Adaptive Flood Resilient City Design Strategies: An Exploratory Analysis of the Impact of Flooding on Street Network of Dhaka City

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Abstract

Flood incidents are becoming a common circumstance all over the world due to rapid urbanization and climate change. The dependence on flood control structures is becoming unsustainable and modern approaches are taking place with improved spatial planning, design strategies, adaptation techniques, and forecasting. All the major cities in developing countries like Bangladesh are facing flooding issue. The immediate impact on the urban environment is found in the street network due to flooding. Most of the previous studies are focused on the topography to understand the flooding or vulnerability of transport networks with traffic issues, but less attention is given to the street network performance during flooding and possible strategies for solving those issues. This research aims to understand the appropriateness of flooding resilience vs flooding prevention from a context-sensitive point of view of Dhaka city by identifying flooding impact on the road network. Spatial network analysis with sDNA and flooding data from World Bank helped to understand the relationship between street networks, and before-after situations during flooding. The circumstantial impact on the street network by flooding was visualized with GIS and sDNA analysis to define its performance and possible alternative solutions. This research will help to dictate future planning policy frameworks of Dhaka city derived from this exploratory study. Also, this research endeavors to help the government and corresponding authorities of flood-prone cities to enhance an inclusive strategic tool for the existing and future planning policy by developing short-term and long-term strategic vision.

Keywords

Flood resilience, Adaptation, Living with flood, sDNA, Network analysis

1. Introduction

Flooding is one of the mass-spreading natural phenomena and globally the greatest cause of destruction in cities (Ashley et al., 2007; Dewan, 2013). Even though considerable efforts on flood control measures like dams, diversion channels, pump stations, levees, and wires, cities remain vulnerable to flood (Andersen & Marshall Shepherd, 2013). Most urban regions are situated in coastal areas or beside rivers, and major rivers all over the world (Small & Nicholls, 2003; Ward et al., 2011). Cities in developing world are more at risk of flood due to higher urban population growth and limited expansion scope of city infrastructure leading to a scarcity of adaptation measures (Anunobi, 2013; Lindley et al., 2006). A large number of communities are endangered both in lowland and highland locations, due to the increase in key urban drivers such as haphazard land-use changes, population growth, land subsidence, etc. along with climate change like precipitation, sea-level rise, and water run-off (Atreya et al., 2017; Bouwer, 2011).

Lifestyle of living with floods is mostly found in development plans, and settlements of rural regions (Laituri, 2000). In recent years different nations have faced floods and natural disasters including Bangladesh. In most cases, developing countries are facing severe economic losses than developed ones (Haque, 2016). Nowadays, some of the cities are benefiting from impactful flooding strategies, like restoration of the marshes in the deltaic plain of Mississippi (W. et al., 2007) and Boston, Rotterdam, and Lagos from the limited flood-prone surface wetlands.

Flooding has a significant impact on street network and transport infrastructure (van Ginkel et al., 2021). The damage caused by floods is still unexplored though it is a vital issue in urban environments (Doll et al., 2014; Koks et al., 2019). Vulnerability to flooding and extreme population often makes the urban environment inferior in terms of mobility and emergency rescue operations (Huang, 2021). The road network can be affected by flooding, both in direct-indirect and tangible-intangible ways. Heavy precipitation and lack of efficient drainage systems often render flash floods in congested urban areas damaging property as well as blocking certain parts of the street network. During flooding, the transport system assumes the role of drainage for stormwater, severely affecting road traffic and infrastructure quality. Very rarely has the impact of flooding on urban transportation systems been studied in developing cities such as Dhaka.

Although there are some new ideas about dealing with flood, it is limited within the landscape realms and flood-controlling system of urban areas (Dewan, 2013). The flood-controlling paradigm of flood prevention should be reconsidered eventually (K.-H. Liao, 2014). Most of the flood resilient and living with floods, concepts are adapted in rural contexts, but not in developing urban cities like Dhaka.

This paper aims to highlight a new proactive strategy in flood resilience that urban communities in Dhaka can adopt for living with water. Since road network is the first element to bear

the brunt of flooding, and due to the lack of studies on this relationship, this research raises the question, "How can we measure and spatially visualize the impact of before-after flooding on street networks?" and "What are the flood-resilient strategies that can be materialized from exploring such a relationship?"

Finally, this research aims to understand the appropriateness of flood resilience vs flood prevention from a context-sensitive point of view of Dhaka city and identify:

(i) Flooding has an impact on the road network of Dhaka city,

(ii) The use of network analysis and flooding data to understand the relationship between roads and flooding, and

(iii) The conclusions derived from this exploratory study that can help dictate future planning policy frameworks in Dhaka

Urban redevelopment of existing areas which are vulnerable to flood or new town development like Uttara, Purbachal, and Savar areas can be developed based on the argument of this study.

2. Critical Literature Review

Flooding has a serious negative impact on the road network and the particular road can have a different degree of disruption (Arkell & Darch, 2006). Most of the time Flood risk assessment is done on a directly affected site where that is occurring. But the property and street network adjacent to the flood risk area also suffers and faces indirect consequences (Gil & Steinbach, 2008). Disruption in the transportation network changes the journey time and distance of commuters. This evaluation can be constructed by analyzing pre and post-network links with flooding simulation. Flooding on the streets reduces the speed of vehicles and expands travel time. Flooding depth over 300mm eventually closes the road and stops the traffic flow (Arrighi et al., 2021). Sometimes all the road access is disrupted by the flood in some areas, and they become an island without any land access. From any peninsula with only a single route becomes more difficult even in times of emergency.

