

Urbanization-Driven Waterlogging in Coastal Bangladesh: A Case Study of Narail Sadar Municipality Using Remote Sensing and Hydrological Modeling

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Abstract: An integrated approach combining satellite imagery, hydrological analysis, and field-based data was employed to assess the causes, spatial distribution, and severity of waterlogging in Narail Sadar Municipality. Land Use Land Cover (LULC) analysis from 2014 to 2024 reveals a significant expansion of built-up areas, increasing from 318 ha to 659 ha, accompanied by a loss of over 500 ha of vegetated land. The waterlogged area significantly increased from 476 ha to 789 ha during the post-monsoon period (October), as identified using the Modified Normalized Difference Water Index (MNDWI). The average soil infiltration rate in the study area was calculated as 2.31 mm/hr, based on a comparative assessment of hydraulic conductivity, soil texture, LULC, and underlying lithological characteristics. Topography and slope maps reveal that most of study area lies between 7 meters near the riverbank areas (with slopes below 1.73°) and less than 3 meters above msl in the flood basin zones, indicating limited gravitational drainage potential. The average water level rises from 2.21 m in the dry season (October–June) to 3.40 m during the monsoon (July–September), leading to reduced percolation and increased surface runoff under heavy rainfall. The municipality's drainage system, comprising six outlets (two natural streams and four engineered drains), has a maximum discharge capacity of 10,152 m³/hr. However, the estimated infiltration volume is 26,425 m³/hr, with an additional 974 m³/hr of wastewater generated by existing population (156,000), collectively exceeding the drainage capacity and contributing to frequent waterlogging. A numerical model developed using the Rational Method indicates that the existing drainage system can accommodate a maximum rainfall of 38.5 mm/day or an intense precipitation rate of 3.2 mm/hr without triggering waterlogging. However, Rainfall nearing or exceeding 41.5 mm/day or 4.9 mm/hr surpasses the 2-hour drainage threshold, posing a critical risk for increased frequency and severity of urban waterlogging.

Keywords: Urbanization, Waterlogging, Infiltration rate, Satellite imagery, Rational method.

Introduction

Bangladesh is undergoing rapid urbanization, which, while driving economic growth, has also led to severe environmental challenges such as waterlogging. The southwest coastal region, including Narail Sadar Municipality, is highly vulnerable due to climate-induced factors like intense rainfall, storm surges, and sea-level rise, compounded by non-climatic drivers

such as unplanned urbanization, inadequate drainage, and the encroachment of natural waterbodies. Narail, with its growing population, limited drainage infrastructure, and increasing impervious surfaces, faces frequent waterlogging that disrupts livelihoods, damages infrastructure, and heightens health risks (Subrina and Chowdhury, 2018). This study aims to investigate both natural and anthropogenic causes of waterlogging, analyze land use and drainage capacity changes from 2014 to 2024, and develop a dynamic waterlogging model incorporating rainfall, infiltration, wastewater discharge, and drainage efficiency. The findings will delineate hazard zones and provide a foundation for sustainable urban planning and effective waterlogging mitigation in vulnerable municipalities.

Methodology

The methodological flow chart (Figure 1) illustrates the systematic approach employed for developing a numerical model to analyze waterlogging conditions. The process begins with the acquisition of multi-temporal satellite data and ASTER DEM, which are processed using digital image processing techniques. From this, several thematic layers are derived, including MNDWI (2014 and 2024), LULC (2014 and 2024), elevation and slope variation, distance buffer mapping, and soil permeability. These datasets are then integrated using GIS-based overlay analysis, enabling spatial correlation and analysis of key parameters. The methodology also incorporates change detection and interpretation for temporal analysis and utilizes analytical equations to estimate runoff and water discharge.

