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PREDICTING STORMWATER REDUCTION USING RTC-RWH IN THE SELECTED PARTS OF CHATTOGRAM CITY

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ABSTRACT

During the monsoon, urban part with combined sewer systems is particularly vulnerable to nuisance floods and severe water logging. Rain Water Harvesting (RWH) has been a key solution to mitigate local urban flooding. Among all the RWH approaches, recent advances have indicated promising improvements in system performance through the application of Real-Time Control (RTC) technologies. In this study, we proposed a system to visualize how at source RTC based RWH system can influence the combined sewer system of Chattogram City, a densely populated urban area. The study is solely focused on roof runoff because of the proliferation of rooftops in metropolitan area. Simulation is performed by interconnecting drainage model in SWMM with RTC logic using python language. Two scenarios were simulated: conventional network (i) with no RWH (baseline) and (ii) with RTC RWH systems, to compare flood volume and peak flow differences. Two different types of metropolitan areas were considered for the study, residential and commercial. For designing the RTC algorithm, based on yield after spillage rule - based logic is used, for 7 – day lead rainfall forecast, to ensure minimum spillage with high yield. Study results demonstrates that rooftop enabled RTC RWH systems can significantly attenuate generated surface runoff in a combined sewer system. Residential roofs, covering roughly 36% of study area, delivers more than 80% flood volume reduction, relative to no RWH systems, with 40L/m^2 storage capacity. Alternatively, commercial roof areas, constituting about 43% of the study area provides around 51% flood volume reduction which is approximately 12% more than a simple RWH system. Both catchments showed a declining rate (around 80% and 35% respectively) of total system discharge volume, along with decreasing peak outfall flow. Upon a closer look of pre – storm release (i.e. proactive release of stored water before any storm) rate, a RTC RWH storage outperforms a conventional storage with proliferation of available controlled systems in catchment. Moreover, the study denotes that higher numbers of RTC RWH systems in a catchment would provide more aid in lowering not only roof runoff volume but also overall catchment discharge volume, rather in simply extending storage capacity, as benefits are plateaued at higher storage volumes. Thus, RWH system implemented with RTC provided greater benefits not only in mitigating water logging but also for managing the resultant runoff. This study suggests that RTC RWH systems applied throughout a catchment can significantly enhance the performance of existing drainage network along with providing a decentralized water supply system by means of a cost-effective solution.

Keywords: *RTC RWH systems, SWMM, nuisance floods*

1. INTRODUCTION

Urbanisation is inducing critical issues in water management. Due to change in rainfall patterns and increase in impervious urban areas, major cities like Chattogram are facing inundation in Bangladesh. Moreover existing combined sewer systems, which aims to drain storm water, faces excessive runoff during heavy rainfall periods. Rainwater harvesting systems (RWH) are used in developing countries around the world, as supplementary water supply system, due to its easy maintenance and cost effectiveness. These systems also function as Stormwater Control Measure (SCM), from capturing the runoff from impervious surfaces such as roofs, which is used to fulfil parts of domestic demand like toilet flush. This significant role play provides, retention that reduces volume and frequency of runoff and peak discharges, mitigating overflows in networks and urban flooding risks (Burns et al., 2015; Jamali et al., 2020; Schubert et al., 2017). Moreover, this SCM's has potentiality in delaying expand of drainage infrastructure and water supply (Coombes & Kuczera, 2003).

Application of technology like Real-Time Control (RTC) offer benefits in enhancing RWH performance, beyond their conventional features of water supply and flood mitigation (Roman et al., 2017; Xu et al., 2021). RTC consist of collection of software, sensors, communication devices and actuators (Bennett, 1994), which is combined and integrated with digital information e.g. rainfall forecast to provide RWH systems to adapt its function relative to operating conditions in real time. This transition helps in evolving the static nature of RWH systems to highly adaptive storm water control units (Kerkez et al., 2016). Generally, RWH systems coupled with RTC technology stores rainwater prior to the actual rainfall event and release it later, termed as pre storm releases, by a remotely controlled discharge structure, for creating sufficient capacity, thus reducing both magnitude and frequency of uncontrolled drainage overloads. Prior empirical studies and modelling have indicated that RTC provides superior performance compared to conventional RWH systems in retaining stormwater and peak flow reduction (Gee & Hunt, 2016; Roman et al., 2017), along with no significant effect on water supply performance (Melville-Shreeve et al., 2016; Xu et al., 2018). Recent researches have applied RTC approaches to leverage longer-range of rainfall forecasts. Using a 7- day lead precipitation forecast, with increase in forecast window, enhances the performance of predicted pre-storm releases, resulting in a better reduction in storm water (Xu et al., 2020). This shift in application could potentially help in counteracting negative hydrologic impacts occurs in urban areas (Poff et al., 2010). So far, application of RTC technology to RWH remained largely untested on stormwater networks (Xu et al., 2021). Understanding whether this performance gains can be translated to large scale such as the catchment, it is important to assess the behaviour of a distribution network of RTC RWH systems and the stormwater network.

