EVALUATING THE IMPACTS OF REDUCING THE RETENTION POND AREA IN KALLYANPUR, DHAKA, BANGLADESH

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ABSTRACT

Kallayanpur retention pond’s catchment is located in the western part of Dhaka where 95 ha retention pond area with 20 cumec pumping capacity was sufficient. However, the retention pond area was reduced to 42 ha in 2020. The catchment experiences waterlogging in every monsoon. It is also expected that, in the future extreme rainfall events will be more frequent. The drainage situation is likely to deteriorate. This study tried to predict the hydrological and hydrodynamic responses of Kallyanpur drainage system during intense to moderately intense rainfall events by using MIKE URBAN.Various data were collected and analyzed to develop hydrological, 1D hydrodynamic, and 1D-2D coupled overland flow model. The calibration and validation were carried out using water level data from the Kallayanpur pumping station. Multiple model scenarios were simulated to assess the effects within the catchment area and explore potential solutions. The model development included both JICA (1987) for Dhaka and Alternative Block Method (ABM) design rainfall hyetographs. An acceptable and satisfactory level of model accuracy has been achieved during model calibration and validation. The result shows that, if pump failure occurs the water can reach up to 7.50 mPWD while the existing pump start level is 4.00 mPWD. Future maximum inundated extent in the catchment with the existing pump setup will vary from 23.21% - 28.87%. Also, additional requirement of pumping capacity varies from 22 - 55 cumec. But the requirement pumping capacity has reduced to 17 - 45 cumec with the new operating rule. Moreover, inclusion of LIDs like rainwater harvesting, permeable pavement and green roof can reduce the requirement to 9 - 37 cumec. As intense rainfall events are likely to be more frequent, the study recommends 37 cumec additional pumping capacity with new operation rule and combinations of the LIDs.

Keywords: *Retention Pond, MIKE URBAN, Rainfall Hyetograph, Pumping Capacity, LIDs*

1. INTRODUCTION

The capital city Dhaka, one of the densely populated cities of Bangladesh where in the past, lowland, and open channels used to form an effective drainage network. Shrinking of wetlands due to landfilling and encroachment has made the drainage system vulnerable, leading to waterlogging issues and their associated consequences (Mahmud et al., 2011). In 2008, compared to 1960, the total area of water bodies in Dhaka had decreased by 32.57% and also the lowlands had experienced reduction of 52.58% (Islam et al., 2010). The decrease of water bodies and lowlands is among the primary reasons for worsening the drainage situation with the passage of time (Ishtiaque et al., 2014). In sum, change in land use, decreasing wetland area and encroachment of water bodies brought changes in urban hydrological regime (DWASA, 2015).

Kallayanpur is located on the western part of Dhaka city. Kallayanpur is a densely populated area and is a key contributor to Dhaka's economy (Dasgupta, et al., 2015). The drainage system of the study area is containing eight nos. khals, about 39.5 km pipe networks, a retention pond and a drainage pump station. About 95 ha retention area with 20 cumec pumping capacity was sufficient for efficient drainage for Kallayanpur. RAJUK also proposed 92 ha area as retention pond for Kallayanpur catchment (RAJUK, 2010). But retention area has reduced to 69.4 ha (IWM, 2013). As preservation of the retention pond area could not be achieved the area is decreasing as shown in Figure 1, the area experiences flooding in every monsoon season.

