

Assessment of the Urban Storm Water Drainage System of Kakinada Smart City Using GIS and EPA SWMM under Design Storm

Balireddy Satya Chandu¹, P. Mynar Babu, Assistant Professor (c)²

¹ M. Tech. Scholar, Department of Civil Engineering, University College of Engineering Kakinada(A), JNTUK, Kakinada, Andhra Pradesh, India

² Assistant Professor (c), Department of Civil Engineering, University College of Engineering Kakinada(A), JNTUK, Kakinada, Andhra Pradesh, India



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Abstract

Rapid urbanization, encroachment on natural drainage channels and intense rainfall have made flooding a recurrent problem in Kakinada Smart City, a low-lying coastal city in Andhra Pradesh, India. This study evaluates the performance of the city's storm water drainage network and proposes modifications to reduce flooding. Intensity–Duration–Frequency (IDF) curves were derived from rainfall records distribution, and design storms were generated with the Alternating Block Method. The study area was delineated in ArcGIS into 29 catchments and 120 sub-catchments, out of that mainly consider 5 subcatchments (Three Temple (Gudari Gunta), Dairy Farm Centre, Doodh Factory, KKD Port Station Back Side, and Subbaya Gari Street Culvert). Land use/Land cover (LULC) was classified by maximum likelihood classification, and curve numbers were computed for each sub-catchment. A dynamic-wave EPA SWMM model with tidal outfall boundary conditions was calibrated against observed water levels at five locations, giving Nash–Sutcliffe efficiency (NSE) values of 0.856–0.949 and correlation coefficients (R) of 0.871–0.971. Simulation of the 2-years (2022&2023) and 5-years (2021–2025) design storms, with peak intensities of 53.27 and 78.81 mm/h, showed overtopping in most of the drains. After the drains were widened, without increasing their depth, the re-simulated network showed lower water levels and less surcharging at nearly all locations.

Keywords—urban storm water, drainage systems, urban flooding, GIS, SWMM, IDF curves

Corresponding Author Email: bsatyachandu2002@gmail.com

1. Introduction

Urbanization replaces natural, water-absorbing surfaces with concrete and asphalt, which increases storm water runoff and overwhelms drainage systems that are often inadequate or poorly designed. Climate change adds to the problem through more frequent heavy rainfall, while sea-level rise and extreme weather raise the flood risk of coastal cities. The consequences include disruption of transport, loss of property, economic losses and health risks from water-borne diseases.

Kakinada is a fast-developing coastal city in Andhra Pradesh whose growth has not been matched by adequate planning of its drainage. Encroachment on natural drainage channels, a lack of storm water outlets and interference with the natural flow of water have led to frequent flooding during heavy rain, and the major and minor drainage canals are clogged with silt and encroachments. The 2021 monsoon, with more than 20 cm of rainfall in a single day, inundated low-lying areas and disrupted traffic. Better storm water management is therefore urgently needed.

Flood modelling supports such management by simulating rainfall–runoff processes with hydrological models and drainage performance with hydraulic models. The Storm Water Management Model (SWMM), developed by the U.S. Environmental Protection Agency, is a dynamic rainfall–runoff simulation model widely used for this purpose. The present study applies GIS and EPA SWMM to the storm water drainage network of Kakinada Smart City with three objectives: (i) to develop IDF curves from 15-minute rainfall data and simulate storm water flooding for various return periods; (ii) to evaluate the urban storm water network and develop a flood map using spatial technology; and (iii) to develop flood management strategies and mitigation measures. The work is intended to support Kakinada Municipal Corporation (KMC) with proposed modifications and recommendations for the drainage network.

