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Climate change and urban road transport – a South African case study of vulnerability due to sea level rise

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The focus of this investigation was the impact of predicted sea level rise on the road transportation network of the eThekwini Municipality, South Africa. The main objective was to identify the areas within the municipality which are most vulnerable to sea level rise and to develop adaptive responses and interventions in order to maintain road functionality. For the identification of the most vulnerable areas a multi-criteria analysis supported by geographical information system modelling was used. Three areas were identified, namely, the Isipingo, Bayhead and the Umgeni mouth areas. Adaptive road responses have been researched by employing a network analysis of each of the areas identified. Parameters modelled were traffic volume changes, travel time and volume to capacity ratio – for the main roads in the areas identified. The adaptive responses required for each area were found to be different, varying from the addition of a lane to changes in signal settings. Overall this study presents a model of how vulnerability and the development of adaptive strategies to sea level rise could be addressed by municipalities.

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INTRODUCTION

Background information

Urban transportation systems are important contributors to greenhouse gas emissions and climate change, but they are also some of the systems most exposed to changes in weather and climatic conditions. Infrastructure like bridges, roads and railway lines, can be affected by sea level rise, flooding and increased storm events, and adaptation plans should be developed to cater for these events. However, most of the research and regulatory efforts on the issue of transportation and climate change are directed towards quantifying, reducing and limiting carbon emissions. These efforts became particularly relevant in the context of the Kyoto protocol where developing countries committed themselves to reducing overall carbon emissions. This resulted in many countries producing guidelines, inventories and even laws and bills in order to measure and target carbon emissions from all sectors, including transportation. However, "to date the consequences of climate change and changing weather conditions for the transport sector have not received much attention in the literature" (Koetse & Rietveld 2009). Internationally, there is a recognised need to integrate climate change in the transportation planning process (Suarez *et al* 2005; Schmidt 2008; Koetse & Rietveld 2009) in order to cater for, and plan adaptive responses at local and regional level.

This paper explores such adaptive responses for roads, with regard to sea level rise in the local context of the eThekwini Municipality, South Africa. It presents a model on planning adaptive responses in small-scale road networks in the event of major roads being flooded and becoming un-operational.

The eThekwini Municipality has a population of approximately 3,1 million and covers an area of about 2 300 km^2 (eThekwini Municipality IDP 2005). The core city of the municipality is Durban, which is the largest South African port city on the Indian Ocean. Inland it is surrounded by other urban nodes, as well as other more sparsely populated peri-urban areas. These areas are linked through a network of roads. The expected changes in the climate of the eThekwini Municipality area have been researched (CSIR 2006) and the predicted consequences are summarised as follows:

- Increases in the maximum and minimum temperatures by about 2-3°C are predicted, with an increase in the number of hot days experiencing temperatures exceeding 30°C.
- Rainfall will increase slightly. However, the distribution of this rainfall will

change, with longer periods of no rainfall and shorter periods of intense rainfall.

- The sea level rise and increased extreme weather events will result in damage of infrastructure and coastal vegetation. Increased flooding is also predicted. Flooding will result in an increase in the high-level tide and coastal erosion.
- Water availability in the local catchment is predicted to decrease by 157,8 million m^3 for the period 2070-2100, thus resulting in less water being available for human and industrial consumption.
- Loss of biodiversity due to temperature and precipitation changes.

International studies (Dasgupta *et al* 2007) agree with the local study (CSIR 2006) that an increase in the projected frequency of natural hazards (extreme weather events, flooding and sea level rise) is expected at regional level. Therefore, it is necessary to critically assess existing transportation infrastructure and operational systems, and their ability to withstand such changes. This research aims to identify some of the most vulnerable areas within the eThekwini Municipality with regard to sea level rise, and to assess the impacts of projected changes on the surrounding road transportation network.

Defining road vulnerability

One of the most important terms that had to be defined for this study was 'vulnerability'. This is a relatively new notion used in transport network studies, and in the literature the definition is still debated (Lam 1999; Bell & Cassir 2000; Bredica 2002; Iida & Bell 2003; Taylor & D'Este 2004; Jenelius 2008). The concept is linked to reliability, serviceability, incidents and risk. A definition proposed by Bredica (2002) is: "Vulnerability in the road transportation system is a susceptibility to incidents that can result in considerable reductions in road network serviceability. These incidents may be more or less predictable, caused voluntarily or involuntarily, by man or nature". The same author states that "road vulnerability analysis regards the network as a whole and involves identifying a spectrum of incidents, collecting data on probabilities and consequences to estimate risk, performing various studies and experiments to set values for desirable/acceptable serviceability, as well as investigating and assessing the effects of possible mitigation measures and improvement strategies". A review of the studies on this topic shows that vulnerability assessments in road transport networks have been performed at national, regional and international level. Very little work has been done on impacts and vulnerability at local, micro-level, with only a few studies from developed countries (e.g. Suarez *et al* 2005; Jacob *et al* 2007).

The application of road vulnerability used in this study was narrowed down from the definition presented above. Most of the studies reviewed did not take into consideration sea level rise, although extreme weather events (as predicted in climate change) and their consequences were enumerated as risks by some authors. Sea level rise does not fall into this category because it is not seen as a sudden event, as it is predictable to a certain degree through modelling and affects the network at local level, i.e. roads near to coastlines. Therefore, road vulnerability for this study was aimed at the local context and was defined as fulfilling certain specified criteria, as presented further on in this paper in the vulnerability assessment section of the methodology under the headings "The multi-criteria decision analysis model and the use of ArcMap" and "Road vulnerability assessment".

METHODOLOGY

In conducting this study, four distinct steps were delimited. These were: defining the boundaries of the study and collection of data, development of the multi-criteria and vulnerability assessment models and the application of the ArcMap and Emme/2 models, followed by an analysis of the limitations and uncertainties. Through the multi-criteria assessment (supported by the use of ArcMap) three geographical areas were identified. Roads in these areas would have the potential to be affected by sea level rise. The road transport network within these three areas was subsequently investigated by using the Emme/2 transportation network model. Worst case scenarios, in which affected major roads were considered unusable, were modelled and the consequences of changed traffic patterns were measured using specific traffic criteria, i.e. volume, travel time and volume to capacity ratio.

