



NETWORK CENTRALITY ASSESSMENT (NCA): ASSESSING THE TRANSPORT NETWORK RESILIENCE TO URBAN FLOODING

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ABSTRACT

This study presents a methodology to assess transport network resilience to urban flooding. The proposed methodology is developed based on the centrality measures and graph theory. The study utilises Open-Source GIS tools to compute betweenness and closeness centrality values. The case study was carried out in Greater Colombo - Sri Lanka, with reference to three significant urban flooding events in 2010, 2016, and 2017. The study assessed the resilience of road network in terms of topological impacts and accessibility changes.

The results revealed three key findings. First, over 60% of road network revealed a significant change in its topological structural coherence during each flooding event. This was particularly pronounced in vehicular movements relative to pedestrian movements. Second, the study revealed a redundant depreciation of the transport accessibility as it shifted from city centre to peripheral areas creating temporary accessibility hotspots in the periphery. Third, a significant drawback of the resilience of road network was identified in terms of the deviation from the shortest path, increasing the travel time and trip length. In overall, the study concluded that the proposed methodology can be utilised as a planning and designing tool to assess road network's resilience devising precautionary measures to mitigate disaster risk.

Keywords: *Urban Flood, Transport Planning, Network Centrality Assessment, Open-Source GIS, Transport Network.*

1. INTRODUCTION

Flooding is considered one of the most destructive natural hazards in both local and global contexts which impacts urban livelihood in multiple ways [1]; [2]. According to the World Meteorological Organisation (WMO), 47% of flood and storm-related events have affected 2.3 billion people in the world during the decade from 1995 to 2015 [3]. Therefore, mitigating flooding impact and making cities safe and resilient has been a widely discussed subject in major global agendas, particularly when examining how to make cities more inclusive, safe, resilient, and sustainable, notably under Sendai Framework for Disaster Risk Reduction 2015-2030, the Sustainable Development Goals (SDG) for 2030 and the World Humanitarian Summit Commitments to Action and the New Urban Agenda [4].

In the urban context, flooding impacts built environment, land, properties, and population; thus defined as urban flooding [5], [6]. It severely impacts the transport system, disrupts the flow of essential services and weakens the accessibility of the residential population in urban areas [7]. Extreme rainfall or uncertainties, an agglomeration of population, unplanned urban development, increasing imperviousness and poorly maintained drainage systems lead to frequent flooding causing damage to surface infrastructure and disruption to transport networks in urban areas [8], [9]. However, in the contemporary urban development process, evaluation of flooding impact on transport system is usually a micro-scale in-situ impact assessment. This severely underestimates and misrepresents the actual flooding impact and causes the failure of disaster-resilient measures [10], [9]. An alternative framework, therefore, becomes necessary to assess transport network resilience in a holistic and reliable manner.

Transport networks feel the immediate impact of flooding because roadways become the preferred path for storm water to flow. leading to fast inundation. Thus, it may cause accessibility breakdowns within the urban system. However, considering past urban flooding events in the Western Province in Sri Lanka (refer to Table 1), the impact on the transport system appears considerably low (impacted on less than 5% from the entire transport network of the Western Province). As the transport system is an interconnected network, a failure in one road segment may impact the transport flow of the entire network. This is an aspect that may not have been adequately quantified in recent studies [9], [11]. Further, knowledge regarding the behaviour of transport systems under flood conditions provides deep insights into the development of disaster resilience measures for cities.

Hence, this study attempted to consider the transport network as a holistic interconnected system, and to apply the Network Centrality Assessment (NCA) method to estimate the transport system's resilience in coping impacts from urban flooding.

Table 1: The impact of major flooding events on the transport System in the Selected Area.