2. Literature Survey

Low impact development (LID) and green infrastructure feature prominently in the storm water literature. Nazari et al. coupled the SWMM and SUSTAIN models to optimise LID techniques in a case study in Tehran, Iran, considering six options (green roofs, rain barrels, bioretention cells, porous pavements, vegetated swales and dry ponds), and reported that certain LID combinations could reduce runoff volume by up to 72%. Rujner et al. presented a case study of green infrastructure drainage for a commercial plaza without directly connected impervious areas and showed that source-control measures can reduce surface runoff and improve infiltration. At policy level, Chang et al. analysed LID policies across regions and concluded that policy support, public awareness and incentives are needed for successful adoption. Yang and Chui examined the surface and contributing areas of bioretention cells for managing runoff quantity and quality, finding that properly sized cells attenuate peak flows and improve water quality, while Palanisamy and Chui studied the rehabilitation of concrete canals with LID techniques such as vegetated swales and permeable liners.

3. 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 centre 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. 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 Godavari Urban Development Authority (GUDA), an organization that facilitates urban planning and development.

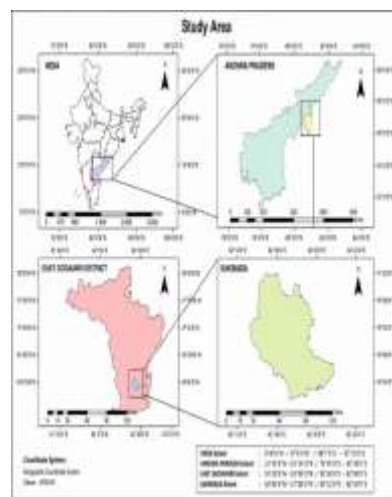


Figure 1: Location of the Study area

4. Methodology: The methodology of this study involves assessing the urban stormwater drainage system using Geographic Information System (GIS) and the EPA Storm Water Management Model (SWMM). Initially, the study area is identified, and relevant spatial and hydrological data are collected. Rainfall data are analyzed to understand rainfall patterns and develop design storm conditions for 2-years and 5-years return periods. Land use and land cover (LULC) maps for 2016–2023 are prepared to evaluate changes in urban development and their influence on surface runoff. GIS tools are used to process spatial data, delineate subcatchments, identify drainage paths, and prepare the stormwater drainage network. The collected information is then incorporated into the EPA SWMM model by defining subcatchments, junctions, conduits, and outfalls. Relevant parameters, including subcatchment area, slope, imperviousness, and drainage characteristics, are assigned to simulate rainfall-runoff processes and hydraulic performance. The model is used to assess runoff, conduit flow, junction water levels, and potential drainage overloading. Calibration and validation are carried out using available rainfall and observed flood information. Finally, critical flooding locations

are identified, and proposed drainage improvements are evaluated to determine their effectiveness in reducing water stagnation and improvement.



Figure 2: Methodological Flow chart

4.1 GIS Workflow and Catchment Delineation

The municipal boundary, drains, canals (including the Buckingham Canal), roads, water bodies, junctions and outfalls were digitised in Google Earth Pro and exported as KML files. These were converted to feature classes in ArcGIS with the KML to Layer tool, stored in a geodatabase and projected to WGS 1984 UTM Zone 44N. Raster datasets such as scanned drainage maps and satellite screenshots were georeferenced using control points (road intersections, canal junctions, bridges) and a first-order polynomial transformation. Topology tools were used to remove spatial errors in the drainage network. The DTM was used with ArcGIS hydrology tools to analyse topography, flow accumulation and slope, and to delineate the catchments and sub-catchments on the basis of the natural drainage pattern, slope, road alignment and land use. Area, drain length and slope, sub-catchment width, percentage imperviousness and elevation were extracted including with field observations for using in SWMM. The final base map was exported as a 300 dpi JPEG and imported into SWMM as a backdrop.