This study incorporates a strategy to mitigate induced flood volume during the wet season, with a simulation period of four months, for two distinct types of catchments such as Commercial Area and Residential Area. Total network flooding volume and peak flow reductions are characterised against a scenario of no RWH systems (baseline) and more detailed analysis of RTC integrated storage tanks against conventional tanks. The hypothesis for this strategy is that, RWH systems operated by RTC could mitigate the risks involving flood volume by storing roof runoff that will reduce the overload on stormwater network while providing a scope for further application of supplementary water supply system. The results demonstrates that implementing higher proportions of RTC systems in a large catchment could provide more benefits compared to simply increasing storage capacities, which would help in designing future storm water networks.

2. METHODOLOGY

For the assessment of the behaviour of the RTC RWH, a structured modelling workflow was formulated. It contains three sequential components: 1) the rainfall-runoff component, (S1); the real-time control component, (S2); and the drainage-network component, (S3). The first component applies a hydrological model to produce five-minute runoff estimates along with a daily runoff forecast, both of which act as boundary conditions for (S2). The latter component calculates the regulated outflows from each rooftop storage unit using predefined control rules. Those controlled outflows are used as input by S3, which simulates the hydraulic response of the stormwater network. S1 and S3 were enabled by SWMM, while S2 was implemented through a custom-written RTC algorithm in Python language.

2.1 RTC Strategy

The focus of the study is to understand how RTC RWH system could reduce the flood volume of the drainage network. To reduce storage overflow, the strategy was designed to release, total predicted overflow within the upcoming seven days, uniformly over the next 24 hours. As in the strategy is dependent on the forecast rainfall, assuming the forecast data correct. Moreover, the forecast data has little to no impact when applied on rolling basis on overall system (Shishegar et al., 2021). To complete the whole algorithm a simple forecast assisted rule based algorithm in python language is used, which aligns with the heuristic strategy reviewed in literature (Brasil et al., 2021).

2.2 Modelling Procedure

For evaluating the proposed plan a modelling procedure was developed, which constitutes of three sections. These sections (Fig 1) are a) rainfall – runoff (S1), b) RTC algorithm (S2) c) drainage simulation (S3). Amid all these, SWMM was used for section S1 and S3, whereas RTC logic was implied through python language. Individual 5 min catchment runoff of all designated roof was generated from S1 through hydrologic model, which is used for further implication in the algorithm for RTC logic. The inflows derived after logic-based decision from S2 were then used to fed into the hydrological model of the drainage network in S3. Only in S3 section roof as well as other surrounding areas are considered for simulation.

2.2.1 S1 Rainfall – Runoff Section

In S1, for considering only roof runoff, sub catchments defined under RTC logic in the next stage was separated. The hydrologic model comprised of only roof areas were simulated using historical rainfall data. Roof areas were modelled separately than other surrounding areas, because RTC RWH system cannot be implemented directly on SWMM. Therefore, the prediction and controls of RTC logic was implemented on S2 section. Roof areas were obtained through mapping of each household and each sub catchment had cluster of four to five building roofs and considered as a single roof area. That is why, the imperviousness for roof areas were assumed to be 95% and the depression storage 1.5 mm (ASCE, 1992). The mapping of the surrounding areas was then done excluding the roof areas and the imperviousness was recalculated based on the study sub catchment.