Flood resilience is the capability of an area to endure flooding and avoid mass disaster risk during the flood time but not prevent it. It also encounters the capacity for quick recognition of the physical damage and socioeconomic breakdown that had already occurred (K. H. Liao, 2012). The flood tolerance capacity of an area is defined as the undamaged and functional potential when it is flooded (K. H. Liao, 2012). Resilience thinking is a key framework in the context of increased risk and uncertainty with assessing the nature of spatial planning contained by flood risk management.

Adaptation is denoted in the literature on climate change as an all-inclusively means to adjust to the climatic conditions and effects of actual or expected conditions (UNISDR, 2009), which also includes the flood controlling system (Wilby & Keenan, 2012). The role of citizens in flood adaptation plays an important character

in the contemporary flood policy (Butler & Pidgeon, 2011; Johnson & Priest, 2008; Scott et al., 2013). The modern urban lifestyle is widely different from living with flood lifestyle which discourages flood management (Cuny, 1991; Thaitakoo et al., 2013; Zevenbergen et al., 2011). This is more about shifting the paradigm from flood defense to flood risk management where the society is proactive in its strategies for living with water and is resilient enough to experience expected periodic floods (Scott et al., 2013).

3. Street network and flood vulnerability of Dhaka

Bangladesh is one of the most densely populated countries in the world with around 167 million people living in a 148,460 km² area (Bangladesh Population (2022) - Worldometer, 2022; The World Bank, 2022). Dhaka is the capital city of Bangladesh, and one of the fastest-growing megacities in the world with an annual population growth of 4.2% (Bangladesh Bureau of Statistics, 2022). The continuous growth of the city shows a massive migration from rural areas to this urban region. The total population of Dhaka city represents 40 percent of the urban population of the country (Ahmed & Ahmed, 2017). Historically, Dhaka is developed in an unplanned and arbitrary way

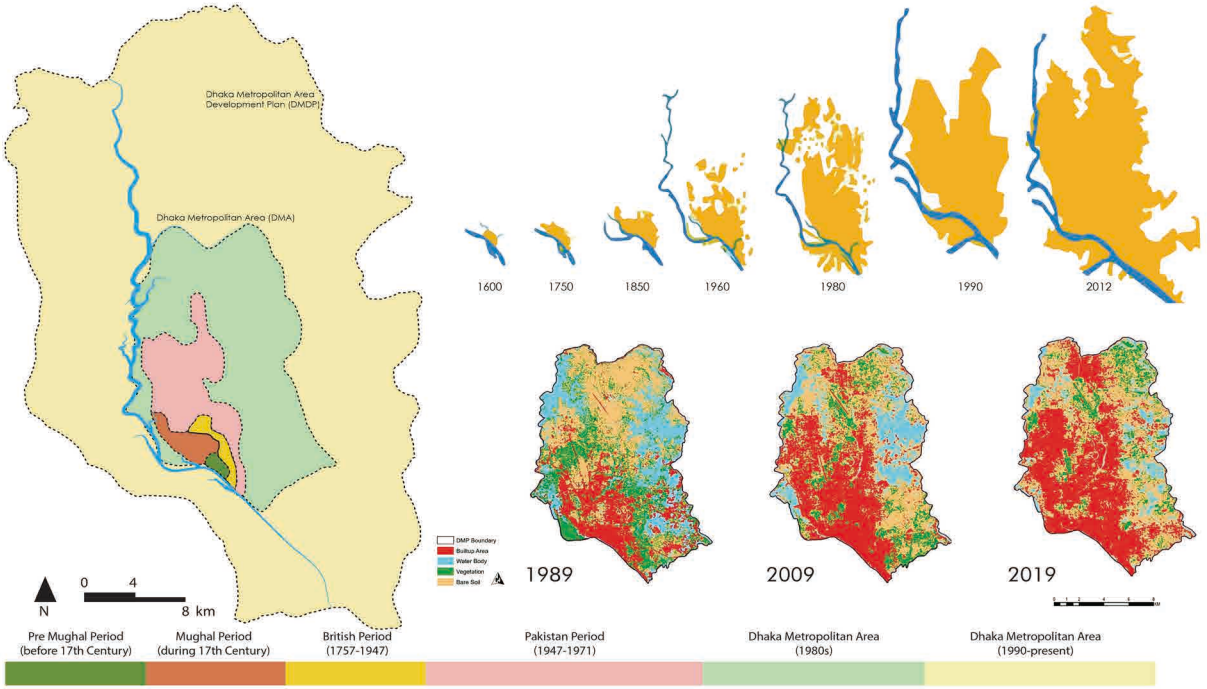

Figure 1 Development of Dhaka City, source: Author

(Figure 1) different urban elements constantly fighting for space (Hasan et al., 2013). Transport demand for this city is growing with the increase in population growth and the situation worsens during flooding when some of the main roads are submerged under water due to a lack of efficient drainage systems. Because of the economic condition, rapidly growing population, and scarcity of land, people are forced to develop their settlements in unprotected low-lying flood-prone areas. The unplanned growth of the city and random development of land is reducing the natural flood plains and blocking the stormwater drainage channels. Therefore, the city faces recurring devastating floods, a shortage of drinking water, a reduction of the recharge area for groundwater, a loss of biodiversity, and a loss in productivity because of traffic jams.

Usually, a well-articulated road network often carries 20-40 percent of land in the urban area depending on the function, character, and size of the city (Chowdhury, 2001). Dhaka city has only 9 percent of the total area as road space (Figure 2), but every road does not contain pedestrian space. Only 6 percent of space is used for pavement in the DMA area (Dhaka Metropolitan Area). Among the total road space of 1286 km, the minimum portion is occupied as primary (61 km), some of the portions are for secondary and connector (108 km and 221 km) and the rest of the spaces are for the local and narrow roads (573 km) (Mahmud et al., 2009).

