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Delhi Floods - 2023

A Case Study

Hydrology (Urban) Directorate

Hydrological Studies Organization

Central Water Commission

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1. Executive Summary

During July, 2023 widespread heavy rainfall across the Yamuna River catchment led to significant runoff and an enormous discharge, causing a rapid rise in the river's water levels. This surge resulted in extensive landslides and flooding throughout the hills and plains of the Yamuna River basin. The intense rainfall, mainly driven by Western Disturbances and the southwest monsoon, occurred from 9th July to 13th July 2023, affecting various locations across Himachal Pradesh, Uttarakhand, Punjab, Delhi and Haryana within the Yamuna catchment area.

Present study focuses on the Submergence area estimation for different return period floods, embankment overtopping analysis, Identification of Drainage congestion and afflux of existing structures through a 2-D modeling study for the reach of river Yamuna from 21 km upstream of Wazirabad barrage to 10 km downstream of Okhla barrage.

The study reveals that July 2023 flood in Delhi was slightly less than a 1-in-50-year return period flood event. Simulations indicated no overtopping along the entire Delhi reach up to a 1-in-25-year flood, which has a flow of 6587 cumec. However, for a 1-in-50-year flood event i.e. 7648 cumec, the model predicts significant overtopping from Metcalf House to Nili Chhatri/Yamuna Bazar Ring Road on the right bank of the Yamuna.

The Old Railway Bridge (ORB) in Delhi, with a bottom girder level at 207.4 meters, faced a significant threat, as modeled simulations suggested this threshold could be exceeded when flows reached 5974 cumec. For a 1-in-100-year flood i.e. 8701 cumec, water levels are projected to rise to 209.35 meters, which may exceed this bridge's structural limit and could result in substantial damage or failure. Such an event would necessitate a comprehensive study to understand the impacts on the bridge and surrounding infrastructure.

The study shows a significant difference in water surface elevations between the existing terrain (i.e. all the bridges crossing the river are resting on embankment) and pier terrain (i.e. these embankments are replaced with piers) in the middle reach of the study area.

The results underline the need for proactive measures to enhance flood defenses, such as raising embankments and improving drainage systems, to prevent overtopping and reduce flood risks in vulnerable areas like Nili Chhatri/Yamuna Bazar Ring Road. Additionally, a

reevaluation of flood protection strategies is necessary to accommodate extreme flood scenarios, ensuring they meet design standards and reflect current ground conditions.

2. Introduction and Background

Yamuna River

The river Yamuna originates from Banderpunch glacier in Uttarakhand near Yamunotri and travel about 1376 km before meeting the river Ganga at Sangam (at Prayagraj). The river basin lies in the states of Uttarakhand, Himachal Pradesh, Haryana, Uttar Pradesh, Rajasthan and Delhi. Before its confluence with River Ganga at Sangam in Prayagraj district of Uttar Pradesh, important tributaries such as Tons, Giri, Hindon, Chambal, Sindh, Betwa and Ken join the river along its way. A line diagram of River Yamuna is shown in **Figure-1.**

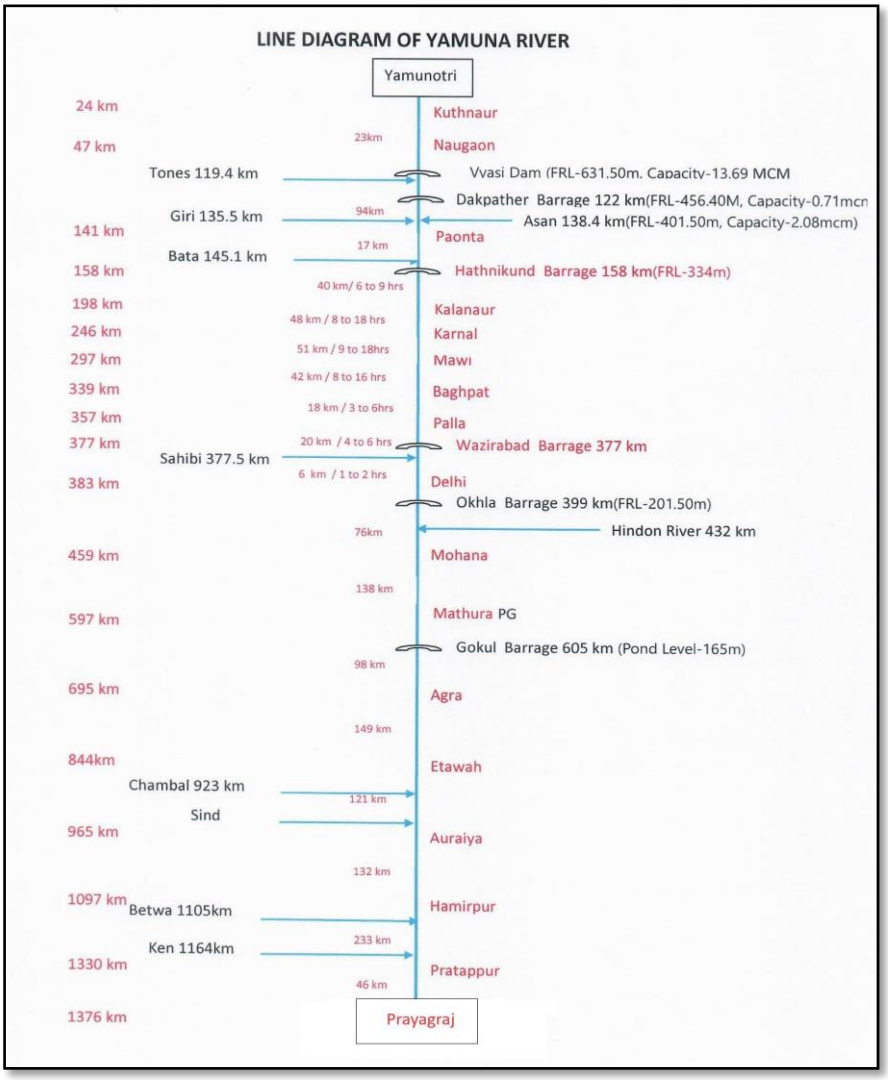


Figure 1: Line diagram of Yamuna River

Yamuna has six functional barrages and one proposed barrage. The functional barrages are Dakpathar Barrage, Hathnikund Barrage, Wazirabad Barrage, ITO Barrage, Okhla Barrage and Gokul (Mathura) Barrage. From Hathnikund Barrage, water is diverted to Eastern and Western Yamuna Canals. The river water takes about 2-2.5 days to travel from Hathnikund to Delhi.

River Yamuna flows on the eastern side of Delhi and acts as the only natural drain that takes storm water out of Delhi. On the western side, the major natural drainage is Najafgarh drain which accounts for around two thirds of the Delhi area. The natural drainage map of Delhi is given in **Figure-2**.

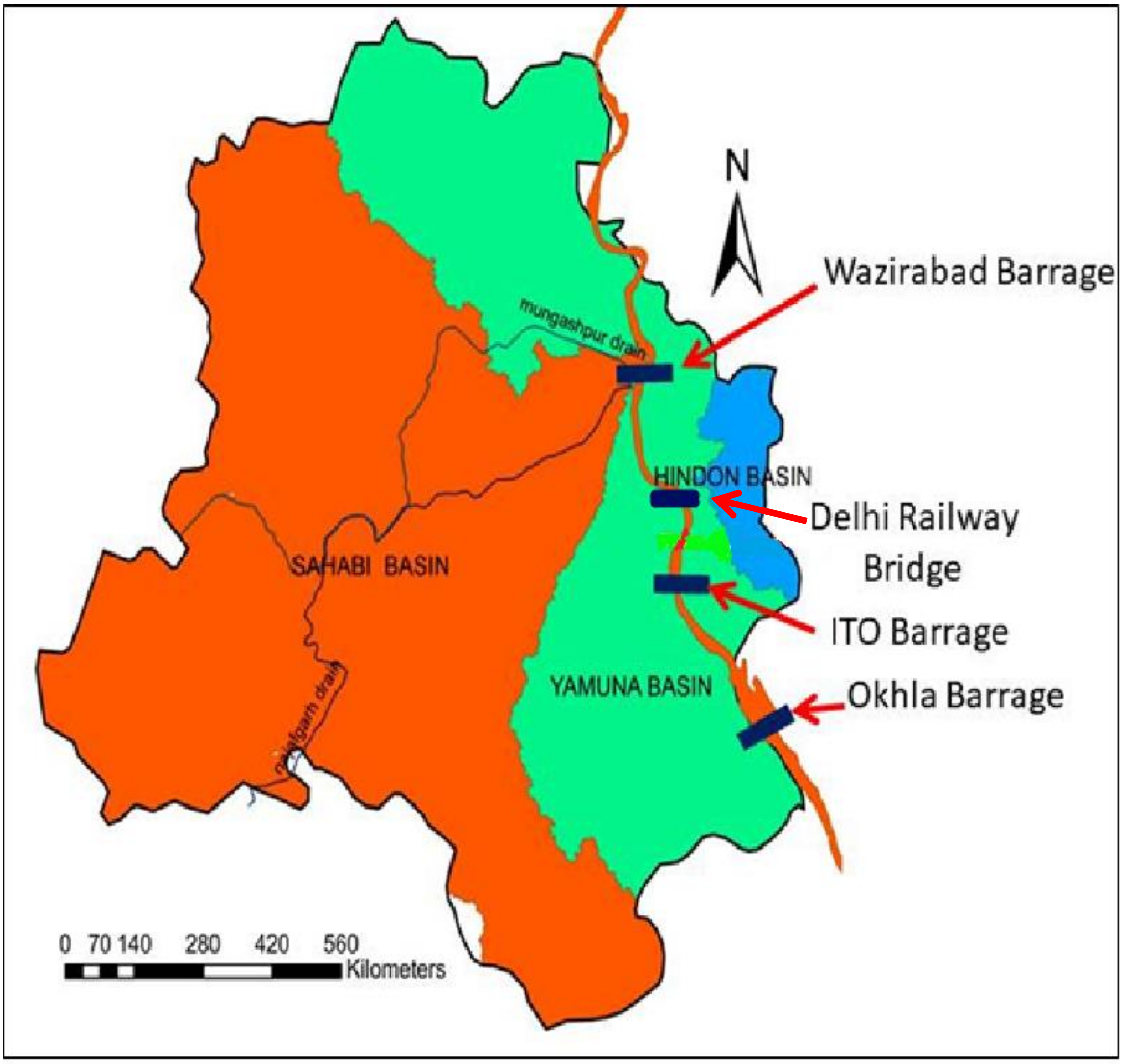


Figure 2: Natural drainage map of River Yamuna in Delhi

2.1. Flood events during 09-13 July-2023

Due to a combination of Western Disturbances and Southwest Monsoon, there was heavy rainfall in different places of Himachal Pradesh, Uttarakhand and Haryana during 09-13 July

2023, leading to extensive landslides and flooding in the hills and plains. The heavy rainfall in the catchment area of river Yamuna resulted in huge runoff in the river, due to which an earlier Highest Flood Level (HFL) of 207.49 m recorded at the CWC gauging site of old Delhi railway bridge on 6th September, 1978 got surpassed by a new HFL of 208.66 m observed on 13th July 2023.

The heavy rainfall led to increased flow at Hathnikund Barrage on 11th July, 2023 as a result Hathnikund Barrage released peak discharge of 3.59 Lakh cusecs (10165 cumec) at 11:00 hrs on 11th July, 2023. The same flow was continued for two hours and after that flow reduced gradually. The high discharge downstream of Hathnikund Barrage created flood situation in the river Yamuna. Due to this, the flow of Delhi Railway Bridge site increased continuously and crossed the previous HFL of 207.49m at 13:00 hrs on 12th July, 2023 and achieved the highest peak of water level of 208.66m at 18:00 hrs on 13th July, 2023. This new H.F.L. of 208.66m at DRB site resulted in overtopping of embankment of Yamuna River along with drainage congestion situation at several drains out falling in the river Yamuna at different locations.

2.2. Present Study

This flooding event necessitated a fresh look at the river's flood management in its reach from Hathnikund Barrage up to Okhla Barrage. In this regard, DoWR, RD&GR, Ministry of Jal Shakti constituted a committee dated 6th August 2023 for conducting a joint flood management study of river Yamuna for its reach between Hathnikund and Okhla barrage.

The committee was headed by Chairman, CWC along with the members from Haryana, Uttar Pradesh, NCT of Delhi and expert organizations to examine the meteorological aspects, return period of floods, Submergence area estimation, embankment overtopping analysis, Identification of Drainage congestion and its operating mechanism, afflux of existing structures, discharging capacity of barrages, functional requirement of ITO barrage etc. The committee directed the Hydrology Urban Directorate, Central Water Commission to analyze following flooding aspects of River Yamuna in the Delhi reach.

1. Submergence area estimation
    a. Submergence area estimation w.r.t. 2, 5, 10, 25, 50 and 100 year flood
    b. Embankment overtopping analysis

2. Identification of Drainage congestion and its operating mechanism
3. Afflux of existing structures

The present case study focuses on the above mentioned flooding aspects of River Yamuna. To achieve this, 2-D modeling study has been performed on HEC RAS software for the reach of river Yamuna from 21 km upstream of Wazirabad barrage to 10 km downstream of Okhla barrage.

