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Application of Numerical Model for Drainage Improvement of Dhaka-Narayanganj-Demra (DND) Area of Dhaka city, Bangladesh

*Md Shamim Shams[1], Parvez Sarwar Hossain[2]

Abstract— After 1971 independence of Bangladesh DND area of Dhaka megacity has become victim of unplanned development due to proximity of central business district of Dhaka and Narayanganj district. Land use of DND area has been transformed from the originally agricultural land to residential, industrial plots and roads. The generated runoff has been increased more than design runoffs which effects existing drainage system. Consequently, the existing pump drainage system was unable to drain out storm water along with the excess domestic wastewater. Besides, drainage canals have been badly diminished due to unauthorized encroachment of canals. To mitigate drainage congestion in DND area and to find an improved solution a numerical model studies have been initially undertaken during 2010 by Bangladesh Water Development Board with the association of DDC, Ltd. which would lead up-to set design parameters for building of future drainage infrastructure of DND area. The required data-set used by popular numerical modeling tool named MIKE11of DHI Water and Environment was collected from various sources. From numerical studies it has been examined by multiple options based drainage system on the basis of flood depth inundation for 2 days consecutive heavy rainfall of 5 year return period. Flooding extent for different options in terms of flood depth-level and drainage path length for different interventions has also been assessed. After rigorous analysis a feasible and cost-effective 97% flood free with improved drainage system of DND area has been idealized from the numerical analysis output for future implementation.

Index Terms—Drainage improvement, Drainage model, Flood-depth, Numerical analysis, Option development, Unplanned city, Water logging.

1. INTRODUCTION

Developing countries experience the urbanization in exceptionally fast rate than any other first world countries (United Nations, 2002). But the urbanization process in the mega-cities of the developing countries grows up with the lack of efficiency in the urban infrastructure which creates serious problems for cities, including flooding damage increase and water logging (Verol et al., 2011). Cities of Latin America, Asia and Africa which are belong to developing countries with fast economic growth facing this acute problem. Some parts of Dhaka (Bangladesh), Lucknow, Mumbai (India), Sao-Paulo (Brazil), Port-Elizabeth (South-Africa) etc are the prime exemplar megacities of developing countries that are notable for prolonged water-logging during wet season. Although parts of these cities are vulnerable to the impacts of water logging but the benefits of living nearer sources of employment have made disadvantage association with flooding for the low-income communities. Water logging due to drainage congestion in urban areas is not just associated to heavy rainfall events but it is also related to changes in the built-up urban areas themselves. Unplanned rapid urbanization restricts flood waters ways by covering large land mass due to concretization, thus obstructing natural channels (Douglas et al., 2008). Basically due to unauthorized and uncontrolled filling of low lying areas and canals, encroaching of natural canals, subsequent development of the infrastructure, planned flood control activities are hampered (Ashish &

- **Md Shamim Shams is currently working at Bangladesh Water Development Board,Dhaka, bangladesh. E-mail: shamsce@gmail.com*
- *Parvez Sarwar Hossain is currently working at Local government Engineering Department, Dhaka, Bangladesh. E-mail: parvezlged@gmail.com (*Corresponding author)*

Sheiji, 2004). To mitigate and improvement of drainage congestion various structural and non-structural methods are practicing all over the world. Among those, flood drainage modeling is a kind of non-structural application which is fundamentally a numerical modeling approach on urban drainage and flood modeling system.

Applications of numerical models have been used as a traditional industry practice for urban drainage and flood modelling work for many years (Vojinovic et al, 2011). Among the models 1D urban drainage network model is widely used because of less data-set requirement and computational efforts. "This kind of model solves the Saint-Venant one-dimensional flow equations to simulate the behavior of the flow within a drainage pipe network, including complex devices such as pumps, gates, weirs and valve. The quality of such models is highly dependent on the quality of the input dataset and calibration."(Justine et al., 2010). Software packages such as MIKE (DHI), SWMM (US EPA), INFOWORKS (Wallingford), SOBEK (Deltares); etc have found widespread commercial use for this purpose.

The study research project presented in this paper based on application of numerical model for drainage improvement of DND area of Dhaka city, Bangladesh. From the 1970s there has been a steady progression in the development for urban flood and drainage modelling (Boogard et al, 2010). But urban flood and drainage model was first introduced in Bangladesh on 1997 as a pilot based project in Dhaka city due to damage response of 1996 flood event (Ole et al, 2001). At that time DND area was excluded. DND project area was implemented during 1962-1968 at outskirt commercial portion of today's megacity of Dhaka. At the beginning it was like flood-proofed agricultural area bounded by high embankment around under Flood Control Drainage and Irrigation (FCDI) project. The main objectives of the project were to protect Dhaka and Narayanganj towns from major flood events and to accumulate inner croplands from overflowing rivers. For achieving the self-reliance in food grain production DND project was a special irrigation project. But soon after the independence of Bangladesh DND area continued to develop as an unplanned residential area as many lower middle income people buying land and building homes haphazardly. The development gained tempo after the 1988 major flood event which welcoming more people inside of dam protected area. As a result most of the agricultural land was transformed into residential and industrial zone without any plan. This unplanned housing and settlement made an adverse impact on the existing drainage system of DND area which generates water logging even at minor rainfall events situation inside DND area.