Figure 3: Field Observations Images

TABLE 1. Comparison of Observed and Simulated Water Levels (in meters) at Different Locations

S.no	Date	Rainfall (mm)	Water Level (m) Location									
			Three Temple		Dairy Farm Centre		Doodh Factory		KKD Port Station Back Side		Subbaya 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	16.10.24	71.60	0.74	1.20	1.20	1.75	0.83	1.20	1.00	1.20	2.13	2.50

4.2 Land Use/Land Cover and Runoff Estimation

LULC was classified into six classes by supervised classification with the maximum likelihood method, using training points for each class; the Kappa coefficient and accuracy assessment were used to check the classification. The LULC and soil maps were then used to compute the curve number (CN) of each sub-catchment. In the SCS-CN method the potential maximum retention S and the direct runoff Q are given by

$$S = 1000/CN - 10 \quad (1)$$

$$Q = (P - I_a)^2 / (P - I_a + S) \quad (2)$$

where P is the total precipitation and the initial abstraction I_a is taken as 20% of S (i.e. $I_a = 0.2S$).

4.3 Rainfall Analysis and Design Storms

Rainfall records for 2007–2024 (18 years) from IMD were used to extract maximum rainfall values for varying durations. Gumbel's Extreme Value distribution was applied to obtain rainfall intensities for return periods of 2, 5, 10, 25, 50 and 100 years, which define the IDF curves. Design hyetographs were produced with the Alternating Block Method: the storm duration T is divided into intervals Δt , intensities for Δt , $2\Delta t$, $3\Delta t$, ... are read from the IDF curve, cumulative depths are obtained by multiplying intensity by duration, and the peak intensity is placed at the middle of the hyetograph with the remaining blocks alternated around it. Areal average precipitation was computed with the Thiessen polygon method,

$$P_{AVG} = \sum (A_i / A) \times P_i \quad (i = 1 \dots m) \quad (3)$$

where P_{AVG} is the average areal precipitation (mm), P_i the rainfall at the i -th station (mm), A_i the area associated with that station (km^2), A the total study area (km^2) and m the number of rainfall stations. The resulting intensities were entered in SWMM as a time series at a 15-minute interval.

4.4 Hydrologic–Hydraulic Model in EPA SWMM

The drainage system was represented in SWMM by junctions (at manholes, road intersections, drain crossings and changes in alignment), outfalls (discharging to the Buckingham Canal, municipal canals, natural drains and low-lying coastal channels), storage units and conduits, with sub-catchments each draining to one outlet junction. Invert elevations were derived from field observations, municipal drawings and DEM analysis. Conduit roughness was set to Manning's n of 0.013 for concrete, 0.015 for masonry and 0.025 for earthen drains. Sub-catchments were assigned area, width, slope, percentage imperviousness, depression storage, roughness and Horton infiltration parameters. Appropriate conduit offsets were applied to remove unrealistic discontinuities in the water level profile.

Distributed hydraulic routing was carried out with the Saint-Venant equations,

$$\partial A / \partial t + \partial Q / \partial x = 0 \quad (4)$$

$$\partial Q / \partial t + \partial (Q^2 / A) / \partial x + gA(\partial h / \partial x - S_o) + gAS_f = 0 \quad (5)$$

x is the distance along the channel (m), t is time (s), A is the flow cross-sectional area (m^2), Q is the flow rate (m^3/s), h is the water surface elevation (m), S_o is the bottom slope, S_f is the friction slope and g is gravitational acceleration (m/s^2). Dynamic wave routing was selected because it captures backwater effects, flow reversals and rapid variations in flow in the coastal drainage system. Flow units were CMS, the routing time step was 30 s, the wet and dry steps were 5 minutes and 1 hour, and the rainfall interval was 15 minutes; the continuity error was reported to be within acceptable limits.

The model was set up for the land-use conditions of 2016, 2020 and 2023 and simulated for the rainfall event of 16 October 2024, in order to compare runoff depth, peak discharge, runoff coefficient and percentage imperviousness. For the 2020 conditions, design storms of 2, 5, 10, 25, 50 and 100 years were applied to the existing network. The natural drainage network was also modelled to identify flooding nodes and conduits, which were then redesigned for the 2-year and 5-year design storms.