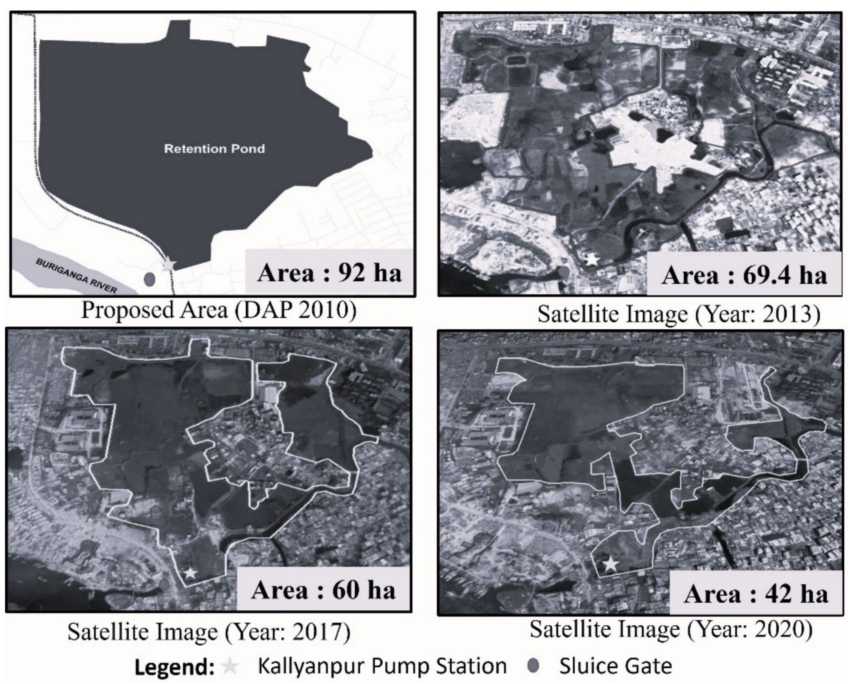

Figure 1: Reduction of retention pond area with the passage of time

To develop an efficient drainage system, stormwater drainage modelling tools plays an important role (Bisht et al., 2016). In this study MIKE URBAN has been used. The study encompasses four objectives. Firstly, it aims to develop Hydrological and Hydrodynamic Model for the Kallyanpur drainage system using MIKE URBAN, with subsequent calibration and validation processes. Secondly, the study focuses on assessing the impact of a reduction in retention pond area on the drainage system. Thirdly, it aims to evaluate pump failure events and determine the additional pumping requirements for the future, anticipating changes in demand and system resilience. Lastly, the study addresses the integration of Low

Impact Developments (LIDs) such as rainwater harvesting, permeable pavement, and green roofs into the drainage system through model simulations.

2. METHODOLOGY

2.1.1 Study Area

The study area is about 19.60 km^2 as shown in Figure 2 and the area is protected from river flooding by the Western Embankment. A sluice gate is located along the embankment which remains closed during the monsoon season and stormwater of the area is pumped from the Kallayanpur retention pond. Most of the area is within the range of 5.0 mPWD to 9.0 mPWD. The existing drainage system includes 8 no. open channels locally known as khals of about 11.7 km, about 39.60 km of pipe drains, and a retention pond with a pump station. The diameter of the pipe ranges from 450 mm to 3000 mm. All the outfalls of pipe drains are in nearby khals. Total capacity of the pump station is 20 cumec. Pumping starts if water level reach 4.0 mPWD and stops at 3.50 mPWD. During monsoon river water level is usually high (higher than 6.45 mPWD) and sluice gate remain close. The pumps of the pump station remain in operation, pumping out the water from the retention pond.