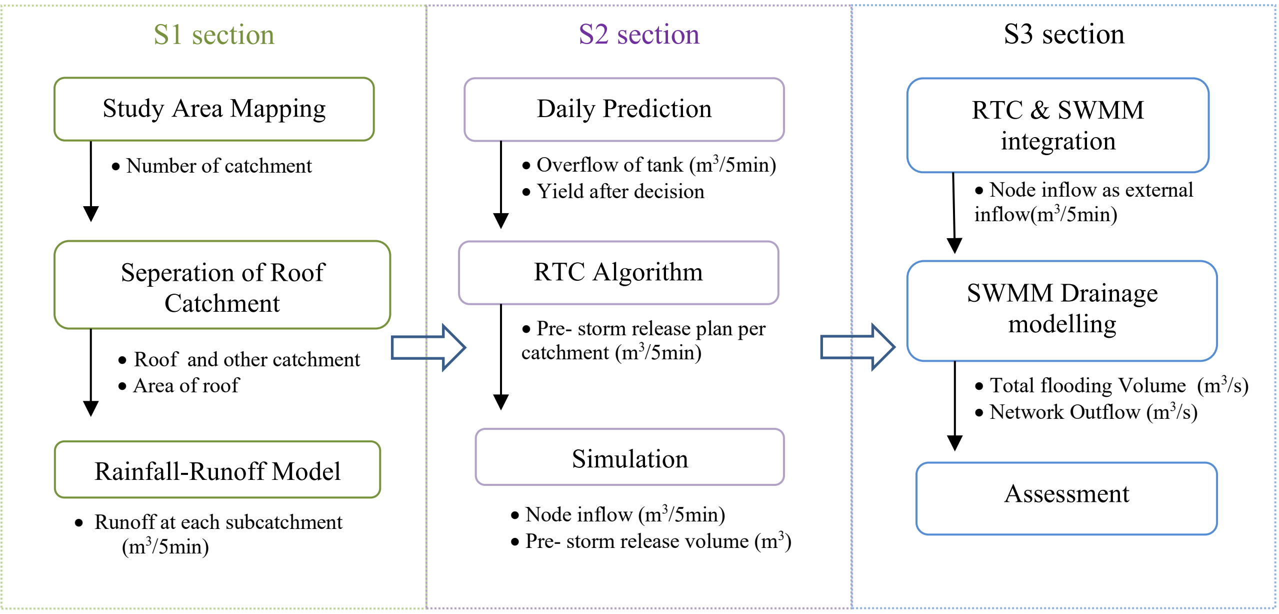

Figure 1: Adopted methodology

2.2.2 S2 Real Time Control Section

This section focuses on determining the pre-storm release through multiple control variables and simulates the performance of RTC systems under the strategy of flood mitigation. It consists of three stages. In the first stage, Daily Prediction, utilizing the RWH Behaviour Model operating at a daily time-step, predicts storage overflows for RTC decision-making using (Eqs. 1–3). To provide a more accurate estimation of yield, yield-after-spillage rules were applied (Xu et al., 2022). Prior to the actual rainfall events, runoff forecast as in for each roof sub catchments was extracted from S1 section's hydrologic model. Since, pre-release decisions are based on future hydrological conditions, each daily time step is considered as the current system state, while the subsequent segment of the historical time series is interpreted as the forecast horizon. As the forecast data is updated every 24 h, before each decision RTC logic was designed to look up the upcoming rainfall intensity of seven days. Overflows are occurred whenever the maximum capacity of the storage is exceeded. First flush diversion system was omitted in this model, since filtration devices are added variables.

$$Q_{oi,t} = max\begin{cases} V_{i,t-1} + Q_{ai,t} - S_i \\ 0 \end{cases} \tag{1}$$

$$Y_{i,t} = min\begin{cases} D_{i,t} \\ V_{i,t-1} - Q_{bi,t} \end{cases} \tag{2}$$

$$V_{i,t} = min\begin{cases} V_{i,t-1} + Q_{ai,t} - Y_{i,t} - Q_{bi,t} \\ S_i - Y_{i,t} - Q_{bi,t} \end{cases} \tag{3}$$

Where,in system i at time t the rainwater yield is denoted as $Y_{i,t}$ (m^3/timestep) and $Q_{bi,t}$ (m^3/timestep) is the RTC logic based pre-storm release from system i. After timestep t and t – 1 the volumes (m^3) in system are $V_{i,t}$ and $V_{i,t-1}$ respectively. S_i (m^3) is current tank storage at each step, $D_{i,t}$ (m^3/timestep) is the demand for the catchment and tank overflow is termed as $Q_{oi,t}$ (m^3/timestep). Inflow for the sytem is denoted as $Q_{ai,t}$ (m^3/timestep), here system i represents each tank where $i \in N_T$ and N_T represents number of tanks. The initial storage volume was considered zero for the simulation.