The year of Flooding Event	Inundated Road Length by Type			Inundated Road Length as a % of total Road Length		
	A Class	B Class	Other Roads	A Class	B Class	Other Roads
2017	4,823m	4,125m	64,097m	1%	0%	1%
2016	6,814m	4,761m	86,074m	2%	1%	1%
2010	8,493m	6,958m	117,821m	3%	1%	1%

A number of recent studies have been examining the impact of flooding on the vulnerability of road networks with reference to traffic speed, travel time, inundation area, flood depth, and level of accessibility. The existing flood impact assessment methods can be categorised into four approaches: scenario-based, strategy-based, simulation-based, and mathematical model-based [12], [13]. Additionally, some studies have developed vulnerability indices for anticipated flooding events [8], [14]. This paper has focused on simulation-based approaches. Under simulation-based approaches, existing studies have employed several simulation tools including GIS-based applications, SWMM, City CAT, Spatial Importance Measure (SIM), Macroscopic Fundamental Diagram (MFD) etc. [15], [16]. A few of the recent studies have utilised advanced computational assessment methods based on Machine learning algorithms [17], [18].

Road networks perform a crucial role during emergency flood situations, ensuring accessibility to amenities, and providing alternative pathways avoiding inundation areas (flood preventive route options). But lack of studies about the resilience of transport networks in real case studies with extreme flooding events. In the era of Anthropocene, where climate change and environmental degradation have become a reality, planning for infrastructure resilience, particularly for transport networks, has become a national and worldwide imperative in recent years [19]. In order to fill this gap, this research developed a methodology to assess the transport network's resilience for urban flooding utilising the Network Centrality Assessment (NCA) tool [20], [21], [22]. The case study was carried out in Colombo, Sri Lanka. The analysis was primarily based on free and open-source geospatial software. The study conceptualised the impacts of urban flooding on the transport system as a three-dimensional concept as depicted in Figure 1.

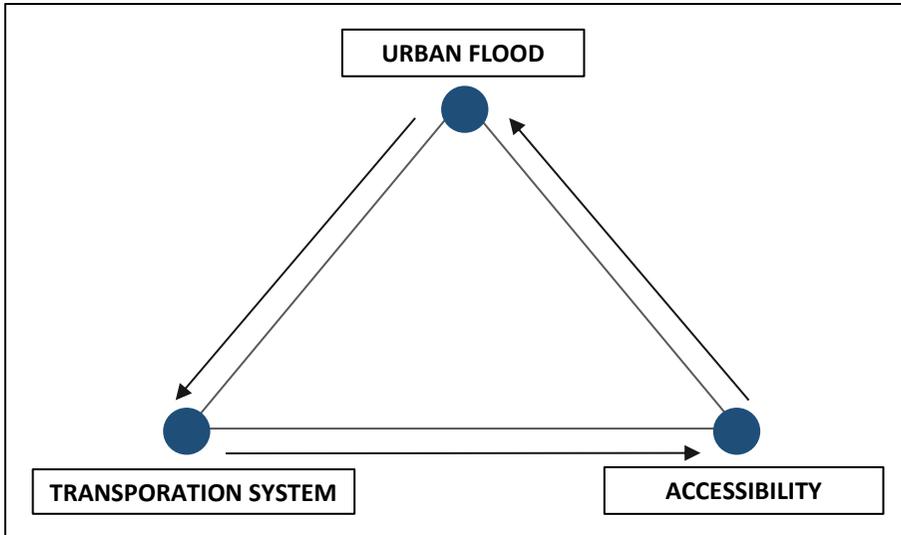


Figure 1: Conceptual framework of the study

The main objective of the research is to develop a methodology to assess the transport network’s resilience to urban flooding. The study first investigates the changes in topological characteristics of road networks due to flooding, then investigates the changes to the relative importance of road segments under flood-inundated situations, and finally, proposes a framework to assess the transport networks’ resilience for urban flooding.

1.1 Network Centrality Assessment

The concept of ‘Centrality’ originated in the 19th century as a concept explaining the interactions and interrelations of systems [23]. Network Centrality was developed based on graph theory and frequently applied to assess the transport system’s accessibility [21], [24], [22]. In classic urban geography, network centrality was applied to measure the attraction and interaction of each node in a road network based on topological and geometric properties [25]. Currently, the concept has been extremely successful and permeated the methodologies employed for a myriad of urban models for measuring accessibility [26]; [27]. Therefore, this study utilised the network centrality to assess the transport network’s resilience to the urban flooding.