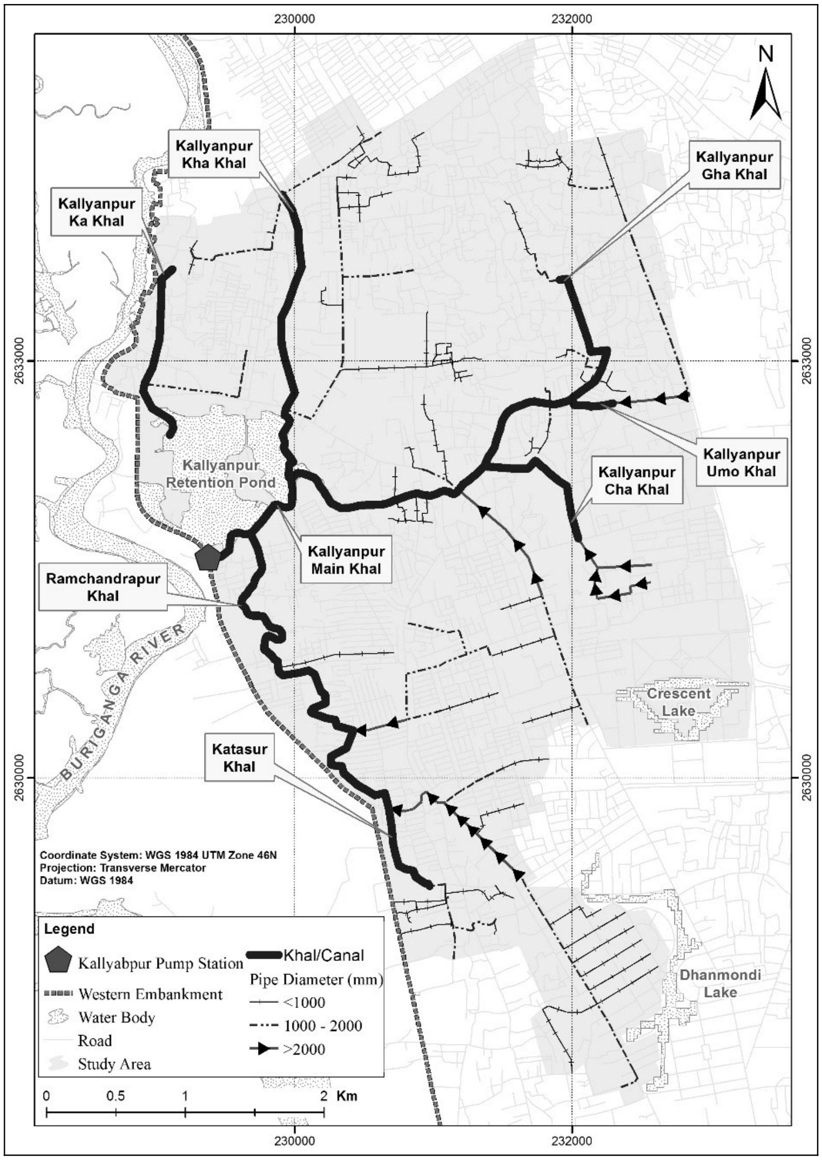

Figure 2: Map showing the study area

2.1.2 Data Analyses

The necessary data are collected from various sources. Table 1 summarizes different data which are required for the present study.

Table 1: Summary of data analyses

Data Type	Data Source	Required for
Rainfall	• Bangladesh Meteorological Department (BMD), • (1991-2020)	a. Actual rainfall event for model calibration and validation b. Generation of design rainfall hyetograph
Drainage network	• Dhaka Water Supply and Sewerage Authority	a. Hydrological modelling b. Hydrodynamic modelling

Data Type	Data Source	Required for
	(DWASA), Institute of Water Modelling (IWM)	
Landuse	• Rajdhani Unnayan Kartripakkha (RAJUK)	a. Sub-catchment delineation b. Spatial planning of adaptive measures
DEM	• Catchment from RAJUK (2010), Retention Pond from IWM (2013)	a. Input data for 1D-2D hydrodynamic couple modelling b. Input data for retention pond geometry c. Determining sub-catchment slope
Pumping data	• DWASA	Model calibration and validation

2.1.3 Design Rainfall Hyetographs

Drainage Master Plan by DWASA (2015) has proposed design rainfall for pump stations and onsite detention as 2-day 5-year event. The design rainfall has been computed as 262.60 mm. By considering climate change (CC) projections (AR6, 2021), the design rainfall is likely to increase to 300.42 mm. In this study for generation of design rainfall hyetograph two methods have been followed.

2.1.3.1 JICA Study Method

The JICA study (1987) has established that the duration of heavy rainfalls of high frequency is about six hours (Sakib et al., 2023). For a two-day event, rainfall in second day have same pattern as the daily rainfall and its starting time is 24 h after the starts of first day rainfall. The amount of second day rain can be found by subtracting one-day design rainfall from two-day design rainfall.

2.1.3.2 Alternating Block Method (ABM)

The design hyetograph produced by this method specifies the precipitation depth occurring in n successive time intervals of duration Δt over a total duration T_d which is equated as equation (1).

$$T_d = n \times \Delta t \tag{1}$$

After selecting the design return period, the intensity is read from the IDF curve or IDF curve equation for each of the durations Δt, 2Δt, 3Δt etc. and the corresponding precipitation depth found as the product of intensity and duration. By taking differences between successive precipitation depth values, the amount of precipitation to be added for each additional unit of time Δt is found. These increments, or blocks, are reordered into a time sequence with the maximum intensity occurring at the centre of the required duration T_d and the remaining blocks arranged in descending order alternately to the right and left of the central block to form the design hyetograph.

2.1.4 Mathematical Modelling

In this study, model is developed by using MIKE URBAN modelling tool. In that case MIKE URBAN MOUSE engine has been used. There are two parts of the drainage model: hydrological/rainfall-runoff & hydrodynamic. The hydrological model deals with the rainfall-runoff simulation. The output of the hydrological model is used as input for the hydrodynamic model. Modelling framework for the ongoing study is shown in Figure 3.