In the second stage, to minimize the system overflows pre-storm release plans are developed, based on the defined strategy. The overflow volume predicted according to system capacity for the RTC algorithm belongs to all roof sub catchments connected to RTC RWH system. The RWH Simulation (Fig. 1) uses the RWH behaviour model to simulate the performance of defined controls in the third section. This simulation is completed on a 5-min time step to capture the dynamics of system inflow and outflow. To prevent this initial condition from resetting at each occurrence, continuous simulation is used, assuming that all storages were empty at the beginning of the simulation period. Lastly, each system's outflows—that is, pre-storm releases and any overflows—are individually defined and fed into the Drainage Simulation Section (S3). For the tank to node release connection, a orifice system was incorporated using:

$$Q_{req} = \frac{V_{\text{tank}}}{\text{t}_{\text{drain}}} \tag{4}$$

$$Q_{req} = C_d A\sqrt{2gh} \tag{5}$$

$$D = \sqrt{\frac{4A}{\pi}} \tag{6}$$

For, each system capacity (10, 20, 40, 60, and 80 L/m²) V_{tank} (m^3) is calculated according to consecutive subcatchment are, and required uniform discharge rate Q_{req} (m^3/s) is calculated for 24 hour, t_{drain} , which is later used to determine orifice area, A (m^2) and diameter D (m) with the variables discharge Coefficient, C_d as 0.65 and head, h as 3m (including free head).

A rolling horizon of seven days is used for both prediction and simulation components. The Model Predictive Control of urban drainage systems has made use of this setting, which is also referred to as receding horizon (Lund et al., 2018).The RTC plan accustomed to the ability to take decision for a controlled release, long before the actual event, for the upcoming 7-day period (Xu et al., 2020).

However, the simulation component only implements the actions within the first 24 hours of that rolling horizon; it is then routinely repeated for each updated forecast data. In order to decrease the influence of prediction mistakes on system performance, this approach of renewed data, makes it possible to account for forecast errors.

2.2.3 S3 Drainage Simulation

S3 section is comprised of both python and SWMM model, to understand the impact of integrating RTC and RWH systems, through the resultant outflow, based on RTC logic (S2), in combined sewer system. For each targeted roof catchments, the outflow time series data are fed into their specified nodes as external inflow and these inflows eventually represents the flow of roof after logic-based decision. Since outflow time series data is used from S2 as external inflow as roof runoff, imperviousness was set to be 0% with depression storage of 99 mm. Since the roof runoff was simulated in both section S1 and S2 as per the followed strategy required. Finally, this section's results i.e., the total flooding volume and network outflow are stored for further evaluation under multiple assessment parameters.

2.3 Study Area

Two study areas are considered for the strategy, one is a commercial area, and the other one is residential area (Fig 2). The commercial area is a part of Agrabad C/A situated in Chattogram City with an area of approximately 15.8 ha, along with an area of around 6.91 ha of sub catchments under RTC scenarios. In case of residential area, the selected area for roof catchment is around 14.4 ha of a total area 39.8 ha. The residential land use is a part of Nasirabad Housing Society in Chattogram. Both study area has an imperviousness of more than 60% and the average roof area for each building was around 621m^2. For infiltration, Curve Number method was used and the required values were collected according to literature for the subcatchments (Chowdhury & Akter, 2023).