In order to assess the transport network’s resilience for the urban flooding, this study utilised two NCA parameters, which can measure centrality in terms of topological characteristics of the transport system.

First, this study utilised closeness centrality (CC) [23] parameter to measure the relative impact on each road segment in terms of accessibility (i.e., the attraction to trip destinations) during the flood-inundated situation compared to the baseline situation.

$$CC_{i[r]} = \frac{(N - 1)}{\sum_{j \in N, j \neq i} d_{ij}} \quad (1)$$

Wherein,

- CC_i : Closeness centrality of the road segment ‘ i ’
- N : The total number of segments in the road network
- d_{ij} : The shortest path distance between road segments ‘ i ’ and ‘ j ’
- r : The radius of influence of the road network

Secondly, the study utilised the betweenness centrality (BC) [23] parameter to measure the relative impact upon each road segment in terms of the attraction of pass-by trips during the flood-inundated situation compares to the baseline situation.

$$BC_i = \frac{1}{(N - 1)(N - 2)} \sum_{j,k \in N; j \neq k; k \neq i} \frac{P_{jk(i)}}{p_{jk}} \quad (2)$$

Wherein,

- BC_i : Betweenness centrality of the road segment ‘ i ’
- N : The total number of segments in the road network
- P_{jk} : The number of geodesics between road segments ‘ j ’ and ‘ k ’
- $P_{jk(i)}$: The number of geodesics between road segment ‘ j ’ and ‘ k ’ that passing through road segment ‘ i ’

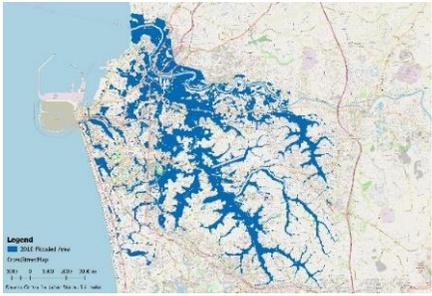
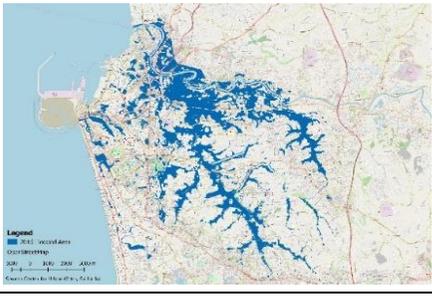
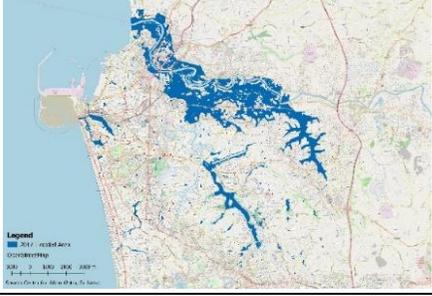
In order to compute the above-discussed network centrality parameter, the study utilised the transport data extracted from the Open Street Map (OSM). Further, the study utilised sDNA toolkit [28] to carry-out the network centrality assessment under the Qgis (Quantum Geographic Information System) environment. The detailed steps are discussed under the methodology section of this paper.

2. METHODOLOGY

2.1 Study Area

In order to assess the transport network’s resilience for urban flooding, the study area was selected as the 40km buffer zone of the Colombo Core Area, which is severely affected by urban flooding incidents. The selected area consists of a highly-urbanised zone and covers 2260 sq km of land area with an approximate population of 4.7 million [29]. The selected area consists of two major rivers (i.e., Kalani Ganga and Kalu Ganga), and a stream (i.e., Aththanagalu Oya). Those water bodies caused heavy flooding every rainy season. The study only included three significant flooding events considering the spatial data availability. Table 2 depicts the characteristics of the selected flooding events.

Table 2: The characteristics of the Selected Flooding Events.

Flooding Event	Impacted Area	Affected Population in the study area	Flood Inundation Area
17 th May, 2010	41 Sq.km	91,000	
15 th May, 2016	32 Sq.km	228,871	
25 th May 2017	22 Sq.km	21,000	

Source: Author compilation based on Center for Urban Water (CUrW) Database.