Figure 1: Chronic problem of water logging of every year during monsoon inside of DND area

(Adopted from local newspaper)

2. Study Area Profile

DND area is situated between the river Buriganga and Sitalakhya and is in the flood plain of the Meghna. The Buriganga River covers both the south and a part of west side and the Lakhya River is in the east side. At the beginning of DND Project (1962-68) the area was primarily rural and the land was mainly agricultural excluding existing canals and homesteads. Now it has changed from the agro-rural to agro-urban area. Urbanization process is randomly progressing without any urban planning. Areas devoted to agriculture and water bodies are continuously engulfed by urbanization. Demra, Shyampur, Kutubpur, Matuail, Siddirganj, Godnail, Madaninagar, Bhuigar, Pagla, Fatulla etc. of DND area are approaching to an urban area at a very fast rate. Already wards (small administrative part of city corporation) 88, 89 of Dhaka City Corporation, Wards 1,2,3 & 4 of Narayanganj and Siddirganj Pourashava (local city council) are declared urban areas within the project. Other Pourashavas under consideration for declaration are Kutubpur, Fatulla and Matuail. In 1962 DND project consisted of over 80 percent agricultural land, and as on 2008 agricultural land is less than 25 percent. In a separate study by JICA[3] it has projected that, on 2032 there will be 94 percent of urban related area while other minor part will be water bodies or just open space. Land of DND area is generally low in the middle and medium high in the periphery. Slope of the land is form northwest to southeast. The elevation of low land is 2.0 - 2.5m PWD[4] and medium high land is 4.0-5.5m PWD. There is hardly any land above 5.5m PWD. The whole DND area is bounded by road-cum-embankments and floodwalls. The major project components were 31.25 km (now 31.00 km) road-cum-flood control embankment, 55.20 km irrigation canal, 45.40 km. drainage canal, 1.00 km intake canal, 216 nos. water control structures and one pump station at Shimrail with 4 pumps (14.52 cumec capacity). As the area is developed for drainage and irrigation, it is supplied with irrigation water in December to May and generally flood free.

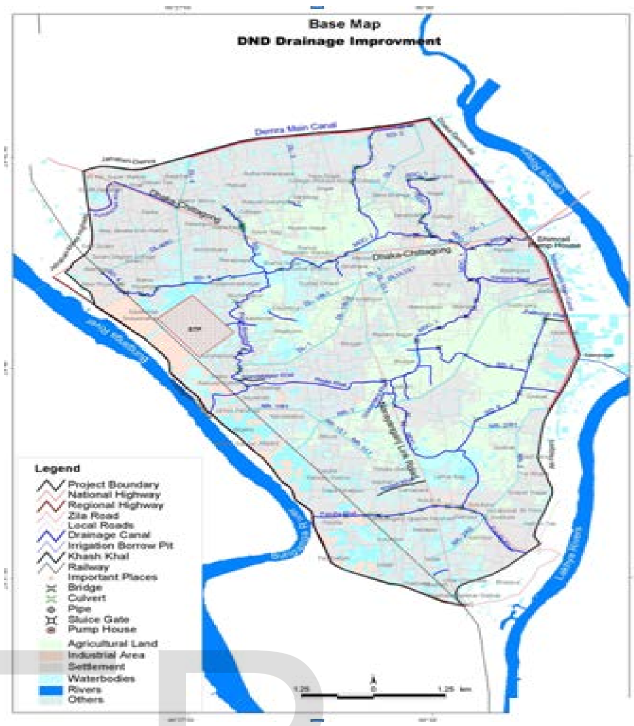

Figure 2. Base Map with existing features of the Project Area

3. Application of Numerical Modelling

Aim of the application of numerical modeling tool is to find out the multiple option based improved drainage management in the DND area and reassess the existing drainage condition. To understand drainage system inside the DND area MIKE11 of DHI, Water and Environment is being used. MIKE11 is capable to analyze various drainage options and ability to assess the impact of alternative measures for achieving controlled drainage, flooding and irrigation. At the end output would be processed using MIKE11 GIS to develop flood inundation and impact maps in getting the comparative assessment. Computation inside of MIKE11 modelling environment can take place in two steps; one is Rainfall Runoff component by MIKE11 NAM model and another is Hydrodynamic Model or MIKE11 HD. The fundamental function of MIKE11 NAM model is to estimate the runoff generated from rainfall occurring in the basin. The catchments of the rainfall runoff model are delineated according to the topographic barriers or watershed boundaries, roads and river networks. The NAM validation can be done by real time data set for proper assessment. On the other hand, MIKE11 HD works from NAM model output together with components of channel bathymetry, flood cell topography, location of infra-structures, resistance of channel bed-form; etc. The performance of the HD model can be evaluated with known point observed water level of the river.

