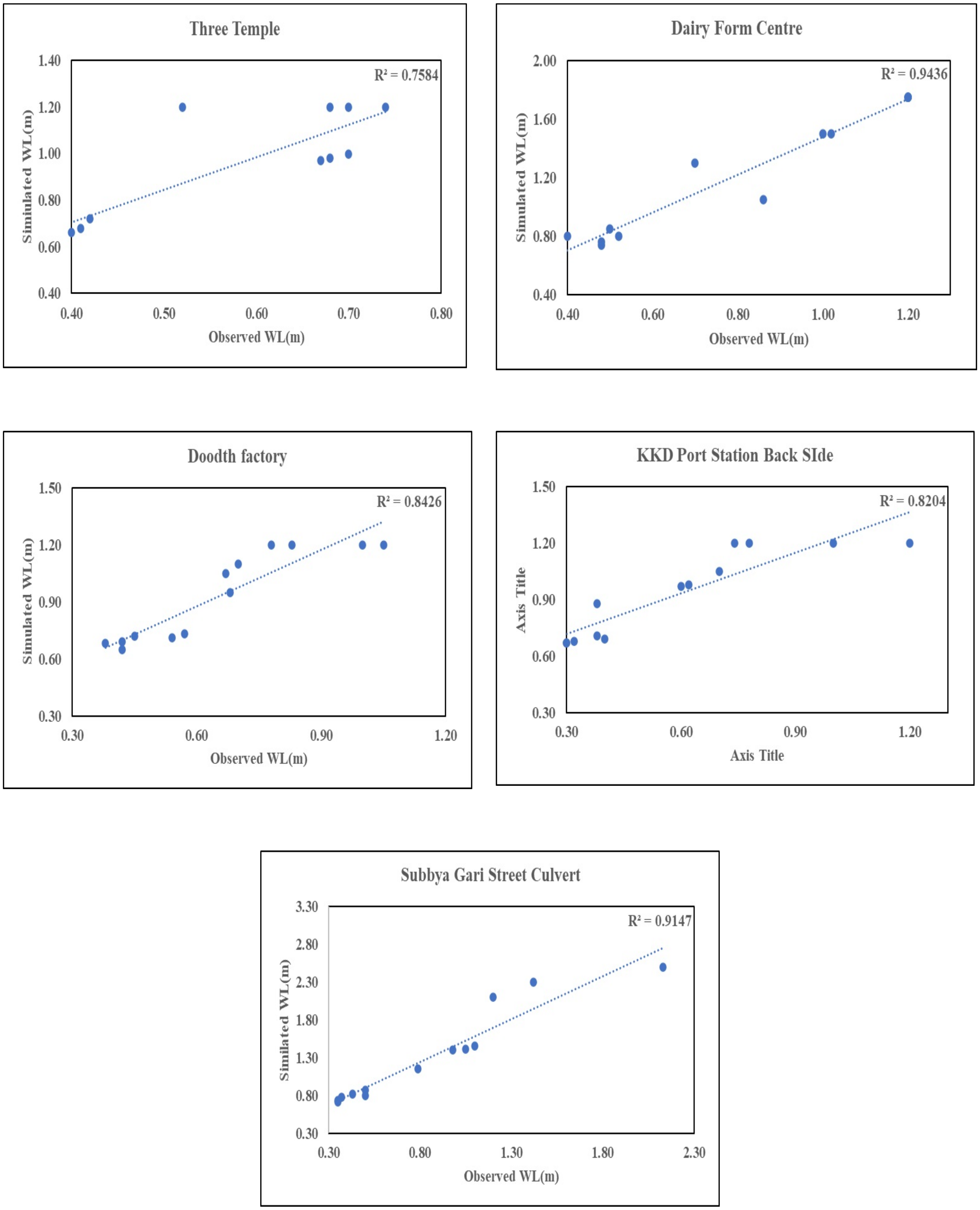


Figure 17. Scatter plots of observed vs simulated water levels and statistical performance indicators at five key locations in the Kakinada Smart City.

5.6 Design Strom Analysis

The design storm analysis utilized 15-minute interval rainfall data spanning from 2007 to 2023 to assess extreme rainfall events that contribute to flooding of urban areas. As noted previously, intense rainfall occurring over a short duration directly affects the performance of urban drainage systems, especially in coastal locations such as Kakinada where drainage performance is affected by tidal backwater. The 15-minute rainfall data was used to derive intensity-duration-frequency (IDF) curves by using EV1 distribution, which can be useful for estimating peak rainfall intensities used in flood models. The records of high-resolution rainfall durations will help to reveal extreme storm events, which can cause the rapid accumulation of runoff and flooding in urban areas. Also, the design storm characteristics produced from the rainfall data was used as input into the SWMM model to simulate the response of the system under the profile of extreme rainfall.

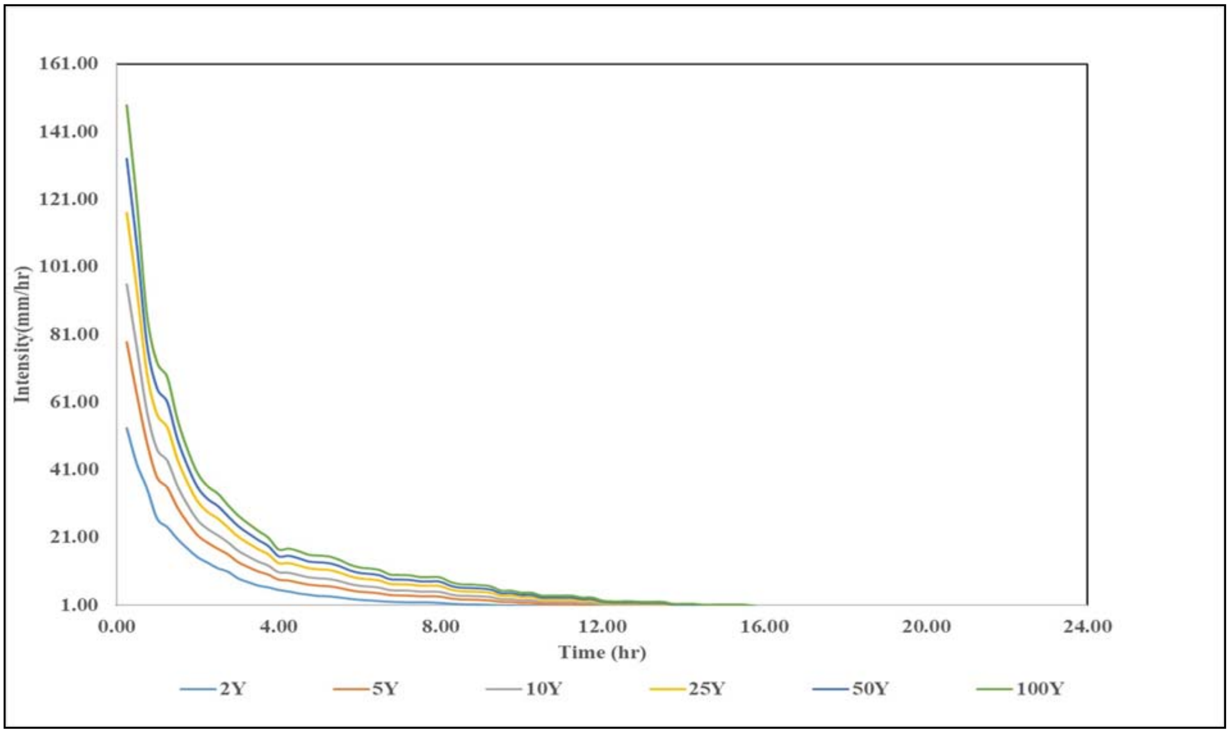


Figure 18. KMC IDF Curves (2007-2024)

The design storm analysis was carried out using EV1 distribution as shown in Figure 18 with 15-minute interval DRC NIH rainfall data from 2007 to 2023 to develop storm events for 2-year and

5-year return periods, which are commonly applied in urban flood modeling and stormwater infrastructure design. The rainfall intensity values corresponding to these return periods were derived from historical rainfall records and used to construct synthetic storm events. The two-year and five-year design storms were developed as time series distributions, characterized by an increase in rainfall intensity, with a peak intensity typically in the middle of the storm duration, before tapering off towards the end of the storm. In the case of the two-year design storm, the rainfall intensity remained low for the first few hours and then increased to a peak intensity of 53.27 mm/hr before tapering off. In the case of the five-year design storm, the storm intensity reached a peak intensity of 78.81 mm/hr , and featured a more pronounced rate of climb and descent. The design storms developed were inputted into the SWMM model to simulate flood behavior and assess how the existing drainage system would perform under various levels of rainfall intensity. The simulation and analysis is used to gain an understanding of areas that are pivotal to flood-prone situations, which will further enhance the development of efficient and resilient urban drainage strategies.