Study boundaries and data collection

In the first step of the study the boundaries were defined, and the components of the transportation system and the choices around natural hazards were narrowed down. With regard to infrastructure, it was decided that the study would focus on **roads** only. With regard to vehicle type, **all vehicles** that made use of the road network were considered. Both public and private transportation were considered. **Operations** were the focus of the Emme/2 modelling and vulnerability assessment. A significant proportion of the analysis and discussion is based on operational performance of the road network. Performance measures mentioned by the National Department of Transport (2005a and 2005b) are mobility, accessibility, liveability and sustainability. Mobility measures were linked to three performance characteristics (volume, travel time and volume to capacity ratio) used by Emme/2. This is also supported by the literature on road vulnerability analyses, as these performance characteristics are used in reliability studies (Bredica 2002 & Jenelius *et al* 2006) and accepted as measurements for the performance of road networks.

From the climatic changes predicted for the eThekwini Municipality (as mentioned above) it is obvious that the two factors that have a major influence on the road network are flooding and sea level rise. This study focused on sea level rise and associated flooding. Such flooding was included in the analysis of one of the case studies (the Umgeni River mouth area), as in this specific case it proved to be very relevant. The projected rise in sea level for this study was based on calculations done by the CSIR (2006). An initial proposed 100-year sea level rise of +0,5 to +0,9 m formed the starting point. The CSIR (2006) study then considered the added effects of severe wind set-up, maximum hydrostatic set-up and wave set-up, as well as the likelihood of the mean high-water spring tide or high astronomical tide occurring simultaneously, and proposed two probable scenarios. This paper used a 100-year sea level rise of 2,8 m (assuming a 0,9 m initial sea level rise and taking into account the added effects), as recommended both by a local specialist (Mather 2008) and the CSIR (2006) report. Although it is unlikely that all factors considered would occur simultaneously, it nevertheless represents a 'worst-case' scenario. During March 2007, exceptional waves reaching the 8 m contour line were recorded in Durban at a few locations for several days (Gordon-McKenzie 2008).

The multi-criteria decision analysis model and the use of ArcMap

A series of vulnerability selection criteria were identified through a process of multiple criteria decision analysis (MCDA). The procedure generally followed was that presented by Belton and Stewart (2002), but in a more simplified form, as a comprehensive MCDA approach was beyond the scope of this study. A model for assessment was built by using the following criteria (presented in decreasing order of preference): within eThekwini, affecting major roads, within the 2 m contour and within the 4 m contour following the coast and river mouths.

Initially it was hoped that the 100 year sea level rise projection of 2,8 m could be used as the only contour criterion. However, contours were only available at 2 m intervals at the time of modelling. Thus the 2 m contour was

Table 1 Vulnerability assessment process (Source: Adapted from Mehdi 2006)

Step 1. Engage affected parties.
Engage and retain decision-makers and those affected by future climate change.
Step 2. Assess current vulnerability.
Use experience to assess impact and potential damage. Understanding adaptive capacity, critical threshold and coping ranges is helpful.
Step 3. Estimate future conditions.
Use climate environmental and socio-economic scenarios to determine future policy and development.
Step 4. Estimate future vulnerability and identify adaptation strategies.
Use the two previous steps (current vulnerability and future conditions) to identify future vulnerability and adaptation strategies.
Step 5. Decision and implementation.
Incorporate results into risk management strategies and follow through with these.

Table 2 MCDA characteristics of areas identified to be vulnerable to sea level rise

Characteristics	Isipingo Area	Bayhead Area	Umgeni River Mouth
Land use	Industrial and residential. The Southern Durban Basin to which the area belongs is one of the most important industrial hubs in the region	Industrial (linked to the harbour)	Residential, commercial and recreational (including a mangrove nature reserve)
Extent of area below 2 m predicted to be affected by sea level rise	About 5 km^2	About 4 km^2	Large areas of land, reaching up to 10 km inland along the Umgeni River and spanning 8 km along the coast
Number of major roads situated below the 2 m contour line	Two, i.e. Prospecton Road and Joyner Road	One, i.e. Bayhead Road	Several bridges intersected the 2 m contours, closest to the sea being the M4 bridge and the Masabalala Yengwa Avenue bridge
Number of major roads situated below the 4 m contour line	One, i.e. N2 Highway	Two, i.e. Bluff Road Iran Road	Same as above
Essential services in proximity to the area	1 school 1 major hospital 1 fixed clinic 2 police stations 1 fire station railway lines gas lines	3 schools 1 police station substantial lengths of railway important for the harbour activities	4 schools 1 clinic

considered as 'extremely vulnerable' and the 4 m contour was created as a 'safety net' since it represented the next contour interval.

The vulnerability selection criteria established through the MCDA were plotted onto a spatial map by using ArcMap. ArcMap is part of the ArcView software, which is a GIS software developed by ESRI (ESRI 2008). This software allows users to view and edit GIS data held in flat files, known as shape files which form different layers of features. In this case, each layer represented a criterion (or feature used in the value-added judgement process) from the MCDA. ArcMap modelling therefore served as a useful tool to summarise the MCDA process in one step. The outcome was a map showing the areas fulfilling the four criteria (within the municipality, affecting major roads, within the 2 m or 4 m contour), and therefore considered the most vulnerable. This lead to the identification of three geographical areas within the eThekwini Municipality, which became the case studies on which Emme/2 modelling was performed. These areas are: Isipingo, Bayhead and the vicinity of Umgeni River mouth.

In addition to the MCDA analysis and the use of ArcMap, visual inspection was undertaken, and with the help of maps, the location of basic or essential services in the three study areas was further investigated. The essential services considered were: hospitals, fixed clinics, South African Police Services, fire stations, educational institutions, railway lines, landfill sites and gas lines. These were listed in decreasing order of preference.

Vulnerability assessment

To assess the specific vulnerability within each of the three areas (Isipingo, Bayhead and Umgeni mouth) identified through the MCDA analysis, the process outlined in Table 1 was adopted.