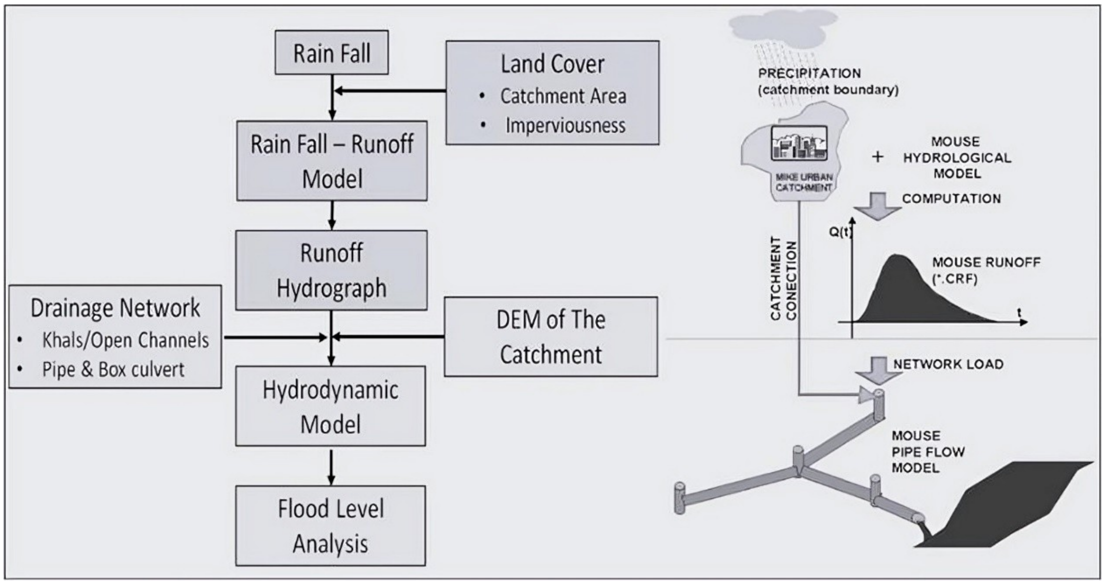

Figure 3: Modelling framework

2.1.5 Delineation of sub-catchments

Primarily sub-catchments are delineated based on Thiessen Polygon formulated from drainage network nodes or outfall. The auto delineated sub-catchments are then modified by considering flow direction, drainage network as-built drawing, road network, elevation and surface slope, outfall location and field observations. Total 432 nos. sub-catchment have been delineated in the study area.

2.1.6 Time of Concentration

The equation used for the calculation of the time of concentration (t_c) for the sub-catchments has been taken from Drainage Master Plan by DWASA (2014) as specified in equation (2), (3) and (4).

$$t_c = t_0 + t_d \tag{2}$$

Where,
t_0 = Time of overland flow
t_d = Time of travel in roadside swales, drains, canals and khals

$$t_0 = \frac{107 n^{¿} L^{1/3}}{S^{1/5}} \tag{3}$$

Where,
t_0= Overland sheet flow travel time (minutes)
L = Overland sheet flow path length (m)
S = Slope of overland surface (%)
n^* = Horton's roughness value for the surface

$$t_d = \frac{nL}{60 R^{2/3} S^{1/2}} \tag{4}$$

Where,
t_d = Travel time in drain (minutes)
n = Manning's roughness coefficient
R = Hydraulic radius (m)
S = Friction slope(m/m)
L = Length of reach (m)

2.1.7 Imperviousness

In this study, imperviousness of sub-catchments has been calculated based on impervious percentage for various land uses and population density as stated by Jahan (Dasgupta, et al., 2015). The population densities of different sub-catchments have been considered from Dhaka Water Supply Master Plan by DWASA (2014).

2.1.8 Hydrological Model Setup

Rainfall-runoff Model (Type A) has been used for estimating runoff of the sub-catchments. In the model, the amount of runoff is controlled by the initial loss, size of the sub-catchment area and hydrological loss, and the shape of the runoff hydrograph is controlled by the concentration time and time-area (T-A) curve.

2.1.9 1D Hydrodynamic Model Setup

Key considerations for development of 1D hydrodynamic model are as follows:

a) Retention pond has been considered a basin.
b) The initial operating efficiency of pumping station is considered 75%.
c) Initial Manning's roughness (n) for pipe and canal is considered as 0.018 and 0.025 respectively
d) The maximum allowable water level in retention pond is 5.0 mPWD for assessing additional pumping capacity
e) Existing operating rule: pump start level is 3.5 mPWD and stop level is 4.0 mPWD.
f) Efficiency of existing pumps for adaptive measures evaluation have been finalized after calibration & validation.
g) Area of reduced retention pond have been finalized after calibration & validation, and the pond area will remain same for future scenario simulation.

2.1.10 1D-2D Couple Model Setup

Key assumptions for 1D-2D couple model are as follows.

a) For 1D-2D couple model to simulate flooding, RAJUK DEM 2010 is considered for both base and future scenarios except for retention pond.
b) Retention pond area in base condition (2014), IWM surveyed DEM 2013 is considered.
c) For future scenarios, reduced retention pond area and filled area's elevation have been updated based on satellite image (Google Earth) analysis and conducted site visit.
d) Coupling have been done in pipe manholes and open channel nodes.

2.1.11 Initial and Boundary Conditions

Key considerations for initial and boundary conditions are as follows.

a) For hydrological model simulation, rainfall and wastewater contribution is boundary for sub-catchments.
b) For hydrodynamic model, simulated runoff is the upstream boundary condition for network nodes and manholes.

c) The initial water level for Kallayanpur retention pond is considered as 3.0 m PWD for adaptive measures simulation.
d) The Kallynapur system is protected from river flooding by Western embankment. As during monsoon season river water level is usually higher than retention pond that's why sluice gate is considered to be closed for simulations. Thus, outside river water levels have no influence on the flooding and have not used as external boundaries.