Figure 19 and Figure 20 show the system response for the design storm for the 2-year and 5-year return periods. The graphs show the changes in total inflow, outflow, and flooding over time as modeled simulated in SWMM. The inflow curves show a steep peak for both return periods, which reflects the high intensity in rainfall over a brief time associated with the storm events. The green flood curve shows that the current drainage capacity could not handle a large part of the flow, which has caused flooding at the surface. The outflow hydrograph curve, illustrated in pink, is well below the inflow peak, which also suggests the drainage capacity could not release any stormwater. With the 5-year design storm, the inflows and recorded flood levels are greater than those of the 2-year design storm also indicating the system is more susceptible to more severe storms. These Figures emphasize the need to upgrade the drainage system to withstand frequent and moderate severity rain events.

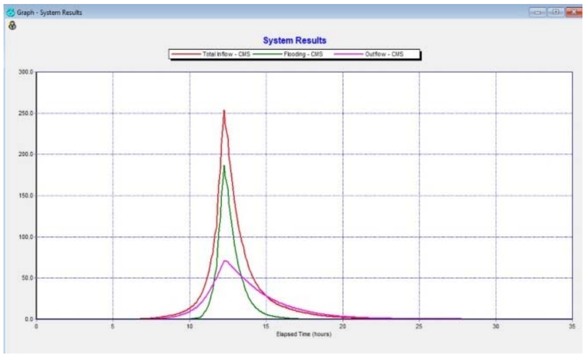


Figure 19. 2-year design storm flooding with existing network

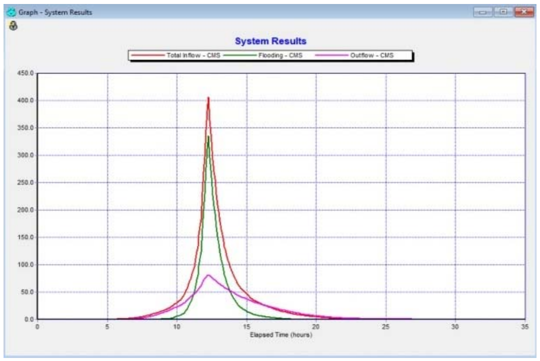


Figure 20. 5-year design storm flooding existing network

The Figures 21 and 22 illustrate the longitudinal profiles of significant open rectangular drains located in Kakinada city that were simulated using EPA SWMM models for the 2-year and 5-year design storms. The section of the drains published was Gudari Guntha, Dairyfarm Centre, Doodfactory, Indrapalem (Subbaya Gari Street), Kakinada Port Station (back-side), and KMC & Market area. For each profile, the drain is on the x-axis in terms of distance, and the elevation is on the y-axis. The blue shaded area represents the water level during storm events. The results clearly indicate that there is overtopping in most of the drain systems during both storm events indicating flooding. The flooding is more prevalent during the 5-year return-period storm, indicating that the existing drainage system is insufficient at least during the moderate intensity rainfall events and flooding location maps generated with 2-year & 5-year design storm as shown in Figure 23 and 24. This emphasizes the need for redesign or upgrade of the drainage systems to improve the flood resilience of the city and lessen the chance of urban inundation during extreme weather events.