3. Data collection -

A 2-D flood modeling study involves the simulation and analysis of flood scenarios in a two-dimensional spatial domain. The data used in present study typically includes a combination of topographical data, hydrological data, Land use Land cover data, Soil data and Drainage network of Delhi. High-resolution elevation data is crucial for accurately representing the terrain. DEMs provide information about the topography of the study area, including elevation variations, slopes and landform features. Further, Land Use Maps are crucial for understanding how different surfaces will interact with water during a flood event. Drainage network is a crucial component in 2-D flood modeling because it represents the interconnected system of channels, pipes and other conduits that govern the flow of water within a given area. Including a drainage network in 2-D flood modeling allows for a more accurate simulation of surface water movement and its interaction with the existing infrastructure. Historical flood data, including water levels and extent, is used for model calibration and validation. This helps to ensure that the simulated results accurately reflect real-world flood events. Soil data is a crucial input in 2-D flood modeling because the properties of the soil significantly influence how water is absorbed, retained and transmitted across the terrain. Including accurate soil data in the model helps simulate the interactions between rainfall, infiltration, and runoff more realistically. Data used in the present study are given in **Table-1** below**.**

Table 1: Data used in the study

Sl. No.	Type of data	Data used
1	Topographic data	30m ALOS DSM (Digital Surface Model) and 30m Copernicus DTM (Digital Terrain Model)
2	Land use Land cover data	Sentinel-2 : 10m Land Use/Land Cover

3	Gauge and Discharge data	Old Delhi Railway bridge site G&D data
4	Cross section details, Embankment levels and Drainage details	Provided by Irrigation & Flood control department, Govt. of NCT Delhi
5	Soil data	FAO Harmonized World Soil Data

Monsoon peak discharge data (June to September) from period 1970 to 2020 at Delhi Railway Bridge (DRB) HO site of central Water Commission has been considered in the study and the same is given in the **Table-2** below.

Table 2 : **Monsoon peak discharge data from period 1970 to 2020 at Delhi Railway Bridge HO site of CWC**

Year	Max Observed Peak Discharge (Cumec)	Year	Max Observed Peak Discharge (Cumec)
1970	1867	**1996**	2592.82
1971	2931.34	**1997**	5207.02
1972	2547.08	**1998**	3383.09
1973	3819.66	**1999**	1947.82
1974	3009.26	**2000**	3366.18
1975	8858.59	**2001**	3476.26
1976	9318.94	**2002**	2125.69
1977	4480.71	**2003**	1735.92
1979	1152.93	**2004**	716.21
1980	3013.84	**2005**	1302.2
1981	1925.28	**2006**	826.74
1982	1275	**2007**	1143.01
1983	4012.4	**2008**	2119.32
1984	1220.93	**2009**	1425.2
1985	1990	**2010**	3466.48
1986	1767.39	**2011**	2017.78
1987	148.35	**2012**	1219.06
1988	5642.19	**2013**	3239.04
1989	4336.62	**2014**	793.25
1990	2193.06	**2015**	1072.33
1991	507.31	**2016**	1189.38
1992	3103.4	**2017**	865.58
1993	1344.7	**2018**	2490.14
1994	2766.55	**2019**	2890
1995	7027.52	**2020**	829

Also the flood peak for July, 2023 at Delhi Railway Bridge site has been used in the study which is provided by YBO, CWC and the same is shown in **Figure-3** below-

GD Curve of Delhi Railway Bridge Site on River Yamuna

Zero of Gauge 197m

Water Level (m)	Discharge (Cumecs)	Water Level (m)	Discharge (Cumecs)
203.00	138.98	206.00	1575.34
203.10	153.44	206.10	1683.10
203.20	169.13	206.20	1796.93
203.30	186.13	206.30	1917.10
203.40	204.54	206.40	2043.90
203.50	224.44	206.50	2177.60
203.60	245.92	206.60	2318.51
203.70	269.10	206.70	2464.47
203.80	294.06	206.80	2615.33
203.90	320.92	206.90	2770.89
204.00	349.80	207.00	2933.88
204.10	380.81	207.10	3104.58
204.20	414.08	207.20	3283.24
204.30	449.73	207.30	3470.16
204.40	487.90	207.40	3665.62
204.50	528.74	207.50	3869.90
204.60	572.38	207.60	4083.32
204.70	618.98	207.70	4306.16
204.80	668.70	207.80	4538.75
204.90	721.71	207.90	4781.40
205.00	778.17	208.00	5034.44
205.10	838.26	208.10	5298.19
205.20	902.17	208.20	5573.00
205.30	970.09	208.30	5859.21
205.40	1042.21	208.40	6157.16
205.50	1118.75	208.50	6467.22
205.60	1199.91	208.60	6789.75
205.70	1285.91	208.70	7125.13
205.80	1377.00	208.80	7473.72
205.90	1473.39	208.90	7835.92
		209.00	8212.11

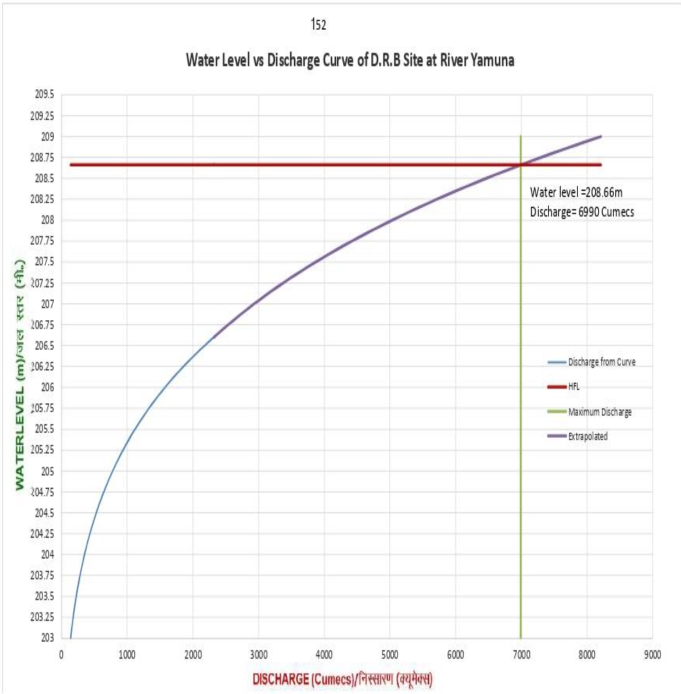


Figure 3: Flood peak for July, 2023 at Delhi Railway Bridge

4. 2D Hydrodynamic Modeling with HEC-RAS

4.1 Model Setup:

HEC-RAS software has been used the present study, which is an open-source software developed and maintained by the U.S. Army Corps of Engineers. The software solves hydraulic problems either by using the 2D Saint Venant's equations (with optional momentum additions for turbulence and Coriolis effects) or the 2D Diffusion Wave equations. In the present study, 2D Diffusion Wave equations has been used as it allows the software to run faster and have greater stability properties.

In this study, 2-D hydrodynamic model has been developed using HEC-RAS to simulate the flooding caused by the July 2023 rainfall in the Yamuna River basin. The 2-D modelling approach allows for a detailed representation of water movement across the floodplain, capturing complex interactions between the river channel and the river embankments including surrounding areas. The study area was carefully defined for Delhi reach of river Yamuna from the 21 km upstream of Wazirabad barrage to 10 km downstream of Okhla barrage to include the stretch of the river passing through Delhi and adjacent flood-prone areas, ensuring a comprehensive analysis of potential flood impacts.

Further, a model grid of 30m*30m has been utilised to accurately capture the detailed flow patterns of the rivers. This resolution was selected to account for the complex terrain and built environment, allowing the model to simulate flow dynamics around critical infrastructure such as bridges, culverts and other hydraulic structures.

4.2 Input DEM Data and its Modification

In the present study, 30m ALOS DSM (Digital Surface Model) and 30m Copernicus DTM (Digital Terrain Model) both has been used. For the main channel, DTM and for the floodplain, DSM has been used. Use of DTM for the main channel ensures that there is no obstruction in the natural flow of the river whereas use of DSM for the floodplain ensures that surface features like bridges, embankments, bunds etc. are truly represented in the model. Finally, a composite DEM by merging both DTM & DSM is prepared for feeding as terrain in the HEC-RAS 2-D model as shown in **Figure-4.**

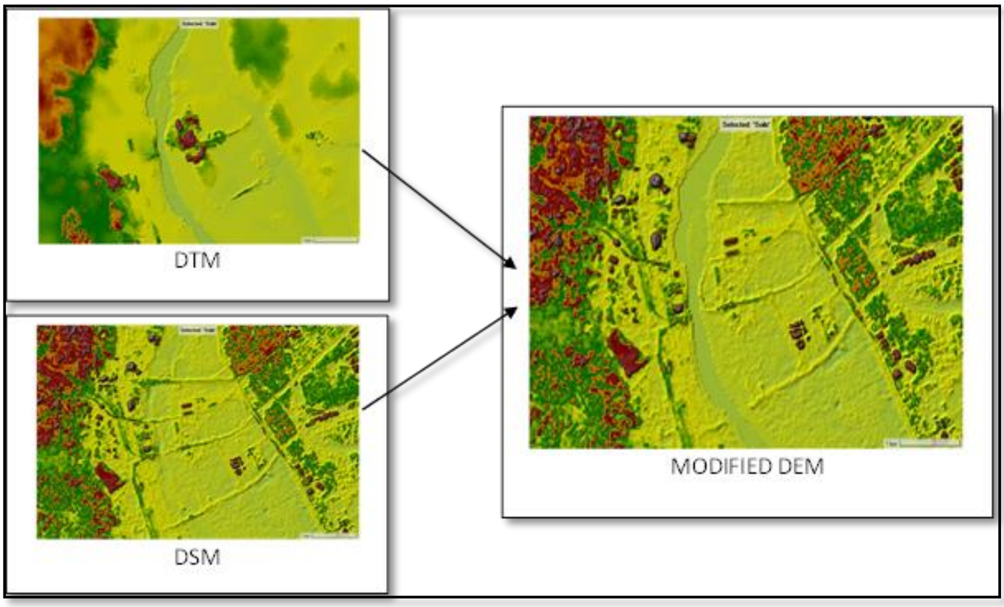


Figure 4 : Composite DEM from DSM and DTM

4.3 DEM modification for putting structures and correcting cross sections

The Delhi reach of River Yamuna has three Barrages and around 10 main bridges. The DEM used in the model poorly represented these structures. To resolve this issue the technique of DEM modification has been used by means of which original DEMs were modified and the structures like barrages and bridge piers were inducted in the terrain. The **Figure-5** below shows the pre and post modification sections of Okhla Barrage. Likewise, all other structures were modified and inducted in the terrain.

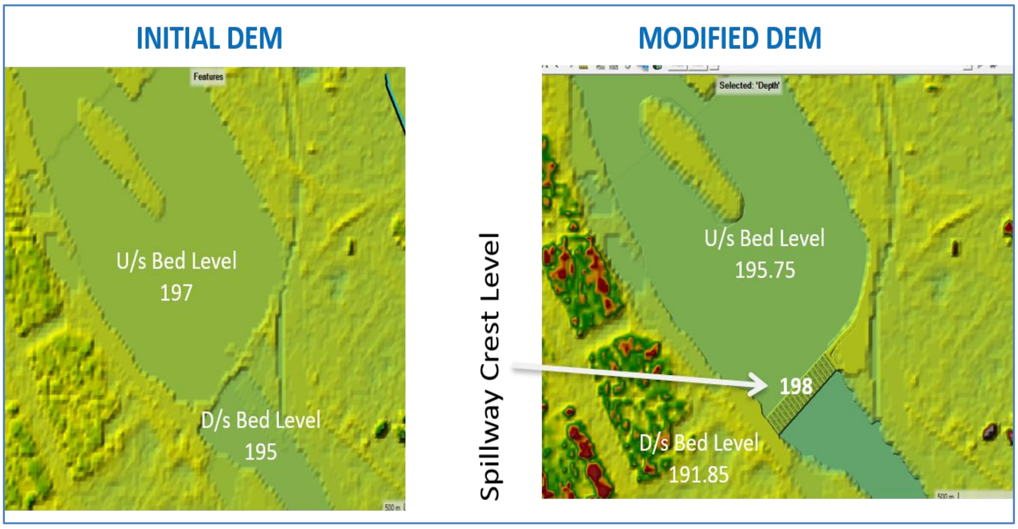


Figure 5: Okhla Barrage: DEM Modification

Similarly, cross-section at Delhi Railway Bridge (DRB) site in the original DEM was not correctly represented. It was corrected using the observed cross-section and performing necessary modifications in the DEM. The **Figure-6** below shows pre and post modification cross-section at DRB.

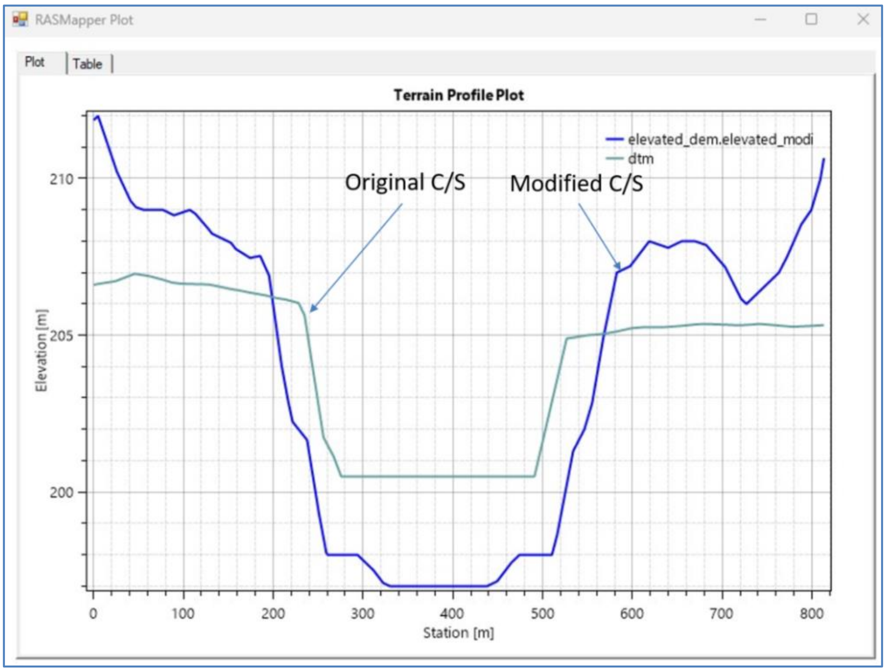


Figure 6 : Pre and Post modification cross-section at DRB

4.4 Boundary Condition

Boundary conditions are critically important in 2D flood modeling as they define the external influences and constraints on the simulated water flow within the computational domain. These conditions play a key role in accurately representing the interaction between the modeled area and its surroundings. Accurate representation of boundary conditions ensures that the model closely reflects real-world scenarios. Properly defined boundaries help in simulating the actual behavior of water flow, accounting for external influences that can affect the study area.