2.2 Description of Data

The data used for the study is summarised in the Table 3. The study completely utilised open-data as it is financially affordable in developing countries.

Table 3: Data Description

Data Type	Year	Source	Description
Road Network	2020	Open Street Map, (OSM)	GIS File (Polyline)
Flood Maps	2010, 2016 & 2017	Center for Urban Water, Sri Lanka, (CUrW)	Image Files (JPEG)

2.3 Study Framework

The study utilised the above-mentioned transport network to calculate the network centrality. The study assessed the transport network centrality considering two scenarios as (i) road network at the baseline situation, and (ii) road network under the flood-inundated situation. The overall method of study is depicted in the Figure 2.

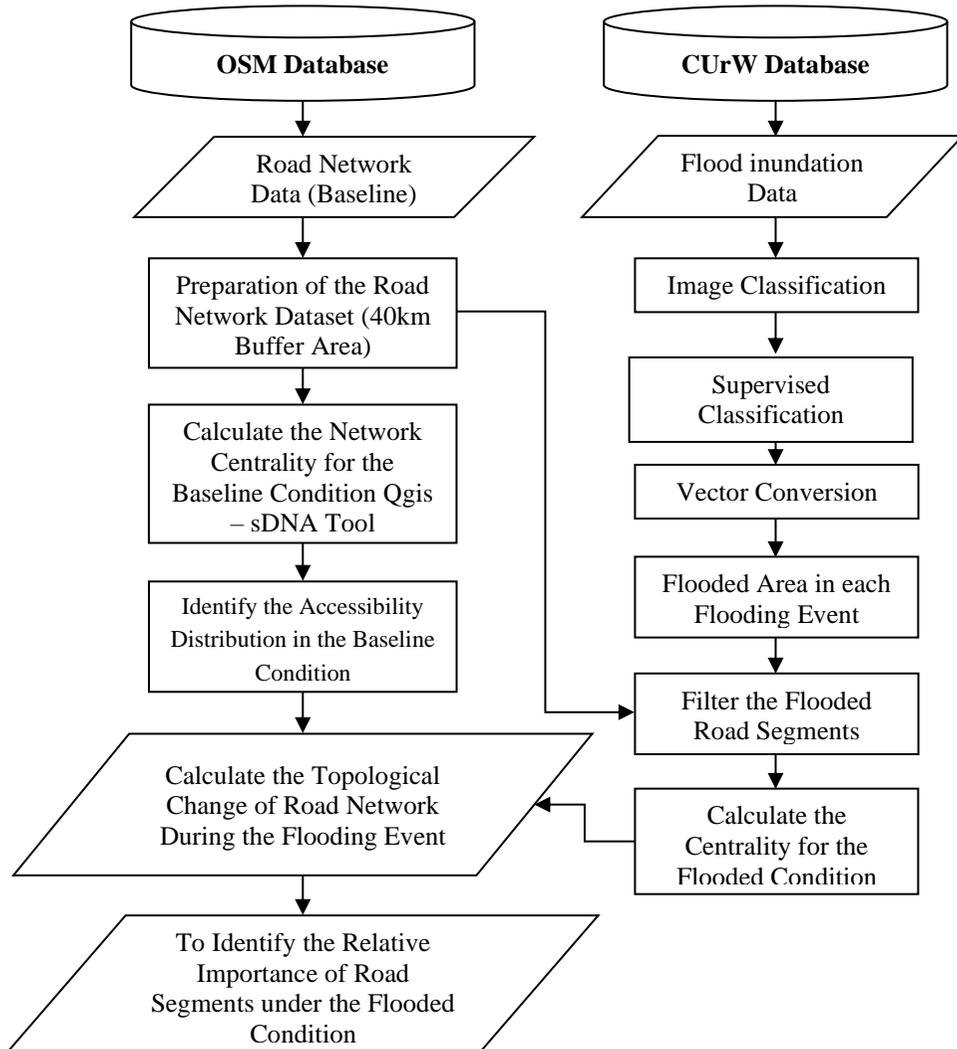


Figure 02: Study Framework

2.4 Computation of Network Centrality

The study utilised the Spatial Design Network Analysis (sDNA) tool [30] in Qgis environment to compute BC and CC. This study utilised ‘road-segments’ graph method [31] to convert the real road network into the network graph. In the road-

segments graph method, the road segments are termed as 'links' and the road intersections are termed as 'nodes'. In preparation of the graph, the study utilised 'road centerlines' (i.e., vector line data that represent the geographic centre of the rights-of-way of a given road segment). In the graph, segments represent the physical locations of trip origins and destinations. The study considered two influence areas as $r=1\text{km}$ and $r=10\text{km}$ to capture pedestrian movements and vehicular movements respectively.