3.1 Model Setup for study area

Rainfall Runoff and Hydrodynamic Models of MIKE11 have been setup as base model for analyzing the different drainage options. Model setup includes the model schematization, calibration and validation of rainfall runoff and hydrodynamic model.

3.1.1 Rainfall Runoff (NAM) Model:

Rainfall Runoff Model (NAM) has been developed to assess the contribution of runoff generated from rainfall within DND area using MIKE11 NAM. DND area is divided into 19 drainage sub catchments (Table-1 and Figure 3), derived from the digital elevation model. These 19 sub-catchments have been schematized and validated through field investigation. Mean Areal Rainfall (MAR) and Mean Areal Evaporation (MAE) for the year 2007-2008 have been used in this model. Rainfall stations of Dhaka and Shimrail are used for MAR calculation. Evaporation data of Dhaka station is used for the NAM model.

Rainfall Runoff Model has been calibrated and validated for the period of 2007-2008. Model parameters are initially considered from a previously developed model by IWM[5] named North Central Regional Model (NCRM) which covers the DND and the peripheral river system. Then the NAM model has been calibrated and verified against observed groundwater level of DND area.

3.1.2 Hydrodynamic Model (HD)

Drainage part of Hydrodynamic Model consisting of all the main drainage canals is separately developed to examine the capacity of the existing drainage system for conveying the design runoff generated from different catchments. Largely, all the main, secondary and other existing drainage canals have been schematized in the model for representing the present situation of the area which has further been modified during option development. MDC-1, MDC-2, Pagla Canal, Fatulla Canal, SD-1, SD-2 and SD-3, Shampur Canal (secondary drainage or SD-4), SD-5, SD-6 have been used for setting up the base model. All irrigation borrow pits, like DL-1(Demra Left), DL-2, DL-3, DL-4, NR-1 (Narayanganj Right), NR-2, and Kangsho Nadi have been used during option development. The result of Rainfall Runoff Model of the drainage sub-catchments have been incorporated as lateral inflow (pointed/distributed) to the existing canals. Cross section data at every 300 m interval, collected under this study, have been used in the HD model. Peripheral hydrodynamic model has been set up with peripheral river system. The peripheral HD model has also been coupled to examine the external river water level. Cross section data of BWDB has been used in the MIKE11 HD model simulation.

Like the NAM model Hydrodynamic model has also been calibrated and validated for the year of 2007-2008. The model has been calibrated and validated against observed water level at specific 7 locations (Figure 4). Similarly hydrodynamic model of external river system has also been calibrated and validated against observed water level of 31 years for the period of 1976-2007 from collected BWDB data series.

TABLE 1
SUB-CATCHMENT OF THE DND AREA

Sl. No	Drainage Catchment	Drainage Canal	Area in Ha
1	C-1	SDC4/Shampur Canal	710
2	C-2	SDC-3	455
3	C-3	MDC-2	250
4	C-4	SDC-2 Dogair Canal	279
5	C-5	SDC-1	190
6	C-6	MDC-2	178
7	C-7	MDC-1	085
8	C-8	Kangsho River (KN)	031
9	C-9	SDC-5	574
10	C-10	MDC-1	825
11	C-11	Fatulla Canal (FK)	383
12	C-12	-Do-	196
13	C-13	-Do-	081
14	C-14	Pagla Canal ((PK)	276
15	C-15	-Do-	229
16	C-16	Pagla Branch (PB)	156
17	C-17	MDC-2	538
18	C-18	MDC-1	226
19	C-19	MDC-1	160
Total Catchment Area in Ha			5822