For the present study, apart from the upstream and downstream boundary conditions, few side boundary conditions have been applied on the model to restrict the flow within the 2D flow area of the model. Detail set of boundary conditions used in the model is shown in the **Figure-7** below. A flow hydrograph at the Mawi HO site has been given as the upstream boundary condition in the model, whereas, for downstream boundary condition and for all side boundary condition, a normal depth of 0.01 has been adopted.

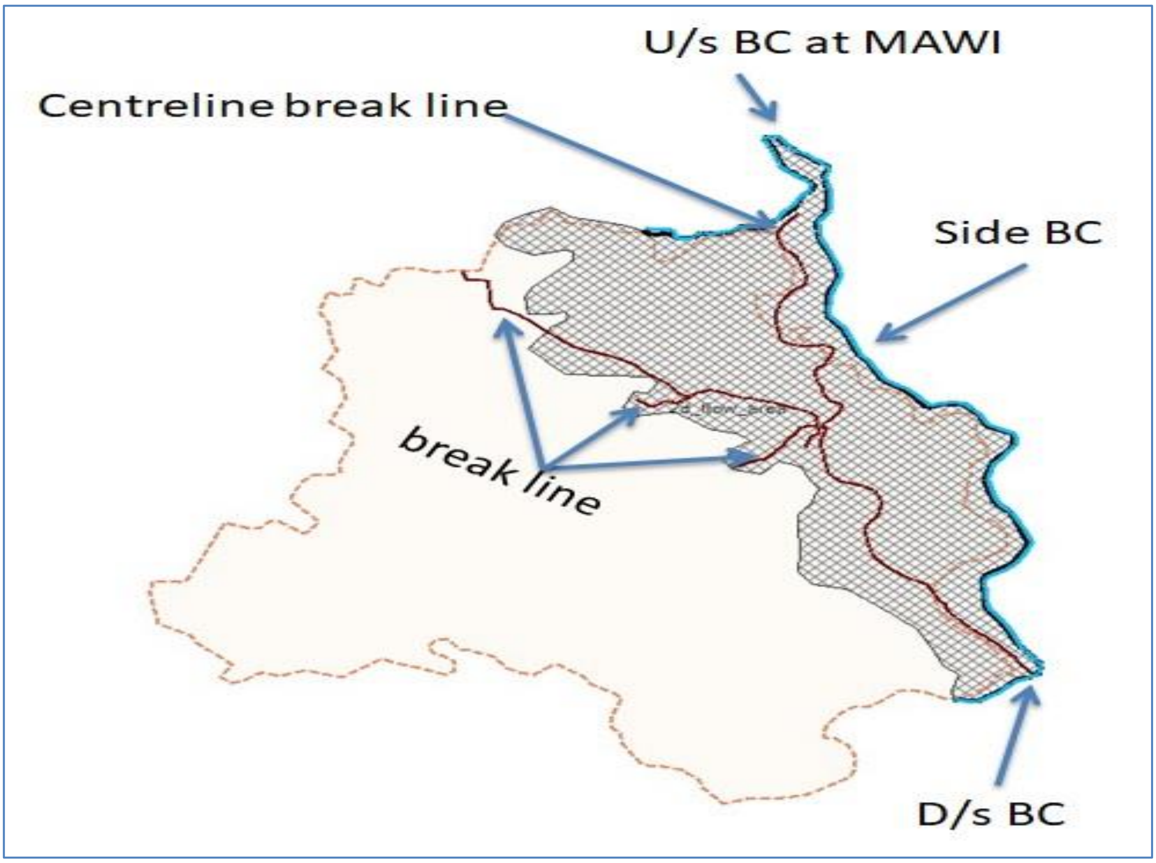


Figure 7: Detail set of boundary conditions used in the model

4.5 Model Calibration

a. Calibration Event

Flow hydrograph at Mawi HO site from 8 July 2010 to 31st Oct 2010 as shown in the **Figure-8** has been given as upstream boundary condition in the model. The model is calibrated using 2010 flood event as it has three back-to-back peaks. The calibration is done at old Delhi Railway Bridge (DRB), the only HO site of CWC in Delhi region.

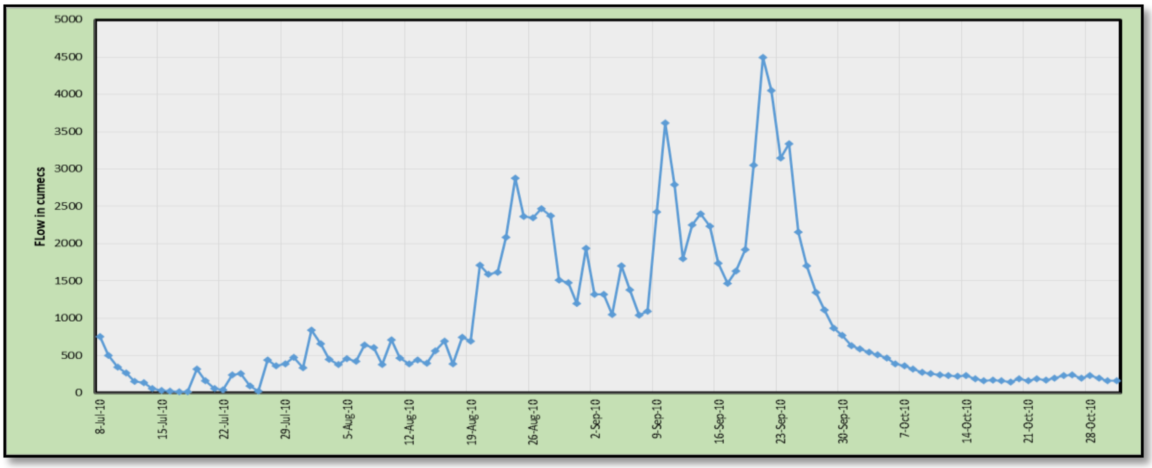
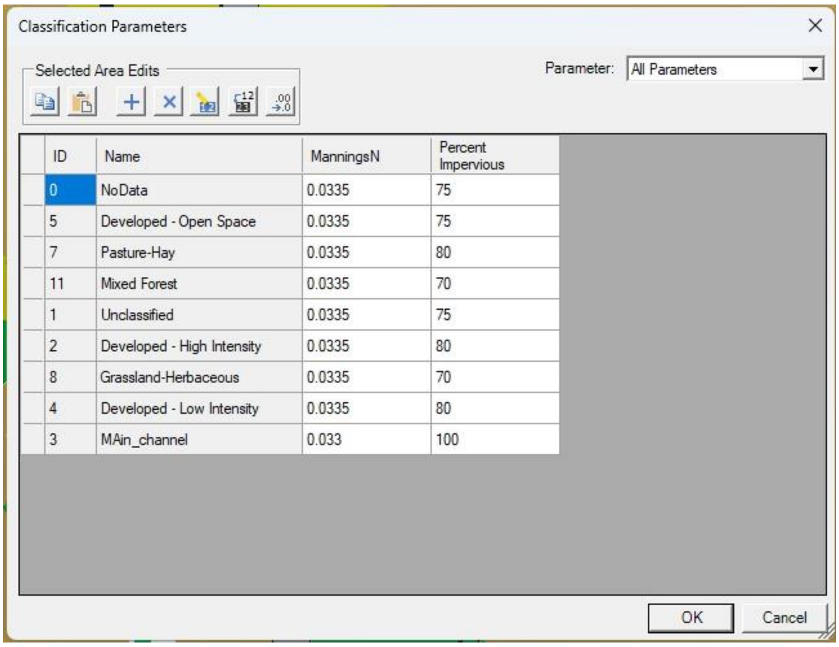


Figure 8: Flow hydrograph at Mawi HO site from 8 July 2010 to 31st Oct 2010

The calibration is done using other inputs like Sentinel-2 Land Use Land Cover data of 2022, making classification polygon for the main channel and Harmonized World Soil data from FAO.

b. Calibration Results

The model is calibrated on 2010 flood event at Delhi Railway Bridge (DRB) getting the final R^2 value of **0.94** and correlation coefficient of **0.97**. List of calibrated parameters is shown in the **Figure-9** below.



Classification Parameters

Selected Area Edits

Parameter: All Parameters

ID	Name	ManningsN	Percent Impervious
0	NoData	0.0335	75
5	Developed - Open Space	0.0335	75
7	Pasture-Hay	0.0335	80
11	Mixed Forest	0.0335	70
1	Unclassified	0.0335	75
2	Developed - High Intensity	0.0335	80
8	Grassland-Herbaceous	0.0335	70
4	Developed - Low Intensity	0.0335	80
3	MAin_channel	0.033	100

OK Cancel

Figure 9: List of calibrated parameters

The value of Manning's N for the main channel is calibrated as 0.033, whereas for the flood plain Manning's N value is taken as per the Land Use Land Cover data. For Barrages the value is taken as 0.018. The graph between observed and simulated flow is given in **Figure-10**. Looking at the graph, it could be inference that a reasonably sound level of calibration has been achieved.

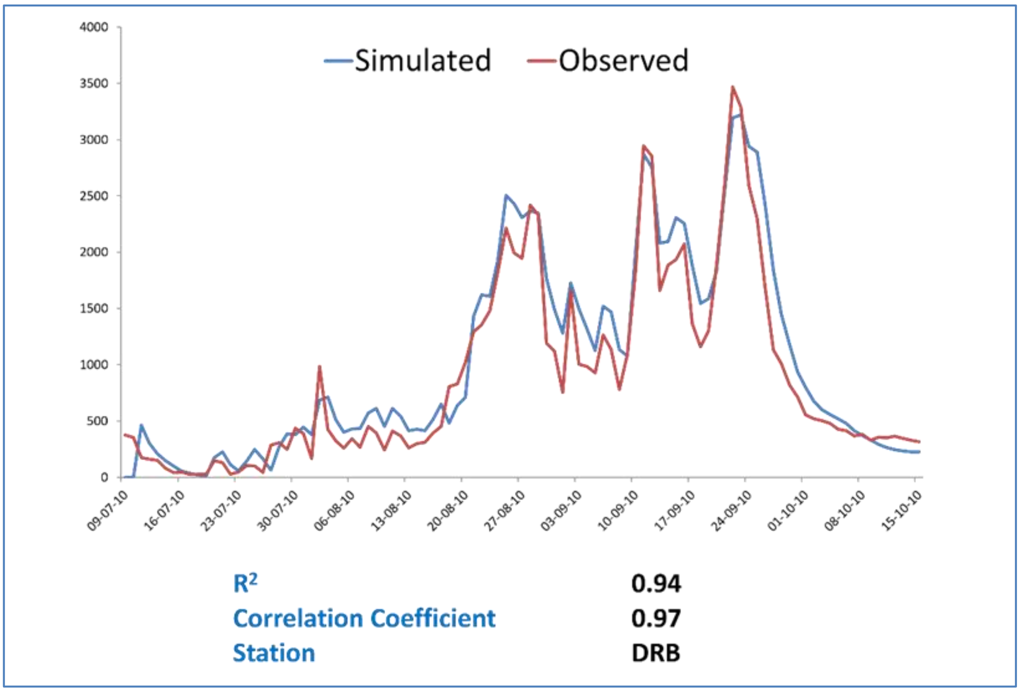


Figure-10 : Graph between observed and simulated flow at DRB

5. Model Simulation and Results

5.1 2-D Modeling and Submergence Area estimation

I. Submergence area estimation w.r.t. 2, 5, 10, 25, 50 and 100 year flood

Flood frequency analysis has been performed on the monsoon peak discharge data (June to September) from period 1970 to 2020 at Delhi Railway Bridge (DRB) HO site and accordingly, the estimated flood values for 2 year, 5 year, 10 year, 25 year, 50 year and 100 year return period at Delhi Railway Bridge HO site were computed which are shown in **Table-3** below-

Table-3 : **Estimated flood value at Delhi Railway Bridge HO site**

S No	Return Period	Flood value at Delhi Railway Bridge HO site (cumec)
1	2	2316
2	5	4025
3	10	5157
4	25	6587
5	50	7648
6	100	8701

In the 2D hydrodynamic model simulation, these flood values of different return periods (i.e. 2, 5, 10, 25, 50, 100 years and also 2023 flood) were passed through DRB to get the corresponding water level at different locations and flood submergence areas over the Delhi reach of River Yamuna. The model incorporated the observed cross-section data, open drain data, Bunds and Embankment data as received from the Delhi government.

a. 2-Year Return Period Simulation

For the 2-year return period flood of 2316 m^3/s, total inundated area is found to be around 26.42 Km^2, and flood water mainly confined to Main channel of the river. The simulated water level at Delhi Railway Bridge is about 204.2m. Details of which are shown in **Table-4** & simulated 2 year flood Inundation map is shown in **Figure-11**.