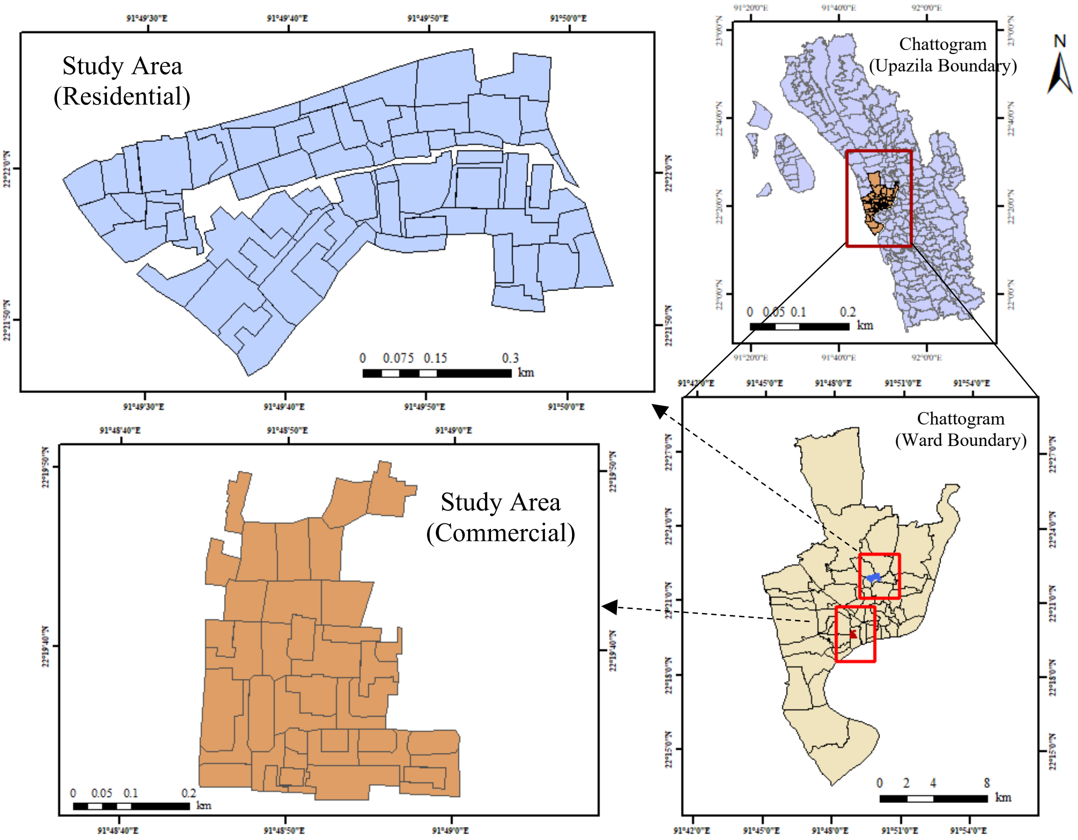

Figure 2: Study Area

From Bangladesh Meteorological Department (BMD) rainfall data of 3-hour interval was collected and historical rainfall value from May to September 2024was considered for study with annual 3 hour maximum rainfall of 144mm. The networks total flow drained into Moghultuli Khal and Mirza Khal respectively; though commercial area was away from the khal / channel, and it is excluded in map.

2.4 Scenarios and Model setup

For the model, the commercial area has been divided into 39 sub catchments, along with 63 junctions and 40 links, whereas, the residential area consists of 70 sub catchments, 188 junctions and 139 links and this area has better conditioned drainage network with comparatively less record of flooding issue. The average slope of catchment is around 4.28% and 5.07% respectively. To map these sub catchments boundary shapefile of Chattogram City, satellite image from Google Earth Engine was used; field visit was also conducted before catchment definition. Existing secondary drainage network details is collected from Chattogram Development Authority (CDA). For LULC mapping and DEM analysis for elevation data, inputs are collected from United States Geological Survey (USGS) earth explorer. Through visual interpretation the flow width was calculated from Google Earth and then width (m) was calculated for each sub catchment by applying Eq 7,

$$W = \frac{A}{L} \tag{7}$$

where, area of each sub catchment A (m^2) and maximum flow length of the catchment, L (m^2). The existing drainage systems is a combined sewer system with recorded flooding issue on upstream nodes due to limited capacity. For, every model simulation Kinematic Wave routing was used for simplicity. In the commercial area, 20 out of the 39 sub catchments (Fig. 3) were designated as roof catchments, while in the residential area, 27 roof catchments were selected out of 79 sub catchments (Fig. 3) for RTC RWH application. A set of scenarios with controlled variations is developed to examine how RTC affects network flows during the wet season. Five storage capacities, viz. 10, 20, 40, 60, and 80 L/m² were evaluated in combination with the RTC system coverage levels of 25%, 50%, 75%, and 100% of the total roof catchments. All scenarios are assessed relative to a baseline case. To evaluate the influence of logic-driven outflow compared to a conventional storage system, the external inflow produced by the standard RWH configuration is introduced into the drainage network.