Most of the urbanized area of Dhaka city has an elevation of 6 to 13 meters (Figure 3) above

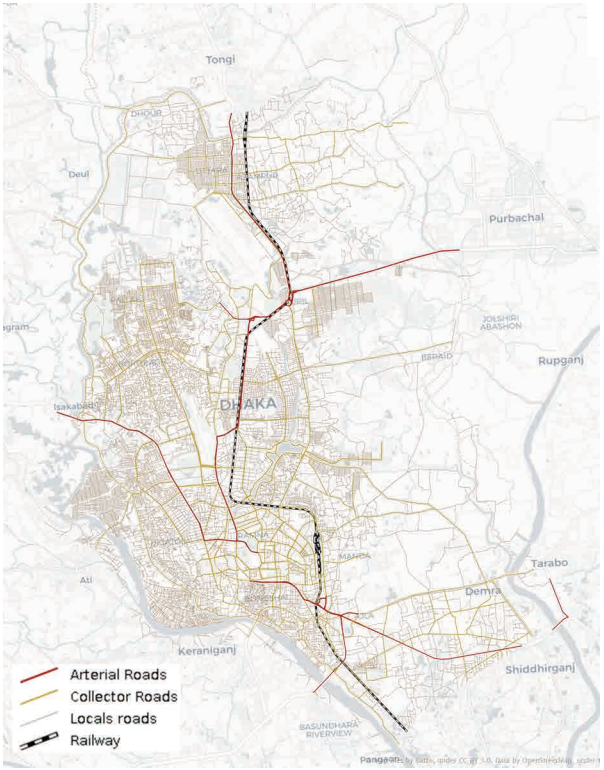

Figure 2 Road Network of Dhaka City, source: world bank, 2022

the mean sea level (msl). The average msl of the greater Dhaka city is between 2 meters to 16 meters where only a 20 square kilometer area is over 8 meters (Mahmud et al., 2009). Around 170 square kilometer area is lying under 6 meters and most of the area is vulnerable to flood (JICA, 1991). Due to the low topographic condition, most of the area lies below the natural water level. As a result, the unplanned urbanization with the narrow and haphazard road network is developing an uneven size of the city. Therefore, rainwater cannot release to the river,

khal, lakes, or water retention areas smoothly and remains clogged in the low-lying areas of the city. Often these low-lying lands face eavy consequences due to an increase in water level of rivers and canals (Figure 4).

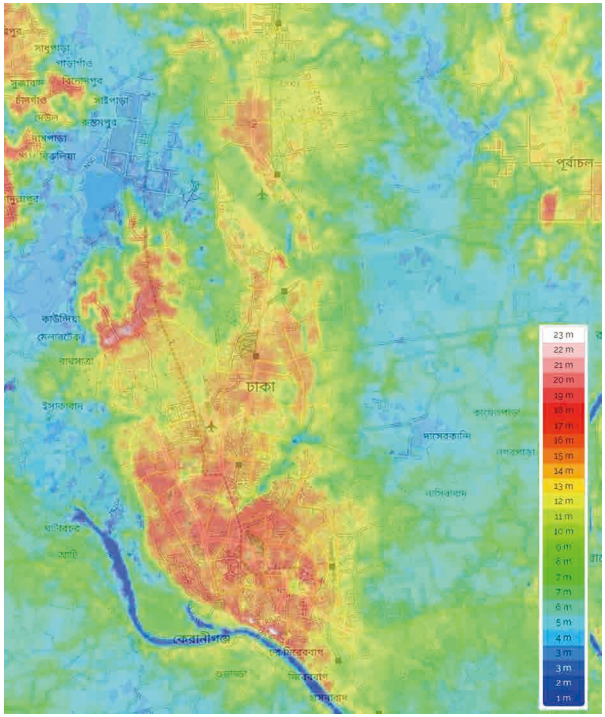

Figure 3 Topographic map of Dhaka, source: topographic-map.com, 2022

4. Methodology

During flooding, street network analysis methods could be more accurate to understand the scenario rather than other typical methods (Capaccio & Ellis, 2005). This research introduces a methodology comprised of sDNA to demonstrate the network analysis and visualize the impact on the street network before and after flooding. Understanding the consequences and level of flow from the path overlapping from both scenarios. Before and after scenarios of flooding with the road network will show the impact of flooding on the street network in Dhaka city. GIS and sDNA will help to analyze and visualize the circumstantial impact of flooding on the street network and determine its performance.

4.1 sDNA Analysis

Spatial Design Network Analysis (sDNA) is a tool that works with ArcGIS, AutoCAD, and QGIS through Python API for 3-d spatial network analysis. Network links are used to analyse the network data for urban, street, or path network analysis. The accessibility measures like mean distance, or closeness centrality, and the flow rates such as bidirectional betweenness

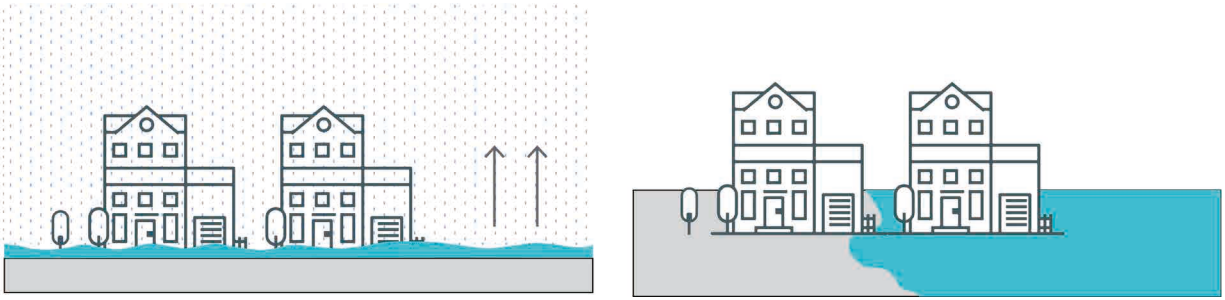

Figure 4 Pluvial flooding scenario (left) and Fluvial flooding scenario (right)