Note: MDC – Main Drainage Canal, SDC–Secondary Drainage Canal

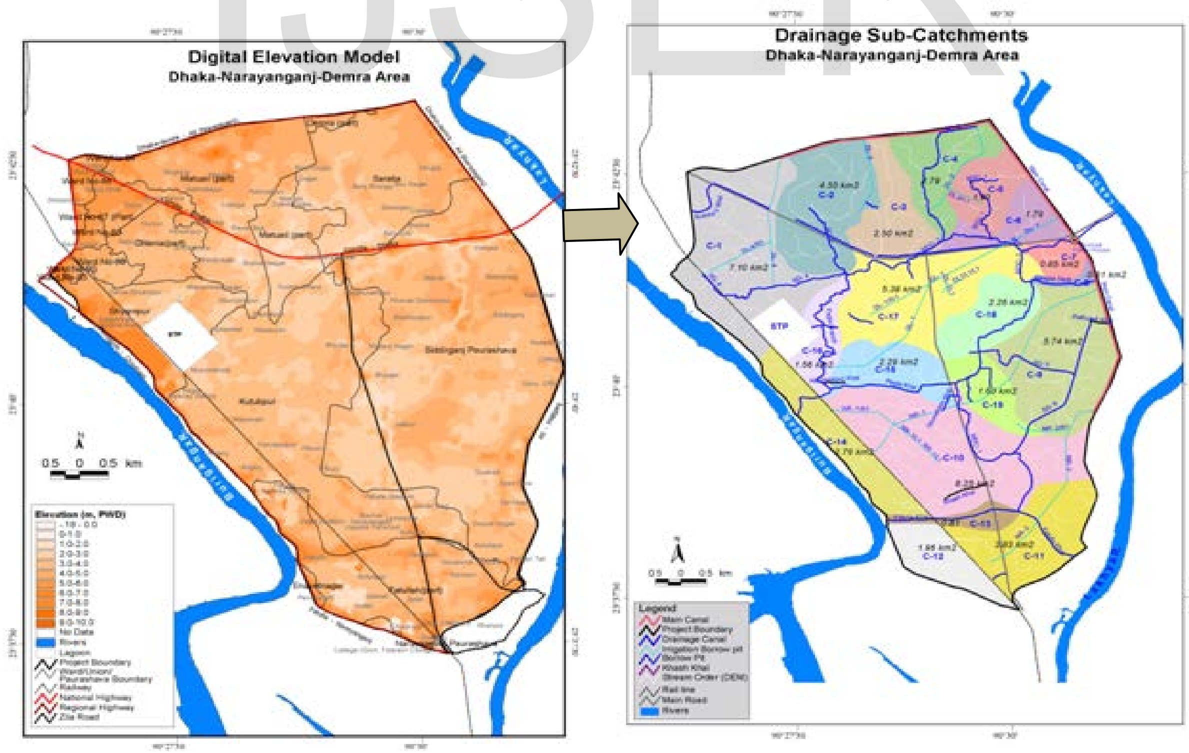

Figure 3 Drainage sub-catchment based on digital elevation model of DND area

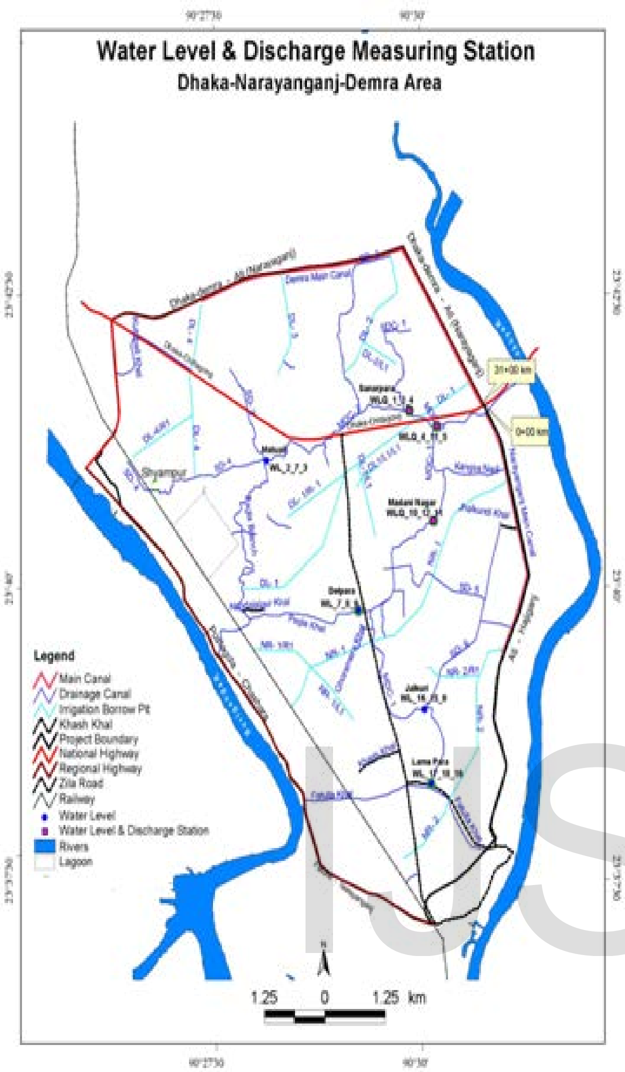

Figure 4 Measured water level and discharge measuring station of DND area

3.2 Estimation of design drainage events

3.2.1 Successive rainfall analysis

Maximum of successive rainfall obtained from the processed data at selected rainfall stations have been calculated from 1 day, 2 day, 3 day, 5 day and 10 day data. MAR has been estimated using Thiessen Polygon method, where relative area ratio for Shimrail and Dhaka has been considered as 82% and 18% respectively due to proximity of study area. Monthly distribution of areal rainfall pattern shows that average annual rainfall in the DND area is 2,083 mm while the maximum rainfall occurs during the month of September with historical average of 325 mm. Historical rainfall of 820 mm has been found as maximum rainfall occurred during September, 2004 from BMD[4].

3.2.2 Probability of design storm

Probability analysis has been carried out on the yearly maximum data for 1-day, 2-day, 3-day, 5-day and 10-day consecutive rainfall. Probable design rainfall for successive duration and return period has been estimated using Gumbel-Chow method (EV Type-I) and the results are given in Table 2.

TABLE 2
COMPARATIVE STATISTICS SHOWING DIFFERENT DESIGN RAINFALL EVENTS IN MM

Return Period	1 day	2 day	3 day	5 day	10 day
2	117.73	167.23	200.87	231.94	310.26
2.33	125.27	179.63	214.37	247.83	328.65
3	136.79	198.58	235.01	272.13	356.75
5	158.03	233.50	273.02	316.89	408.53
10	184.71	277.38	320.80	373.14	473.59
50	243.44	373.96	425.94	496.93	616.78
100	268.26	414.79	470.38	549.27	677.31
500	325.64	509.13	573.10	670.20	817.20

As per existing BWDB practice, 2 day consecutive rainfall with 5 year return period is usually considered as design rainfall event. Therefore, 2-day consecutive rainfall event with 5 year return period have been estimated as 234 mm. Enumerated design event is also very close to the estimate as provided in different study report 239 mm and 245 mm (JICA, 1992 and JICA, 1987 respectively). The difference found is due to the use of only one station by JICA for their study, while the mean of two stations is used in this study. Considering the coverage of a drainage area, the value of the design rainfall has been used for runoff analysis to determine the design capacity of the main drainage canal, structure, regulator and pump station. To be in the safer side, this study has considered the design rainfall amounting to 245 mm. So, rainfall data of BMD has been used in all analyses.