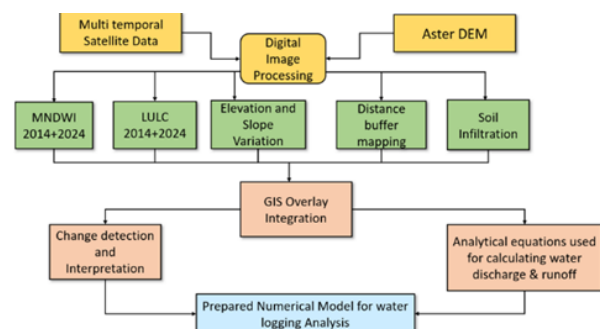


Figure 1, Methodology chart

Numerical analysis of water logging

$$Net\ Runoff = Net\ Loss$$

$$\int \left(\sum_{i=1}^n Runoff + \sum_{i=1}^n Waste\ Water \right) = \int \left(\sum_{i=1}^n Infiltration + \sum_{i=1}^n Drain\ Discharge \right)$$

$$Infiltration : Q_{inf} = \frac{I_{inf} \times A_{inf}}{1000 \times 3600} \text{ (Haan et al., 1994)}$$

$$Wastewater : Q_{waste} = \frac{W \times P}{24 \times 3600} \text{ (Metcalf and Eddy, 2014)}$$

$$Drainage : Q = \frac{1}{n} \times A \times R^{\frac{2}{3}} \times S^{\frac{1}{2}} \text{ (Chow et al., 1988)}$$

$$Runoff : Q_{runoff} = \frac{C \times I \times A}{1000 \times 3600} \text{ (Chow et al., 1988)}$$

$$\frac{Net\ Runoff}{Net\ loss} > 1, \text{ then waterlogging}$$

$$\frac{Net\ Runoff}{Net\ loss} < 1, \text{ then no waterlogging}$$

$$\frac{Net\ Runoff}{Net\ loss} = 1, \text{ then discharge by drains}$$

Results and discussions

The study shows a strong link between rainfall intensity and waterlogging, confirming rainfall as the primary cause of flooding in this low-lying municipality. Figure 2 indicates that the drainage system can handle up to 38.47 mm/day; beyond this, drainage time exceeds the 2-hour limit, causing recurrent floods. Figure 3 shows that low rainfall (3.2 mm/hr) poses minimal risk, while moderate to high intensities (around 14 mm/hr) increase drainage time to over 8 hours, demonstrating the system’s limited capacity.

Land-use analysis in Figure 4 shows major changes over the past decade: built-up areas expanded from 318 to 659 hectares, while vegetation and agricultural lands declined by more than 500 hectares, reducing infiltration to 2.31 mm/hr. Figure 5 (MNDWI) highlights expanding waterlogged zones in central and southern wards, where poor drainage and low infiltration increase flood vulnerability (Rashid, 2023).

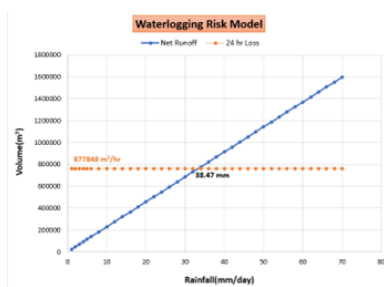


Figure 2, Graph of Water logging Risk Model in Narail Sadar Municipality

Conclusions and recommendations

Waterlogging in Narail Sadar Municipality is driven by rapid urbanization, land-use change, and poor drainage, with GIS and hydrological analyses showing that flat terrain and disconnected drains worsen saturation, highlighting the need for resilient planning, preserved permeable areas, improved drainage, and nature-based solutions.

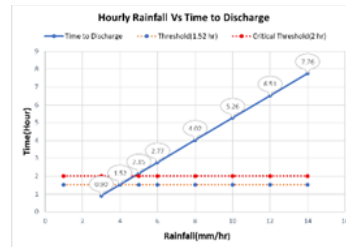


Figure 3, Graph of Hourly Rainfall Vs Time to Discharge

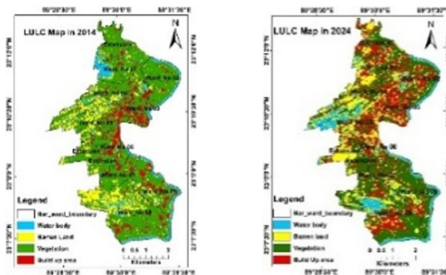


Figure 4, LULC maps for 2014 and 2024.

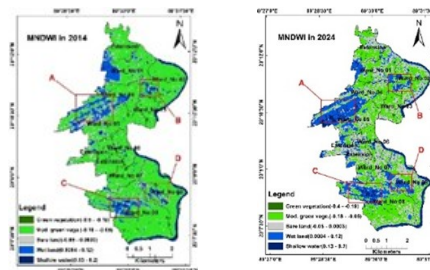


Figure 5, Spatial distribution of MNDWI for 2014 and 2024

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