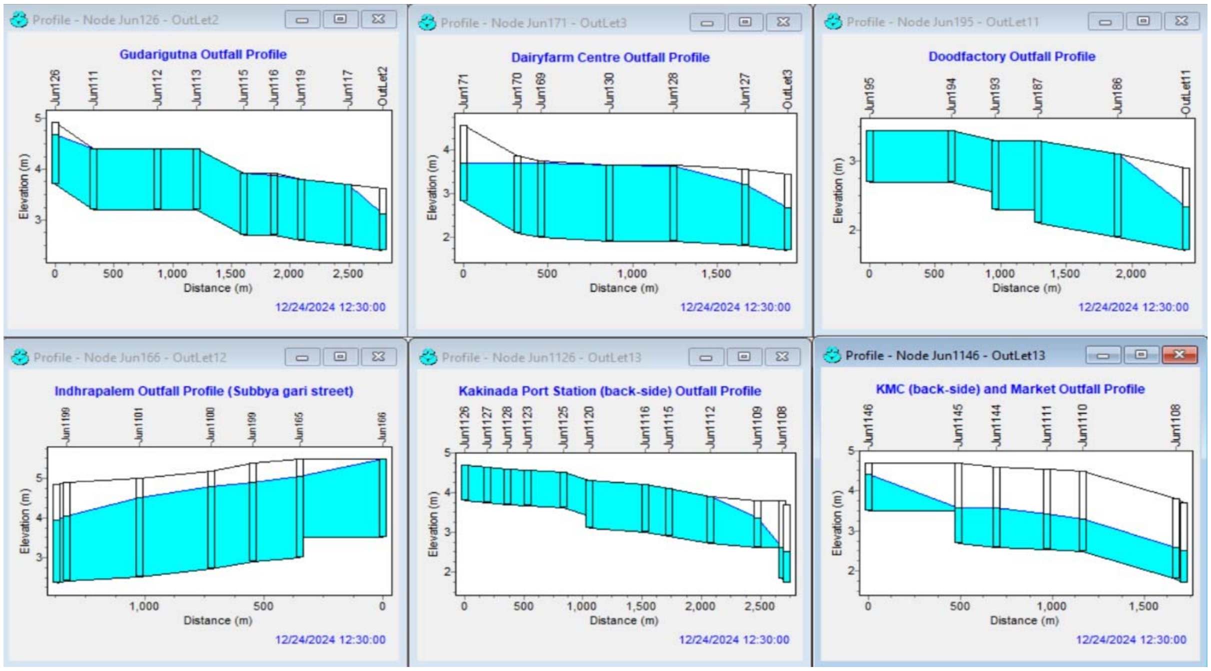


Figure 21. 2-year design storm water surface profile existing network

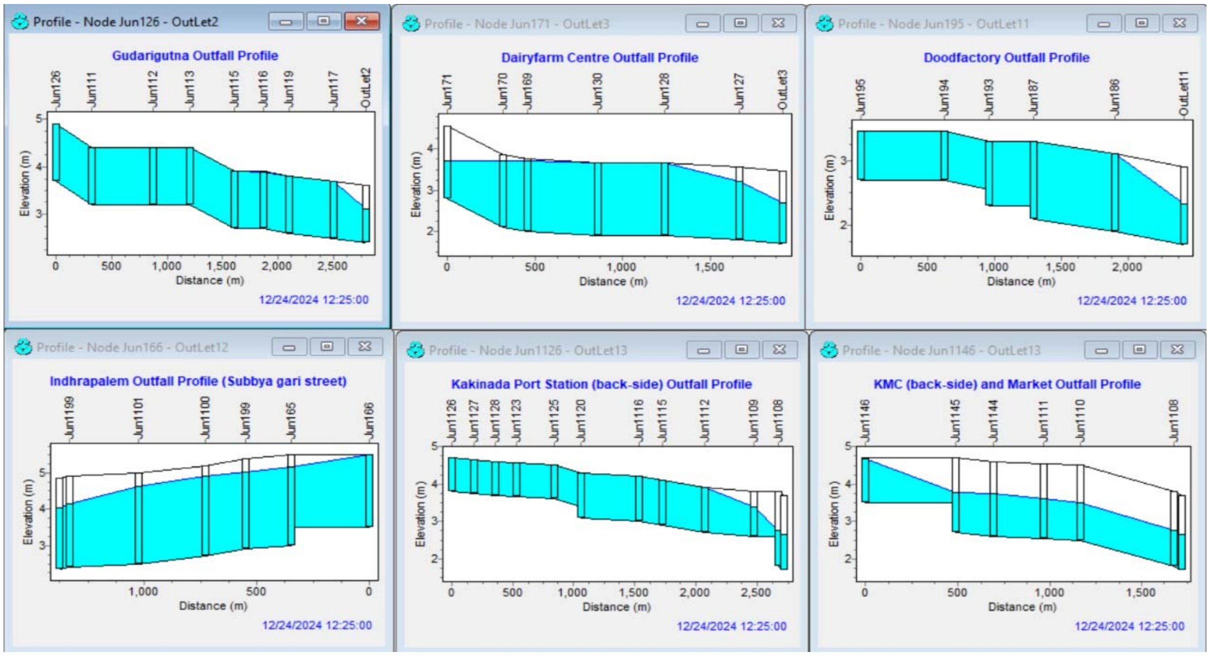


Figure 22. 5-year design storm water surface profile with existing network

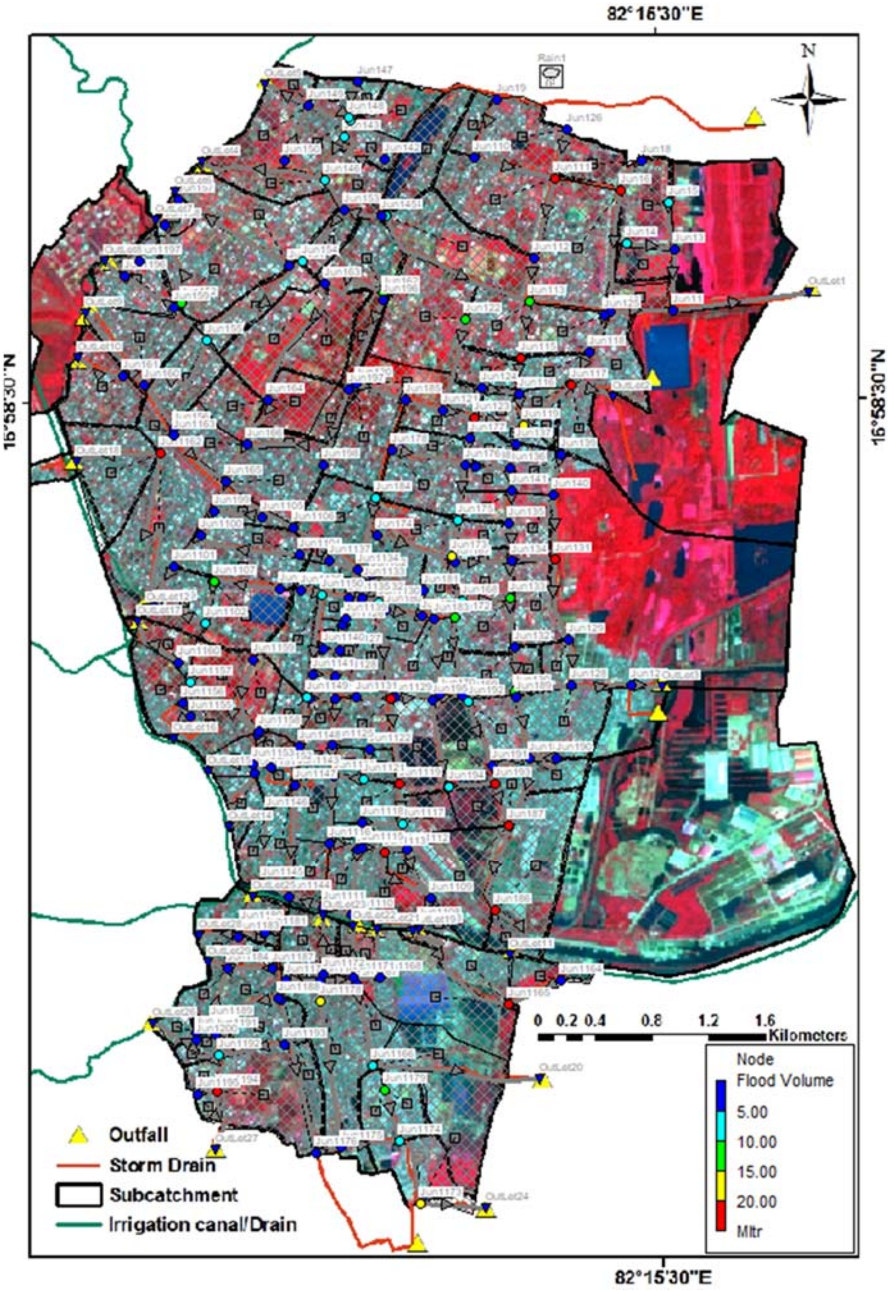


Figure23. 2-year design storm flooding locations of KMC with existing network

The initial simulations indicated considerable flooding in nearly all of the drainage network under both design storms. This demonstrates that the existing infrastructure has an inadequate hydraulic capacity. The dimensions of the drains were modified in response to this flooding to account for the maximum discharge assumed for each design storm independently. Given the coastal characteristics of the study area, increasing the depth of drains was not a viable option. Only the width of the drains was modified, and in some cases, the number of barrels (i.e., the number of parallel conduits) was increased to ensure improved flow conveyance.

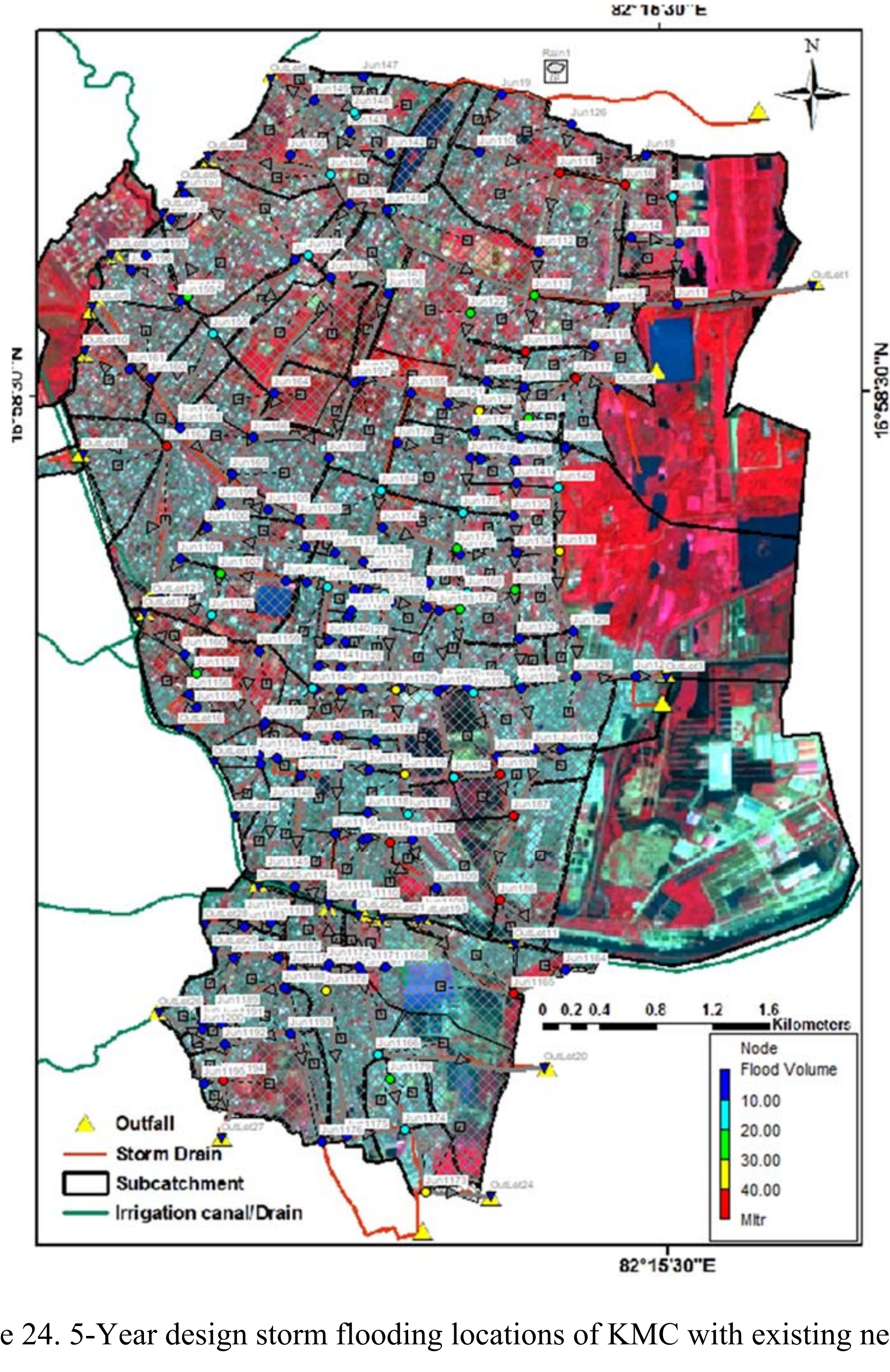


Figure 24. 5-Year design storm flooding locations of KMC with existing network.

After making these modifications, the model was rerun and the updated system results are shown in the Figure 25 and 26. The Figures from the 2-year storm simulation and 5-year storm simulation illustrate the improvement in hydraulic performance with modification of network. Some specific places, like Dairyfarm Centre, Doordarshan Kendra, KMC backside and Kakinada Port station, had observed heavy flooding initially, which eventually got resolved through resizing and water surface profiling of channels as shown in Figure 27 and 28 and also minimize the flood locations to meet the mitigation measures as shown in 29 with modified network of 5-year design storm. The changes made to each drain, such as configuration in their width and depth, are summarized in Table 6. These improvements are important to enable proper stormwater management and flood mitigation in the community; particularly with the increased frequency of intense rainfall events attributed to climate variability.

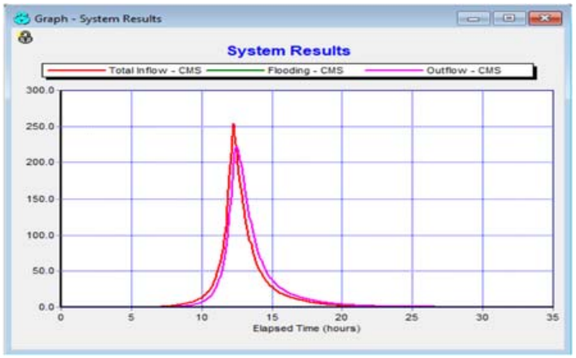


Figure 25.