4.5 Calibration and Performance Evaluation

The model was calibrated by comparing simulated and observed water levels at five locations: Three Temple, Dairy Farm Centre, Doodh Factory, KKD Port Station Back Side and Subbaya Gari Street Culvert. Manning's roughness coefficient, infiltration rates and conduit losses were adjusted to bring simulated values close to observations; imperviousness, depression storage and conduit

dimensions are also listed as adjustable parameters. Performance was assessed with the correlation coefficient (R), coefficient of determination (R^2), root mean square error (RMSE) and Nash–Sutcliffe efficiency (NSE).

5. Results and Discussion

5.1 Drainage Network and Land Cover

On the basis of the natural drainage network the area was divided into 29 catchments and 163 sub-catchments, and the soils were identified as alluvial types with codes 197, 201, 210 and 215. The SWMM inputs computed for the 120 sub-catchments show percentage imperviousness between 11.92% and 99.59% and CN values between 83 and 98; the lowest CN (83) occurs in Sub185 (14.24% impervious) and the highest (98) in Sub1159 (99.59% impervious).

The LULC maps for 2016, 2020 and 2023 show an expansion of built-up areas and roads and a decline in mangrove cover and water bodies. Reading the bar chart of class distribution, the urban share rises from about 26% in 2016 to about 31% in 2020 and 2023, water bodies fall from about 8% to about 4%, and mangroves fall from about 29% in 2016 to about 23% in 2023 (approximate values, as the chart carries no numerical labels). The increase in impervious surfaces is consistent with the higher runoff and flood vulnerability discussed in the thesis.

5.2 Model Calibration

Table 1 and Fig. 1 summarise the comparison of observed and simulated water levels at the five locations for 13 rainfall events between 16 June 2024 and 16 October 2024, with event rainfall ranging from 23.80 to 71.60 mm. NSE exceeded 0.85 at all locations. Dairy Farm Centre showed the best agreement (NSE 0.949, R 0.971) followed by Subbaya Gari Street Culvert (NSE 0.930), whereas Three Temple and KKD Port Station Back Side had lower R² (0.758 and 0.820) and NSE (0.856 and 0.866), indicating scope for further refinement of the input parameters. The RMSE was highest at Subbaya Gari Street Culvert (0.490), where the observed water levels also spanned the widest range (0.35–2.13 m).