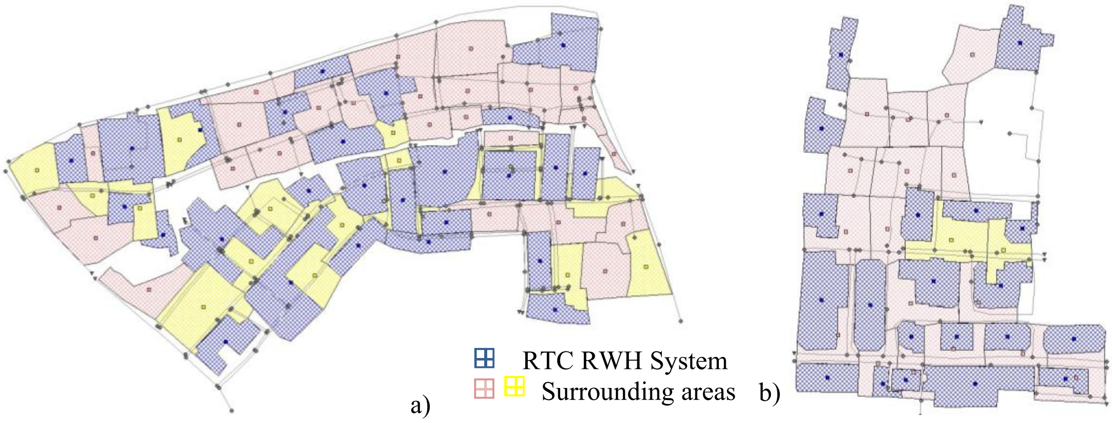

Figure 3: Sub catchment of both study area of hydrological model from S3 section
a) Residential, b) Commercial area classified based on imperviousness

2.5 Assessment Metrics

In order to recognize the impact of RTC RWH system on the drainage network flow, quantitative parameters, namely flooding volume and peak flow reduction (Eq. 8-9) was adopted (Xu et al., 2022) At catchment scale, peak system flow (m^3/s) at outfall and node flooding volume (m^3), are quantified through addition of all outfall flow rate and the node flood volume respectively, then compared with the performance of baseline scenario. To assess the performance gain compared to tank with variety in change of storage volume, total system overflow was plotted against RTC percentage scenario.

$$\text{Peak Flow Reduction (\%)}, \ \rho_{peakflow} = \frac{Q_{out,\,max\,baseline} - Q_{out,\,max\,RTC}}{Q_{out,\,max\,baseline}} \tag{8}$$

$$\text{Flooding Volume Reduction (\%)}, \rho_{flooding} = \frac{V_{flooding\,baseline} - V_{flooding\,RTC}}{V_{flooding\,baseline}} \tag{9}$$

3. RESULTS

3.1 Flooding Volume Reduction

For both study area, since the amount of cumulative roof catchment is approximately 43% (commercial) and 36% (residential), relative to the total area, flood volume was only compared for 100% RTC Scenario. Because of the location being highly impervious along with large area the effect of flood volume is diluted amid all the runoff from other sub catchments. Even though a city-wide scale comes with its own challenge, post simulation results are still very promising. For the residential area, around 24% flood reductions are gauged for a system capacity of 40L/m^2 relative to baseline scenario (no RWH system).