Table 4: 2-Year Return Period Flood Simulation

Return Period	2 Year
Inundated Area (Km^2)	26.42

Net Inundated Area (Km^2)	0.00
DRB Discharge (m^3/s)	2316
DRB Water Level (m)	204.2

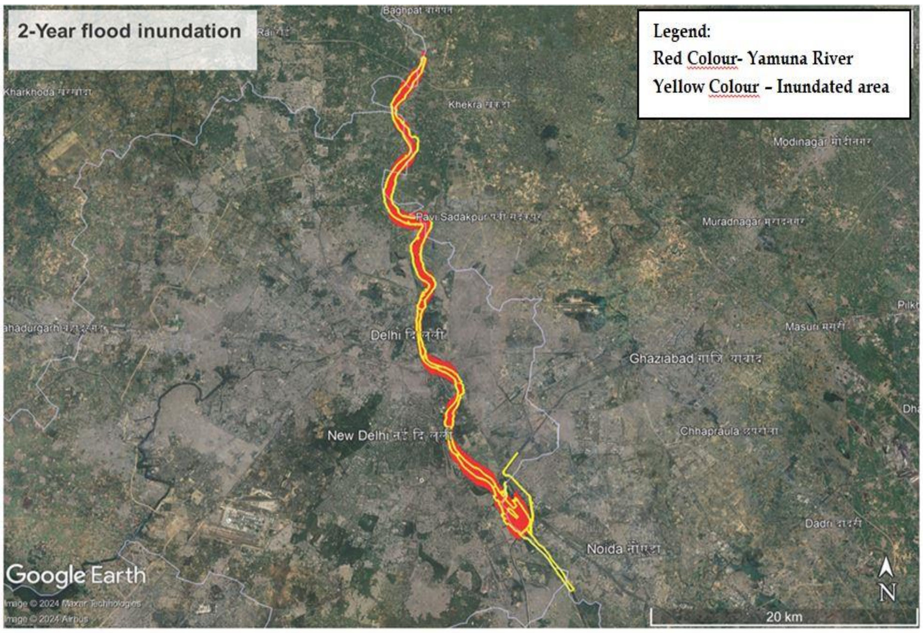


Figure 11: Simulated 2 Year Flood Inundation Map

b. 5-Year Return Period Simulation

For the 5-year return period flood of 4025 m^3/s, total inundated area is found to be around 30.82 km^2, whereas the net inundated area is about 0.4 km^2. The simulated water level at Delhi Railway Bridge is about 205.99m. Details of which are shown in **Table-5** & simulated 5 year flood Inundation map is shown in **Figure-12**.

Table 5: 5-Year Return Period Flood Simulation

Return Period	5 Year
Inundated Area (Km^2)	30.82
Net Inundated Area (Km^2)	0.4
DRB Discharge (m^3/s)	4025
DRB Water Level (m)	205.99

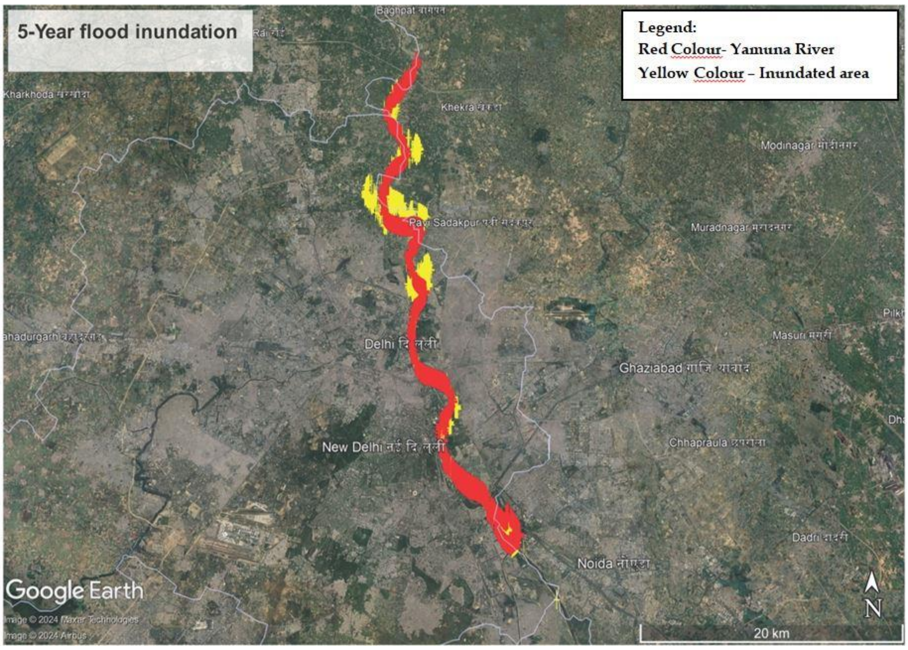


Figure 12: Simulated 5 Year Flood Inundation Map

c. 10-Year Return Period Simulation

For the 10-year return period flood of 5157 m^3/s, total inundated area is found to be around 47.11 km^2, whereas the net inundated area is about 16.7 km^2. The simulated water level at Delhi Railway Bridge is about 206.9m. Details of which are shown in **Table-6** & simulated 10 year flood inundation map is shown in **Figure-13**.

Table 6: 10-Year Return Period Flood Simulation

Return Period	10 Year
Inundated Area (Km^2)	47.11
Net Inundated Area (Km^2)	16.7
DRB Discharge (m^3/s)	5157
DRB Water Level (m)	206.9

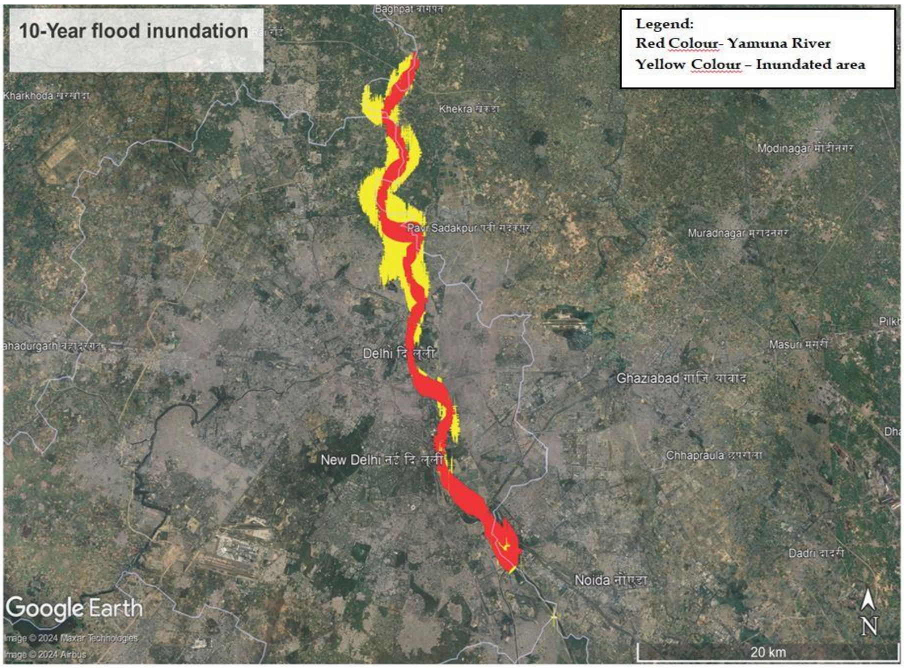


Figure 13: Simulated 10 Year Flood Inundation Map

d. 25-Year Return Period Simulation

For the 25-year return period flood of 6587 m^3/s, total inundated area is found to be around 63.51 km^2, whereas the net inundated area is about 33.1 km^2. The simulated water level at Delhi Railway Bridge is about 207.94m. Details of which are shown in **Table-7** & simulated 25 year flood Inundation is shown in **Figure-14**.

Table 7: 25-Year Return Period Simulation

Return Period	25 Year
Inundated Area (Km^2)	63.51
Net Inundated Area (Km^2)	33.1
DRB Discharge (m^3/s)	6587
DRB Water Level (m)	207.94

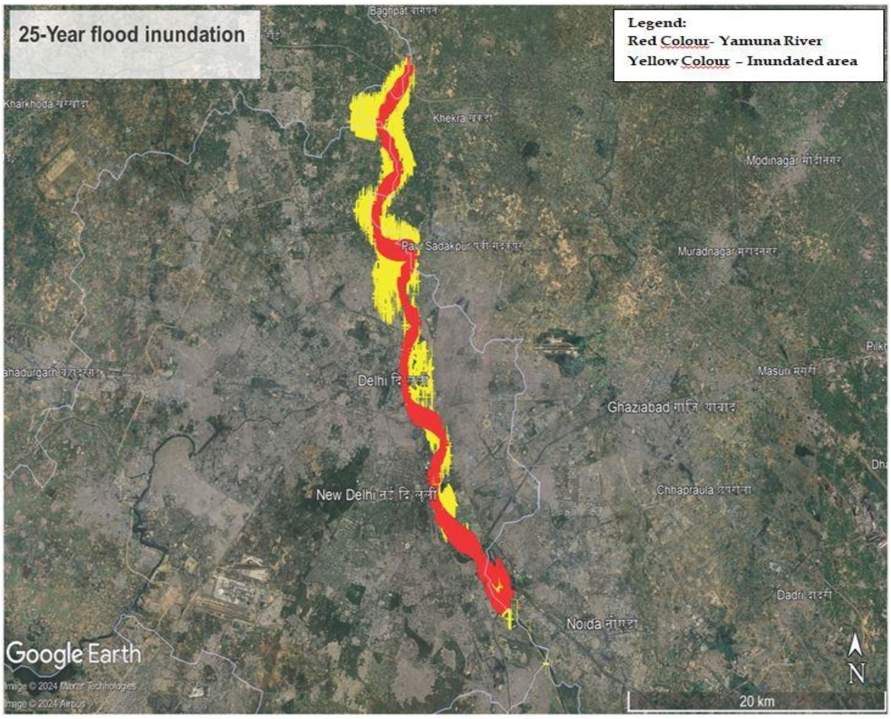


Figure 14: Simulated 25 Year Flood Inundation Map

e. 50-Year Return Period Simulation

For the 50-year return period flood of 7648 m^3/s, total inundated area is found to be around 77.76 km^2, whereas the net inundated area is about 47.3 km^2. The simulated water level at Delhi Railway Bridge is about 208.75m. Details of which are shown in **Table-8** & simulated 50 year flood Inundation is shown in **Figure-15**.

Table 8: 50-Year Return Period Simulation

Return Period	50 Year
Inundated Area (Km^2)	77.76
Net Inundated Area (Km^2)	47.3
DRB Discharge (m^3/s)	7648
DRB Water Level (m)	208.75

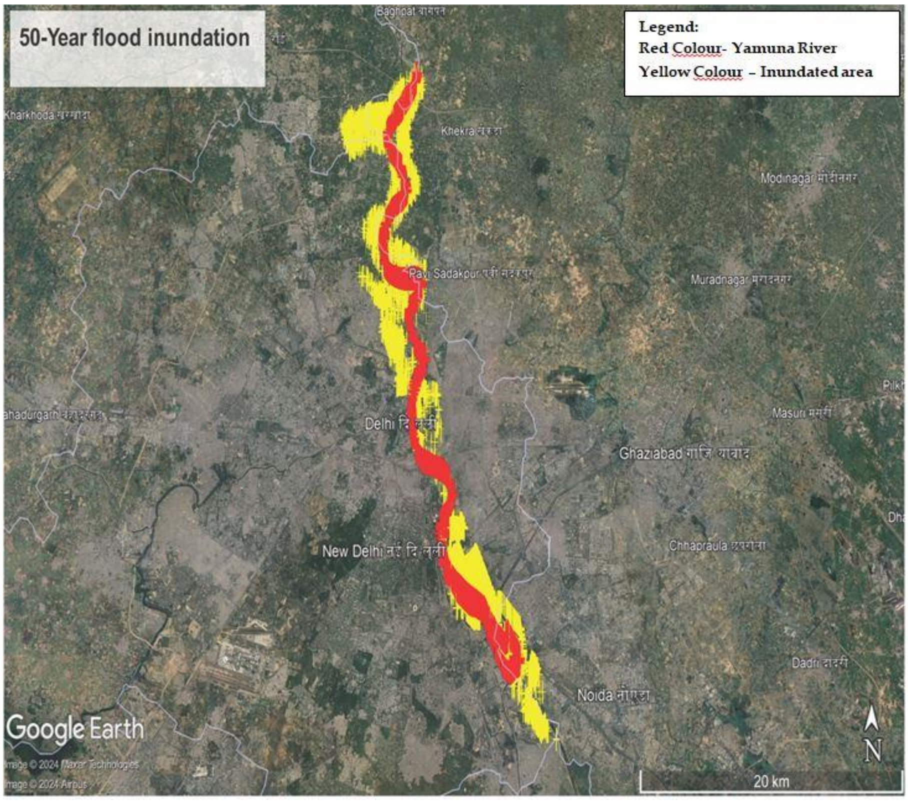


Figure 15: Simulated 50 Year Flood Inundation Map

f. 100-Year Return Period Simulation

For the 100-year return period flood of 8701 m^3/s, total inundated area is found to be around 85.25 km^2, whereas the net inundated area is about 54.8 km^2. The simulated water level at Delhi Railway Bridge is about 209.35m. Details of which are shown in **Table-9** & simulated 100 year flood Inundation is shown in **Figure-16**.