3.3 Rainfall Runoff data

Calibrated drainage model has been simulated using design drainage event (extreme event) of specific return period derived from probability analysis. Catchment parameters have been used and considered with respect to prevailing and future land use considering fully urbanized in the MIKE11 NAM model.

The Rainfall Runoff model of MIKE11 has been simulated for the selected rainfall event of 2005 for generating runoff from rainfall for each catchment within the study area. This runoff has been used as lateral inflow for the drainage as well as irrigation borrow pit canal to be converted as drainage canal for option development inside the DND area to simulate the hydrodynamic model. Using 2-day 5-year event of rainfall for 2005, the runoff generated by the Rainfall Runoff model is presented in Table 2 where the domestic and industrial effluents are not considered. Domestic and industrial effluents have been considered during option development for drainage improvements. It has been found that the total area has to drain out around 99 MCM of surface runoff for the design event during the wet season spread over 5 months period (av. 7.64 cumec). Catchment number ten (C-10) contributes the highest proportion (14.04 MCM av. 1.03 cumec) while catchment number eight (C-8) discharges the lowest (0.53 MCM av. 0.04 cumec).

3.4 Hydrodynamic Model Simulation

The hydrodynamic model has been simulated for the estimated design period of 2005 considering drainage and a part of the irrigation borrow pit canal for whole DND area. From the simulation it is found that, the highest peak discharge (98 cumec) is occurred during mid September. In addition, several other peaks are found in July and August. The next peak values are 65 and 60 cumec. The hydrodynamic model has generated this discharge assuming fully urbanized DND area in 2032 (predict). This model result is the basis for developing different options for drainage solution in the DND area.

A number of command areas (as per land topography) have been planned to drain out the accumulated drainage volume (rainfall runoff, industrial and domestic effluents), which consists of variable proportion of different drainage catchments. These command areas facilitate the option development process. A possible formation of four command areas consisting of nineteen catchments can be treated as one option with four drainage outlet that discharges the internal drainage volume in the peripheral river system. Accumulated drainage volume for each of the possible combination of command areas has been investigated thoroughly to determine the best option.