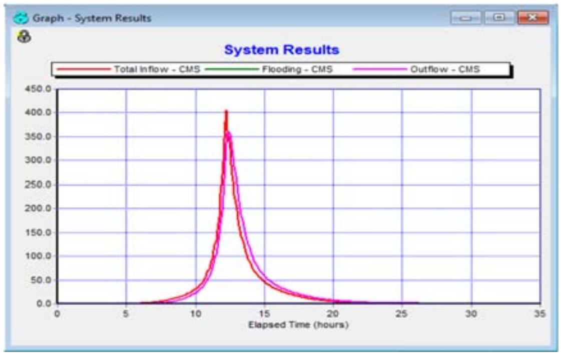


Figure 26. 5-year design storm flooding with modified network

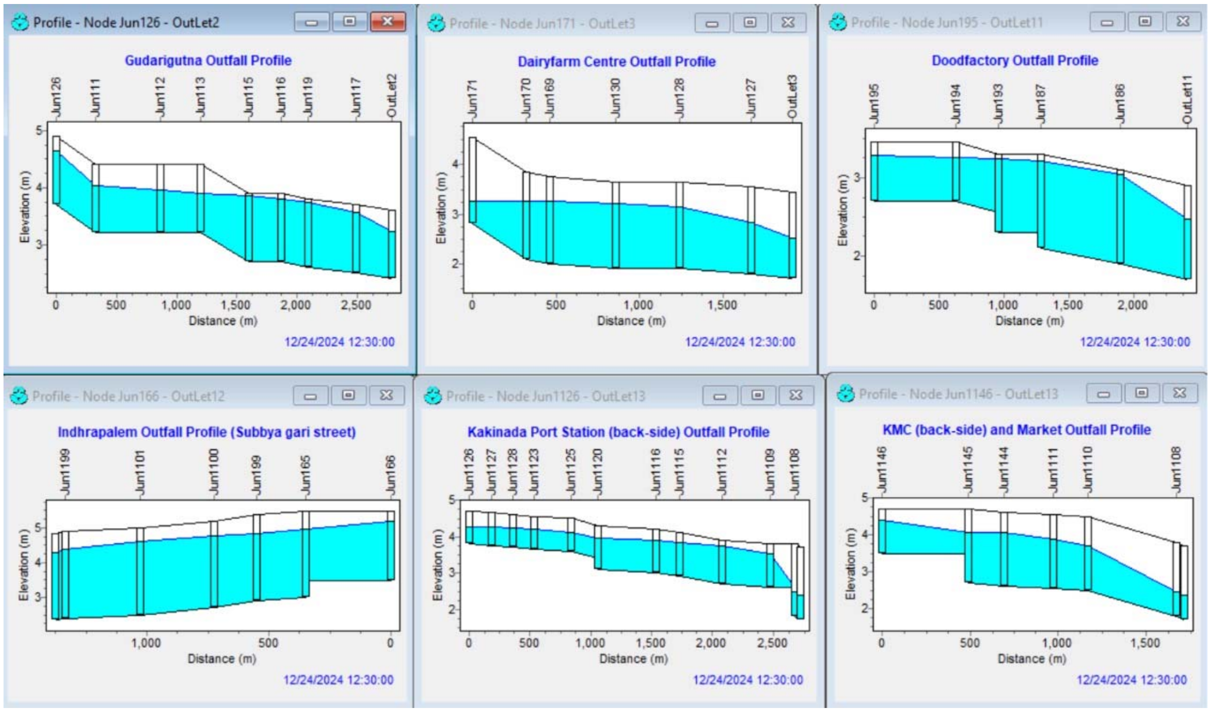


Figure 27. 2-year design storm water surface profile with modified network

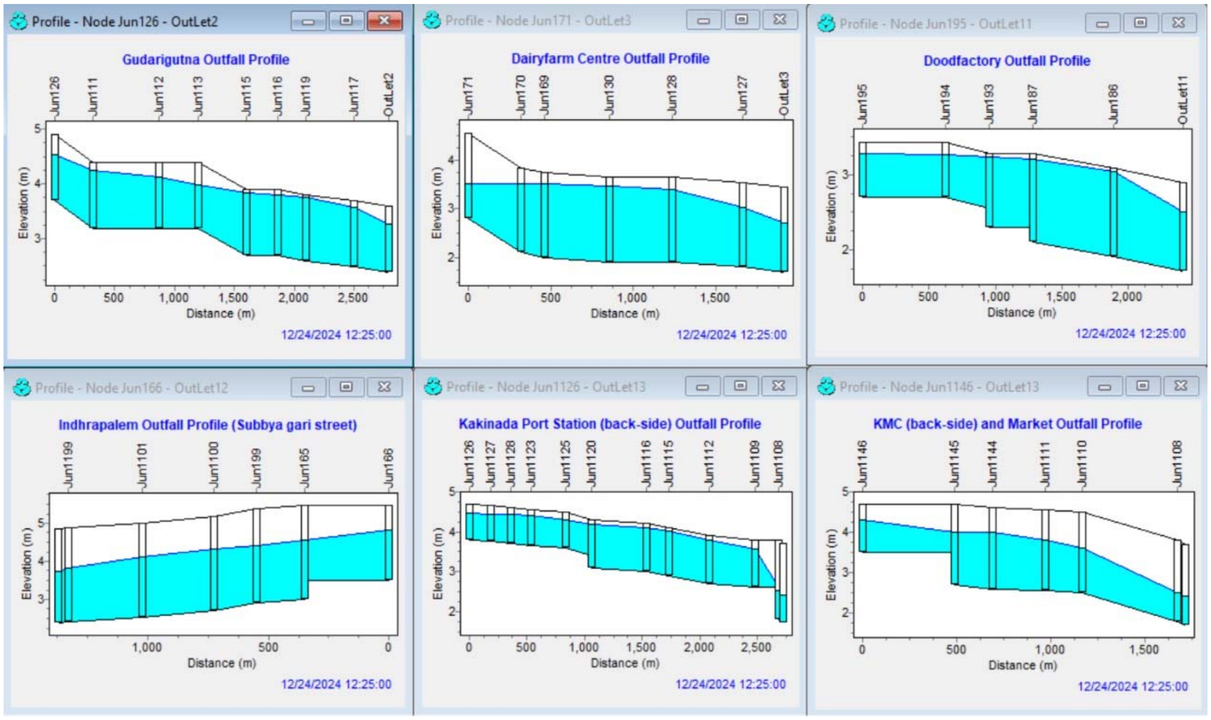


Figure 28. 5-year design storm water surface profile with modified network

Table 6. Hydraulics details with modified network for 2-year and 5-year design storm

S. No	**Conduit**	**Length (m)**	**Existing**		**2-year**		**5-year**	
			Depth (m)	**Width (m)**	**Depth (m)**	**Width (m)**	**Depth (m)**	**Width (m)**
1	Conduit1	737	1.20	1.20	1.20	2.00	1.20	3.00
2	Conduit2	424	1.20	1.20	1.20	2.50	1.20	3.20
3	Conduit3	849	1.20	1.20	1.20	2.50	1.20	3.20
4	Conduit4	291	1.20	1.20	1.20	2.50	1.20	3.50
5	Conduit5	320	0.60	0.60	0.60	1.50	0.60	1.80
6	Conduit7	328	0.60	0.60	0.60	1.80	0.60	2.00
7	Conduit11	403	1.20	1.20	1.20	2.50	1.20	2.80
8	Conduit12	226	1.20	1.20	1.20	2.50	1.20	2.80
9	Conduit13	265	1.20	1.20	1.20	2.50	1.20	3.00
10	Conduit14	399	1.20	1.20	1.20	2.50	1.20	3.00
11	Conduit15	334	1.20	1.20	1.20	2.50	1.20	3.00
12	Conduit16	546	1.20	1.20	1.20	2.50	1.20	3.00
13	Conduit17	582	0.60	0.60	0.60	2.50	0.60	3.20
14	Conduit18	444	0.60	0.60	0.60	2.50	0.60	3.20
15	Conduit20	363	1.00	1.00	1.00	2.50	1.00	3.20
16	Conduit22	245	1.00	1.00	1.00	1.20	1.00	2.00
17	Conduit24	695	1.00	1.00	1.00	1.20	1.00	1.50
18	Conduit25	323	1.20	1.20	1.20	2.00	1.20	2.50