3. ANALYSIS AND RESULTS

After obtaining the network centrality results, the study analysed the topographical change of the road network and accessibility change of the road network during each flooding events.

3.1 Topographical Change of the Transport System

In order to study the topographical change of the transport network due to the flood, the study computes the change of road centrality under each flood event and compared it with the baseline situation. The study utilised Python programming language to calculate the change between the flooded condition and the baseline condition. It helps to process large size databases efficiently compares to the Microsoft Excel or GIS applications.

When considering the pedestrian movement (refer to Table 4 below), flooding directly impacts only 3% - 7% of the road segments from total road length. However, more than 40% of road segments recorded changes in closeness centrality values due to the flood. Therefore, results indicate that, even though the direct physical impact to the road network is less, the flooding event has significantly decreased the road centrality by disconnecting the shortest paths which are connected origin and destination, (i.e., O-D) trips of pedestrian movement in the network. Hence, it severely impacts to decrease the level of accessibility of the entire transport network by more than 25%. Further, it caused to reduction in the BC by more than 23% of the road network. It made a significant impact on the pass-by road segments that are utilised by the pedestrians.

When considering vehicular movement (refer to Table 4 below), more than 90% of road segments have recorded centrality changes due to flood. It is mainly caused in the long-distance travel failures due to the decline of CC and BC values. In general conditions, a majority of trips are generating in the suburban and peri-urban areas and then move towards to the CBD. Hence, failures of shortest paths in the daily transport routes may impact on the entire transport system significantly. This clearly indicates by the findings that even though the direct physical impact to the road network is less than 7%, it caused to reduce around 60% of betweenness and closeness centrality

from the transport network. Moreover, this decline of CC values impacted on the O-D trips in the transport network. Further, the decline of BC values impacted on the pass-by trips in the transport system.

Table 4: The Network Centrality Change by Flooding Event.

Type	Measure	Flood Event	Increase Centrality	Decrease Centrality	Total Change	No Change	Flooded Road Segments in terms of length
Pedestrian Movement (1Km)	CC	2010	2810 (16%)	4658 (26%)	7468 (41%)	9377 (52%)	1204 (7%)
		2016	2818 (16%)	4896 (27%)	7714 (43%)	9385 (52%)	950 (5%)
		2017	2816 (16%)	5081 (28%)	7897 (44%)	9543 (53%)	609 (3%)
	BC	2010	2587 (14%)	4195 (23%)	6782 (38%)	10063 (56%)	1204 (7%)
		2016	2600 (14%)	4426 (25%)	7026 (39%)	10073 (56%)	950 (5%)
		2017	2636 (15%)	4569 (25%)	7205 (40%)	10235 (57%)	609 (3%)
Vehicular Movement (10km)	CC	2010	6801 (38%)	10044 (56%)	16845 (93%)	0	1204 (7%)
		2016	6884 (38%)	10215 (57%)	17099 (95%)	0	950 (5%)
		2017	6799 (38%)	10641 (59%)	17440 (97%)	0	609 (3%)
	BC	2010	5908 (33%)	10562 (59%)	16470 (91%)	375 (2%)	1204 (7%)
		2016	6114 (34%)	10603 (59%)	16717 (93%)	382 (2%)	950 (5%)
		2017	6241 (35%)	10829 (60%)	17070 (95%)	370 (2%)	609 (3%)

In addition to the statistical analysis, the study also measured flood impact to the transport system as a spatial representation as depicted in Figure 3 below.