centrality are measured within a radial band. To analyse the network for route choice and spatial cognition the distance can be angular, Euclidean, or both (C. H. v Cooper & Chiaradia, 2020). Closeness centrality measures accessibility, usually the inverse mean distance of a given link or node on the network to all other links/nodes within a localized radius (C. Cooper & Chiaradia, 2015). Alternatively, Betweenness centrality in the sDNA analysis to count the centrality in the graph and the number of geodesic paths that pass through a vertex.

4.2 Conceptual Framework

For the framework, we analyze and generate a hypothesis for flood resilience and adaptation in cities by understanding the impact of flooding on street networks.

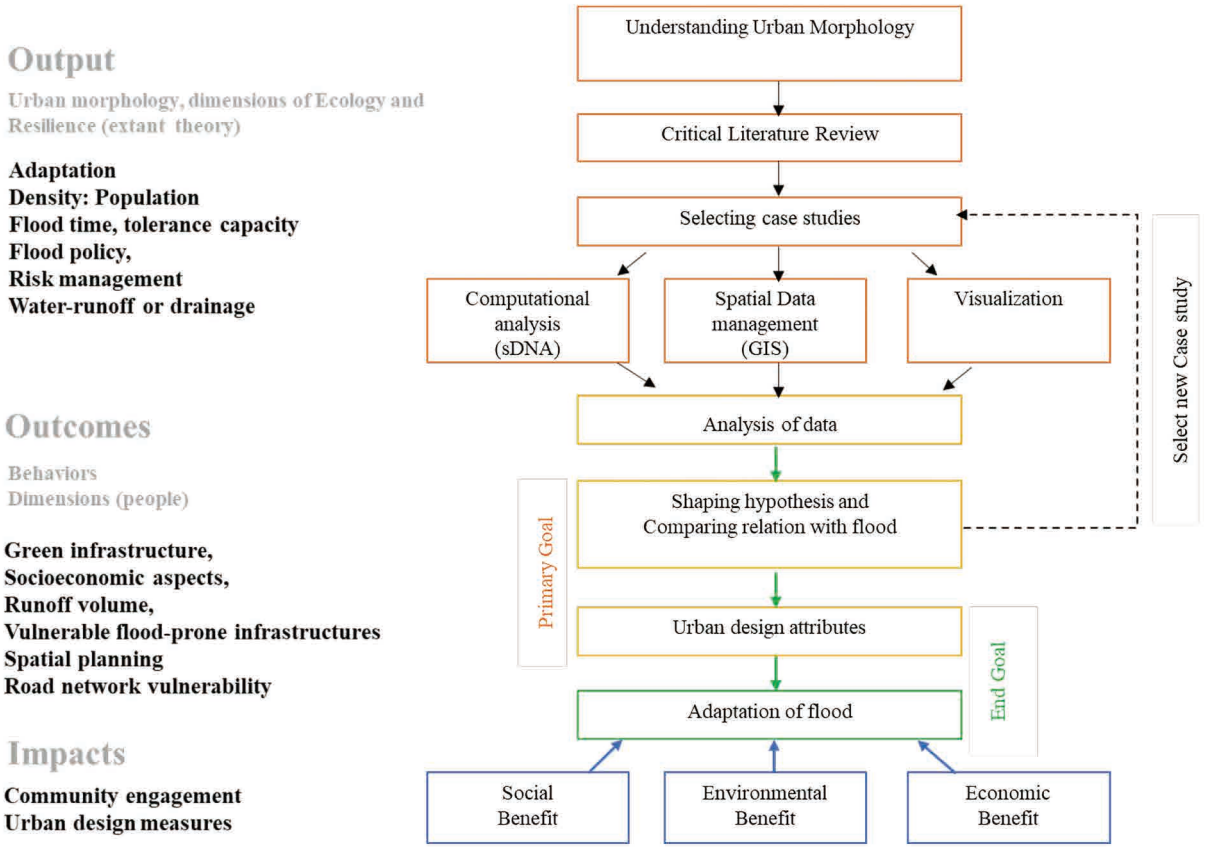

Figure 5 Conceptual Framework

4.3 Data collection strategy

4.3.1 Survey sample

The areas between Dhaka city are randomly selected based on their topographic position and intended to be flooding conditions. Only a few years of GIS data are available in the Asian Development Bank (ADB) and the World Bank database. Though they are not clear about the duration, time, and month of flooding. The data only shows the year and average flood-affected areas of Dhaka city.

4.3.2 Analytical Approach

For a better understanding of living with water opportunities and threats, an illustration is shown in Figure 5 we can start with the urban morphological analysis. Flood level and catchment area mapping (GIS) and Land use distribution over the area (GIS) can give a better understating of the site.