2.1.12 LIDs Simulation Setup

Detail considerations of model simulation setup with LIDs are as follows.

a) Based on landuse and building pattern, two types of rainwater harvesting arrangement were considered i.e., building level RWH and community level RWH.
b) According to BNBC 2020, proposed building on a plot having area greater than 300 m^2, must have RWH facility. This consideration was applied for building level RWH.
c) Building rooftop area have been assessed from Open Street Map (OSM) building footprint shape file and total 4,498 nos. building have been identified for building level RWH.
d) As stated by Ahmed (2018) central RWH underground storage tank were identified for 12 nos. residential colony in study area.
e) The permeable pavement and green roof have been assessed based on recommendations from Stormwater Management Guidebook (DOEE, 2020)
f) The potential storage of all the LID measures, which will not contribute to the surface runoff was will be represented as initial loss in the hydrological model simulation.

2.1.13 Model Scenarios

The summary of model scenarios for the study are shown in Table-2.

Table 2: Summary of model scenarios

Scenario	Model Setup				Outcomes
	Pumping	Landuse	Rainfall	Measures	
SC-1.1	2014 event	Existing	3-h, 2014 event	–	Calibration and validation
SC-2.1	2020 event		3-h, 2020 event		
SC-2.1.a	Existing	Future landuse with reduced retention area (2020)	Design with CC (ABM)		Assessment of impact due to reduction in retention area
SC-2.2.b			Design with CC (JICA)		
SC-3.1.1	-		Design with CC (ABM)		Assessment of pump failure
SC-3.1.2			Design with CC (JICA)		
SC-3.1.a	Increase pump capacity with existing operation rule. Start Level: 4.0 mPWD Stop Level: 3.5 mPWD		Design with CC (ABM)	Increase pump capacity	Assessment for requirement of additional pumping capacity
SC-3.2.b			Design with CC (JICA)		
SC-3.1.1.a	Increase pump capacity with proposed operation		Design with CC (ABM)		

Scenario	Model Setup			Outcomes
SC-3.2.1.b		Design with CC (JICA)		
SC-4.1.a	rule. Start Level: 4.0 mPWD Stop Level: 3.5 mPWD	Design with CC (ABM)	Additional pump capacity + LIDs	Assessment for requirement of optimum additional pumping capacity
SC-4.2.b		Design with CC (JICA)		

3. RESULTS

3.1.1 Design Hyetographs

Hyetographs for 2-day 5-year design event with climate change effect (300.42 mm), are generated by following both Alternating Block Method (ABM) and design hyetograph for Dhaka proposed by JICA study (1987) as shown in Figure 4.