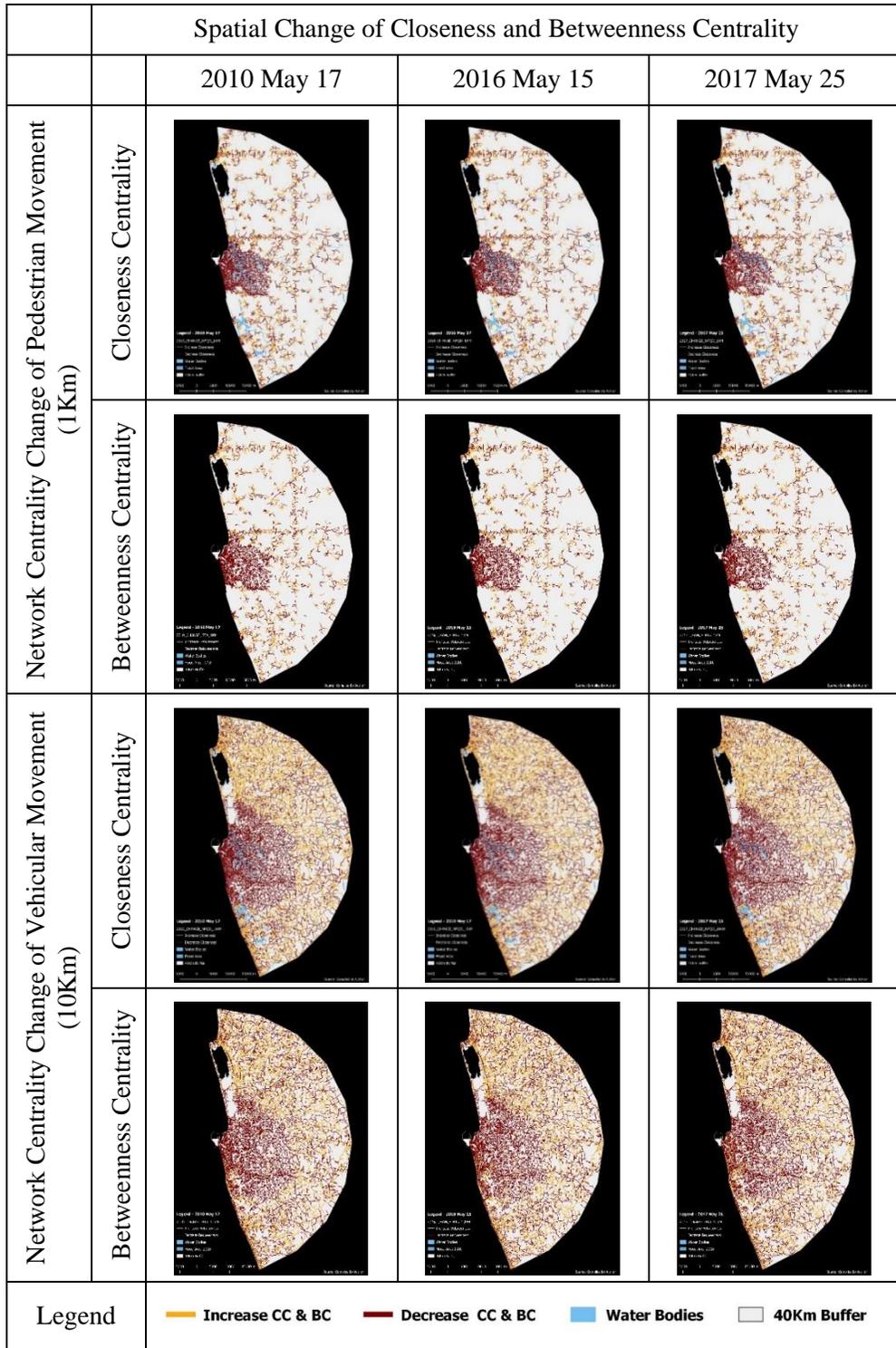


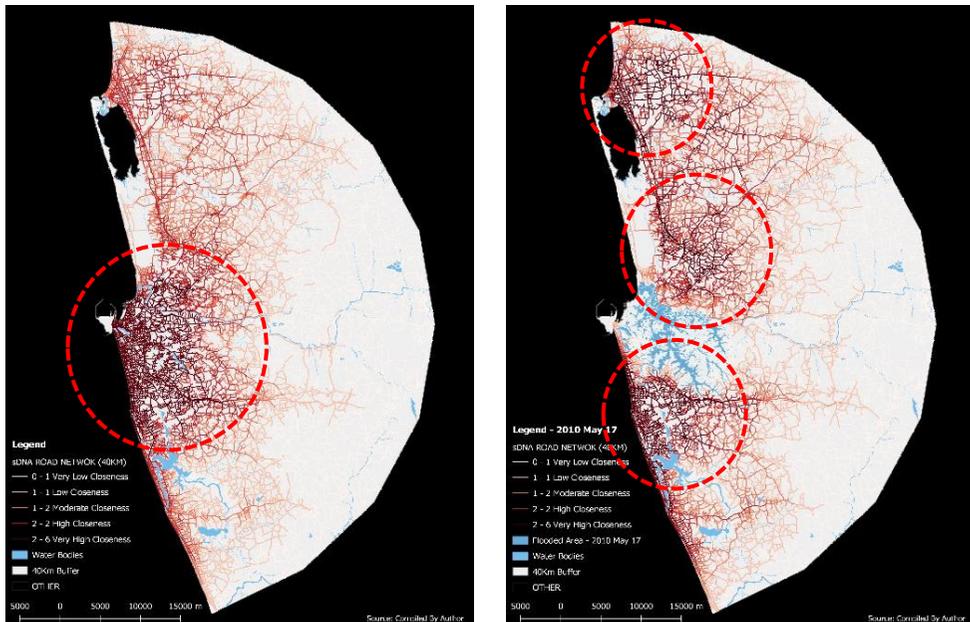
Figure 3: Topographical Change of Closeness and Betweenness Centrality Measures in Pedestrian & Vehicular Movement

As depicted in Figure 3, in the vehicular movement failure of road segments significantly impacts to the entire transport system because in the long-range entire transport system function as an interconnected system. Therefore, it clearly proved that the impact of the urban flood affects the entire transport system in a significant manner.

3.2 Accessibility Change of the Transport System

The study further evaluates the accessibility changes of the transport system due to urban flooding events.

It is important to notice that, in the baseline condition accessibility is predominantly concentrated in CBD area and then gradually trickles down towards the suburban areas through major arteries (Figure 4 – Left). But, with flood temporal accessibility hotspots have emerged in the outer areas, (i.e., suburban and peri-urban areas) of C where have relatively good accessibility during the flooding condition (Figure 4 – Right). Thus, these potential locations can be identified as potential areas for the disaster resilience. Also, these locations are ideal for enhancing facilities and infrastructure to provide adequate service during the flooding events in the future scenarios. However, validating this argument requires further studies regarding the socio-economic, transport and other infrastructure capacities of those temporal accessibility hotspots to understand the functional capability because, this study only focused on the accessibility change of the transport system.



**Figure 4: Accessibility concentrated of In Regular Situation (Left side).
Emerging temporal accessibility hotspots due to the flood (Right side)**

Further, the study considered the statistical distribution of network centrality parameters in the baseline and the flooding events. The study normalised the centrality values of each flood event and distribute them according to the length of the individual road segment (LLen) as depicts in the figure 5. It denotes that in the baseline condition both centrality parameters are significantly higher. However, when it comes to the flooding situations CC value declines from 0.350 (Normalised CC value) to 0.325. Also, the figure denotes, extensive impact on road accessibility in the year 2010 as it covers the 41sq km and declined accessibility up to 0.275. The most significant identification of the graph can be noticed in the tail of the distribution because in the lower scale all the lines are growing in a similar manner and when it comes to the tail it shows a very dynamic distribution. This mainly caused the flooding impact to the larger road segments are significantly impacted on the decrease of road centrality. Further, this considerably higher in the betweenness centrality as the loss of shortest path roads segments significantly impact to the pass-by movements of the transport system (refer Figure 5).