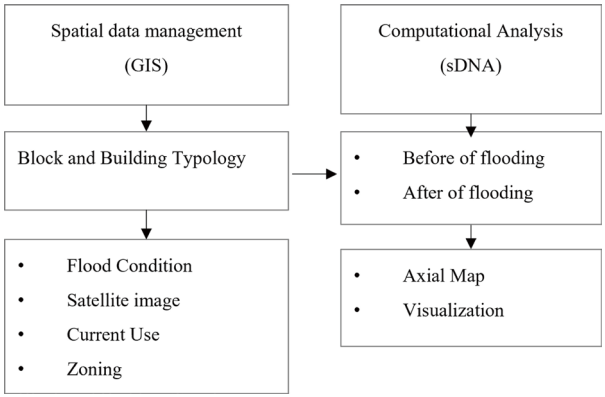

Figure 6 Data processing flow: Spatial data management, computational analysis, visualization

5. Result and Discussion

5.1 Flood scenarios

To analyze the flooding scenario of Dhaka city we started to collect GIS data from the ADB and World Bank databases. We have visualized the data in Figure 7 for the years 2004 (a), 2007 (b), and 2014 (c). The data is not specified with the flooding duration or time, that only shows the impacted area of Dhaka city. It doesn't explain whether the flood is pluvial or fluvial, whereas that shows a cumulative flooding scenario of Dhaka city during the following years. Most of the flooded areas are at the low-lying lands and comprise the new development zones. The flooding intensity is higher in the years 2004 and 2014 because of the heavy rain and a lot of water discharged from the Himalayan rivers. Respectively 2007 faces a less flooded situation whereas Dhaka city faced the most draught situation during that year. In recent years this research was not able to manage the GIS data but some images in Figure 8 show that flooding scenarios are the same every year.

5.2 Network Model

To understand the impact of flooding over the road network in Dhaka city, a macro scale network analysis was done with sDNA. The network analysis shows different values and colors during the regular day and disrupted by flooding. The impacts are visualized in Figure 9 and Figure 11 respectively as before and after scenarios of the flood in Dhaka city.

In Figure 9, the red color lines used to be more

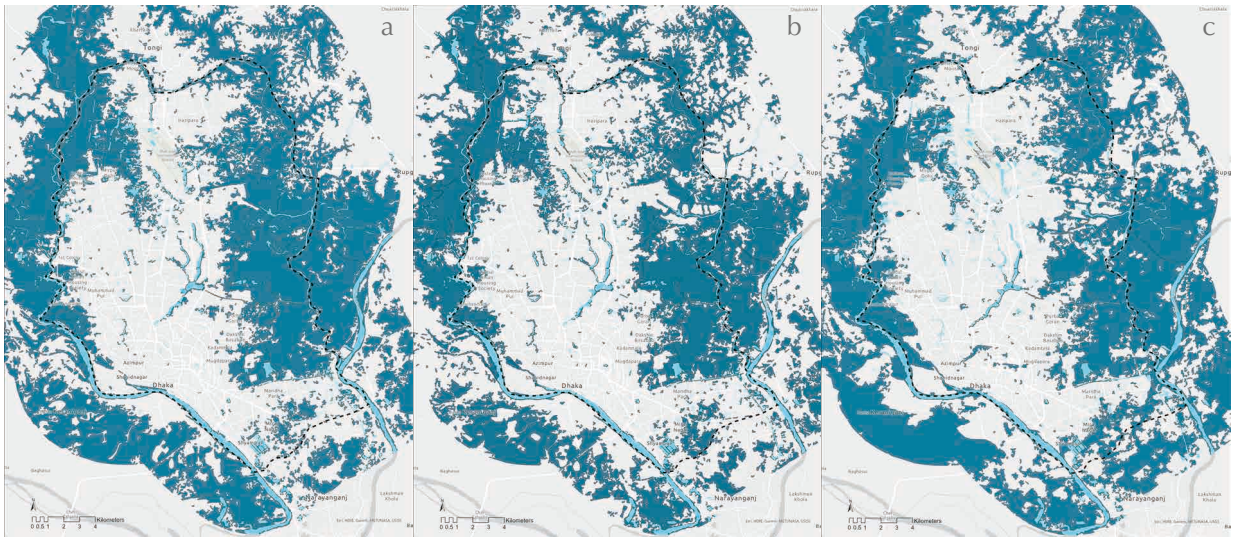

Figure 7 Flood scenario of Dhaka city in (a) 2004, (b) 2007, and (c) 2014.

Figure 8 Current scenario of flood in Dhaka city, 2022, source: https://www.aa.com.tr, 2022

overlapped and connected with a maximum number of other roads. They are the major connection of Dhaka city and any disruption of these roads can hamper regular traffic and daily life of the city. Eventually the orange and yellow are moderate connection and are vibrant at the local scale. The blue with lesser flow potential in the overall network circulation the less vibrant network typologies at the block scale. They may have connections with each other in some areas, but some of them are found in culde-sacs. So, any disruption in them can discontinue the connection between the blocks.