3.5 Peripheral DND area

Flood levels with 100 year return period at different locations have been derived from the Peripheral River Model. At every 500 m interval, water level data have been extracted to enumerate the extreme design event for 100 year return period. This design event has been estimated from the annual maximum series using the Gumbel Chow method (EV Type-I).

4. Option Development

4.1 Formulation of Technical Options

Future scenario for the year 2032 (25 years from this study begins as on 2007) has been taken into consideration while developing options for the DND area. Detailed Area Plan (DAP) by RAJUK [7] has considered that the DND area will be fully urbanized (5 cumec for domestic and 3.42 cumec for industrial with population density 225 per acre) in the year

2030. This study has assumed the same scenario for option development as recommended in DAP for DND area.

4.2 Drainage Options

For this study three options are developed as per DAP report up to year of 2030 with population projection 225 per acre. The options are- Option-1: Two pump stations at Shimrail (46.11 cumec) and Adamjinagar (28.58 cumec), Option-2: Three pump stations at Shimrail (41.06 cumec), Adamjinagar (25.45 cumec) and Pagla (8.19 cumec), and Option-3: Four pump stations at Shimrail (38.41 cumec), Adamjinagar (30.21 cumec), Pagla (2.82 cumec) and Fatulla (3.25 cumec).

4.3 Comparison of Options

All the three options have been analyzed to identify the positive and negative points. Option-1 has a strong positive point that is drainage systems leading to Shimrail and Adamjinagar follow the existing drainage slope and flow direction but has the strongest negative point of having longest drainage travel path to pump stations. On the other side, Option-3 has the best drainage distribution and shorter drainage paths but drainage slope and flow direction toward Pagla and Fatulla pump stations are adverse. For Option-2, drainage distribution is moderate with adverse slope and flow direction toward Pagla Pump Station.

4.4 Impact Assessment of Different Options

The impact of different options has been evaluated by generating and interpreting flood depth maps for 2 days consecutive rainfall. Flooding extent for different options in terms of flood level at specific locations and drainage path length for different interventions has been assessed. The most feasible option has been selected from the output generated from numerical model analysis. The flood depth map i.e. flood impact map has been generated from MIKE11 for two days consecutive rainfall. Standard flood depth classification has been adopted as per MPO[8] classification. F0 land has been considered for less than 30 cm flood depth and F4 land for more than 300 cm. Impact of different options in terms of flood mitigation is given for Option 3 for present land use and for projected land use (2032) in Figure 5. Considering 80% efficiency of the existing Shimrail Pump and 2 days 5 year design rainfall, existing situation shows that nearly 50% area (2880 ha) of the DND area remains inundated during wet season. Active drainage canals and irrigation borrow pits have been considered for this situation. The duration of inundation is two days. In Option 1, it improves to twenty percent. Table 3 shows eighty percent (80%) area might become flood free for present land use situation if Option- 3 is selected, whereas, 61 % for Option 1 and 64% for Option 2. For projected (2032) situation about 97% will be flood free for Option-3.

TABLE 3

OPTION WISE FLOOD DEPTH AREA

Land Type	Existing condition		Option-1		Option-2		Option-3 (Present)		Option-3 (Year 2032)	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
F0 (<30 cm)	1868	32	2450	42	2615	45	3712	64	5071	87
F1 (30-90 cm)	1012	17	1091	19	1086	19	928	16	586	10
F2 (90-180 cm)	1540	26	1406	24	1364	23	978	17	193	2
F3 (180-300 cm)	1270	22	790	14	680	12	174	3	2	0
F4 (>300 cm)	133	2	85	1	77	1	31	1	31	1
Total Area	5822	100	5822	100	5822	100	5822	100	5822	100