S. No	Conduit	Length (m)	Existing		2-year		5-year	
			Depth (m)	Width (m)	Depth (m)	Width (m)	Depth (m)	Width (m)
19	Conduit45	137	0.60	0.60	0.60	2.00	0.60	2.50
20	Conduit47	268	0.75	0.75	0.75	2.00	0.75	2.20
21	Conduit48	327	1.00	1.00	1.00	2.00	1.00	2.20
22	Conduit49	338	1.00	1.00	1.00	2.00	1.00	2.50
23	Conduit50	1027	1.20	1.20	1.20	1.20	1.20	2.00
24	Conduit52	534	1.20	1.20	1.20	3.00	1.20	3.20
25	Conduit53	972	1.20	1.20	1.20	3.00	1.20	3.20
26	Conduit54	939	1.20	1.20	1.20	3.20	1.20	3.50
27	Conduit55	638	0.75	0.75	0.75	3.20	0.75	3.50
28	Conduit56	242	0.60	0.60	0.60	3.20	0.60	3.50
29	Conduit57	32	0.75	0.75	0.75	2.50	0.75	2.50
30	Conduit59	355	1.00	1.00	1.00	2.50	1.00	2.50
31	Conduit60	684	1.50	1.50	1.50	2.50	1.50	2.50
32	Conduit61	549	0.60	0.60	0.60	1.50	0.60	1.50
33	Conduit62	925	2.00	2.00	2.00	2.50	2.00	2.50
34	Conduit63	441	2.00	2.00	2.00	2.50	2.00	2.50
35	Conduit64	348	2.00	2.00	2.00	2.50	2.00	2.50
36	Conduit65	541	1.20	1.20	1.20	2.50	1.20	2.50
37	Conduit66	237	1.20	1.20	1.20	1.50	1.20	2.00
38	Conduit67	408	1.20	1.20	1.20	1.50	1.20	2.00
39	Conduit74	566	1.20	1.20	1.20	1.00	1.20	1.50
40	Conduit82	402	0.75	0.75	0.75	1.20	0.75	1.80
41	Conduit83	559	1.40	1.40	1.40	1.20	1.40	1.80
42	Conduit85	274	0.90	0.90	0.90	2.00	0.90	2.00
43	Conduit88	278	1.20	1.20	1.20	2.00	1.20	2.00
44	Conduit89	405	1.20	1.20	1.20	2.00	1.20	2.00
45	Conduit90	1314	1.20	1.20	1.20	1.50	1.20	2.00
46	Conduit92	519	1.20	1.20	1.20	2.50	1.20	2.50
47	Conduit93	607	1.20	1.20	1.20	2.50	1.20	2.50
48	Conduit94	520	0.75	0.75	0.75	2.50	0.75	3.00
49	Conduit95	440	0.75	0.75	0.75	1.50	0.75	2.50
50	Conduit96	500	0.75	0.75	0.75	1.00	0.75	1.20
51	Conduit98	626	0.75	0.75	0.75	1.50	0.75	2.50
52	Conduit99	331	0.75	0.75	0.75	1.20	0.75	2.00
53	Conduit100	329	1.00	1.00	1.00	1.50	1.00	1.50
54	Conduit101	198	0.60	0.60	0.60	1.50	0.60	1.50
55	Conduit102	649	1.20	1.20	1.20	3.00	1.20	4.00
56	Conduit103	604	1.20	1.20	1.20	3.00	1.20	4.00
57	Conduit104	608	2.00	2.00	2.00	3.00	2.00	4.00
58	Conduit105	202	2.50	2.50	2.50	3.50	2.50	4.00

S. No	Conduit	Length (m)	Existing		2-year		5-year	
			Depth (m)	Width (m)	Depth (m)	Width (m)	Depth (m)	Width (m)
59	Conduit106	175	2.50	2.50	2.50	2.50	2.50	3.00
60	Conduit107	301	2.50	2.50	2.50	3.00	2.50	3.20
61	Conduit108	306	2.50	2.50	2.50	3.00	2.50	3.20
62	Conduit111	763	1.20	1.20	1.20	2.50	1.20	2.50
63	Conduit113	591	1.20	1.20	1.20	5.00	1.20	5.50
64	Conduit114	346	1.20	1.20	1.20	3.00	1.20	3.00
65	Conduit115	204	1.20	1.20	1.20	3.00	1.20	3.00
66	Conduit116	42	2.00	2.00	2.00	2.50	2.00	2.50
67	Conduit117	506	2.00	2.00	2.00	1.75	2.00	1.75
68	Conduit118	198	2.00	2.00	2.00	5.00	2.00	5.50
69	Conduit119	399	1.20	1.20	1.20	2.50	1.20	2.50
70	Conduit121	469	1.20	1.20	1.20	2.50	1.20	2.50
71	Conduit122	199	1.20	1.20	1.20	2.00	1.20	2.00
72	Conduit123	347	1.20	1.20	1.20	1.50	1.20	1.50
73	Conduit124	183	1.20	1.20	1.20	1.50	1.20	1.50
74	Conduit125	288	0.60	0.60	0.60	2.50	0.60	2.50
75	Conduit126	227	1.20	1.20	1.20	2.00	1.20	2.00
76	Conduit127	233	0.75	0.75	0.75	2.00	0.75	2.00
77	Conduit128	192	0.75	0.75	0.75	2.00	0.75	2.00
78	Conduit129	476	1.20	1.20	1.20	3.50	1.20	4.00
79	Conduit131	305	0.90	0.90	0.90	3.50	0.90	4.00
80	Conduit132	218	0.90	0.90	0.90	2.50	0.90	2.50
81	Conduit133	186	0.90	0.90	0.90	3.00	0.90	3.50
82	Conduit134	170	0.90	0.90	0.90	3.00	0.90	3.50
83	Conduit135	177	0.90	0.90	0.90	3.00	0.90	3.50
84	Conduit136	671	1.20	1.20	1.20	1.50	1.20	1.50
85	Conduit137	689	1.20	1.20	1.20	1.50	1.20	2.50
86	Conduit139	119	0.75	0.75	0.75	0.75	0.75	0.75
87	Conduit140	122	0.75	0.75	0.75	2.00	0.75	2.20
88	Conduit141	272	1.20	1.20	1.20	2.00	1.20	2.20
89	Conduit143	350	0.75	0.75	0.75	2.00	0.75	2.20
90	Conduit144	222	0.60	0.60	0.60	1.00	0.60	1.20
91	Conduit146	157	0.75	0.75	0.75	1.20	0.75	1.20
92	Conduit147	101	0.75	0.75	0.75	1.20	0.75	1.20
93	Conduit148	161	0.75	0.75	0.75	3.50	0.75	2.00
94	Conduit149	174	0.60	0.60	0.60	3.50	0.60	4.00
95	Conduit150	265	0.90	0.90	0.90	2.50	0.90	2.50
96	Conduit151	276	2.00	2.00	2.00	2.50	2.00	2.50
97	Conduit152	204	2.00	2.00	2.00	2.50	2.00	2.50
98	Conduit153	489	1.20	1.20	1.20	2.50	1.20	3.00

S. No	Conduit	Length (m)	Existing		2-year		5-year	
			Depth (m)	Width (m)	Depth (m)	Width (m)	Depth (m)	Width (m)
99	Conduit154	767	1.20	1.20	1.20	1.20	1.20	1.20
100	Conduit155	262	0.90	0.90	0.90	1.20	0.90	1.20
101	Conduit156	350	0.90	0.90	0.90	2.50	0.90	3.00
102	Conduit157	568	0.90	0.90	0.90	3.00	0.90	3.20
103	Conduit158	468	0.90	0.90	0.90	3.00	0.90	3.00
104	Conduit159	106	0.45	0.45	0.45	2.00	0.45	2.20
105	Conduit160	339	0.45	0.45	0.45	2.00	0.45	3.00
106	Conduit161	188	0.45	0.45	0.45	2.00	0.45	2.00
107	Conduit162	642	0.90	0.90	0.90	1.20	0.90	1.20
108	Conduit163	670	1.00	1.00	1.00	3.50	1.00	3.50
109	Conduit164	165	1.00	1.00	1.00	3.50	1.00	3.50
110	Conduit165	99	1.00	1.00	1.00	2.00	1.00	2.50
111	Conduit166	236	1.00	1.00	1.00	2.00	1.00	2.50
112	Conduit167	445	0.60	0.60	0.60	4.00	0.60	8.00
113	Conduit169	136	1.20	1.20	1.20	2.50	1.20	2.50
114	Conduit170	627	1.20	1.20	1.20	2.50	1.20	2.50
115	Conduit171	452	0.75	0.75	0.75	3.50	0.75	3.50
116	Conduit172	969	0.75	0.75	0.75	2.00	0.75	2.00
117	Conduit173	596	0.75	0.75	0.75	2.00	0.75	2.00
118	Conduit174	1256	1.20	1.20	1.20	2.00	1.20	2.00
119	Conduit175	267	0.60	0.60	0.60	2.00	0.60	2.00
120	Conduit176	391	0.60	0.60	0.60	2.00	0.60	2.00
121	Conduit177	344	0.75	0.75	0.75	4.00	0.75	7.00
122	Conduit178	363	0.75	0.75	0.75	2.50	0.75	3.50
123	Conduit179	391	0.75	0.75	0.75	1.50	0.75	1.50
124	Conduit180	464	1.20	1.20	1.20	0.75	1.20	0.75
125	Conduit181	479	1.20	1.20	1.20	0.75	1.20	1.50
126	Conduit182	394	0.75	0.75	0.75	2.00	0.75	2.50
127	Conduit183	1047	0.90	0.90	0.90	1.50	0.90	1.50
128	Conduit184	1096	0.75	0.75	0.75	1.20	0.75	1.50
129	Conduit185	188	1.20	1.20	1.20	1.50	1.20	1.50
130	Conduit186	459	1.20	1.20	1.20	1.50	1.20	1.50
131	Conduit187	157	0.60	0.60	0.60	1.50	0.60	1.50
132	Conduit188	468	0.60	0.60	0.60	1.20	0.60	1.20
133	Conduit189	292	0.60	0.60	0.60	2.50	0.60	2.50
134	Conduit190	152	0.60	0.60	0.60	2.00	0.60	3.00
135	Conduit191	181	0.60	0.60	0.60	2.00	0.60	2.00
136	Conduit192	251	0.60	0.60	0.60	1.20	0.60	2.00
137	Conduit195	343	0.60	0.60	0.60	2.50	0.60	3.00
138	Conduit196	502	0.60	0.60	0.60	2.50	0.60	3.00