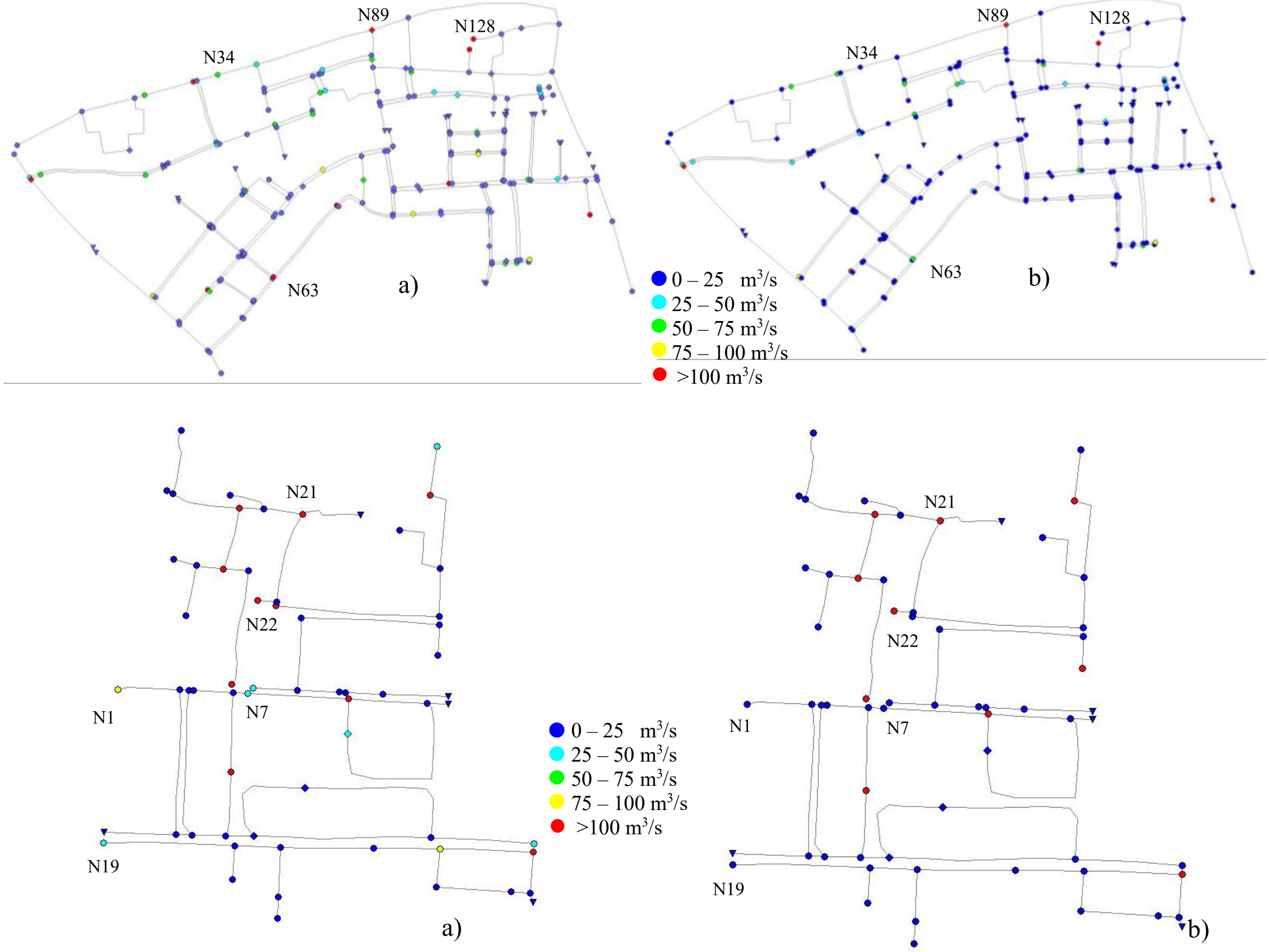

Figure 4: Change in flood volume at node, in residential and commercial area, due to implementation of RTC RWH system a) baseline scenario b) all the roof catchment connected to a RTC system of 40 L/m^2 capacity

3.2 Peak Flow

Integration of RTC RWH system following the strategy of flood mitigation has shown significant changes in reducing peak flow at outfall of the drainage network. For the commercial area, the peak outfall flow was reduced by 12.8% with adoption of RTC RWH system for a capacity of 40 L/m^2, and variation between RWH system and RTC RWH system is numerically small for the same capacity. While the total discharge volume reduction remained equivalent to the peak outfall flow reduction for similar storage capacity with a system capacity reduction of 26%. And this parameter eventually justifies the implementation of RTC RWH system with significant total outfall discharge volume at catchment scale. Since, the residential land use is a larger city scale network, outfalls that are primarily collecting network flow from nodes associated with roof sub catchments are considered for the assessment. For a system capacity of 40 L/m2, the passively controlled systems as well as RTC controlled showed a significant peak flow reduction with a percentage value of 7.3% along with 6.47% discharge volume reduction from catchment. Even though the variation between passively controlled and RTC systems is not monumental, with the roof sub catchment being larger relative to the total inflow from rainfall, implementation of RTC RWH system provides more freedom to alternate discharge rates from impervious roofs. With variation in storage capacity in the total reduction percentage had statistically minor variation, in both cases, which indicates diminishing returns with greater capacity and lesser inflow relative to the capacity.

3.3 Storage Outflow

To assess the effect of RTC logic on a RWH system, which is controlled by multiple control variables rather than passively controlled, comparisons of the total outflow from RTC RWH storages to the conventional RWH systems were made. With implementation of RTC at an increasing rate shows a higher increase in reduction in outflow volume for both study area, which is expected according to the proposed strategy of flood mitigation. The storage capacities used to evaluate the performance of controlled systems are 10, 20, 40, and 60 L/m^2, denoting as different series with respect to the availability of RTC RWH systems (25%, 50%, 75% and 100% of total roof sub catchments) in both catchments. In case of, the catchment at commercial land use, smooth increasing trends (Fig 6) represents the total overflow reduction from storages with greater capacity alongside availability of RTC RWH system. This increasing trend indicates a suitable storage capacity for flood mitigation with number of available controlled system, as in for the commercial area, storage capacity of 40 L/m^2 with all 20 sub catchments being controlled could easily provide a higher percentage of overflow reduction from roof RWH systems. Alternatively, for the residential area, the increasing trend went up with a higher rate of change with variation in system capacity from 10 to 20 L/m^2 (Fig 7) indicating more water retention with higher volume of storage.