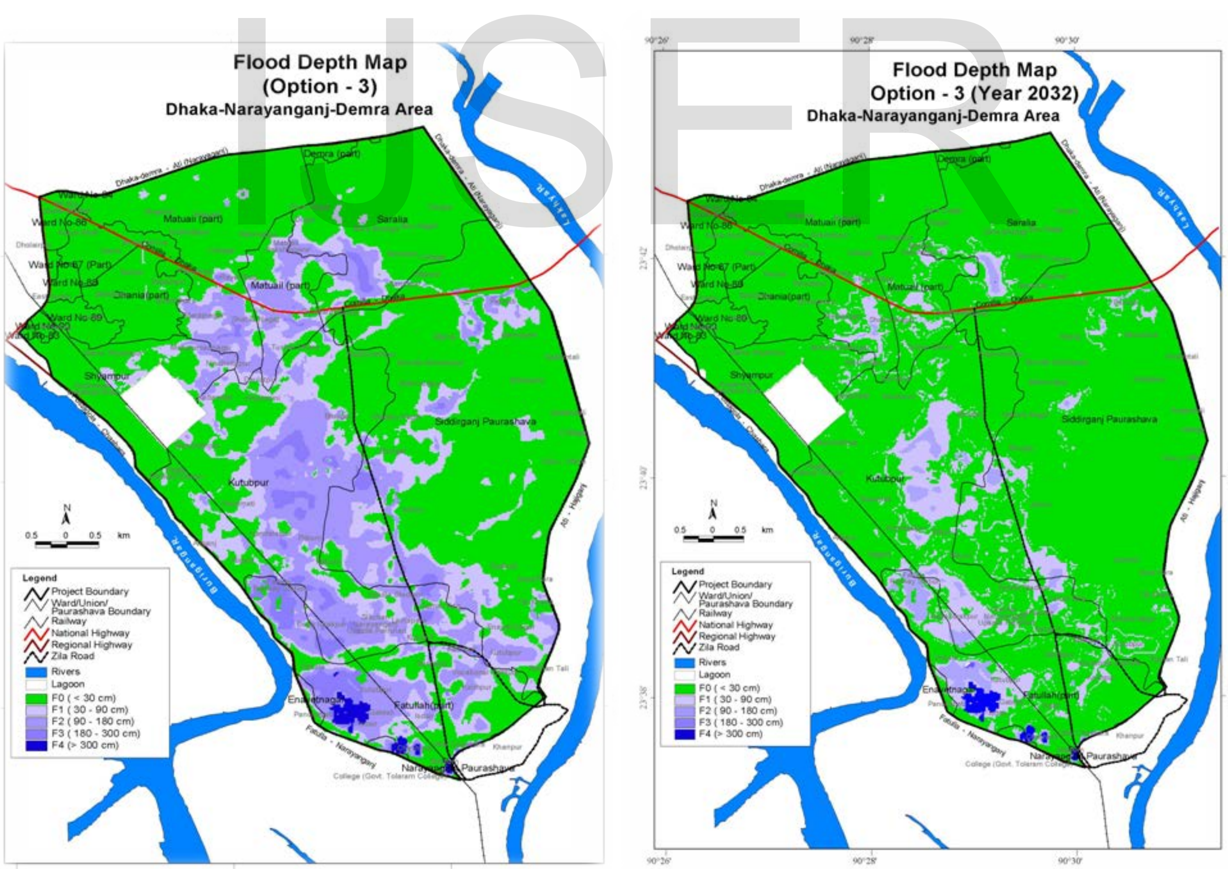

Figure 5: Impact of flood depth for option3 for recent years land use and 2032 (predicted)

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5. Examining Impact of pump failure under various pump operation scenarios

Option-3 with two pump stations (Shimrail-38.41 Cumec and Adamjinagar – 30.21 Cumec) and two pumping plants (Pagla – 2.82 Cumec and Fatulla – 3.25 Cumec) are considered for examining impact of pump failures. Failures of pumps/pump stations/pumping plants are taken into consideration on seasonal basis from June to October and two days period for the design rainfall (245 mm).

The results are shown in terms of area inundated of the each command area and total area inundated of the project for the seasonal and design duration considerations and also in terms of % (percent) of areas. Table 4 shows the interpreted results of flooding by area considering Option-3.

Table – 4
Flooding by Area, Water Level and Percent Area

P.S./PP	Command Area (Ha)	Seasonal Pump Failure (Jun-October)				Design Period Failure (2-days)			
		Generated R.O. (Ha-m)	Flooding Level (mPWD)	Flooding Area (Ha)	% flood-ing	Generated R.O. (Ha-m)	Flooding Level (mPWD)	Flood-ing Area (Ha)	% Flood-ing
Shimrail	2994	5226	5.70	2720	90	734	3.60	1350	45
Adamjinagar	2355	3879	6.20	2325	99	577	3.90	1470	62
Pagla	220	360	5.25	184	84	54	3.70	113	51
Fatulla	253	444	5.80	234	92	62	3.05	42	17
Total :	5822	9909	NA	5463	94	1427	NA	2975	51

6. Multi-criteria analysis for selecting the best option

Multi criteria analysis of options on selected criteria has been conducted and is given in Table – Multi-criteria analysis below for assessing the best option. Each option has been judged in terms of Technical Feasibility, Economic Viability, Environmental Sustainability and Social Acceptability using a number of indicators as per output derived from numerical models. Each of the broad feasibility criteria and the respective indicators has been given a weight and each of the indicators has been scored qualitatively in terms of a 1 to 10 scale, where 10 is the best possible score and 1 is the lowest. Weighted score has been calculated from the multiplication of score and respective weights, thus a subtotal score have been calculated after the normalization (representing out of 10). Finally, a normalized total score has been enumerated by weighted averaging the normalized scores and given in Table 5.