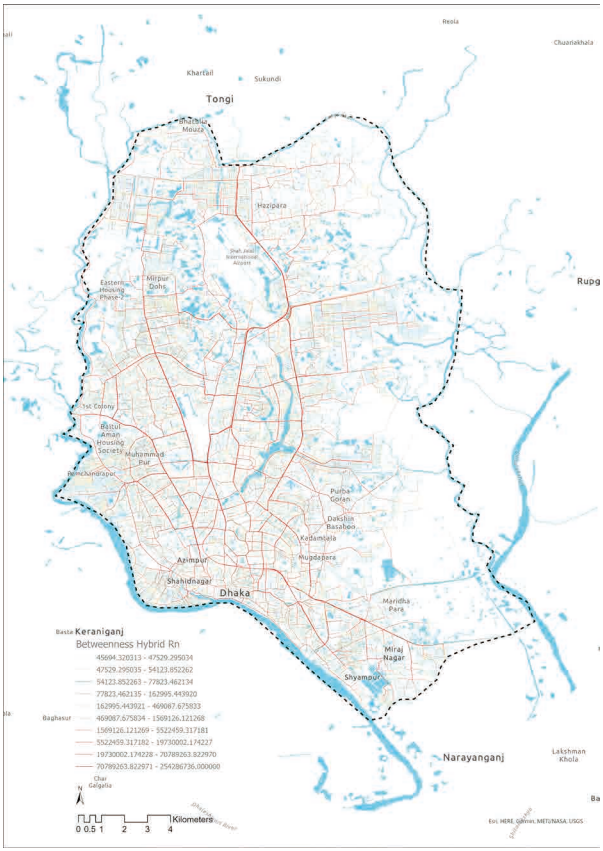

Figure 9 Road Network during a regular day

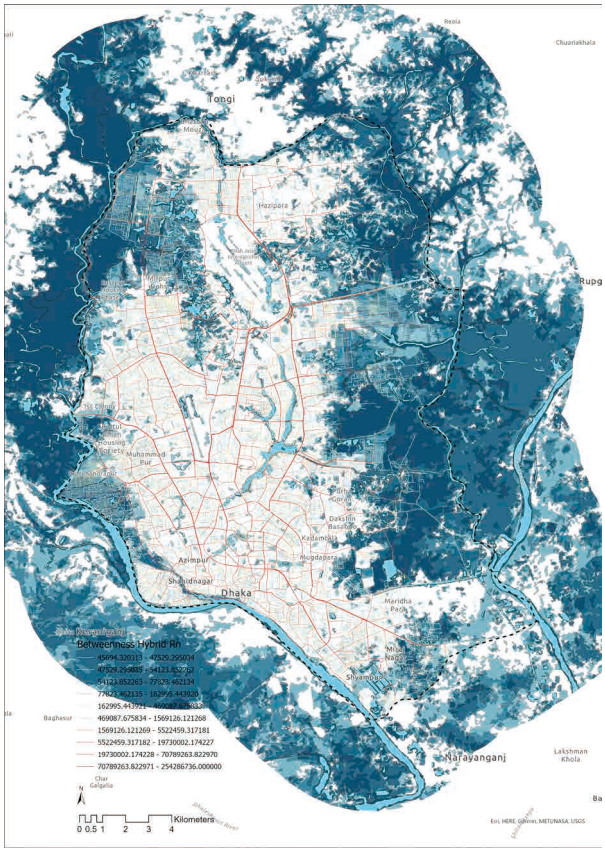

Figure 10 Road Network affected by the flood

Figure 10 visualises the GIS flooding data overlapped with the network analysis of Dhaka city. Using flood data for the years 2004, 2006, 2014, and 2016. Darker shades of blue express the area which is flooded most of the time during the respective years. We can conclude from the data that, only a few of the major connections are flooded during this year. Most of the impact of disruption of the road network is the low-lying areas. At the meso-scale some of the blocks are entirely flooded, while few of them are impacted partially. Because of the lack of comprehensive pluvial and fluvial data, the central part of Dhaka shows no significant impact of flooding. Here we are discussing only the area which is flooded during the given years. The light blue color is showing the water network of Dhaka.

In the Figure 11, three strategic areas of Dhaka city are selected to understand the relationship at Meso-Micro scales. Some of the road connections which show significant impact from flood-

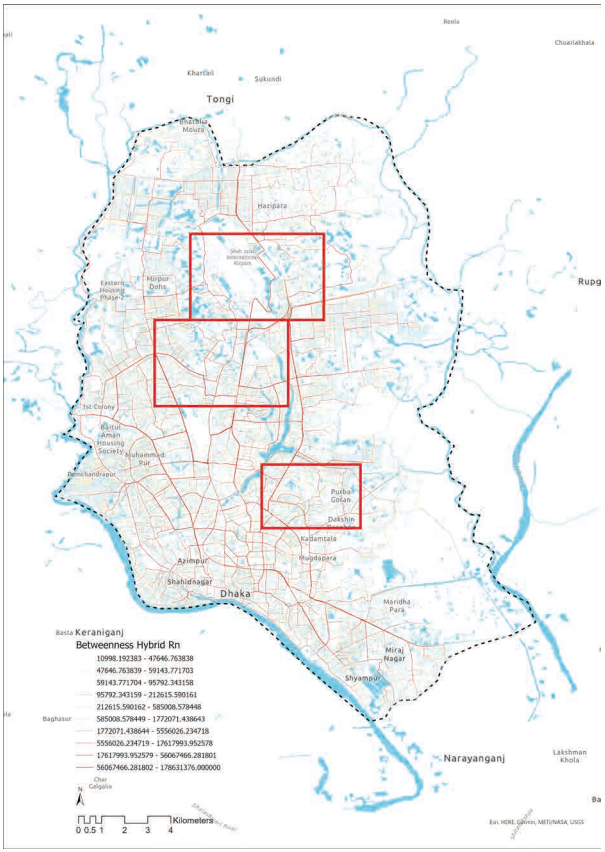

Figure 11 Impact of flood over the street network of Dhaka

ing are discontinued to analyse and visualise an "after" flooding scenario using sDNA and GIS. Here the impact of flooding has massive traffic implications on the adjacent network. Some of the less busy and narrower roads become liable for higher capacity of vehicles going through them, in order to maintain connectivity with different parts of the neighbourhood. Based on the understanding of possible alternatives from the street network we can propose some guidelines for them as well.

5.2.1 Flood exposure: impact on street network

Meso-scale street network analysis is illustrated in Figure 12, Figure 13, and Figure 14, where the impact of flooding over the street network is visible. To identify the level of disruption and change in the street network we analyzed that again. The Street network before flooding is illustrated in Figure (a) and after flooding scenario is shown in Figure (b). By sDNA analysis in Figure 12, it is visible that traffic flow rate increases into the surrounding flooded areas. Disruption in a major road between the eastern and western parts of Dhaka is affecting the local roads. For this instance, network analysis is helping to find out the best alternative fastest and shortest route. Therefore, the local road with minimum width becomes the best alternative and that has many possibilities to make traffic congestion in this area. The possible alternative road with maximum traffic flow is shown in red color in Figure 12(b) has only a 3.5meter road width and eventually travel distance increased by 68%. Some other local roads also become possible alternatives as well as less traffic flow to high flow by changing the color from yellow to orange and red.