Table 9: 100-Year Return Period Simulation

Return Period	100 Year
Inundated Area (Km^2)	85.25
Net Inundated Area (Km^2)	54.8
DRB Discharge (m^3/s)	8701
DRB Water Level (m)	209.35

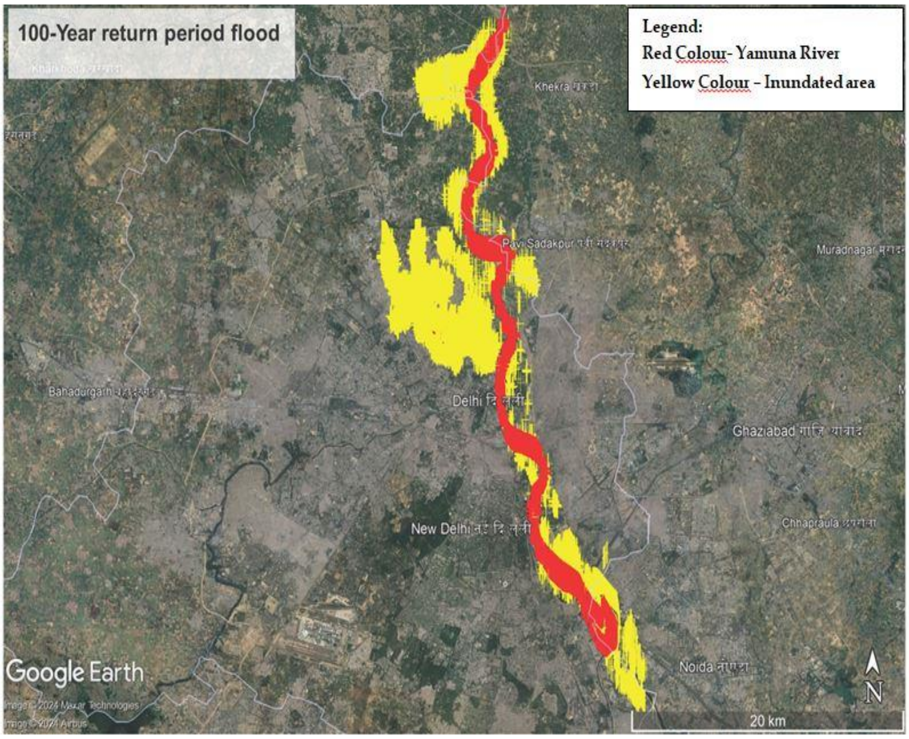


Figure 16: Simulated 100 Year Flood Inundation Map

g. 2023 Flood Simulation

For the recent 2023 flood, the recorded flood value is about 6999 m^3/s. The total simulated inundated area is found to be around 74.525 km^2, whereas the net inundated area is about 44.1 km^2. The water level simulated at Delhi Railway Bridge was 208.60m. Details of which are shown in **Table-10** & simulated 2023 flood Inundation is shown in **Figure-17**.

Table 10: 2023-Year Return Period Simulation

Return Period	2023 Flood
Inundated Area (Km^2)	74.525
Net Inundated Area (Km^2)	44.1
DRB Discharge (m^3/s)	6999
DRB Water Level (m)	208.6

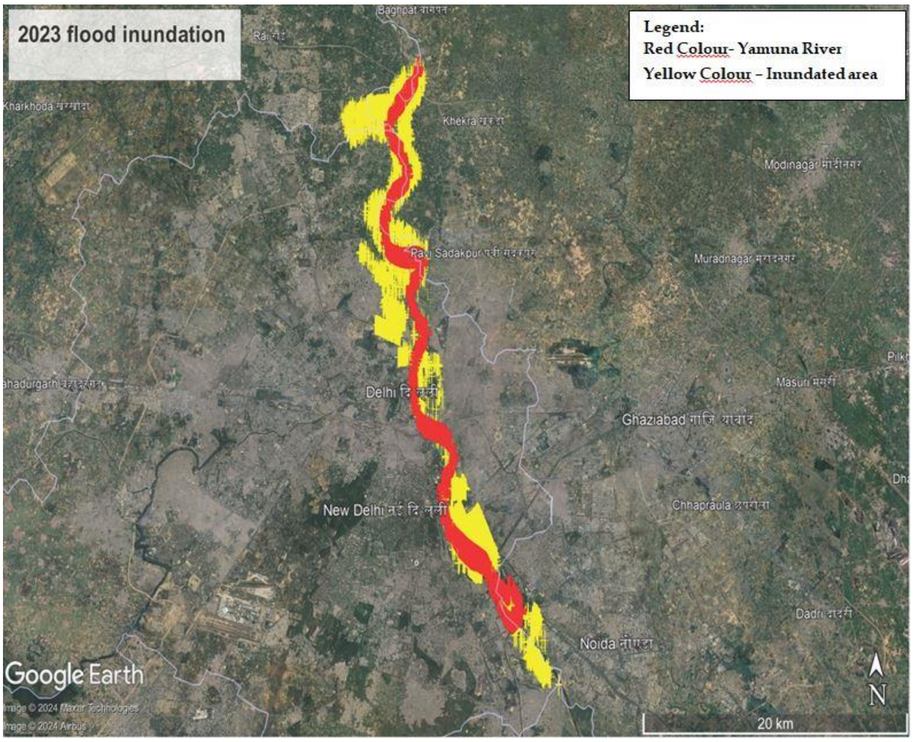


Figure 17: Simulated 2023 Flood Inundation Map

Results

The results of the model simulation are tabulated in the **Table-11** below. And the variation of submergence area and water level at DRB site with respect to different return period are shown in **Figure-18** and **Figure-19** respectively.

Table 11 : Simulation Results of Submergence Area over Delhi reach of River Yamuna

Return Period (Year)	DRB Discharge (m^3/s)	DRB Water Level (m)	Submergence Area (Km^2)	Net Submergence Area (Km^2)
2	2316	204.2	26.42	0
5	4025	205.99	30.82	0.4
10	5157	206.9	47.11	16.7
25	6587	207.94	63.51	33.1
2023 Flood	6999	208.6	74.525	44.1
50	7648	208.75	77.76	47.3
100	8701	209.35	85.25	54.8

Net Submergence area = Submergence area- Main channel area ie. 30.46 Km^2 (with in banks)

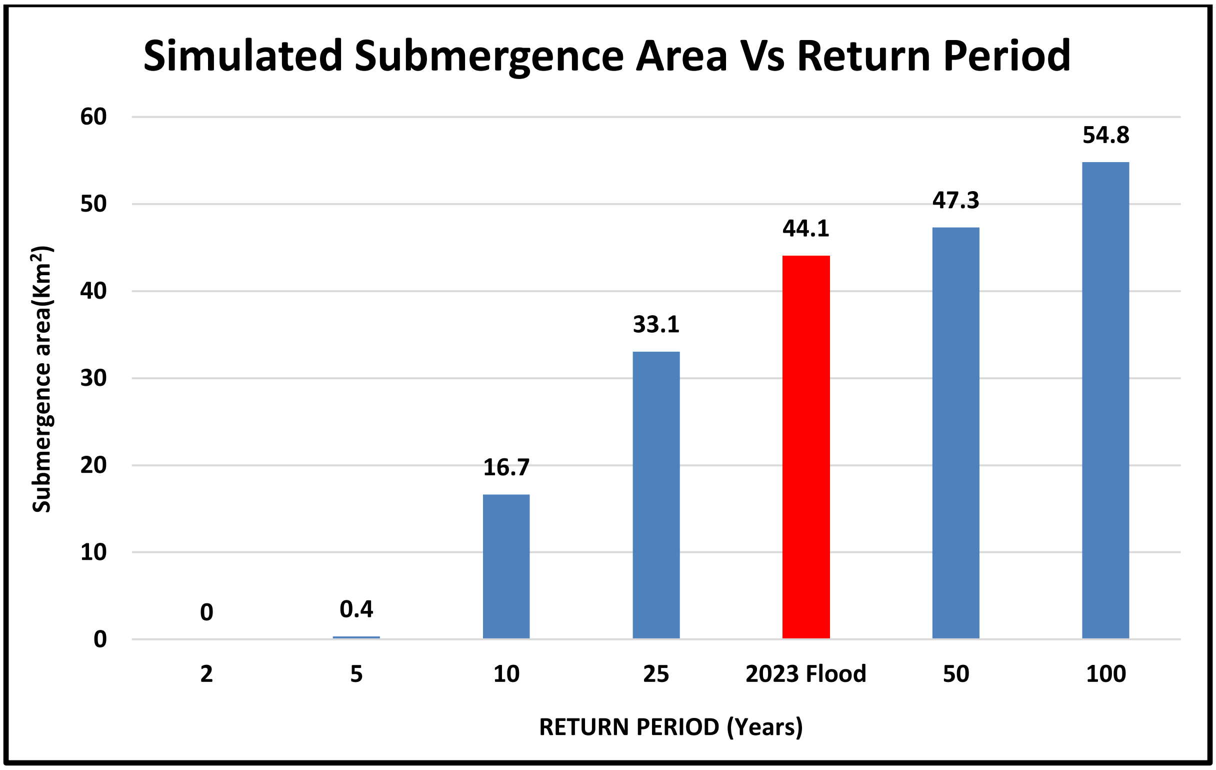


Figure 18: Submergence Area Vs Return Period

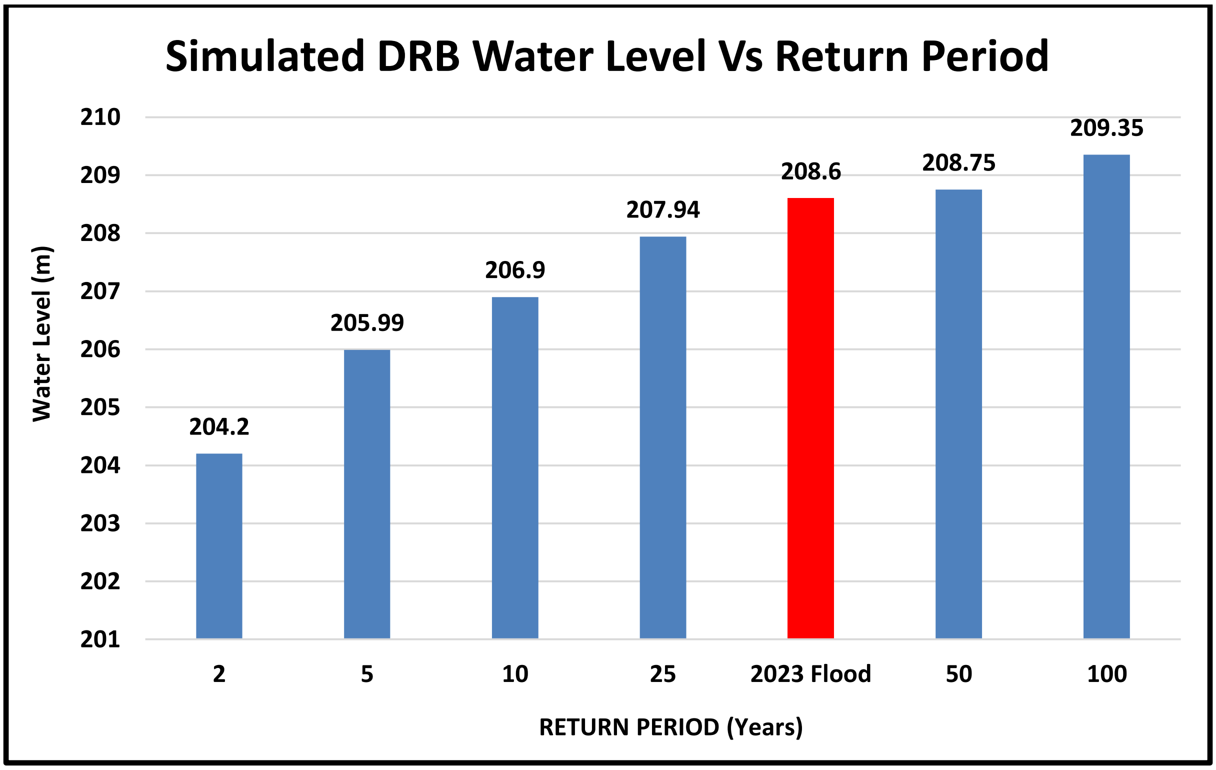


Figure 19: Water Level vs Return Period

Further, **Table-12** and **Figure-20** below shows the Maximum longitudinal Water Surface Elevations starting from 21 km u/s of Wazirabad Barrage. The water surface elevations is for entire 48 km reach at 1-Km interval for 2, 5, 10, 25, 50 & 100 Year Return period Floods.