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It has been found that Option-3 is the most feasible option in terms of Technical Feasibility, Environmental Sustainability and Social Acceptability; although it's economic viability is less attractive from other options due to higher capital cost involvement.

TABLE-5

MULTI CRITERIA ANALYSIS

Criteria	Weight	Score (Out of 10)		
		Option-1	Option-2	Option-3
A. Technical Feasibility	0.30	7.66	8.14	9.63
B. Economic Viability	0.25	8.33	6.67	5.00
C. Environmental sustainability	0.25	6.67	7.31	7.12
D. Social Acceptability	0.20	5.53	7.45	9.03
Total Score (Weighted average of Normalized Score)		7.05	7.39	7.69

7. DESIGN DRAINAGE SYSTEM AFTER NUMERICAL SIMULATION AFTER OPTION SELECTION

Option 3 with two pump stations at Shimrail and Adamjinagar and two pumping plants at Fatulla and Pagla has been selected as the best option after multi-criteria analysis. Therefore design discharge and design section have been calculated only for Option- 3. Main flow path and generated conveying capacity of drainage system from off-take to pump station are shown in the for Option 3 at Figure 6.

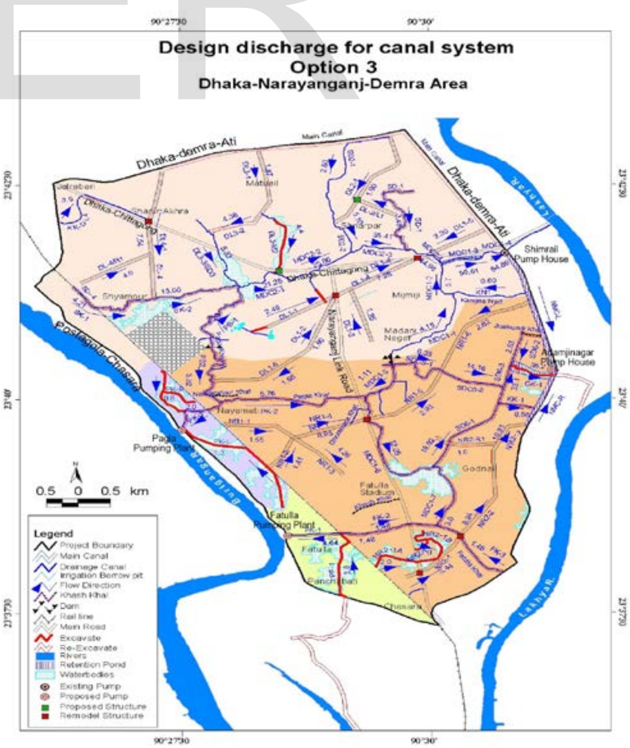

Figure 6. Design discharge output of drainage canal from numerical modeling analysis

8. Conclusion

Application of numerical modeling to mitigate water logging provides better understanding before applying it to the real world system. As the land pattern has changed for DND area so characterization of water-logging turns into complex interaction with prolonged flooding scenario. In this study, applied flow numerical simulation, combined with drainage theory and hydrography, a waterlogging and flooding numerical model is established, which can calculate the depth, area and ratio of water-logging. The option based drainage model results of DND area provide technological support for the water-logging forecasting, assessment and flood and waterlogging control plan. According to numerical model outputs the model shows that, installment of 4 pump stations at Shimrail (38.41 cumec discharge from drainage command area of 2994 ha), Adamjinagar (30.21 cumec, command area 2355 ha), Pagla (2.82 cumec, command area 220 ha) and Fatulla (3.25 cumec command area 253 ha) provide the best suitable option with the design rainfall (245 mm) for 2 day 5 year return period. The 1-D mathematical model also provided design discharge of the re-structured canal system for four command areas of the pump stations at every reach and design section with parameters of drainage system. Moreover, the results of the model are proved practical to determine flood depth by area and inundation maps for different options as well as impacts of pump failureness in any case. Thus using the numerical model helps lot to find a better choice to improve drainage condition for long troubled water logging problems at DND area for economically, environmentally and socially acceptable planning for future.

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Organizations Full Abbreviation

[1] Development Design Consultant; [2] Centre for Environmental and Geographic Information Services; [3] Japan International Cooperation Agency; [4] Public Works Datum in metre; [5] Institute of Water Modelling [6]Bangladesh Meteorological Department; [7] Rajdhani Unnayan Katripakka, Capital Development Authority of Bangladesh; [8] Master Plan Organization, now termed as Water Resources Planning Organization, Bangladesh.

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