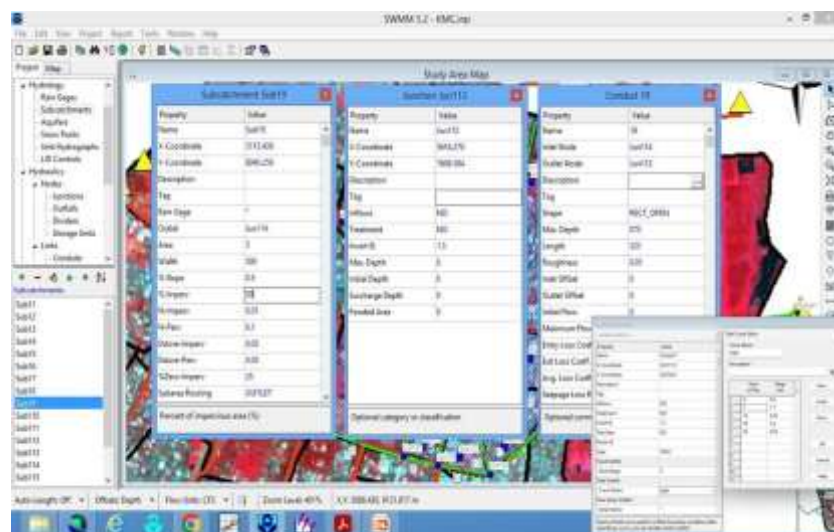


Figure: 4: SWMM Model setup

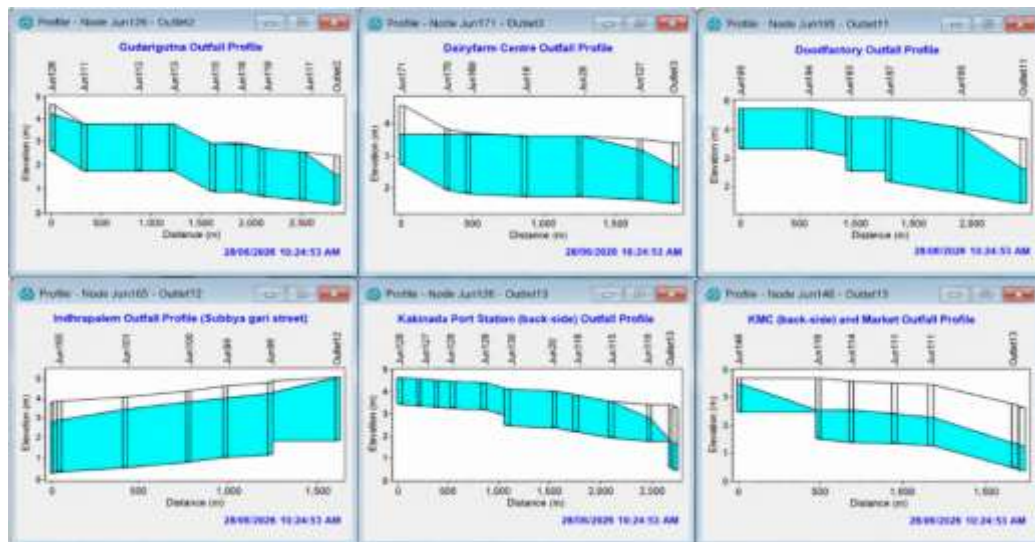


Figure 5: 2 yrs (2022&2023) design storm water surface profile (before adjusting drains)

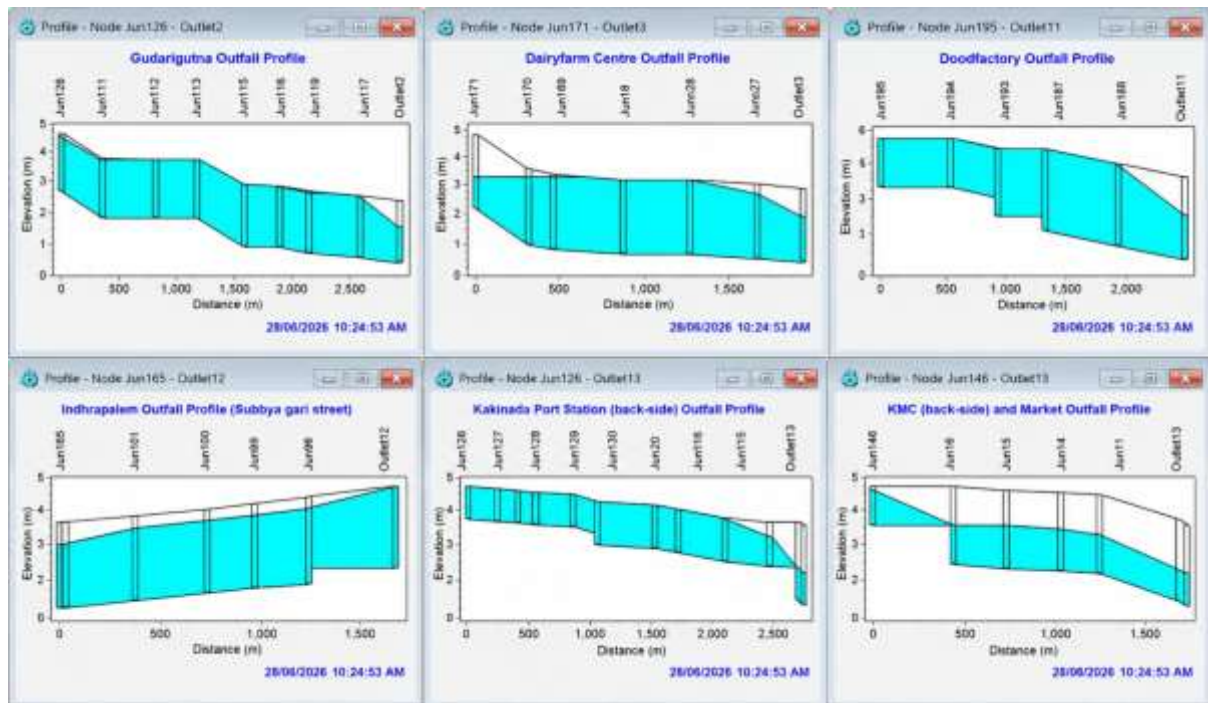


Figure 6: 2 yrs (2022&2023) design storm water surface profile (after adjusting drains)