S. No	Conduit	Length (m)	Existing		2-year		5-year	
			Depth (m)	Width (m)	Depth (m)	Width (m)	Depth (m)	Width (m)
139	Conduit197	557	0.75	0.75	0.75	2.50	0.75	3.00
140	Conduit200	367	1.40	1.40	1.40	2.50	1.40	2.50
141	Conduit201	93	0.90	0.90	0.90	0.90	0.90	0.90
142	Conduit202	411	0.60	0.60	0.60	1.50	0.60	2.00
143	Conduit203	228	0.75	0.75	0.75	1.50	0.75	2.00
144	Conduit204	287	0.75	0.75	0.75	1.50	0.75	2.00
145	Conduit205	129	0.75	0.75	0.75	0.90	0.75	2.00
146	Conduit206	468	0.60	0.60	0.60	2.00	0.60	2.00
147	Conduit207	480	1.00	1.00	1.00	2.00	1.00	2.00
148	Conduit42	883	0.60	0.60	0.60	2.00	0.60	2.00
149	Conduit43	523	0.60	0.60	0.60	2.00	0.60	2.00
150	Conduit46	488	0.60	0.60	0.60	1.00	0.60	1.20
151	Conduit211	248	0.60	0.60	0.60	3.00	0.60	1.20
152	Conduit27	249	1.75	1.75	1.75	2.20	1.75	2.50
153	Conduit73	320	1.75	1.75	1.75	2.00	1.75	3.00
154	Conduit72	140	1.75	1.75	1.75	2.00	1.75	3.00
155	Conduit71	399	1.75	1.75	1.75	2.00	1.75	2.50
156	Conduit29	380	1.75	1.75	1.75	2.50	1.75	3.00
157	Conduit30	427	1.75	1.75	1.75	2.00	1.75	3.50
158	Conduit39	278	1.20	1.20	1.20	1.60	1.20	2.00
159	Conduit38	439	1.20	1.20	1.20	1.00	1.20	1.20
160	Conduit31	656	1.20	1.20	1.20	1.00	1.20	1.50
161	Conduit28	269	1.20	1.20	1.20	0.75	1.20	0.75
162	Conduit58	424	0.60	0.60	0.60	1.50	0.60	1.50
163	Conduit220	140	0.60	0.60	0.60	2.00	0.60	2.00
164	Conduit221	149	0.60	0.60	0.60	2.00	0.60	2.00
165	Conduit222	368	0.60	0.60	0.60	2.50	0.60	3.00
166	Conduit112	470	1.20	1.20	1.20	2.00	1.20	3.00
167	Conduit223	258	1.20	1.20	1.20	1.50	1.20	1.50
168	Conduit37	259	0.75	0.75	0.75	2.00	0.75	3.00
169	Conduit36	152	1.20	1.20	1.20	2.50	1.20	3.00
170	Conduit41	184	1.20	1.20	1.20	2.00	1.20	2.00
171	Conduit40	218	1.20	1.20	1.20	2.00	1.20	2.50
172	Conduit34	250	1.20	1.20	1.20	2.00	1.20	2.50
173	Conduit68	396	1.00	1.00	1.00	1.00	1.00	1.50
174	Conduit69	346	1.00	1.00	1.00	1.00	1.00	1.50
175	Conduit33	317	1.20	1.20	1.20	1.20	1.20	1.50
176	Conduit70	270	1.20	1.20	1.20	0.60	1.20	1.20
177	Conduit86	518	1.00	1.00	1.00	1.50	1.00	1.50
178	Conduit78	560	1.00	1.00	1.00	1.50	1.00	1.50

S. No	Conduit	Length (m)	Existing		2-year		5-year	
			Depth (m)	Width (m)	Depth (m)	Width (m)	Depth (m)	Width (m)
179	Conduit76	396	1.20	1.20	1.20	1.50	1.20	1.50
180	Conduit75	569	1.20	1.20	1.20	1.50	1.20	1.50
181	Conduit84	93	0.90	0.90	0.90	1.50	0.90	1.50
182	Conduit97	263	0.75	0.75	0.75	1.00	0.75	1.50
183	Conduit235	117	1.00	1.00	1.00	1.00	1.00	1.50
184	Conduit138	241	0.75	0.75	0.75	1.50	0.75	1.50
185	Conduit130	698	0.75	0.75	0.75	3.00	0.75	4.00
186	Conduit21	218	0.60	0.60	0.60	1.00	0.60	2.00
187	Conduit109	419	1.20	1.20	1.20	2.00	1.20	2.00
188	Conduit240	43	2.50	2.50	2.50	1.20	2.50	2.00
189	Conduit168	1123	1.20	1.20	1.20	1.20	1.20	2.00
190	Conduit23	385	1.00	1.00	1.00	1.00	1.00	2.00
191	Conduit242	268	1.00	1.00	1.00	1.20	1.00	2.00
192	Conduit10	411	1.20	1.20	1.20	1.20	1.20	1.20
193	Conduit9	199	1.20	1.20	1.20	0.75	1.20	1.50
194	Conduit8	294	1.20	1.20	1.20	1.50	1.20	2.50
195	Conduit44	348	0.60	0.60	0.60	2.00	0.60	2.00
196	Conduit81	162	0.75	0.75	0.75	3.50	0.75	4.00
197	Conduit245	213	0.75	0.75	0.75	2.00	0.75	2.00
198	Conduit238	165	1.00	1.00	1.00	1.50	1.00	1.50
199	Conduit246	293	0.60	0.60	0.60	0.60	0.60	1.00

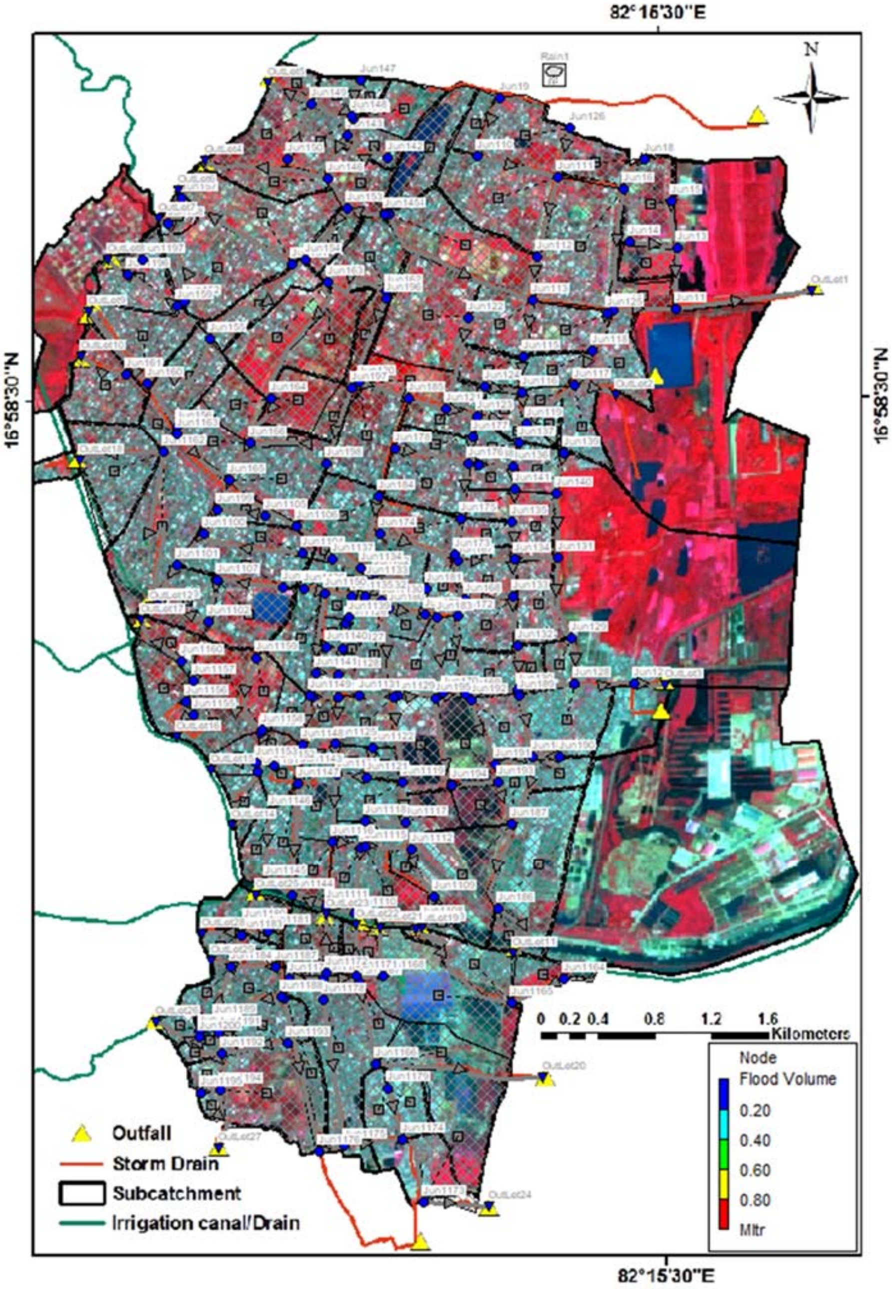


Figure 29. 5-year design storm flooding locations of KMC with modified network.