In the first stage, decision-makers and stakeholders were engaged in a scoping exercise, in order to gauge an initial assessment of the vulnerability of each area. This was done in a limited way and only a few key players at municipal level (from the departments of transport, environment and coastal management), academics and scientists were consulted through a series of open-ended, partially structured discussions. A wider consultation process was beyond the scope of this study.

In the second stage, current traffic conditions were assessed. The Emme/2 model was used to calculate present traffic volumes, travel times and volume to capacity ratios (V/C), based on existing transportation input data. This was done for each of the three areas identified as vulnerable.

In the third stage, future conditions were estimated. This step involved establishing projected scenarios of future environmental, social and economic conditions that were likely to affect the transportation system. Projections were made by experts in four institutions (CSIR, eThekwini Municipality and the provincial and national Departments of Transport).

In the fourth stage, future road vulnerability was estimated and adaptive strategies were proposed (see "Results and Discussions" further on). Practically, this was done by using the Emme/2 model to calculate traffic changes for the three road networks in the areas predicted to be flooded (Isipingo, Bayhead and Umgeni River mouth) and by investigating different adaptive measures in order to maintain the current functionality of the surrounding transportation network.

Stage five, in which decisions should be taken and measures implemented in order to decrease road vulnerability by applying the adaptive strategies proposed, was beyond the scope of this study. Therefore, although some of the steps (i.e. steps 1 and 5) were performed partially or not at all, the vulnerability assessment framework from the literature was nevertheless followed.

Data analysis and simulation – application of Emme/2

Emme/2 is a spatial analysis software package commercialised by INRO (INRO 2009) that models how people move in and over a transportation network under a given set of conditions. It is based on the Travel Demand Forecasting (TDF) process. In this study Emme/2 was used to analyse the traffic networks of areas identified as vulnerable.

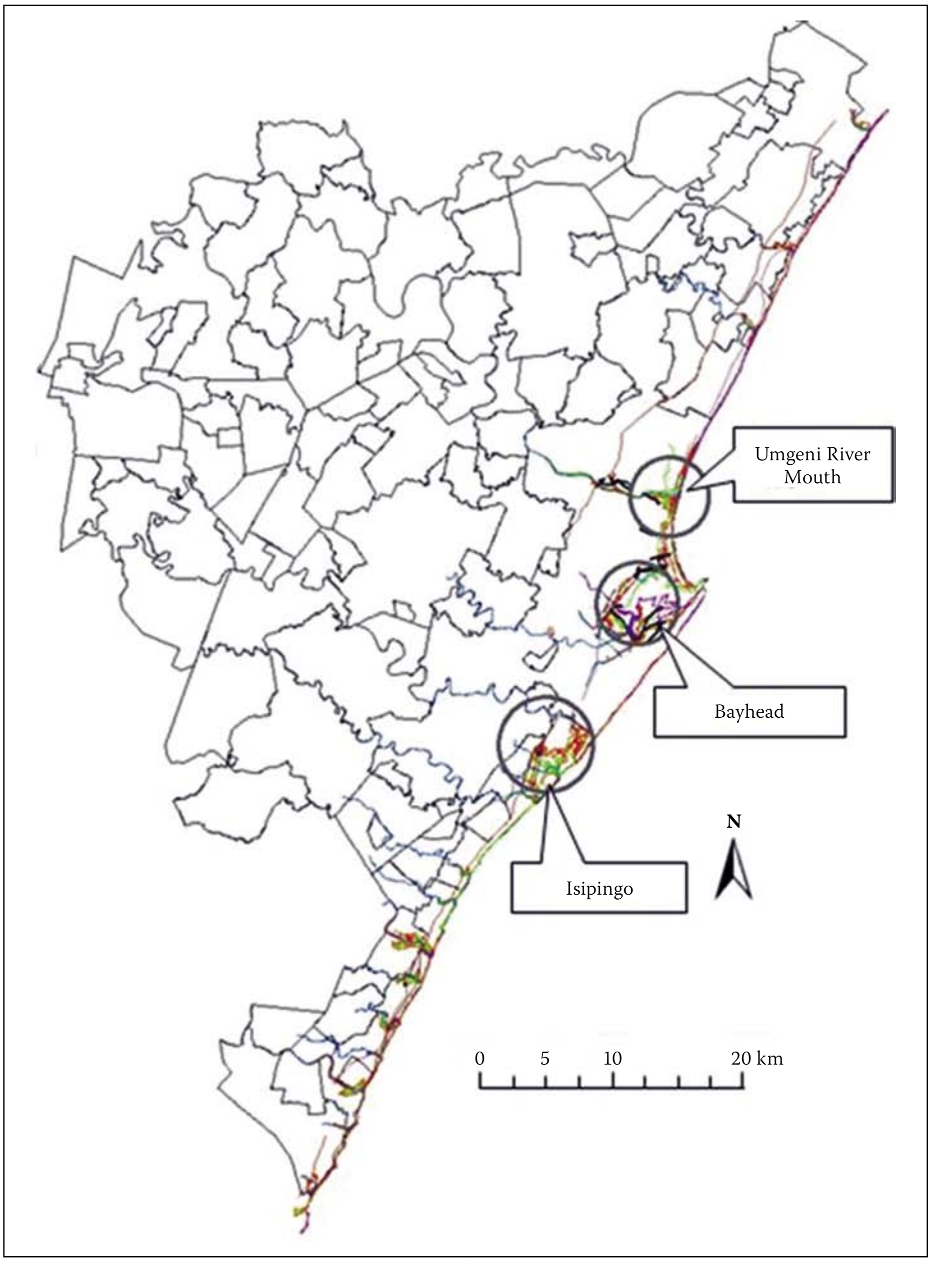


Figure 1 The most vulnerable areas in the eThekwini Municipality with regard to sea level rise presented in the context of the Emme/2 modelling zones

These networks (i.e. the three case studies) were analysed first under current conditions, and then in a second scenario where portions of major roads situated below the 2 m contour line would be rendered unusable due to flooding from sea level rise.

Three mobility performance characteristics were measured in order to assess the impact of flooding on the surrounding transportation network. These were: traffic volume, travel time and volume to capacity ratio.