However, the performance of road network is affected by flooding, but it should be deemed that higher capacity roads suffer most because of this interruption. In Figure 13, a major road linking the entire north and south zone of Dhaka city is interrupted by flood. From analyzing the street networks after flooding situation, it is noticeable that the maximum travel opportunity with red color has also increased here. In Figure 13(b) some of the roads become less to high flow potential by blue to red (tertiary/local

(a) Regular day street network with flood

(b) Street network after interrupted by flood

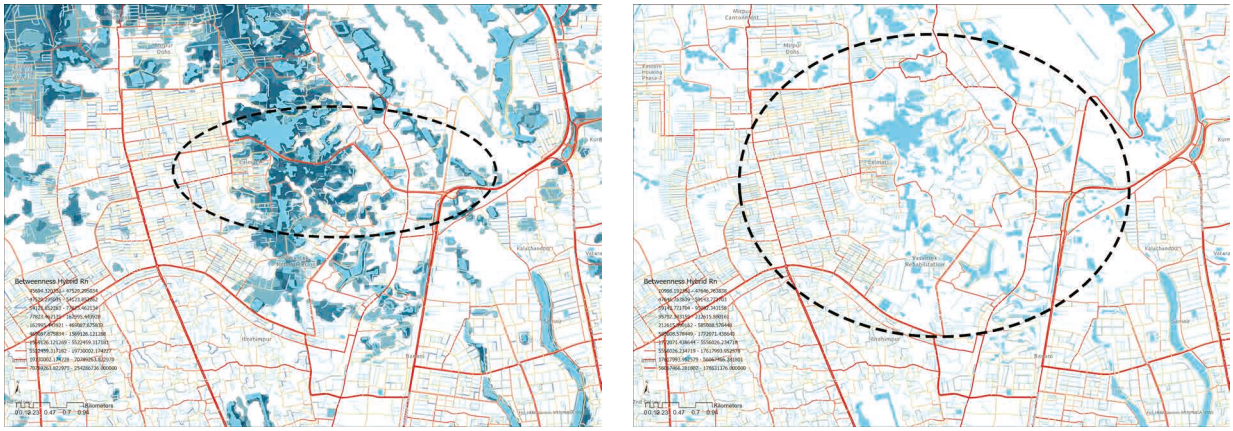

Figure 12 Flood impact on the east-west major connection of Dhaka

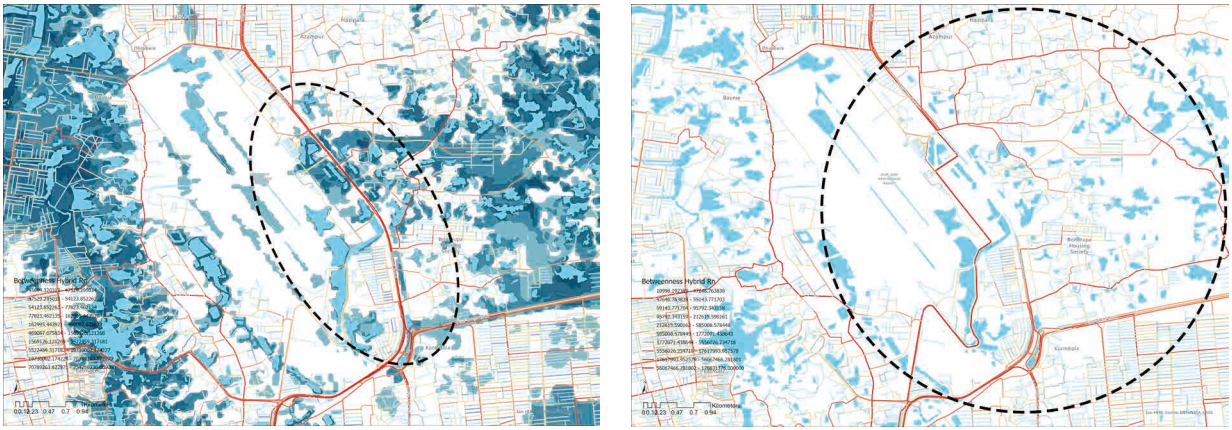

Figure 13 Flood impact on the north-south major connection of Dhaka

road), which denotes that the local roads now become the major connector between the northern and southern parts. Although one of the new major connecting paths connects a private property of Bangladesh Air force and another path is a local road with only 3meter road width. Which cannot support traffic of this major road, also using that road increases the travel distance by 250%.

In the Figure 14 a notable that local roads between Khilgaon and Banasree area faces the disruption in the network during flooding. The angular and shortest connections of this area shift their traffic to the main roads. Because of already having many commuters in the main road makes that more congested. It becomes a dire situation in respect of communication for the habitants of this area. Eventually travel