TABLE 2. Statistical performance of the calibrated SWMM model at the five locations

Location	R	R ²	RMSE	NSE
Three Temple (Gudari Gunta)	0.871	0.758	0.383	0.856
Dairy Farm Centre	0.971	0.944	0.447	0.949
Doodh Factory	0.918	0.843	0.290	0.879
KKD Port Station Back Side	0.906	0.820	0.358	0.866
Subbaya Gari Street Culvert	0.956	0.915	0.490	0.930

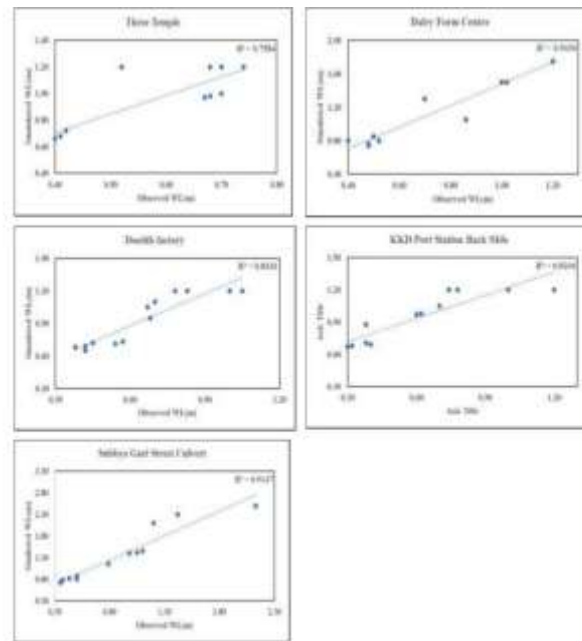


Figure 7: Scatter Plots of Observed vs Simulated Water Levels and Statistical Performance Indicators at Five Locations

Fig. 1. Scatter plots of observed versus simulated water levels (m) at the five calibration locations

The tabulated water levels show that simulated values were higher than or equal to the observed values in all events (equal in only one case, at KKD Port Station Back Side on 31 August 2024), so the strong correlation is accompanied by a tendency of the model to overestimate levels. The thesis also reports that the calibrated model was run for the October 2024 rainfall event and that the simulated flood inundation was validated against flood marks; quantitative details of that comparison are not presented.

5.3 Design Storm Response and Drain Modification

The IDF curves derived from the 2007–2024 rainfall records are shown in Fig. 2; intensity decreases rapidly with duration and increases with return period. The 2-year design storm had low intensity for the first few hours and then rose to a peak of 53.27 mm/h before tapering off, whereas the 5-year storm reached a peak of 78.81 mm/h, with a more pronounced rise and fall.

For both storms the simulated inflow showed a steep peak, the flooding curve indicated that a large part of the flow could not be conveyed by the existing drains, and the outflow remained well below the inflow peak. Inflow and flooding were greater for the 5-year storm than for the 2-year storm. Longitudinal profiles of the main open rectangular drains (Gudari Guntha, Dairy Farm Centre, Doodh Factory, Indrapalem (Subbaya Gari Street), Kakinada Port Station back side, and KMC and Market area) showed overtopping in most drains under both storms, and more so under the 5-year storm. The initial simulations therefore indicated considerable flooding along nearly all drain lengths, i.e. inadequate hydraulic capacity of the existing network even for these moderate storms.