- **Volume** "is the number of vehicles counted (at a given point on the roadway) in a specified time interval" (Banks 1998). The number of vehicles is measured in p.c.u. (passenger car units). This is a unit of measure whereby larger vehicles are converted to passenger cars using multiplication factors. This allows mixed traffic streams to be converted into one unit of measurement. In the two scenarios modelled (before and after sea level rise) current traffic volumes were used and no growth was factored in.
- Time referred to **travel time**, which is "the time required (for a vehicle) to cover a fixed distance" (Banks 1998), in this case from one point to another over a specified route under prevailing conditions. Travel time may also be related to accessibility which measures "the ease with which a desired destination can be reached from a given location" (Banks 1998).
- **Volume to capacity (V/C) ratio** is the ratio between the actual, measured volume and the maximum designed volume. A V/C ratio of 1 would indicate severe congestion, i.e. a low level of service, and a V/C close to zero would indicate an under-utilisation of the road link. V/C can be related to mobility, with a high V/C indicating low mobility and a low V/C indicating high mobility.

Assumptions, limitations and uncertainties

The main assumption in the study was that future road-based travel demand would be similar to the existing scenario. This was done to isolate the impact of sea level rise on traffic patterns and to discount the effects of traffic growth. Considering that only portions of the identified roads would be affected by flooding and the remainder would be operational, the second assumption was that the surrounding development would still exist and traffic would need to re-route to reach the desired destinations.

The limitations and uncertainties in this study were linked to the assumption that the projections used were correct. These included the projections used to calculate predicted sea levels and traffic projections used in the Emme/2 modelling. To overcome the uncertainty of sea level rise projections, both the 2 m contour and the 4 m contours were considered. The Emme/2 model can factor in proposed or recent property developments, but specific data (which might not be available in the initial stages) on these developments are needed in order to calculate the impacts in the future, with regard to road traffic. Therefore, uncertainties due to these unknown future developments could not be quantified.

Another limitation of the study was the use of methodologies (MCDA and vulnerability assessment) in which a larger public participation process was envisaged. However, since this was an academic study and not a municipal planning exercise, it did not warrant such large public engagement. This could, however, be done in a future follow-up study. In addition, the authors do not have any control over the implementation of the recommendations emerging from this study and the way they will be incorporated into further planning. In spite of these shortcomings, the MCDA and the vulnerability assessment provided a good framework for including various unrelated factors in a formal scientific analysis.

RESULTS AND DISCUSSIONS

Following the methodology presented in the previous section, the three most vulnerable areas in the eThekwini Municipality road network, with regard to sea level rise, were identified as: Isipingo, Bayhead and the vicinity of Umgeni River mouth areas. They are presented in Figure 1.

The three areas identified have different characteristics, as presented in Table 2 and these characteristics were considered in the MCDA analysis.

Table 3 Emme/2 results for the most important changes in the Isipingo area

Performance indicators	Current network and traffic conditions	Flooding scenario effects on network and traffic	Differences (change)
1. Volume (p.c.u.)			
Prospecton Road			
■ Section 1 (flooded)			
■ northbound	863	0	-863
■ southbound	92	0	-92
■ Section 2 (functional) – southbound	696	1 509	+813
■ Section 3 (functional) – southbound	1 273	2 537	+1 264
Joyner Road (flooded section)			
■ south/westbound	451	0	-451
■ north/eastbound	35	0	-35
N2 – north between Joyner and Prospecton offramps	3 064	4 026	+962
N2 North offramp to Prospecton Road	279	1 260	+981
2. Travel time (minutes)			
Prospecton Road			
■ Section 1 (flooded)			
■ northbound	1,88	0	-1,88
■ southbound	0,82	0	-0,82
■ Section 2 (functional) – southbound	0,65	10,85	+10,20
■ Section 3 (functional) – southbound	1,13	6,79	+5,66
Joyner Road			
■ south/westbound	1,73	0	-1,73
■ north/eastbound	1,91	0	-1,91
The Avenue – eastbound	1,57	10,16	+8,59
3. V/C Ratio (unitless)			
Prospecton Road			
■ Section 1 (flooded)			
■ northbound	1,01	0	-1,01
■ southbound	0,11	0	-0,11
■ Section 2 (functional) – southbound	0,82	1,78	+0,96
■ Section 3 (functional) – southbound	0,61	1,21	+0,60
The Avenue – eastbound	0,71	1,24	+0,53
Old Main Road* – Section 2 – northbound	1,07	1,08	+0,01
Clark Road – eastbound	1,19	1,18	-0,01
N2 Highway – Section 3 – northbound	0,76	1,01	+0,25