(a) Regular day street network with flood

(b) Street network after interrupted by flood

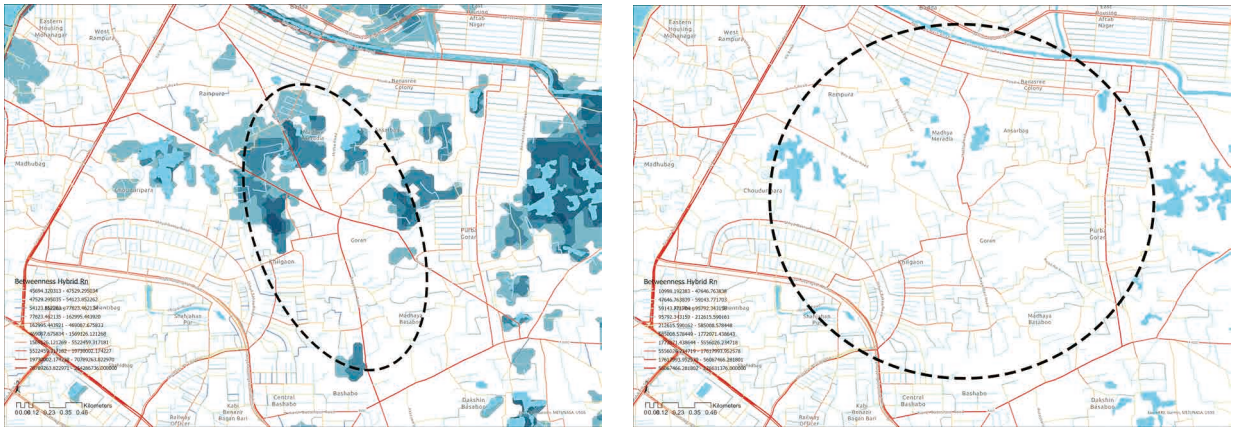

Figure 14 Flood impact at the meso-scale in Khilgaon residential area, Dhaka

Flooding impact scenario /	Flooding situation	Betweenness Hybrid R400		Betweenness Hybrid Rn	
		before	after	before	after
Scene 1		138.33	138.33	3,687,674	9,994,876
Scene 2		32.33	32.33	617,464.3	23,454,930
Scene 3		5.33	5.33	1,306,064	9,055,464

Table 1 Changes in BtHn values in before and after situation of flooding in selected roads

distance can increase by 300% for taking the alternative possible connection. Only few connections with a width of 3meter roads does not support the average traffic flow.

Table 1 defines that that the BtHn values are constant for meso-scale analysis where R=400 for the walking distance convenient. But, at the macro-scale where R=n, the values are changed because the road network has different impact at the city scale. Therefore, during the flooding situation community level pedestrian connection is not interrupted much but the city level, streets cannot hold the situation without possible alternatives.

5.3 Proposed Strategies

Based on the analysis and studies we can propose certain proactive strategies which can help to solve the issue. These strategies can be implemented at the urgency and duration of the implementation. We can propose short and long term strategies, beneficial to planning immediate and future scenarios.

Short-term strategies can be surgent solutions to con-

Figure 15 Existing situation of the potential alternative roads during flooding time

tinue the street network during the flooding event. They could be:

i. Optimize/ redesign/ retrofit
- Widening some existing roads
- Retrofitting roads with water discharge system

ii. Surface strategies
- Permeable pavement
- Breathable construction materials

Long-Term strategies needed for making a permanent solution for this issue. These long-term strate-

gies could be implemented for future development of any flood-prone city and living with water lifestyle. They could be:

i. Improve drainage system
- Underground drainage network
- Expanding the capacity to discharge more water

ii. Introducing new technology
- Floating road
- Bioretention pond and engineered rainwater garden
- Automated water discharge pump
- Traffic warning system

6 Conclusion

This research demonstrates that flooding data applied with network analysis to examine the impact of the flood over mobility of any city. Proposed methodology distinguishes the adverse relationship between them and the direct impact of flooding over street network. Here all the data are analyzed and illustrated visually to show the consequences and possible alternative solutions. The government and authority of flood-prone cities can use this research to enhance flood mitigation policies. Nevertheless, this research still has limitations with data. Recent GIS data and updated spatial network analysis can provide a more accurate result that can be more responsive and practical to implement. The typology of the road network, the flow of vehicles, and the width of the roads may have a different impact of flooding. A comparison between different street networks during flooding and the non-flooding situation can testify to the role of spatial network analysis more precisely to develop a flood-resilient city. Other correlated data like land use, pedestrian connection, and traffic flow

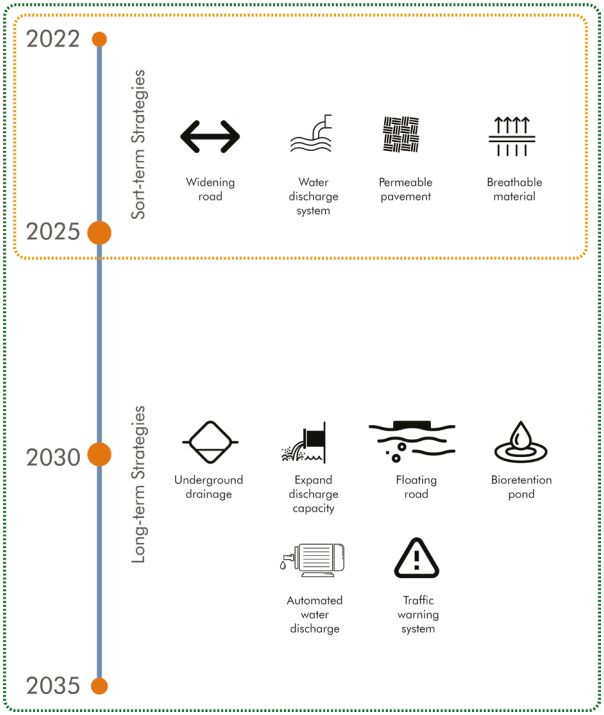

Figure 16 Timeline for the strategies

rate should be considered for a wider insight into the flooding impact on the cities.

Finally, this study adds a comprehensive strategic tool for the existing and proactive planning policy which can assist relevant authorities in developing a forward-looking strategic vision for adaptive flood-resilient city development.