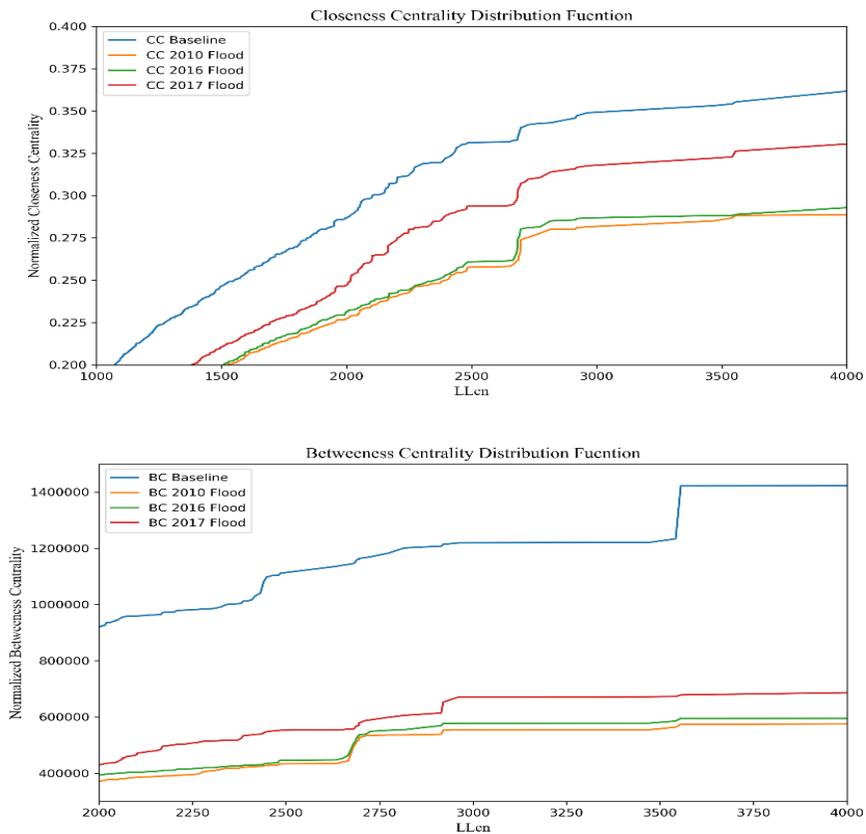


Figure 5: Closeness Centrality (Above) and Betweenness Centrality (Below) Distribution Function (Display Only the Tail of the Distribution)

4. DISCUSSION AND CONCLUSION

The study was intended to assess the transport network's resilience to the urban flooding by utilising an NCA-based approach. The study utilised two centrality parameters: (i) Closeness and (ii) Betweenness centrality to measure network the centrality of a given road network under two different scenarios as the baseline scenario and flood-inundated scenario.

The study discussed the impact of flooding on pedestrian movements and vehicle movements respectively. It was revealed that the impact of flooding is more significant over the vehicle movement as it affects the entire transport network. As revealed through the closeness centrality variations, urban flooding caused a temporal shift of the accessibility, particularly from central business districts (CBD) towards the periphery due to the inundation of road segments. As the peripheral road segments found to be more redundant, the study suggests that improving the infrastructure facilities and services of peripheral areas may help to provide adequate services during the future flooding events. Under the betweenness centrality, it was measured the transport network's resilience, particularly referring to the pass-by (intermediate) trips over road segments. Thus, it was identified a significant drawback of the resilience of road network in terms of the deviation from the shortest path, increasing the travel time and trip length. Therefore, the study emphasised the requirement of a holistic approach in order to enhance the flood resilience of road networks focused on the failure of critical road segments which may affect the entire network.

Future research on this domain may focus on testing the applicability of the proposed method for the other localised natural hazards such as landslides and tsunami in assessing the transport network's resilience. Further, it would be interesting to customise the assessment incorporating the relative importance of road segments in terms of access to other critical infrastructure and evacuation shelters (i.e., hospitals, stations, schools, etc.).

the proposed methodology can be employed to enhancing disaster resilience of road networks, particularly in planning and designing road networks, capacity improvements, and retrofitting of structures.

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