* Please note that Old Main Road was renamed to Phila Ndwandwe Road

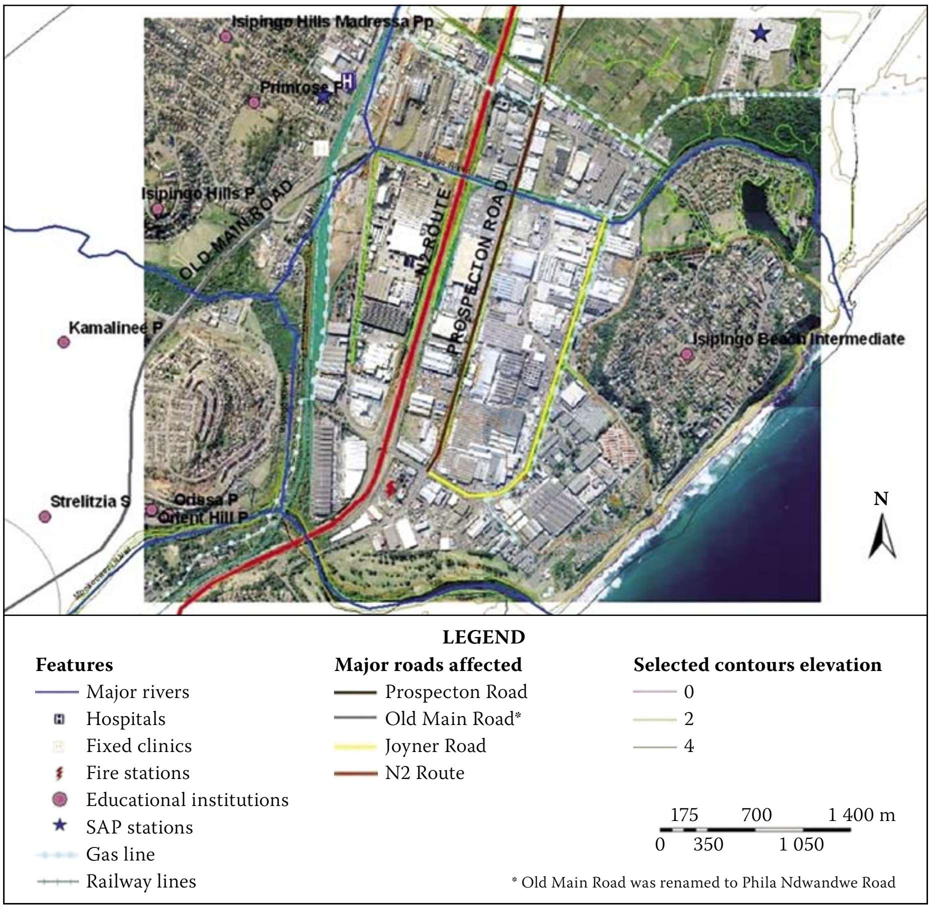


Figure 2 Aerial photograph of the Isipingo area

Road network vulnerability assessment for the Isipingo area

For the Isipingo area (see Figure 2) two road links were broken in the Emme/2 model, namely Prospecton Road and Joyner Road. It should be noted that only sections of these two roads are expected to be flooded. Therefore, these roads would still have operational sections carrying traffic. In this network analysis twelve roads were investigated in detail, as well as the N2 Highway, which in this area has two access interchanges (resulting in eight on- and offramps included).

The N2 Highway and the major roads were modelled in sections as they extended over multiple Emme/2 zones. For example, the length of the N2 Highway included in this area was subdivided into four sections (in both directions resulting in eight segments) and Prospecton Road was subdivided into three sections (including the flooded section and two operational ones). As shown in Table 2 there are a significant number of essential services in the vicinity of the area, which biased this case study towards a social vulnerability analysis. The performance indicators modelled in Emme/2 under current conditions, and in a future scenario in which parts of the two roads are flooded, were traffic volume, travel time and volume capacity (V/C) ratio. These three performance indicators were calculated for the before and after flooding scenarios. Table 3 summarises major changes and highlights problematic sections (e.g. where the current V/C ratio is high).

Data in Table 3 shows that volume changes are most significant on the N2 north between the Joyner Road and Prospecton Road offramps, the N2 North Prospecton Road offramp, the portion of Prospecton Road that leads off the N2 heading southwards (Section 2 and 3), and the sections of Joyner Road and Prospecton Road that were flooded. The greatest volume change occurs on Prospecton Road (Section 3), with an increase of 1 264 p.c.u. This is a substantial figure, suggesting that widening of the road is necessary to accommodate high turning volumes in separate lanes.

With regard to travel time, the two functional portions of Prospecton Road on either side of the inundated areas, and The Avenue, which would have previously linked Prospecton Road with Joyner Road, are the roads with the most significant increases in travel time. The increase in travel times corresponding to these links are ten minutes, six minutes and nine minutes respectively. While this may not be considered significant in the average case, it is considered significant in the context of an ambulance transporting a patient to the Isipingo Hospital (shown on Figure 2) and which has to use these roads.

Table 4 Emme/2 results for the most important changes in the Bayhead area

Performance indicators	Current network and traffic conditions	Flooding scenario effects on network and traffic	Differences (change)
1. Volume (p.c.u.)			
Bayhead Road			
■ Section 1 (flooded)			
■ northbound	658	0	-658
■ southbound	947	0	-947
■ Section 2 (flooded)			
■ northbound	658	0	-658
■ southbound	947	0	-947
Bluff Road* – six out of eight sections will be affected substantially			
■ Average northbound	385	892	+507
■ Average southbound	509	1 108	+599
M7 Edwin Swales Drive**			
■ Section 1 – southbound	555	1 084	+529
2. Travel time (minutes)	No major increases in travel times		
3. V/C Ratio (unitless)			
Bluff Road			
■ Section 4 – northbound	0,39	0,98	+0,59
■ Section 6 – southbound	0,75	1,06	+0,31
M7 Edwin Swales Drive**			
■ Section 3 northbound	0,64	0,98	+0,34

* Average was calculated per direction for the six sections of Bluff Road which showed substantial changes in traffic volume