5.7 Climate Change Impact

To evaluate the potential impact of climate change for rainfall intensity and urban flooding, rainfall data were obtained from the National Institute of Hydrology (NIH), Roorkee, based on future rainfall projections. These projections were accessed by using the Bias Correction and Spatial Disaggregation (BCSD) method under the BNU-ESM model, which is one of the Earth System Models (ESMs) available for climate projections. The dataset consists of rainfall from 2006 to

2100 and provides daily gridded rainfall values. For this study, rainfall data corresponding to the Kakinada grid point were extracted and processed for further analysis. These projections offer valuable insights into long-term rainfall trends and potential changes in hydrologic behavior under climate change scenarios. The future rainfall data specific to Kakinada are presented in Figure 30.

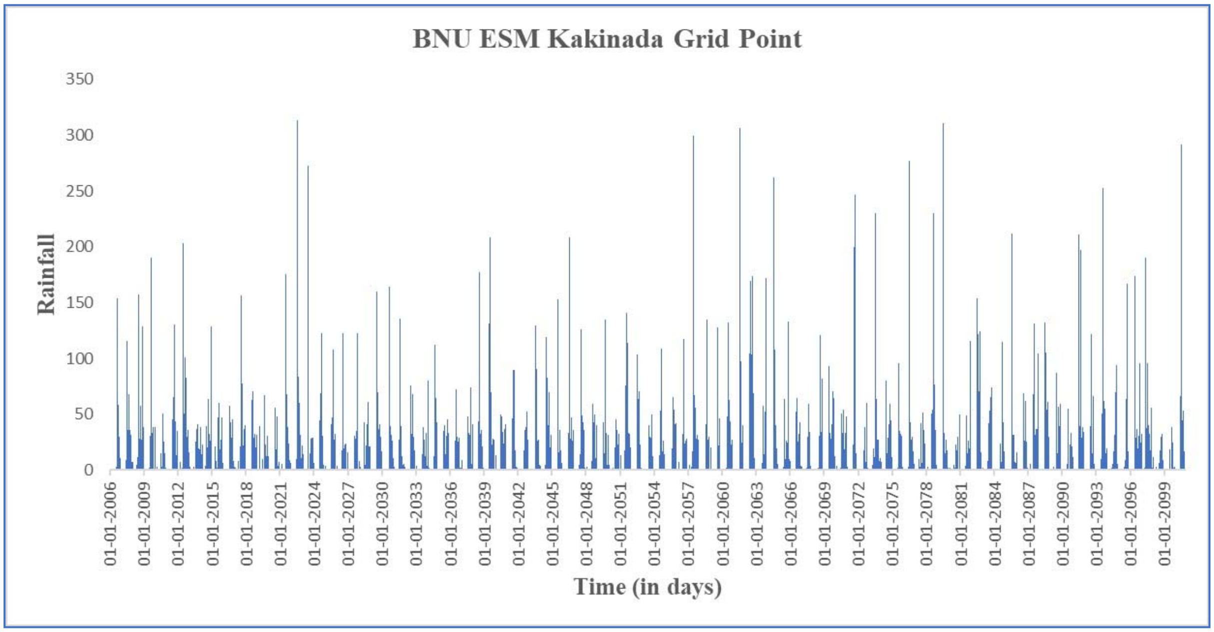


Figure 30. Projected daily rainfall near Kakinada (KMC) grid point (2006-2100) from BNU ESM Model (Bias-corrected spatial disaggregation method)

To determine how future climate scenarios would affect stormwater infrastructure in Kakinada Smart City, IDF curves were derived from historical rainfall data from 2007 to 2024 and compared with projections under climate change scenarios extending to 2100 shown in Figure 31 The results indicate a clear increase in rainfall depths across all design storms and return periods. For instance, the 2-year return period rainfall is projected to increase from 94.05 mm (observed) to 118.28 mm, while the 100-year event rises from 235.95 mm to 357.69 mm. These increases across different return periods suggest that climate change will amplify both the severity and frequency of urban flooding. The IDF curves generated for Kakinada Smart City show that projected rainfall intensities (dashed lines) consistently exceed observed values (solid lines) for all durations and return periods (Figure.32). For high-return-period events, such as the 100-year storm, projected short-duration intensities exceed 180 mm/hr, which could overwhelm the existing drainage infrastructure. The sharp initial rise in projected rainfall intensity further highlights the elevated risk of flash flooding under extreme weather conditions. These findings underscore the necessity of incorporating climate-resilient designs in stormwater infrastructure planning, ensuring that urban drainage systems can accommodate increasingly intense rainfall due to global warming.