Table 12: Max longitudinal Water Surface Elevations

Station (m)	WSE 2-year (m)	WSE 5-year (m)	WSE 10-year (m)	WSE 25-year (m)	WSE 50-year (m)	WSE 100-year (m)	WSE-100-year With elevated bund levels at Nili chhatri
0	210.767	212.289	213.092	213.822	214.389	214.52	214.864
1000	210.331	211.852	212.685	213.435	214.009	214.4	214.493
2000	210.097	211.637	212.476	213.219	213.78	214.2	214.256
3000	209.983	211.509	212.339	213.069	213.622	213.95	214.091
4000	209.72	211.27	212.105	212.836	213.391	213.6	213.866
5000	209.425	210.962	211.793	212.528	213.089	213.3	213.575
6000	209.206	210.731	211.556	212.279	212.829	213.3	213.31
7000	209.05	210.562	211.378	212.083	212.618	213.03	213.089
8000	208.947	210.45	211.259	211.953	212.481	212.88	212.947
9000	208.813	210.307	211.112	211.798	212.322	212.73	212.79
10000	208.656	210.145	210.948	211.633	212.16	212.57	212.636
11000	208.357	209.874	210.696	211.416	211.967	212.43	212.466
12000	208.064	209.603	210.45	211.219	211.81	212.43	212.338
13000	207.92	209.458	210.315	211.107	211.726	212.43	212.273
14000	207.756	209.326	210.196	211.003	211.643	212.1	212.205
15000	207.555	209.148	210.029	210.852	211.52	212.05	212.103
16000	207.379	209.004	209.898	210.741	211.432	211.9	212.03
17000	207.238	208.877	209.78	210.641	211.346	211.85	211.95
18000	207.095	208.74	209.655	210.534	211.251	211.74	211.86
19000	206.896	208.568	209.507	210.415	211.15	211.6	211.77
20000	206.492	208.259	209.244	210.198	210.964	211.46	211.6
21000	206.053	207.903	208.921	209.907	210.693	211.3	211.34
22000	205.813	207.71	208.741	209.733	210.516	211.05	211.16
23000	205.547	207.428	208.454	209.456	210.25	210.79	210.91
24000	205.089	206.963	207.984	208.981	209.78	210.32	210.41
25000	204.764	206.589	207.594	208.576	209.384	210	210.1
26000	204.486	206.315	207.32	208.3	209.105	209.6	209.79
27000	204.196	205.998	206.986	207.954	208.752	209.55	209.68
28000	203.98	205.732	206.693	207.643	208.427	209.05	209.1
29000	203.863	205.589	206.537	207.475	208.252	208.89	208.915
30000	203.525	205.267	206.221	207.161	207.937	208.48	208.59
31000	203.2	204.896	205.83	206.773	207.574	208.25	208.25
32000	202.954	204.605	205.52	206.454	207.26	207.8	207.95
33000	202.855	204.501	205.411	206.341	207.145	207.7	207.84
34000	202.557	204.134	205.012	205.91	206.689	207.3	207.36
35000	202.104	203.557	204.38	205.227	205.966	206.5	206.609
36000	201.44	202.784	203.57	204.386	205.102	205.46	205.73
37000	201.041	202.309	203.073	203.868	204.567	205	205.18
38000	200.889	202.111	202.861	203.643	204.333	204.84	204.93

39000	200.661	201.801	202.524	203.284	203.955	204.5	204.54
40000	199.988	200.84	201.503	202.222	202.862	203.35	203.42
41000	199.664	200.323	200.971	201.692	202.339	202.8	202.9
42000	199.51	200.049	200.697	201.428	202.085	202.5	202.65
43000	199.473	199.975	200.62	201.353	202.01	202.4	202.57
44000	197.943	199.46	200.261	201.065	201.751	202.2	202.33
45000	197.728	199.213	199.996	200.782	201.452	201.87	202.02
46000	197.207	198.64	199.39	200.141	200.776	201.229	201.32
47000	196.481	197.753	198.427	199.102	199.682	200.102	200.19
48000	195.597	196.756	197.364	197.972	198.492	198.871	198.94

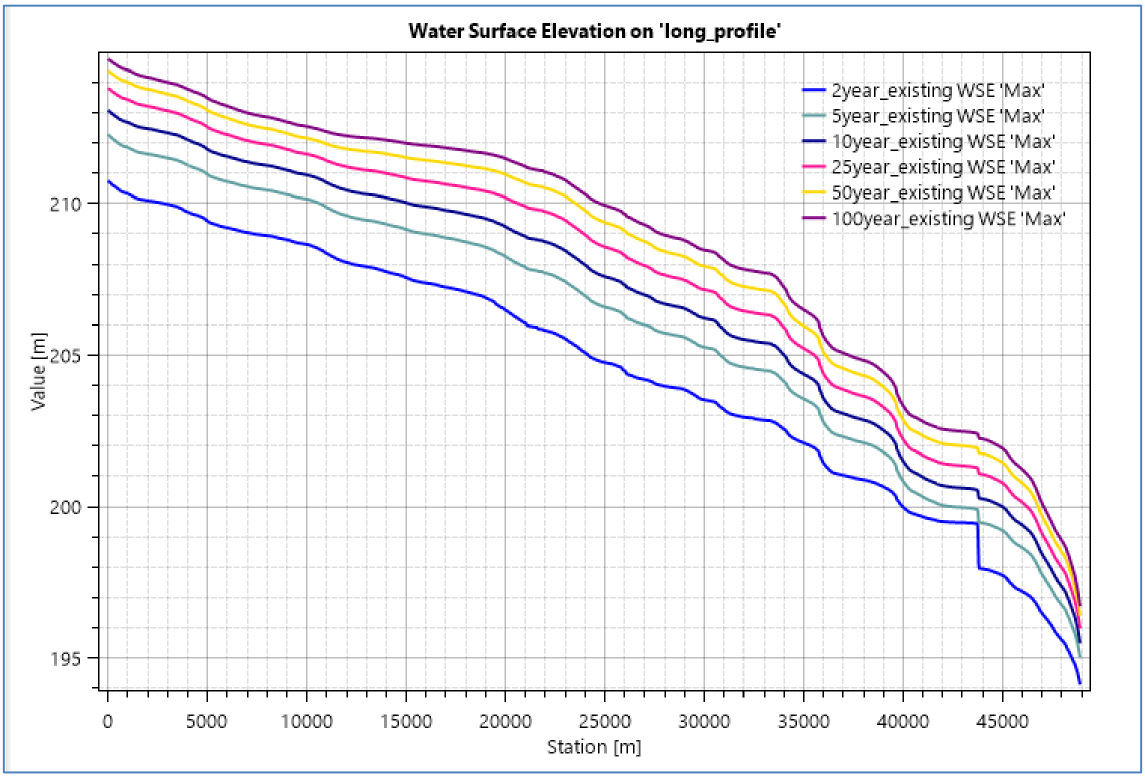


Figure 20: **Longitudinal WSE : 2, 5, 10, 25, 50 & 100 Year Return period Flood**

II. Embankment overtopping analysis

14 embankment locations were identified by preliminary model runs as potential overtopping zones. These locations were further sent to respective state governments for ground-verification. The report on ground-verification submitted by the state government shows that none of the identified locations by the model got overtopped during the 2023 floods.

The model was further corrected by not only incorporating the actual embankment levels provided at these 14 locations but also by incorporating the revised embankment levels provided by the state government for all other locations along the reach. Subsequent runs on the revised model were carried out for different return period floods, the result of which is shown in **Table-13** below.

Table 13: Embankment opertopping analysis

<table>
<tr><th>Return period</th><th>Passing Discharge at DRB (cumec)</th><th>Simulated WL at DRB (m)</th><th colspan="3">Embankment Overtopping locations</th><th>Remark</th></tr>
<tr><td>2-year</td><td>2316</td><td>204.2</td><td colspan="3">No Overtopping</td><td></td></tr>
<tr><td>5-year</td><td>4025</td><td>205.9</td><td colspan="3">No Overtopping</td><td></td></tr>
<tr><td>10-year</td><td>5157</td><td>206.9</td><td colspan="3">No Overtopping</td><td></td></tr>
<tr><td>25-year</td><td>6587</td><td>207.94</td><td colspan="3">No Overtopping</td><td></td></tr>
<tr><td rowspan="2">July, 2023 Flood</td><td rowspan="2">6999</td><td rowspan="2">208.7</td><td>Location</td><td>Bank</td><td>Max WL reached</td><td rowspan="2">Overtopping at Nili chhatri area is observed in simulation. The same is Verified on ground by the Delhi Government during July, 2023 floods. Max water level of 208.88m is reached which is above the existing bund level. No overtopping at any other location shown by the model.</td></tr>
<tr><td>Nili Chhatri</td><td>Right</td><td>208.88</td></tr>
<tr><td rowspan="2">50-year</td><td rowspan="2">7648</td><td rowspan="2">208.75</td><td>Location</td><td>Bank</td><td>Max WL reached</td><td rowspan="2">At Nili chhatri area, max water level of 208.98m may be reached which is above the existing bund level. No overtopping at any other location shown by the model.</td></tr>
<tr><td>Nili Chhatri</td><td>Right</td><td>208.98</td></tr>
<tr><td></td><td></td><td></td><td>Location</td><td>Bank</td><td>Max WL reached</td><td rowspan="3">At Nili chhatri area, max water level of 209.55m may be reached which is above the existing bund level. No overtopping at any other location shown by the model.</td></tr>
<tr><td>100-year</td><td>8701</td><td>209.35</td><td>Nili Chhatri</td><td>Right</td><td>209.55</td></tr>
<tr><td>100-year With elevated Nili Chhatri bund in the model</td><td>8701</td><td>209.44</td><td>Nili Chhatri</td><td>Right</td><td>209.68</td></tr>
</table>

Table-14 below shows Maximum longitudinal Water Surface Elevations for 100-year flood starting 21 km u/s of Wazirabad Barrage at every 1-Km interval against both the Right & the Left Bank Elevations.

Table 14 WL vs Bank Elevations for 100-year Flood

Chainage	Right Bank Elevations (m)	Centreline WL (m)	Left Bank Elevations (m)	Right Bank elevation difference wrt WL (m)	Left Bank elevation difference wrt WL (m)
0	215.9	214.52	215.72	1.380	1.200
1000	215.25	214.4	215.3	0.850	0.900
2000	215.2	214.2	215.3	1.000	1.100
3000	214.6	213.95	214.8	0.650	0.850
4000	214.55	213.6	214.7	0.950	1.100
5000	214	213.3	214.5	0.700	1.200
6000	214.3	213.3	214.3	1.000	1.000
7000	213.6	213.03	214.01	0.570	0.980
8000	213.4	212.88	213.9	0.520	1.020
9000	213.4	212.73	213.7	0.670	0.970
10000	213.5	212.57	213.3	0.930	0.730
11000	213.3	212.43	213.1	0.870	0.670
12000	213.3	212.43	213.1	0.870	0.670
13000	213.3	212.43	213.1	0.870	0.670
14000	213.2	212.1	212.97	1.100	0.870
15000	213.1	212.05	212.5	1.050	0.450
16000	213.1	211.9	212.4	1.200	0.500
17000	212.4	211.85	211.96	0.550	0.110
18000	212.12	211.74	211.77	0.380	0.030
19000	211.77	211.6	211.77	0.170	0.170
20000	211.69	211.46	211.81	0.230	0.350
21000	212.37	211.3	211.6	1.070	0.300
22000	213.35	211.05	211.12	2.300	0.070
23000	212.25	210.79	211	1.460	0.210
24000	211.45	210.32	210.55	1.130	0.230
25000	211.25	210	210.25	1.250	0.250
26000	211.25	209.6	212	1.650	2.400
27000	208.5	209.55	212	-1.050	2.450
28000	210.56	209.05	209.75	1.510	0.700
29000	209.75	208.89	209.55	0.860	0.660
30000	210.1	208.48	210.4	1.620	1.920
31000	209.75	208.25	209.58	1.500	1.330
32000	208.76	207.8	208.55	0.960	0.750
33000	208.35	207.7	208.55	0.650	0.850
34000	208.45	207.3	208.05	1.150	0.750

35000	208.8	206.5	207.43	2.300	0.930
36000	208.8	205.46	206.75	3.340	1.290
37000	206.05	205	206.75	1.050	1.750
38000	206.6	204.84	206.6	1.760	1.760
39000	207.35	204.5	208.5	2.850	4.000
40000	205.4	203.35	206.65	2.050	3.300
41000	204.2	202.8	204.5	1.400	1.700
42000	203.9	202.5	203.52	1.400	1.020
43000	203.99	202.4	203.52	1.590	1.120
44000	203.5	202.2	204.46	1.300	2.260
45000	203.4	201.87	204.4	1.530	2.530