** Note that Edwin Swales Drive has been renamed to Solomon Mahlangu Drive

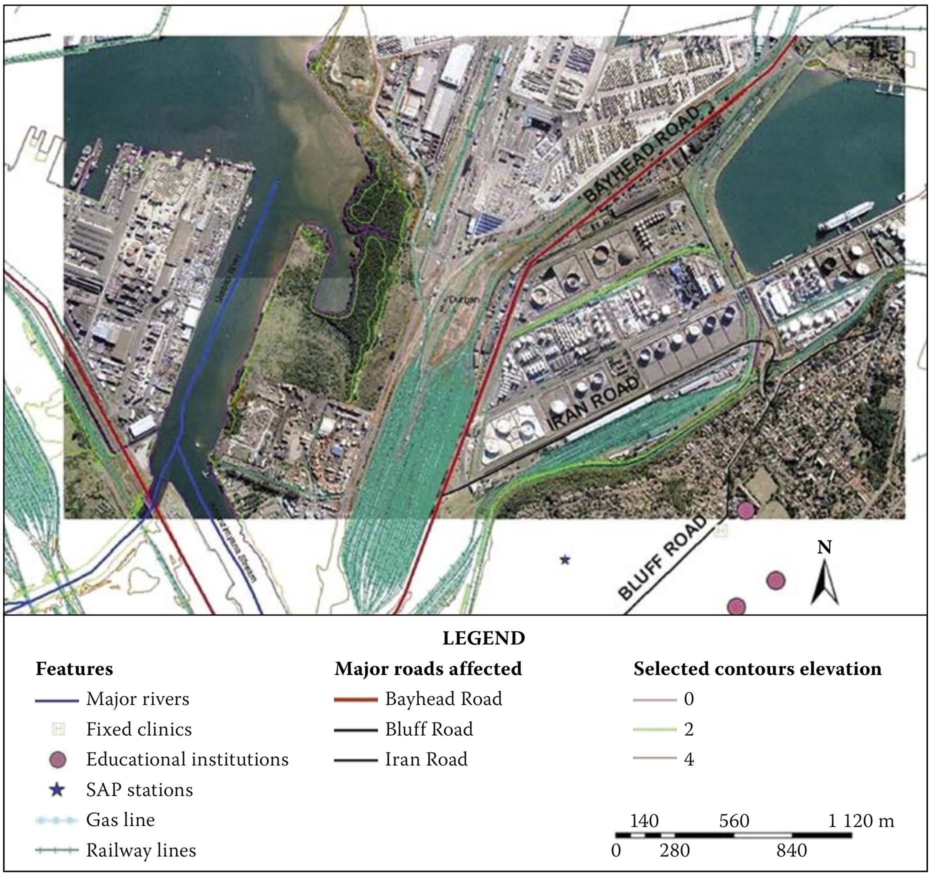


Figure 3 Aerial photograph of the Bayhead area

Current V/C values are already above 1 for Prospecton Road and parts of Old Main Road (recently renamed as Phila Ndwandwe Road) and Clark Road. These figures highlight the pre-existing problem of limited capacity prior to the impact of sea level rising. In a future scenario, the impact of a break in Prospecton and Joyner Road is realised on the remainder of Prospecton Road, The Avenue and the N2, which all exhibit V/C greater than 1. A combination of transport systems management (in the form of revised signal phasing and timing, and the promotion of public transport usage) and infrastructural improvements (via maintenance and repair, and widening of intersections to allow for channelisation of turning movement lanes) needs to be investigated to avoid volumes reaching the capacity of the roads. Of particular concern is the N2. The V/C ratio exceeds 1 after the impact of sea level rise. This, coupled with a volume increase of 962 p.c.u., suggests that the addition of a lane on the N2, at least between the Joyner and Prospecton Bridges, may be necessary to ensure that the highway is not extensively affected.

Note that *decreases* in volumes, times and V/C ratios in the network were not considered, as these amount to positive impacts on the system. For this case study, a combination of effective transportation systems management and long-term infrastructural upgrades are required to adequately cater for the projected scenario in which Prospecton Road and Joyner Road become partially unusable. These measures would ensure that the functionality of the network is maintained and disruptions are minimal.

Road network vulnerability assessment for the Bayhead area

Figure 3 presents an aerial photograph of the Bayhead area, and similar transportation network modelling was done as for Isipingo. For this case study 18 roads were investigated in detail in the Emme/2 transport network. This included one road (called Test Road) which is under planning, as well as the M7 (Edwin Swales Drive – renamed recently as Solomon Mahlangu Drive). Some large roads, as well as the M7, were modelled in sections (i.e. Bayhead Road has four sections, Bluff Road has eight sections and the M7 included has three sections). The Bayhead Road link was broken in the Emme/2 analysis as it falls within the 2 m contour.

Table 4 summarises the major changes for the three performance indicators considered.

Data in Table 4 shows that the most significant changes in volume occur on six out of the eight sections of Bluff Road. There is a 599 average p.c.u. increase on the southbound section of this road, representing a 118% increase. While this is a very substantial increase, V/C ratios generally remain below 1, even in the future scenario. These indicators suggest that there is no great need for infrastructural changes. This conclusion was strengthened by investigating travel times. The highest travel time changes also occurred on Bluff Road, but the actual time differences were small (i.e. 0,46 and 0,76 minutes) and considered not significant enough to cause concern.

Current V/C ratios (see Table 4) for the entire area are generally under 1, and are therefore acceptable. In the future scenario, only one segment of the Bluff Road exceeds a V/C ratio of 1 (at the approach to the intersection with the M7). Some improvements are possible using revised signal phasing and timings.

The above analysis suggests that socio-economic impacts are not significant in this case. The focus should rather be on the construction of Test Road (as it has been identified as a realistic option) to obtain acceptable levels of service in the future, even with a rise in sea level.

Road network vulnerability assessment for the Umgeni River mouth area

In this area a number of bridges crossing the Umgeni River were intersecting the 2 m and the 4 m contour lines. This does not mean that the bridges themselves intersect the 2 m or the 4 m contours, but if extensive areas around the bridges become flooded, the bridges will also be affected. It was decided that the M4 (Ruth First Highway), shown in Figure 4, would be the focus of this case study and a 'worst case' scenario would be considered. It was also decided that the approach in this study would be different, and the investigation would consider the possibility that sea level rise, combined with a flood scenario would increase the risk of scouring around the bridge piers, as well as damage to the piers themselves. This could result in severe damage to the bridge, with collapse occurring in the worst case. The M4 bridge was the closest to the beach, had the most land inundation in the surrounding area, and had the highest current traffic volumes.

It was assumed that the M4 bridge becomes unusable and this link was therefore broken in the Emme/2 transportation network analysis for the area. The results from the modelling showed that the impacts of a break in the M4 bridge link were felt over a much wider region, reaching the N2 Highway, and further. The detailed network analysed in Emme/2 included 53 roads and three highways (N2, N3 and M4). Because of the large scale, the analysis was conducted differently to the previous two cases, and changes in the overall network, as opposed to changes for individual links and sections, were emphasised.

The most significant volume changes occurred on the M4 and N2 and are shown in Figure 5. Roads with projected increases in traffic volume have been highlighted in red and those with projected decreases in green. On the remaining functional sections of the M4, volumes decreased dramatically as a result of the assumed bridge failure. As shown in Figure 5, the link traffic north and south of the M4 bridge decreased in volumes ranging between 1 272 and 2 051 p.c.u for the northbound carriageway, and between 3 380 and 4 099 p.c.u. for the southbound carriageway. More important is the corresponding increase in traffic volume on the N2. Volumes increased by between 225 p.c.u and 1 694 p.c.u., and V/C ratios increased from values of between 0,47 and 0,76 (acceptable) to values of between 0,51 and 1,02. This means that a major upgrade would be needed along portions of the N2, where at least another lane (assuming capacity of 1 800 p.c.u. per lane) would need to be constructed to maintain the same level of service after the re-routing due to the M4 bridge becoming un-operational.