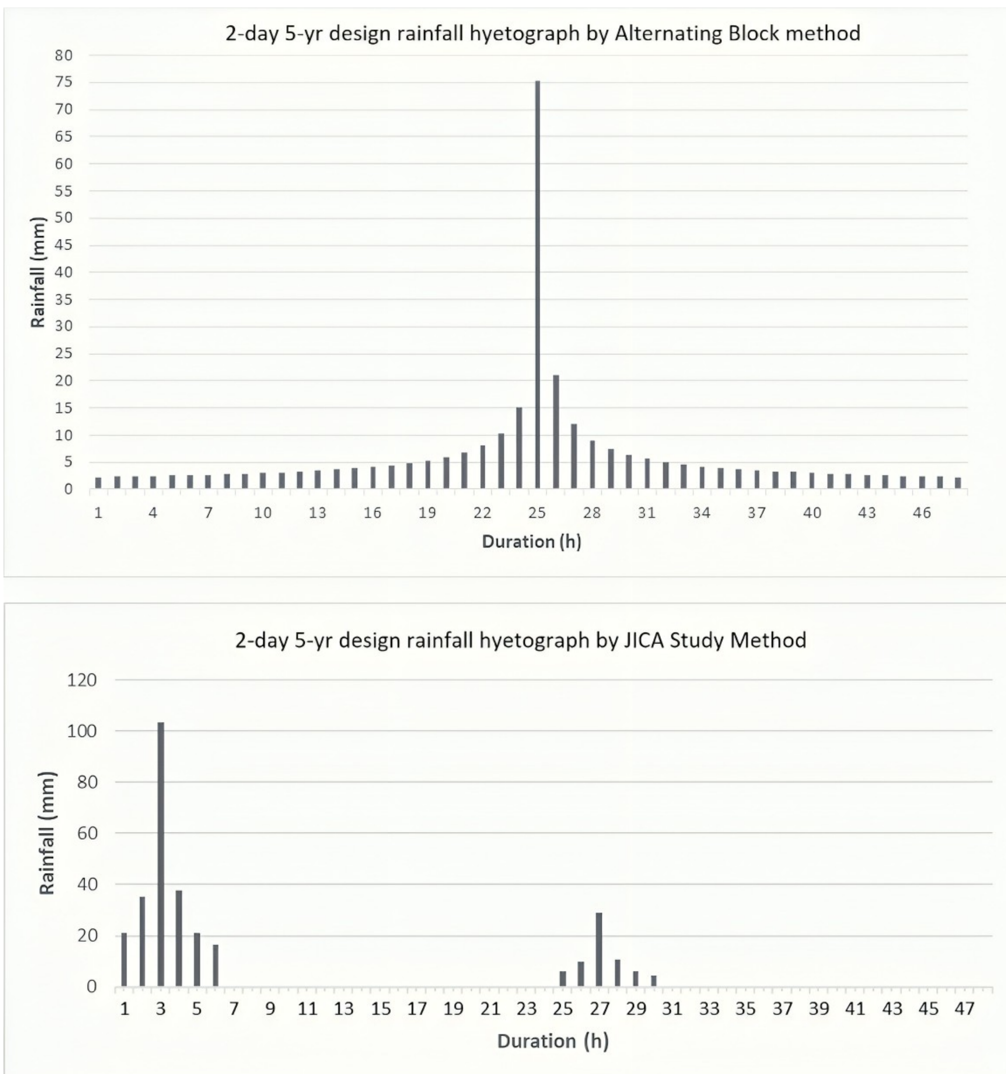

Figure 4: Design rainfall hyetographs

3.1.2 Calibration and Validation

The calibration process spanned a 3-day and 12-hour simulation period, as depicted in Figure 5. During this timeframe, total recorded rainfall was 76.2 mm. Throughout the event, three pumps with a capacity of 13.33 cumec were operational, and their calibrated efficiency was determined to be 80%. The values for Manning's n were adjusted to 0.029 for the canal and 0.020 for the pipe. Additionally, the calibrated weighted average imperiousness for the study area was found to be 59.24%, with a corresponding time of concentration of 188.4 minutes. The validation scenario was simulated for a 4 day and 6-hour period (19.07.2020 00:00 AM to 23.07.2020 6:00 AM). In this validation event, the amount of total rainfall was 194.0 mm and four pumps with a capacity of 16.33 cumec were operational.

From calibration the value of coefficient of determination (R^2) is found to be 0.883 and Nash-Sutcliffe efficiency (NSE) as 0.670. Again, from validation the value of coefficient of determination (R^2) is found to be 0.638 and Nash-Sutcliffe efficiency (NSE) as 0.513. As per earlier study (Moriasi et al., 2007), based on value of R^2 and NSE, it can be said that an acceptable and satisfactory level of model accuracy have been achieved during model calibration and validation.

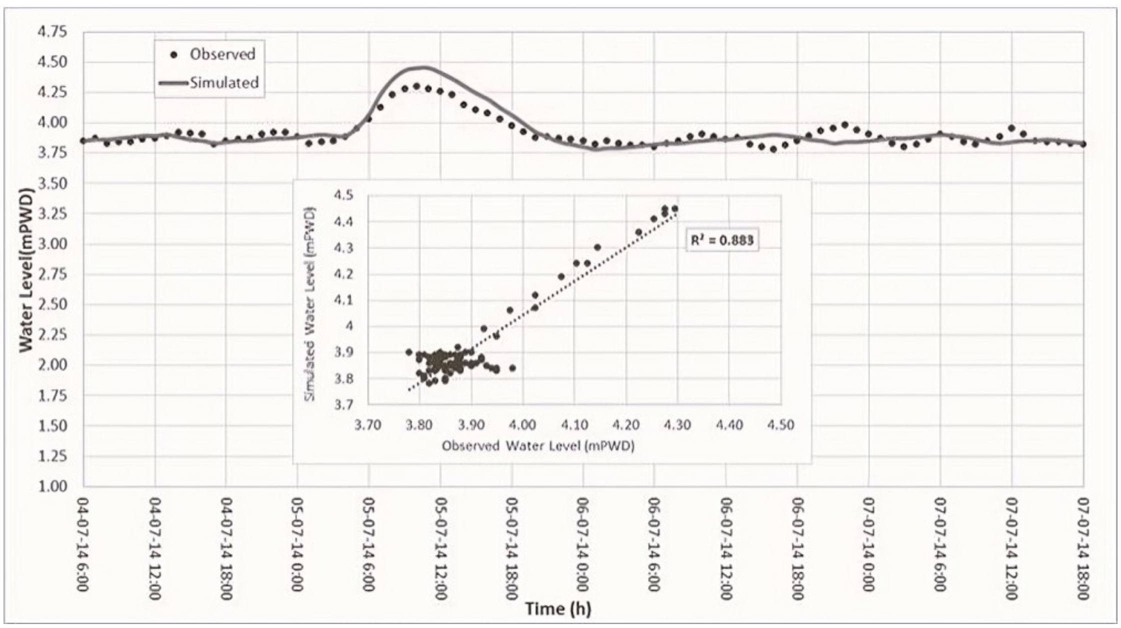

Figure 5: Water level hydrograph for SC-1.1 (calibration) at Kallayanpur Pump Station

3.1.3 Impact Assessment for Reducing Retention Pond Area

In 2020 retention pond area has been found about 37.3% less than IWM surveyed area in 2013. To assess the reduction effect, the retention pond area was considered as 45% less than 2013. In addition, it was assumed that the retention pond area will not decrease further in the future. During these 1D-2D couple simulations, existing pumps were considered following the current operation rule. Details of impact assessment due to reduction in retention pond area is shown in Table 3.