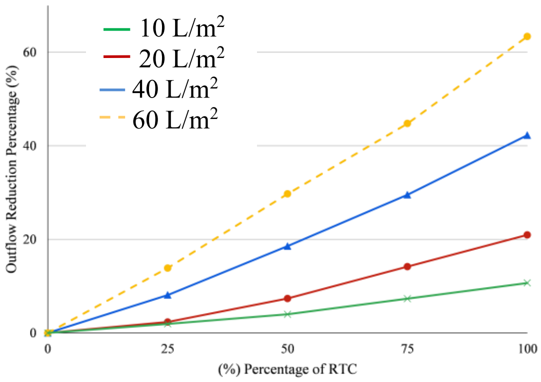

Figure 6: Percentage of overflow reduction in commercial area.

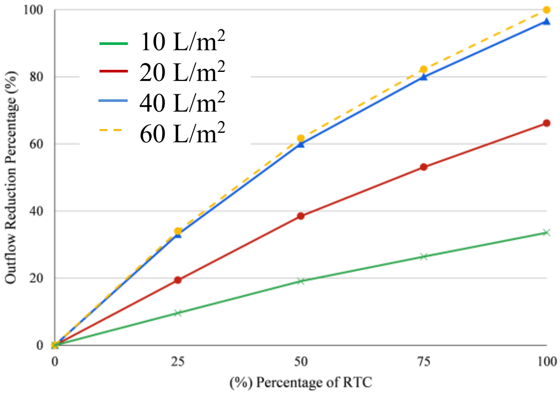

Figure 7: Percentage of overflow reduction in residential area.

Since, the percentage value for 40 and 60 L/m^2 storage coincides; it signifies that storage capacity is constrained by diminishing return relative to the receiving inflow. For this catchment, a storage capacity of 40 L/m^2 with application on 75% roof sub catchments or 20 L/m^2 storage capacity with 100 % application would provide a significant change in overflow.

4. VALIDATION

To validate the complete hydrologic model procedure, observed peak discharge of the drainage network is collected from Chattogram Development Authority (CDA). For, the residential area, the maximum flow (m^3/s) calculated through the hydrologic model and defining it as simulated peak discharge a scatter graph plotted against collected data (Fig 8) for multiple links. The R^2 value for the model is 0.764 and the Root Mean Square Error (RMSE) percentage value is 17%, which defines the model as moderately good for acceptable range.

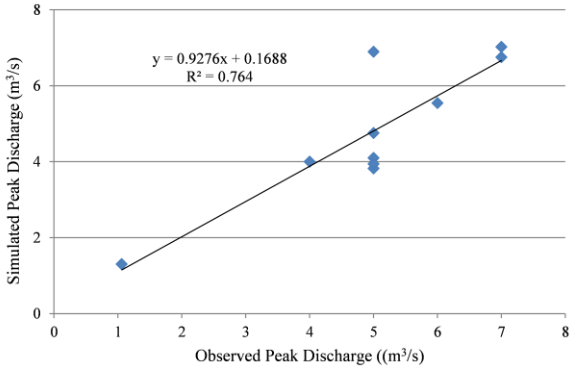

Figure 8: Scatter plot for Validation

5. CONCLUSIONS

The study demonstrates that RTC RWH systems implemented in roof areas with combined sewer network may significantly improve urban flood scenario. Both commercial and residential catchments showed significant flood volume and peak discharge reduction despite the challenges of high impervious cover and large contributing areas. In this residential catchment, where roof surfaces make up a significant share of the total area, controlled storage with a capacity of 40 L/m² achieved nearly 24% flood volume reduction from baseline conditions, with comparable performance persisting for variable capacities (20 and 60 L/m²). The commercial catchment exhibited more variable but nonetheless noticeable results: flood-volume reduction increased from approximately 16.18% when RTC was utilized. Peak outfall discharges likewise declined sharply, with the 40 L/m² scenario reducing flows under baseline conditions by 12.18% under RTC integrated system. The general trend of consistent improvement with increased storage and greater RTC system coverage was observed across both catchments, though marginal benefits reduced at higher volumes due to the inflow being relatively limited compared to the available capacity. Moreover, the controlled systems allowed for more adaptive release patterns that resulted in higher retention and lowered surge flows that usually overwhelm combined sewers during heavy rainfall events. The results indicate that RTC-enabled RWH is a promising approach toward the reduction of hydraulic stress in aging combined drainage networks and the alleviation of recurrent urban flooding. Its ability of peak flow modulation and reduction of outfall loads make it an effective and decentralized intervention capable of delaying upgrade of expensive drainage expansion in rapidly urbanizing cities like Chattogram.

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