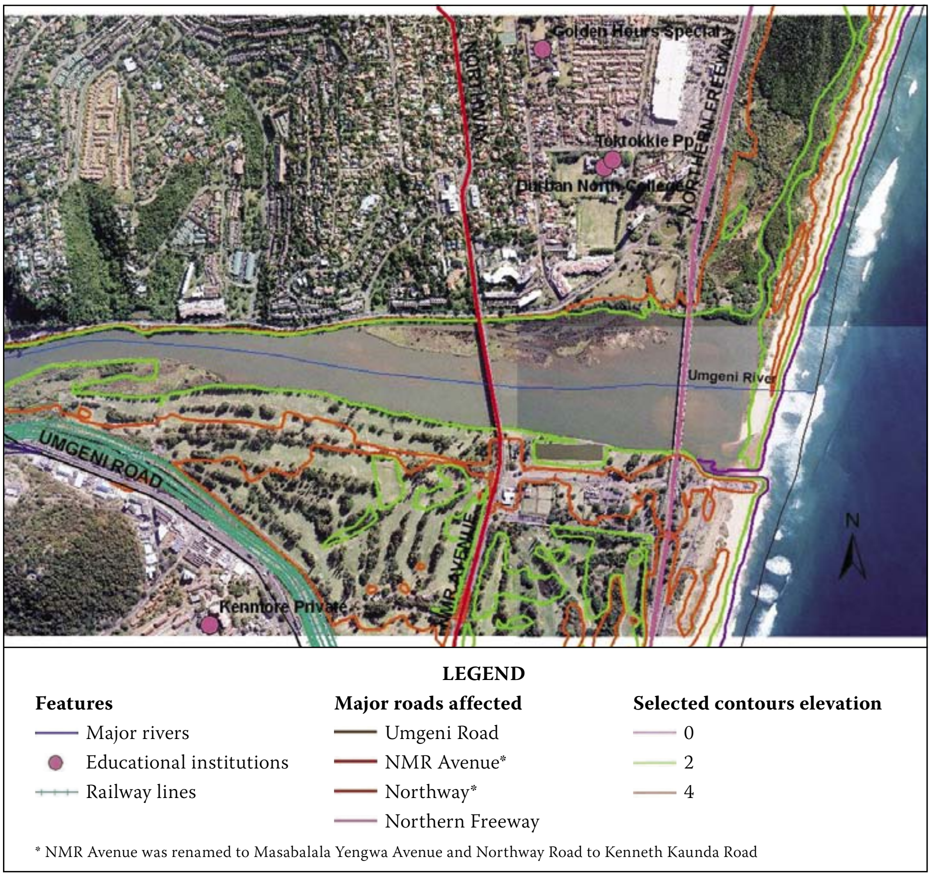


Figure 4 Aerial photograph of the Umgeni River mouth area

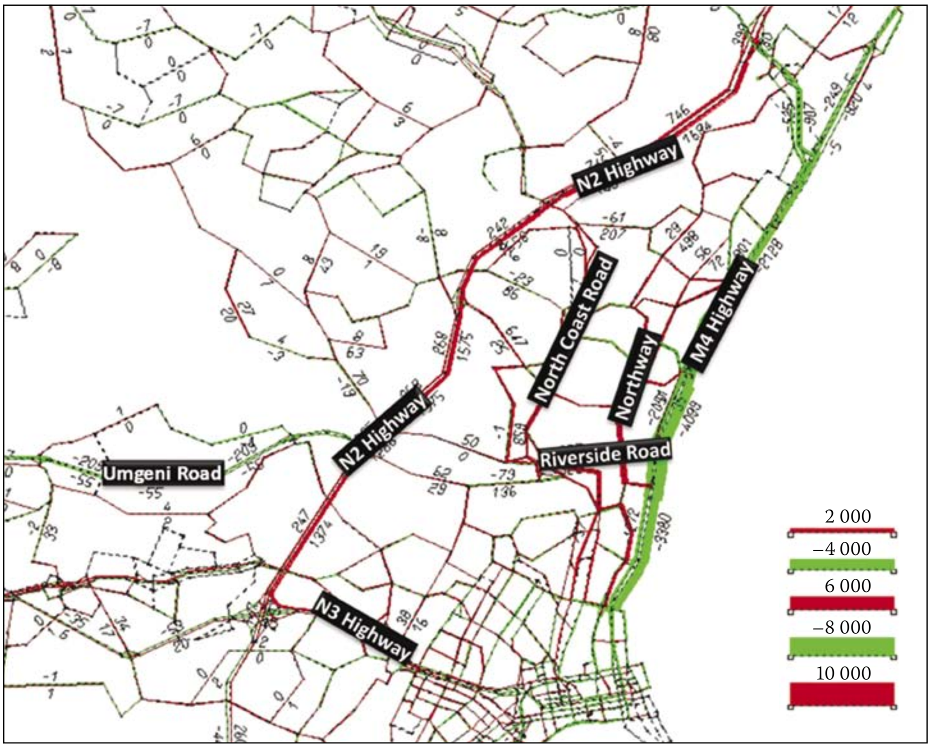
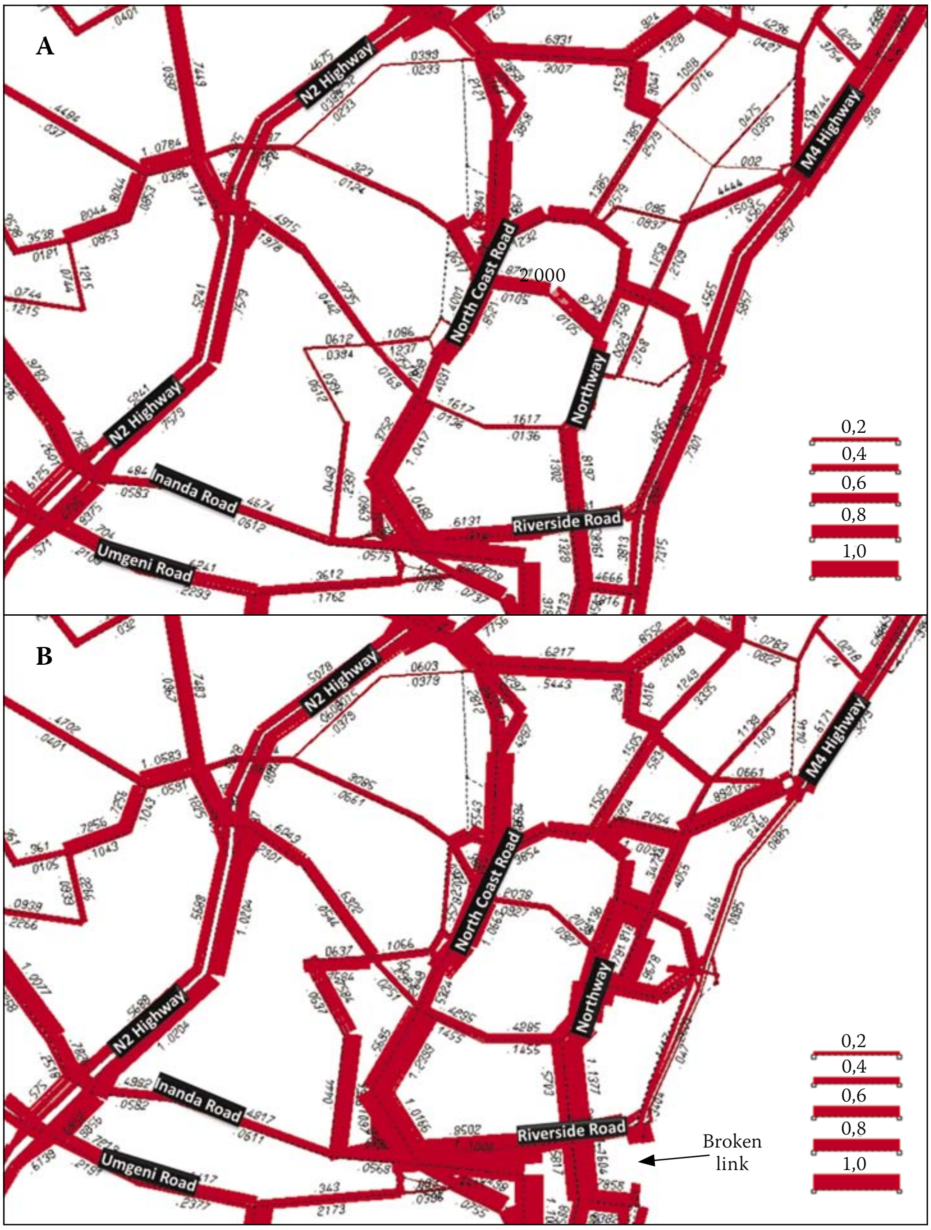