Table 3: Details of impact assessment due to reduction in retention pond area

Scenario	Inundated Area (Km^2)			Total inundated area (Km^2)	Inundated area
	0m - 0.5m	0.5m - 1.5m	>1.5m		
SC-2.1.a	3.46	0.81	0.73	5.00	25.55%
SC-2.2.b	4.18	0.76	0.71	5.65	28.87%

3.1.4 Assessment of Pump Failure

As pumping was not considered for SC-3.1.1 and SC-3.2.1, indicating failure of the Kalyanpur pumping station, the maximum water level at the pump station reached 7.50 mPWD for both scenarios. Additionally, the peak discharges downstream (d/s) of Kallayanpur main Khal were 43.6 cumec and 66.5 cumec for SC-3.1.1 and SC-3.2.1, respectively. The discharge hydrograph generated by the JICA method exhibits a flashy nature, whereas the hydrograph from the ABM method displays a more gradual increase and decrease of discharge. In summary, it is evident that the JICA method would require a greater pumping capacity compared to the ABM method.

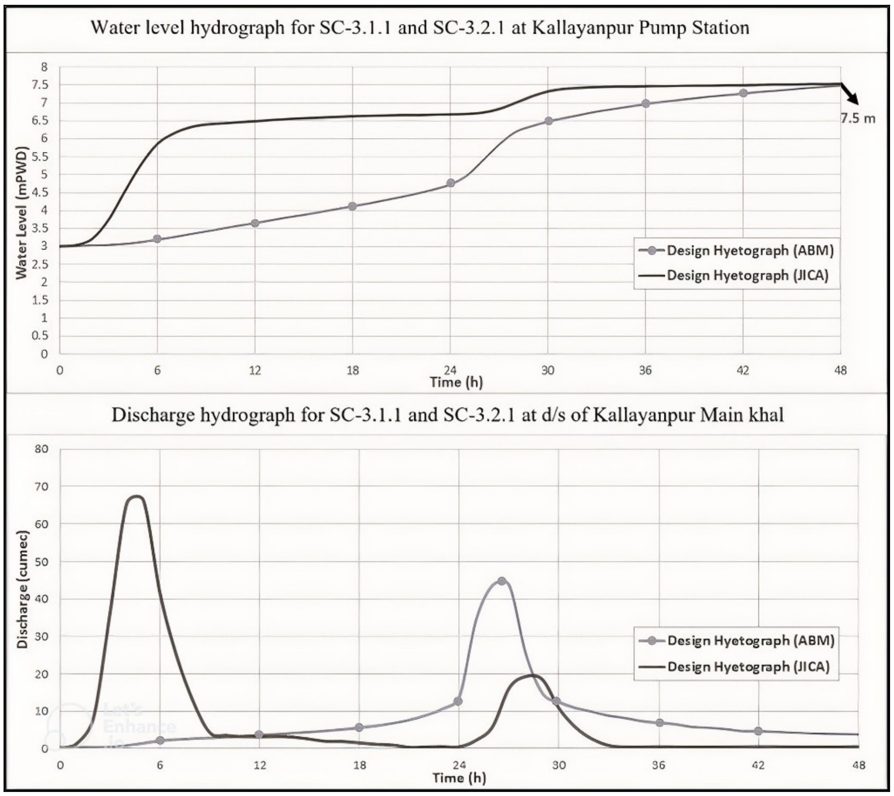

Figure 6: Water level and discharge hydrograph due to pump failure

3.1.5 Assessment for of LIDs Simulation

Based on the methodology, total storage in sub-catchments by LIDs under the study area has been evaluated. By implementing RWH, permeable pavement and green roof about 0.56 Mm^3, 0.11 Mm^3 and 0.07 Mm^3 of water respectively can be stored during design rainfall events in the study area. Total storage amount by LIDs is about 0.74 Mm^3 which is 23% of total accumulated flow in the study area for design rainfall event.

3.1.6 Additional Pumping Capacity Requirement

During finding additional pump capacity, present pumps capacity was considered as 16 cumec (as 80% pump efficiency as per calibration and validation). Details of additional pumping requirement are shown in Table 4.