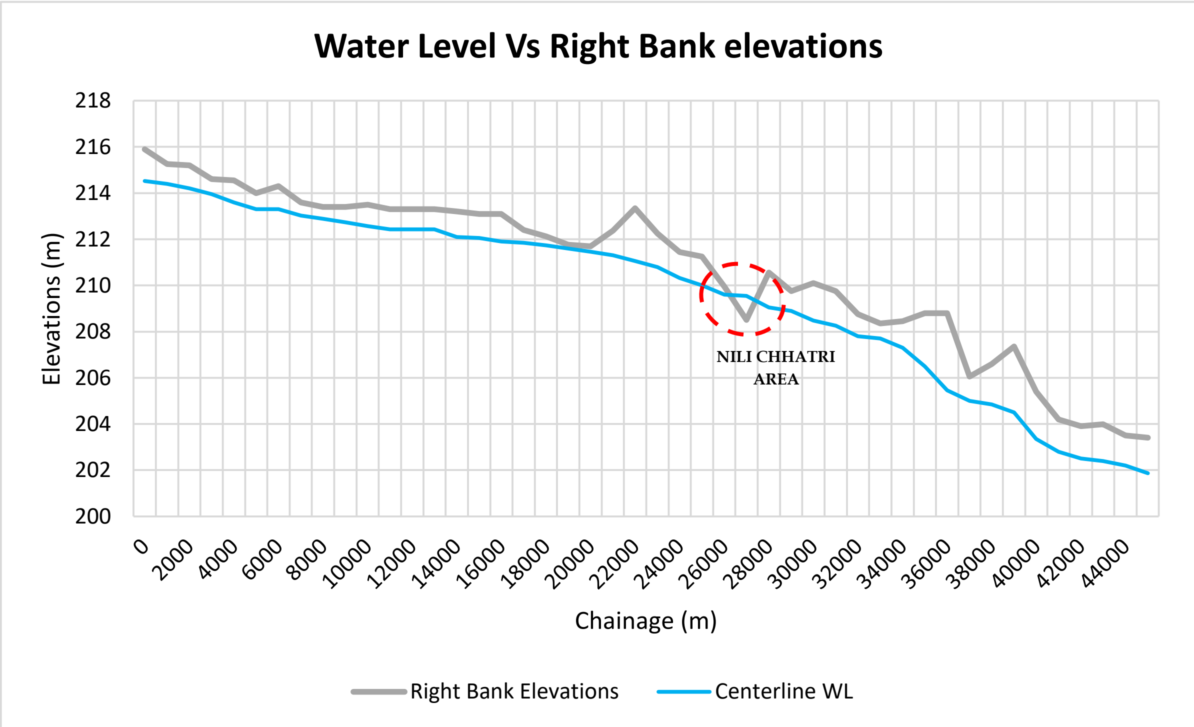


Figure 21 : WL vs Right Bank Elevations

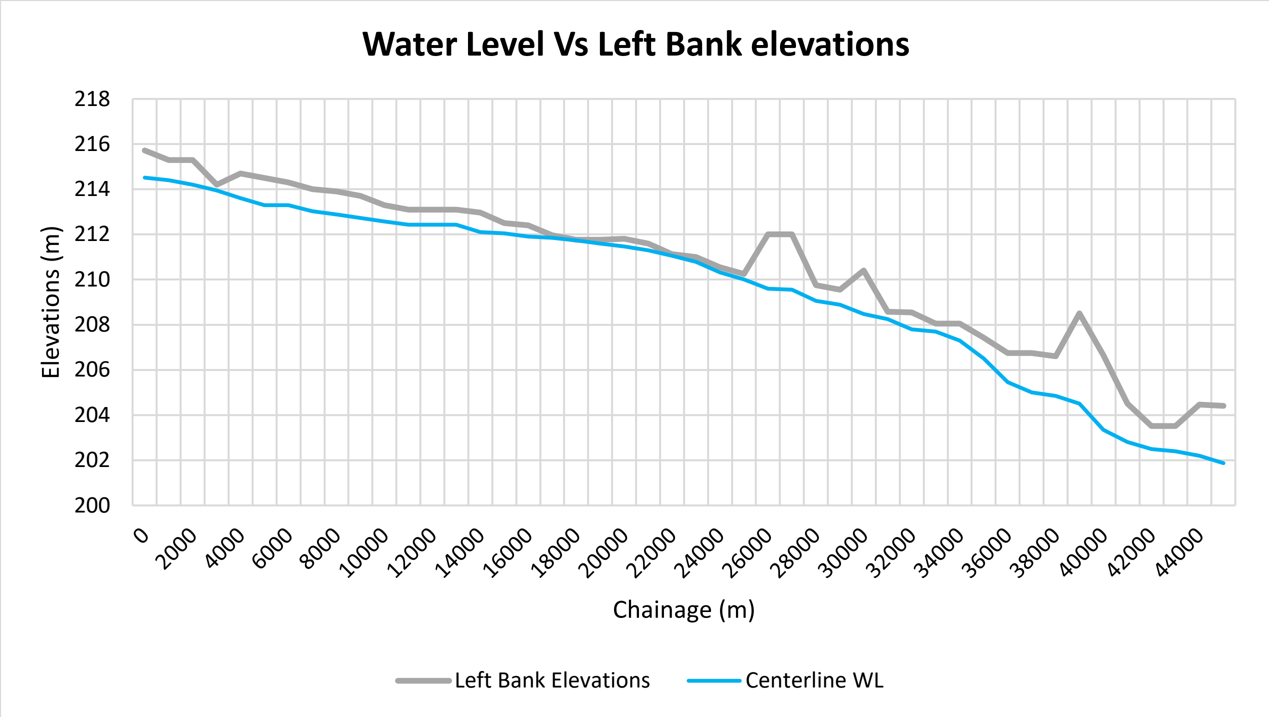


Figure 22 WL vs Left bank Elevations

Submergence Area analysis Conclusion

1. The flood of July, 2023 was slightly less than 1-in-50-year flood.

2. Bottom Girder level at Old Railway Bridge in Delhi is at El.207.4m. As per the model simulation, this level may be attained as the flow at DRB crosses 5974 cumec. Further for 100-year flood the water level may reach at El. 209.35m. Appropriate study may be done to know the actual effect of such high flood on the Bridge and flow.

3. Up to 1-in-25-year flood (6587cumec), no overtopping of embankments shown by the model along the entire Delhi reach.

4. Simulated water level for 2023 flood at DRB is found to be at El. 208.6m against the observed 208.65m. Also, simulated submergence area for 2023 flood is found to be 44.1 Sqkm which is slightly less than the simulated submergence area for 50-year flood at DRB. The model shows overtopping from Metcalf house to Nili Chhatri/ Yamuna Bazar Ring road area on right bank of river Yamuna with max water level reaching upto El. 208.88m. The same has been verified on ground by the Delhi Government.

5. For 50-year flood ie. flow of 7648 cumec, the water may rise upto El. 208.75m resulting in submerging 47.3 Sqkm which is 7.3% more than the area submerged in

July 2023 Flood. This magnitude of flood, may cause embankment overtopping at Metcalf house to Nili Chhatri/ Yamuna Bazar Ring road area on right bank of river Yamuna with max water level reaching upto El. 208.98m.

6. For 100-year flood ie. flow of 8701 cumec, (which is equivalent to the design discharge of ITO/Okhla/Wazirabad barrage, the water level may rise upto El. 209.35m resulting in submerging 54.8 Sqkm which is 24.0% more area as compared to the area submerged in July 2023 Flood. This magnitude of flood, may cause embankment overtopping at Metcalf house to Nili Chhatri/ Yamuna Bazar Ring road area on right bank of river Yamuna with max water level reaching upto El. 209.55m.

7. The discharge of 6700 cumec and above at DRB may cause overtopping at Nili Chhatri area on the right bank of river Yamuna. Further, for 100-year flood ie. Discharge of 8701 cumec at DRB, the max Water Level at the Nili Chhatri area under existing conditions is simulated as 209.55m by the model. Now raising the embankment height beyond this level (say to 210.55m) in the model and again running shows that the max water Level now reached is 209.68m which may be taken as the maximum Water Level reaching for 100-year flood. Suitable flood protection may be provided against it keeping in view the design norms and actual ground conditions. Water Surface Elevation profile with raised embankment height at Nili Chhatri area is given in last column of Table-12.

8. Table-14, Figure-21 and Figure-22 shows the simulated water levels for 100-year flood with respect to the right and the left embankment levels. Upto 100-year flood, no overtopping at any other location is shown by the model, however if required, the simulated water levels given in Table-12 may be matched with the actual bund levels to find the possible overtopping locations.

5.2 Identification of Drainage congestion and its Operating Mechanism

There are 20 drains falling into river Yamuna in the Delhi reach. These drains are operated and maintained by Delhi Government. Details of these 20 drains as provided by the Delhi Government have been used to perform the analysis. The analysis is done to find out the return period flood for which the drain starts getting congested.

Drainage congestion seems to start occurring when the Water Level in the River Yamuna gets higher than the outfall sill level of a particular drain. The **Table-15** below shows the list of drains along with their outfall Sill levels and the River Water levels reached at drain outfall location for different return period floods. The table finally shows the return period flood at DRB for which the drains start getting congested.

Table 15 : Drainage Congestion

Sl.No	Drain	Outfall Sill Level	River Water Level at Drain outfall for various Return period flood			Return period flood at which the congestion starts in the Drains
			2-year	5-year	10-year	
1	Najafgarh Drain (un regulated)	203	206.5	207.8	209.0	2-Year (2316 m^3/s)
2	Shahadra Drain (un regulated)	193.58	197.9	199.3	200.2	2-Year (2316 m^3/s)
3	Magzine Road Drain	206.4	-	207.5	208.7	5-Year (4025 m^3/s)
4	Old Chandrawal Drain	206.4	-	207.4	208.6	5-Year (4025 m^3/s)
5	Khyber Pass Drain	206.5	-	207.3	208.5	5-Year (4025 m^3/s)
6	Metcalf House Drain	204.76	204.9	206.7	207.8	2-Year (2316 m^3/s)
7	ISBT/Mori gate/Qudsia Ghat Drain	204.37	204.5	206.2	207.4	2-Year (2316 m^3/s)
8	Tonga Stand Drain	204.25	204.3	206.0	207.1	2-Year (2316 m^3/s)
9	Vijay Ghat	203.065	204.1	205.7	206.8	2-Year (2316 m^3/s)
10	Civil Military Drain	203.173	203.3	204.9	206.0	2-Year (2316 m^3/s)
11	Delhi Gate	202.154	203.0	204.5	205.6	2-Year (2316 m^3/s)
12	Sen Nursing Home Nalla 12 No.12	202.64	--	204.4	205.5	5-Year (4025 m^3/s)
13	Nalla No.12 (A)	201.45	202.9	204.4	205.5	2-Year (2316 m^3/s)
14	Nalla No.14	202.09	202.3	203.7	204.7	2-Year (2316 m^3/s)
15	Nalla No.15	203.124	-	203.3	204.3	5-Year (4025 m^3/s)

16	Barapullah Drain (un regulated)	199.046	200.8	201.9	202.9	2-Year (2316 m^3/s)
17	Nalla No.17	201.1	-	-	201.1	10-Year (5157 m^3/s)
18	Taimur Nagar (un regulated)	201.1	-	-	201.1	10-Year (5157 m^3/s)

Drainage congestion conclusion

1. For Drain No. 1, 2, 6, 7, 8, 9, 10, 11, 13, 14 and 16 congestion starts with 2-years return period flood.
2. For Drain 3, 4, 5, 12 and 15 congestion starts with 5-years return period flood.
3. All the above drains start to get congested for 10-year and above return period flood.

5.3 Afflux of Structures in the study reach

To study the afflux of the structures in the study reach, following two scenarios of generating the longitudinal Water Surface Elevation (WSE) Profile were simulated in the 2D Hydrodynamic model as shown in **Figure-23** and **Figure-24** below.

1. **Existing Scenario**: Terrain with existing structures including Muck ie. as per current condition.
2. **Pier Scenario**: Terrain with existing structures raised on Piers ie. Embankment replaced by Piers and muck removed.

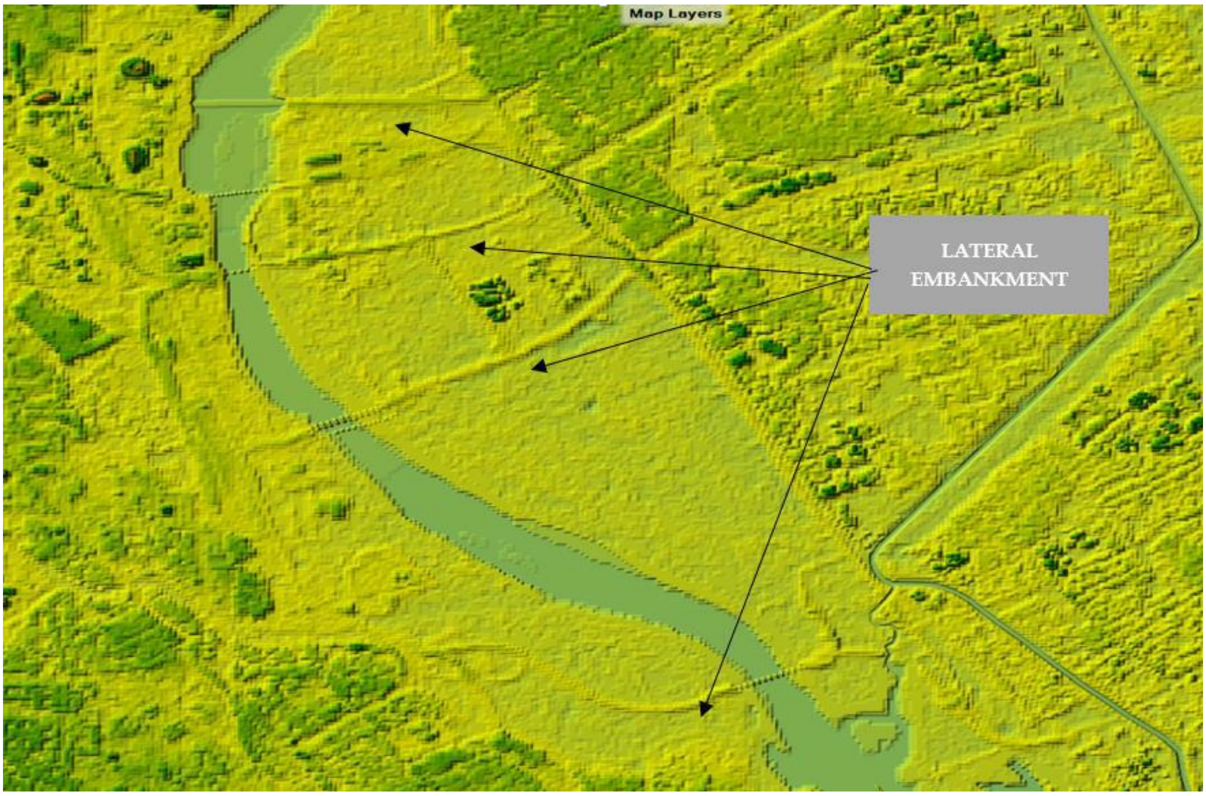


Figure 23 : Existing Scenario: with existing structures ie. as per current condition

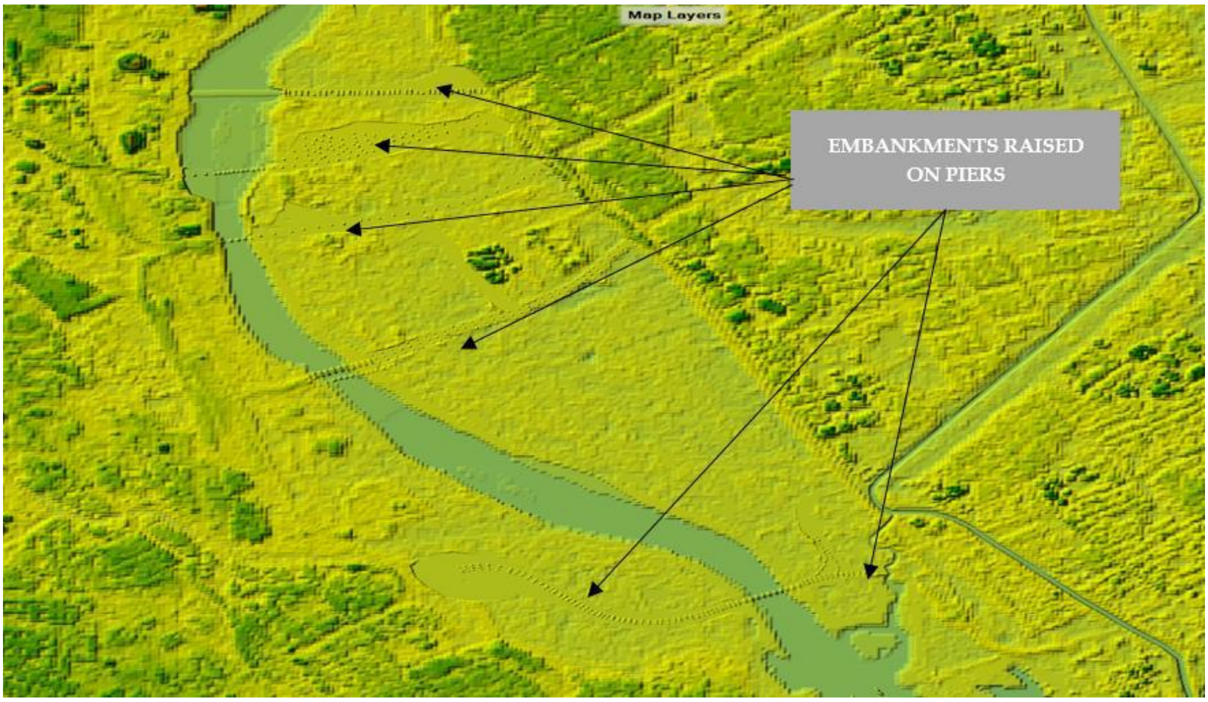


Figure 24 : Pier Scenario: Existing lateral structures raised on Piers

Existing structures mentioned above mainly include all the lateral embankments into floodplain that are possibly obstructing the flow excluding the three existing Barrages.