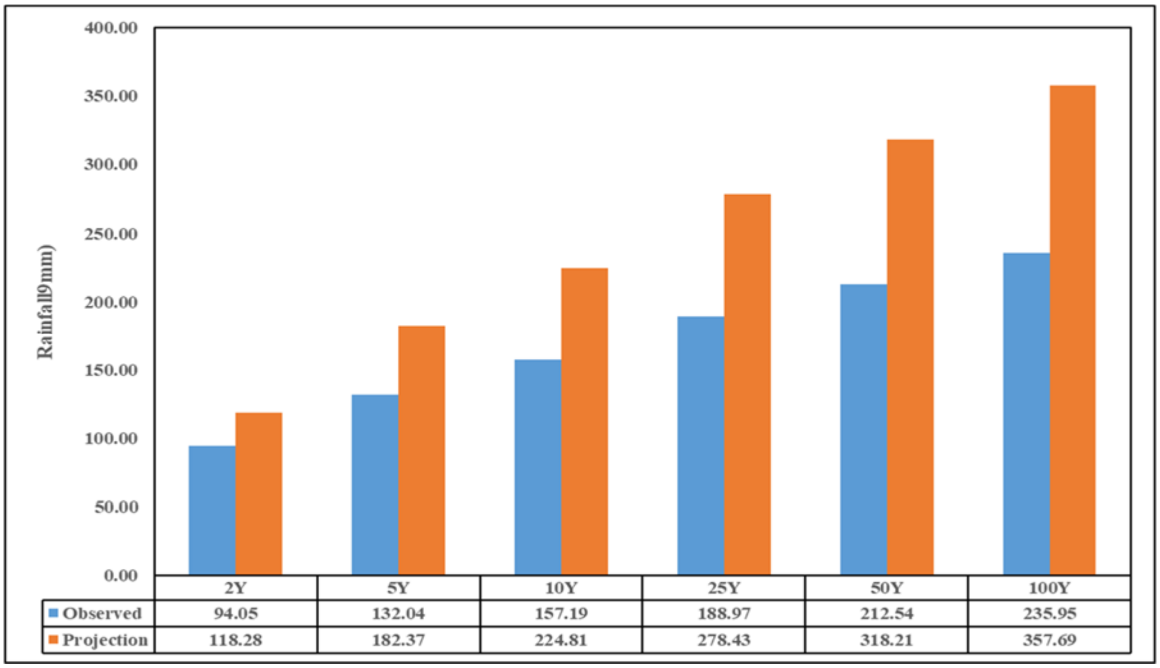


Figure 31. Observed rainfall comparison with projection BNU ESM Model

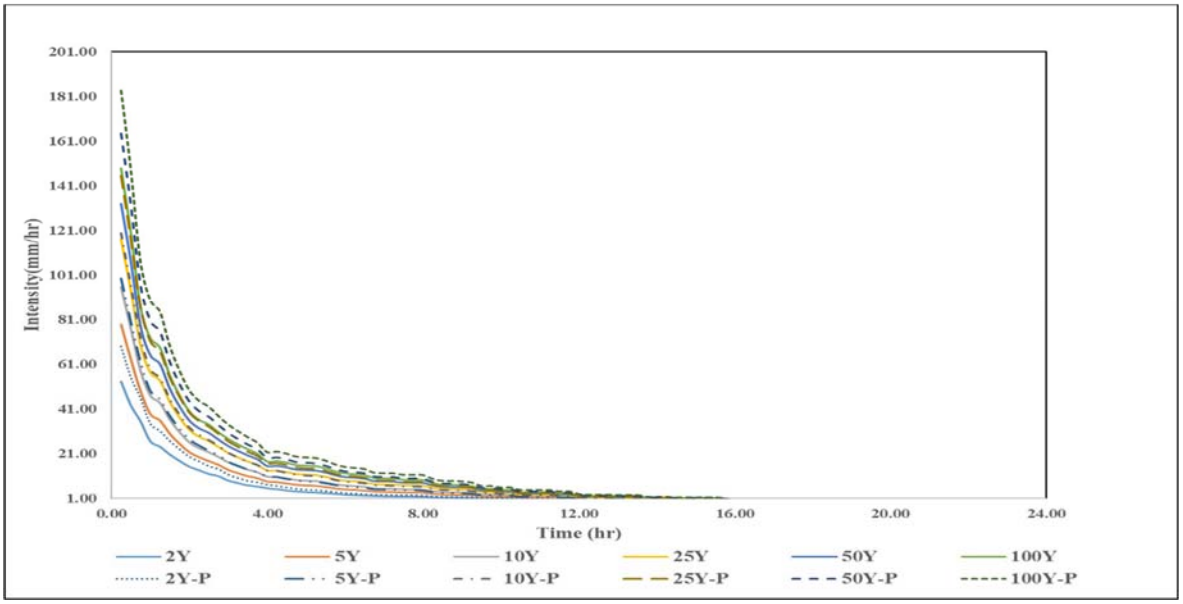


Figure 32. KMC IDF curves observed and climate change projection BNU-ESM

The hyetograph assessment substantial differences between the observed and projected storm profiles in Figure 33. Both of these hyetographs exhibit symmetric, bell-shaped distributions, with peak intensity occurring around hour 12, a pattern typical for alternate box design storms. However, the projected hyetograph shows a markedly higher peak intensity than the observed 100-year storm, with peaks of approximately 180–190 mm/hr compared to 140–150 mm/hr in the observed case. This sharp increase in peak rainfall intensity is expected to generate larger runoff volumes and elevate flood risk. The contrast between observed IDF curves (derived from historical rainfall data, 2007–2024) and projected IDF curves (from the BNU-ESM climate model, 2006–2100) clearly illustrates the anticipated impacts of climate change on rainfall characteristics shown in Figure 34

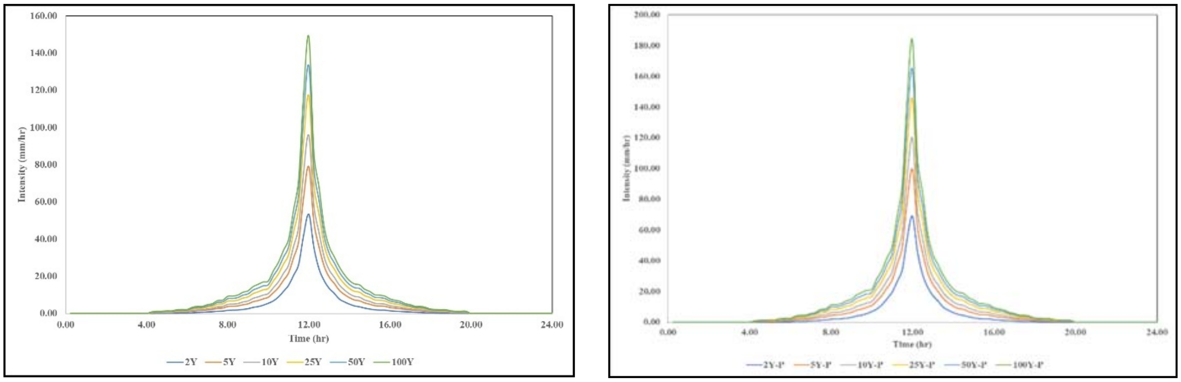
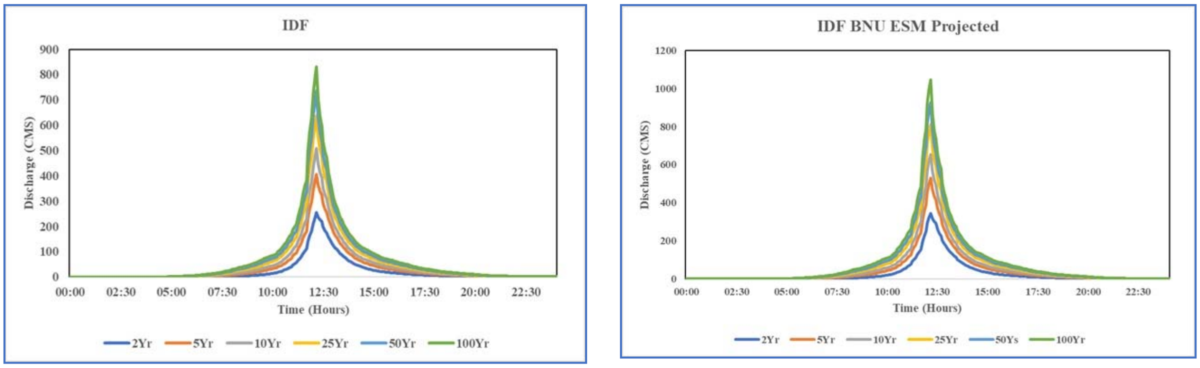


Figure 33. Design storm observed and climate change projection hyetograph.



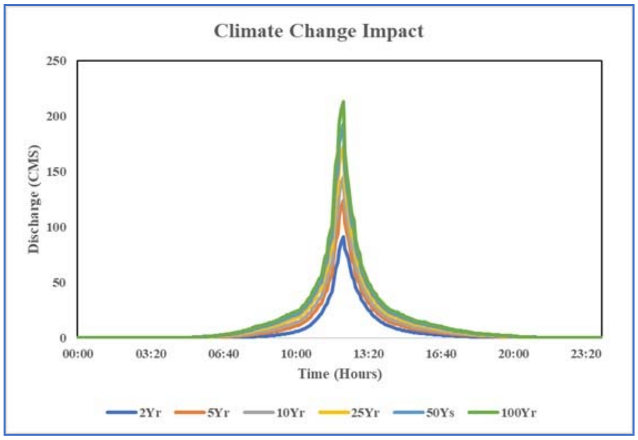


Figure 34. Observed IDF curves, projected IDF curves and climate change impact on rainfall

CONCLUSIONS

Design storm analysis utilized a total of 18 years of historical rainfall data (2007-2024) to construct 2-year and 5-year return period storms. LULC analysis of Kakinada Municipal Corporation (KMC) identified substantial urbanization and corresponding decreases in waterbodies and mangroves from 2016 to 2023. These changes have intensified surface runoff and flood vulnerability in the city. Sustainable drainage planning is essential to mitigate future flood risks. SWMM input parameters such as Node/link characteristics, pervious/impervious area, soil type; average width/slope and SCS-CN have been computed for each sub-catchments in the study area.

Measured water levels during 2024 monsoon period at five locations (Three temple centre, Dairy form centre, Doodt factory, Kakinada port station and Subbya gari street culvert) in the study area. The SWMM model calibrated and evaluated with observed water level. Correlation Coefficient (R) 0.871 to 0.971, Coefficient of Determination (R^2) 0.758 to 0.944, Root Mean Square Error (RMSE) 0.383 to 0.490, and Nash-Sutcliffe Efficiency (NSE) 0.865 to 0.949 respectively. Short interval rainfall data (15 minutes) for the period 2007 - 2023 collected from DRC hydro metrological observation station and developed the IDF curves for various return periods. The 15 minutes' maximum peak intensity of 2, 5, 10, 15, 25, 50 and 100-- years return periods are 55, 81, 98, 108, 120, 136 and 152 mm/hr respectively. Calibrated model is used to simulate flood for 2-year design storm period and tidal effects considered as boundary condition, where the drains join to creeks. It is found that the exiting storm drainage network is not adequate and identified the flooding locations. In order to mitigate urban flood in the KMC with the limitation of topographical conditions it is necessary to expand the width of the storm drains. Therefore, with the help of calibrated SWMM model the KMC drainage network has been modified and simulated with 5-year design storm without any flooding. Develop the outfall hydrographs, water surface profile of the network and flooding location maps with existing and modified network. The climate change is also considered to find the impact of precipitation and discharge in the study area. The evaluation also noted climate change for consideration of future climate variability in rainfall patterns when planning for storm water flood management. Find out the inflow-outflow hydrograph at various outlets and the water surface profile along the storm water drains. Feasibility to integrate the existing drainage network with interflow to mitigate urban storm water flooding in the Kakinada smart city.

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Director: **Dr. M. K. Goel**

Co-Ordinator: **Dr Y. R. S. Rao**

Head: **Dr. S. V. Vijaya Kumar**

Study Group
R. Venkata Ramana
Y. R. Satyaji Rao
V. S. Jayakanthan

Support Staff
P.R. Rao
Allaka Nageswara Rao