Because of the coastal setting, increasing drain depth was not considered viable; only the drain widths were modified and, in some cases, the number of parallel barrels was increased. Of the 199 conduits listed in the thesis, depth was unchanged in all cases, and width was increased in 184 conduits for the 5-year storm and in 172 for the 2-year storm, with the largest widths being 9.5 m and 6 m respectively. Table 2 gives a representative extract. After the modification, water levels in the drains and surcharging decreased at nearly all locations, and heavy flooding initially observed at Dairy Farm Centre, Doordarshan Kendra, KMC backside and Kakinada Port station was resolved by resizing and re-profiling of the channels. Post-modification flood volumes are not reported numerically in the thesis.

TABLE 3. conduit dimensions (depth × width, m) before and after adjustment for the design storms

Conduit	Length (m)	% Slope	Initial	5-year design	2-year design
Conduit1	737	0.0407	1.2 × 1.2	1.2 × 4	1.2 × 3
Conduit11	403	0.0248	1.2 × 1.2	1.2 × 9.5	1.2 × 6
Conduit12	226	0.0442	1.2 × 1.2	1.2 × 9	1.2 × 5
Conduit62	925	0.0216	2 × 2	2 × 4	2 × 3
Conduit115	204	0.0001	1.2 × 1.2	1.2 × 8	1.2 × 6
Conduit116	42	0.2398	2 × 2	2 × 8	2 × 6

5. Conclusion

1. The LULC analysis of Kakinada from 2016 to 2023 revealed substantial urbanization and a corresponding reduction in waterbodies and mangrove areas. The reduction in natural water-retention areas and the expansion of built-up areas have increased surface runoff and the city's vulnerability to urban flooding.
2. SWMM Model Parameter Estimation: The key input parameters for the Storm Water Management Model (SWMM) were calculated for each subcatchment, including node and link characteristics, pervious and impervious areas, soil type, average width, slope, and SCS Curve Number (CN).
3. The initial simulations indicated that several drainage channels could not adequately convey runoff generated by the 2-years(2022&2023) and 5-years(2021-2025) return-period storms, resulting in drain surcharging and localized flooding at multiple locations.
4. The discrepancies between observed and simulated water levels may be associated with uncertainties in rainfall inputs, drainage network characteristics, surface conditions, and model parameter settings.
5. The simulated water levels were generally higher than the observed levels during the recorded rainfall events at five critical locations in Kakinada: Three Temple(Gudari Gunta), Dairy Farm Centre, Doodh Factory, KKD Port Station Back Side, and Subbaya Gari Street Culvert. This indicates that the model tended to predict greater water accumulation .
6. Sustainable urban drainage measures and the protection of natural water-retention areas are important for reducing surface runoff, improving drainage performance, and mitigating future flood risks
7. The SWMM model was established using the drainage network and subcatchment characteristics, followed by calibration to improve its performance in representing observed conditions.

Recommendations:

1. Drainage Network Modification: The geometrical parameters of the drainage channels were modified to improve their capacity to accommodate runoff from both 2-years(2022&2023) and 5-years(2021-2025) return-period storm events.
2. Post-Modification Results: The revised simulations showed reductions in water levels and drain surcharging at nearly all assessed locations, indicating improved drainage performance under the simulated storm conditions.
3. Future stormwater drainage planning should consider potential changes in rainfall intensity, duration, and frequency associated with climate variability and climate change. And to support stormwater drainage planning and improvement by identifying critical locations that may require increased drainage capacity or other flood-mitigation measures.
4. Need for Further Calibration and Validation: Further refinement of the model parameters and validation using additional observed rainfall and flood-level data are recommended to improve the agreement between simulated and observed results.

Future Scope:

The future scope of this study is to develop a more accurate, sustainable, and climate-resilient urban stormwater drainage system. The integration of GIS, EPA SWMM, improved field observations, future rainfall projections, and sustainable drainage techniques can help urban authorities identify flood-prone areas, prioritize drainage improvements, and reduce the impacts of urban flooding.

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