Simulation Results

The **Figure-25** below shows the longitudinal WSE profile along with the longitudinal bed level profile of the Delhi reach for the two scenarios mentioned above. The above simulation is done for the 100-year flood ie. discharge of 8701 cumec passing through DRB.

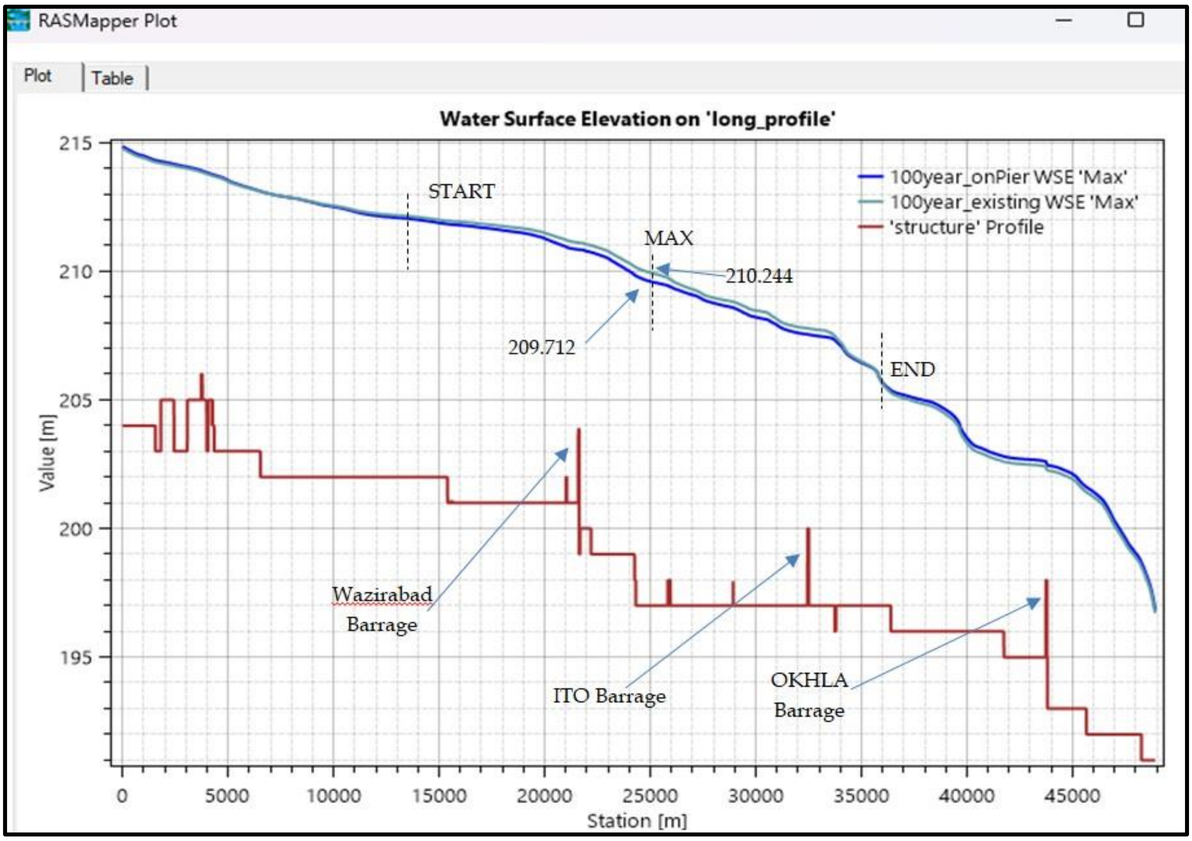


Figure 25 : Longitudinal water surface elevation (WSE) Profile

Conclusion for afflux Analysis

After running the two simulations, following observations could be made:

1. Taking both scenarios together it is observed that the longitudinal water surface profile shows a marked difference in the water elevations in the middle reach only. This difference starts appearing around 12Km u/s from Wazirabad Barrage to 16Km d/s. The Water Surface Elevation profile for the existing Terrain is higher than the Pier Terrain which has all the lateral embankments raised on Piers. The maximum difference between the two Water Surface Elevations is found to be **0.536 meters** at around 26.404 Km station which lies between Wazirabad and ITO Barrage. This possibly indicates the afflux produced due to the lateral embankments and muck lying downstream of Wazirabad Barrage.

The simulated Water Surface Elevations for both the existing and Pier scenario is graphically shown in the **Figure-26** below.

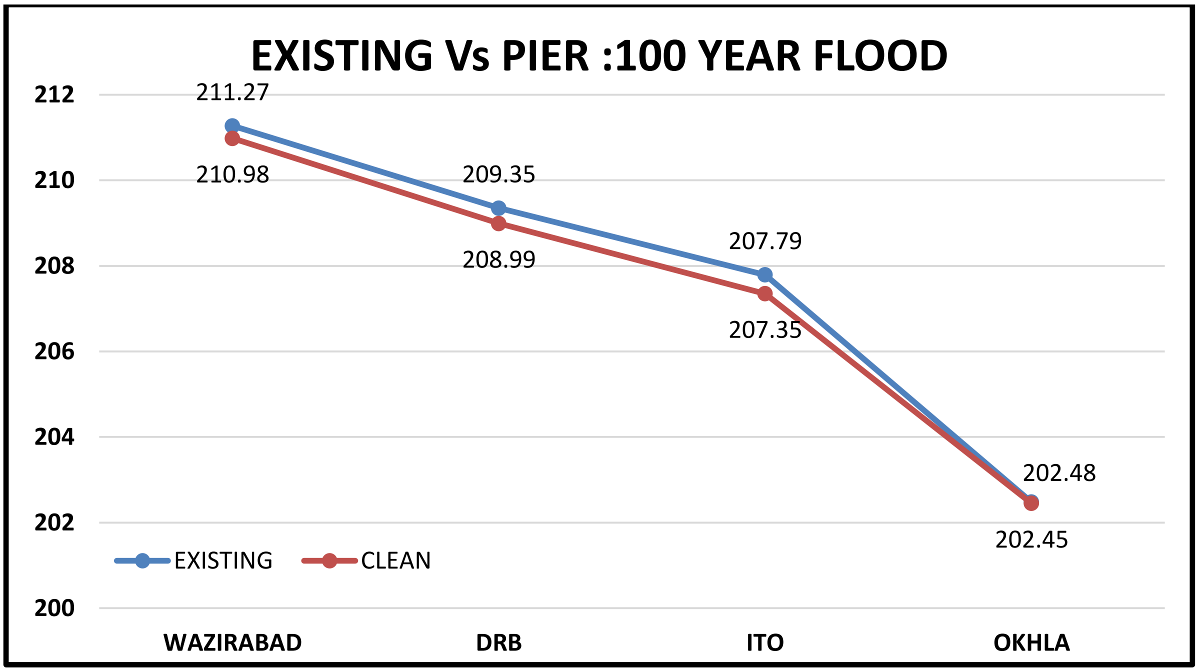


Figure 26: Simulated Water Surface Elevations for both the existing and pier scenario

6. Recommendations

Based upon the 2D Model studies, following conclusions are drawn-

a. Drainage Congestion

i. The assessment of capacities of various drains to carry sewage and storm water may be carried out in order to avoid congestion during floods of various return period in river Yamuna.

ii. The I&FCD, Govt of NCT Delhi may ensure that all the entries/exit which are leading to river Yamuna may be raised above the maximum water level of river Yamuna during floods of various return period in order to avoid spilling of flood waters through these entries/exit points.

iii. I&FCD, Govt. of NCT Delhi to ensure adequate pumping arrangement for discharging of water from drains to river Yamuna at higher level during floods in river Yamuna wherever the drains gets congested due to high stage floods in river Yamuna.

iv. It is observed that the drainage network within the Delhi NCR region is being maintained by different agencies like, I&FCD, Govt.NCT of Delhi, MCD, NDMC, etc. and there is no coordination among various agencies for operation of these drains. A SoP for operation of these drains in Delhi NCR region may be prepared with clear guidelines defining the procedures to be followed for operating these drains depending upon the water level in river Yamuna. There should be one nodal agency which should be responsible for operation of drains in Delhi NCR region. The nodal agency may be entrusted with the task of monitoring of proper maintenance and regular desilting of drains. The SoP for drains should also clearly define the details of pre monsoon and post monsoon inspections that are required to be carried out for the drains.

b. Submergence in varying return periods and adequacy of embankments

i. The flood of July, 2023 was in between1-in-25-year and 1-in-50-year flood.

ii. Bottom Girder level at Old Railway Bridge in Delhi is 207.4m. As per the model simulation, this level may be attained as the flow at DRB crosses 5974 cumec. Further for 100-year flood the water level may reach 209.35m. In such condition, there may be slightly more afflux due to girder. Further, appropriate study may be carried out by the Indian Railways to know the effect of such high flood on the Old Delhi Railway Bridge structural stability.

iii. Up to 1-in-25-year flood (6587cumec), no overtopping of embankments is shown by the model along the entire Delhi reach. Further, model study indicates that there shall be no overtopping for discharge up to 6700 cumec.

iv. Simulated water level for 2023 flood at DRB is found to be 208.6m against the observed 208.65m. Also, simulated submergence area for 2023 flood is found to be 44.1 Km^2 which is slightly less than the simulated submergence area for 50-year flood at DRB. The model shows overtopping from Metcalf house to Nili Chhatri/ Yamuna Bazar Ring road area on right bank of river Yamuna with max water level reaching upto 208.88m. The same has been verified on ground by the Delhi Government.

v. For 50-year flood i.e. flow of 7648 cumec, the water may rise up to 208.75m resulting in submerging 47.3 Km^2 which is 7.3% more than the area submerged in July 2023 Flood. This magnitude of flood, may cause embankment overtopping at Metcalf house to Nili Chhatri/ Yamuna Bazar Ring road area on right bank of river Yamuna with max water level reaching upto 208.98m.

vi. For 100-year flood ie. flow of 8701 cumec, (which is equivalent to the design discharge of ITO/Okhla/Wazirabad barrage), the water level may rise upto 209.35m resulting in submerging 54.8 Sqkm which is 24.0% more area as compared to the area submerged in July 2023 Flood. This magnitude of flood, may cause embankment overtopping at Metcalf house to Nili Chhatri/ Yamuna Bazar Ring road area on right bank of river Yamuna with max water level reaching upto 209.55m

vii. Further, for 100-year flood ie. Discharge of 8701 cumec at DRB, the max Water Level at the Nili Chhatri area under existing conditions is simulated as 209.55m by the model. Now raising the embankment height beyond this level (say to 210.55m) in the model and again running shows that the max water Level now reached is 209.68m which may be taken as the maximum Water Level reaching for 100-year flood. Suitable flood protection may be provided against it keeping in view the design norms and actual ground conditions. Water Surface Elevation profile with raised embankment height at Nili Chhatri area is given in last column of table 4 above.

viii. Table-14, Fig. 21 & Fig. 22 shows the simulated water levels for 100-year flood with respect to the right and the left embankment levels. Up to 100-year flood, no overtopping at any other location is shown by the model. However, the simulated water levels given in Table-14 may be matched with the actual bund levels by I&FC Department, Govt. of NCT Delhi to find the possible overtopping locations and raising the same with free board as per the codal provision.

c. Afflux Condition

i. The simulations results indicate that replacing lateral embankments with piers leads to lower water surface elevations in the middle reach of the river compared to the existing terrain. An afflux of 0.536 meters has been observed at around 26.404 km. This suggests that the current embankments of structures and muck contribute to higher water levels.

7. Limitations of the Study

1. The obtained values of levels and flows in the study are indicative and subject to the errors and uncertainties present in the data and the model.

2. The DEM used in the model has horizontal resolution of 30m which is relatively coarse for such a study. All the levels, depths and extents simulated by the model are subject to the inherent errors present in the DEM and its limitation because of its coarser resolution.
3. The errors in the outcome of the model, if any, are due to the uncertainties already present in other input data like flow hydrograph, land use land cover data, structure details, embankment data etc.
4. For the sake of model stability and shorter simulation period, diffusive wave equation is used as the solver. In Diffusive wave equation gravity and friction are assumed to be dominating forces and the acceleration terms, as well as the eddy viscosity and Coriolis terms are neglected.