Table 4: Details of additional pumping requirement

Scenario	Total pump capacity (cumec)	Additional pump capacity (cumec)	Operation time (h)
SC-3.1.a	38	22	23.09
SC-3.2.b	71	55	11.24
SC-3.1.1.a	33	17	25.16
SC-3.2.1.b	61	45	13.11
SC-4.1.a	25	9	28.15
SC-4.2.b	53	37	13.92

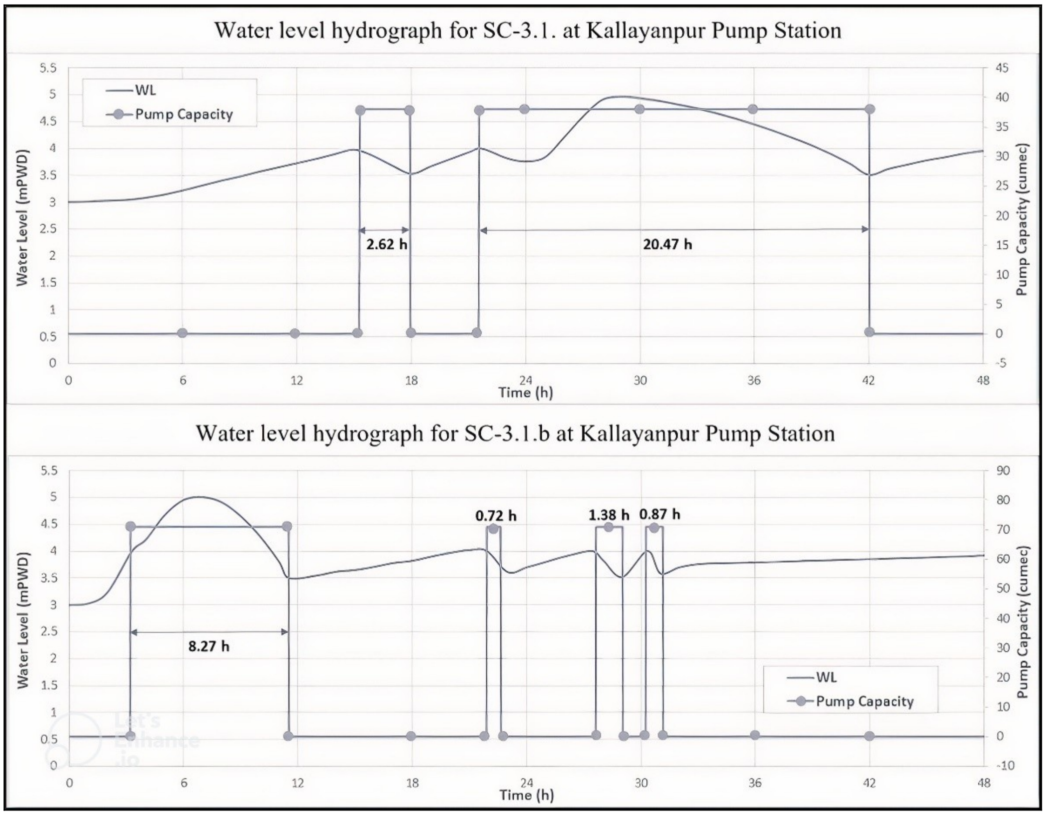

Figure 7: Assessment of additional pumping capacity

4. CONCLUSIONS

The outcomes from various model simulations indicate that the current drainage system in Kallyanpur is mainly pump dependent. The reduction in retention pond areas corresponds to increase in the inundated area, necessitating an augmentation in the pumping capacity of the Kallyanpur pump station to mitigate this impact. But two different rainfall hyetographs show different results. For intense rainfall events like JICA hyetograph, requirement of additional pumping capacity is very high. On the other hand, for moderately intense rainfall events like ABM hyetograph additional pumping requirement is significantly less though a much longer duration of pumping is required. Inclusion of LIDS can alleviate inundation in shallow water depth, but the system remains pump dependant.

From model simulation, additional requirement of pumping capacity varies from 22 cumec – 55 cumec. But requirement of additional pumping capacity has reduced to 17 cumec – 45 cumec with new operating rule to start pumping at 3.80 mPWD. Combining LIDs with new operating rule, requirement of additional pumping capacity has stand to 9 cumec – 37 cumec.

To enhance the safety margin for designing a stormwater pumping station, the study recommends incorporating a more intense rainfall event. In this regard, the study suggests an additional pumping capacity of 37 cumec along with a new operating rule, initiating pumping at 3.80 mPWD. Furthermore, the inclusion of LIDs is encouraged for improved stormwater management. The drainage situation in Kallyanpur is likely to deteriorate without adequate interventions. The area of the Kallayanpur retention pond should be preserved, and if possible, further land should be acquired to improve the retention pond capacity.

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