Figure 5 Volume changes for the Umgeni bridge (M4) network – decreases in volumes are presented in green and increases in red, with the thickness of lines being proportional to changes (note that North Coast Road was renamed to Chris Hani Road and Northway Road to Kenneth Kaunda Road)



Figures 6A and 6B V/C ratios in the current scenario (A) and in the future scenario (B) for the Umgeni area (note that North Coast Road was renamed to Chris Hani Road and Northway Road to Kenneth Kaunda Road)

Travel time analyses between the different Emme/2 zones included in the modelling of this network indicated that the largest increase in travel time occurs for a trip from Umhlanga to the Durban CBD. This increase is also the worst one, relative to original times. A trip from Umhlanga to the Durban CBD would take 1 757 seconds or 30 minutes longer. The second worst case is from KwaMashu / Inanda / Ntuzuma to the Durban CBD, with an increase of 1 232 seconds or 21 minutes. Seeing that a substantial proportion of the population from KwaMashu / Inanda / Ntuzuma use public transport, this could have significant implications for taxis and buses, in terms of travelling time.

Current V/C ratios, as presented in Figure 6A, show that two road links on North Coast Road (renamed Chris Hani Road) have a V/C greater than 1. This is not considered serious, as it is likely that those circumstances would be short-lived, and as the gridlock situation could be absorbed by the surrounding network. In the event of the Umgeni M4 bridge becoming unusable, however, the results show that most of North Coast Road experiences V/C ratios close to or exceeding 1. The assumed bridge closure also results in significant proportions of Northway Road (renamed Kenneth Kaunda Road), Riverside Road and the N2 experiencing V/C ratios greater than 1 (see Figure 6B).

On the whole, the results suggest that closure of the M4 bridge over the Umgeni River is unacceptable from a transportation network view. The functioning of the network analysed would be severely compromised, with many roads being gridlocked, and resilience in this case is minimal. Therefore, the results of this case study indicate that all efforts should be focused on preserving the functionality of the M4 bridge.

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this investigation was to identify areas within the eThekwini Municipality that are most vulnerable to the impacts of sea level rise and to assess the impacts of projected changes on the surrounding transportation network. This study also intended to present a model of vulnerability analysis and the development of adaptive strategies for municipalities. These are needed for transportation network planning. Identification of the most vulnerable areas was done by applying a simplified MCDA model with the help of GIS software. The three most vulnerable areas in the municipal road network were: Isipingo, followed by Bayhead and then the Umgeni River mouth.

Impacts of sea level rise on roads were measured by initially considering breaks in road links identified as most vulnerable. In this way, the vulnerability of transportation infrastructure to projected sea level rise (via inundation of road links) was assessed. Performance indicators were used during the vulnerability assessment phase to measure the efficiency of the road network before and after inundation. The 'before' and 'after' scenarios formed the basis of vulnerability comparison.

Since major roads with current high volumes and volume to capacity ratios were considered, results indicated that the impact of breaks in these road links was significant. Traffic volumes and delays increased on the remainder of the network, with network capacity severely compromised. This was especially valid for the Isipingo and Umgeni River mouth areas. The Bayhead case was less severe, due to the inclusion of an additional road which is currently under planning. Adverse values of performance indicators suggest severe implications, particularly with regard to the provision of basic services such as emergency ambulance services, police and fire response, etc.

In the case studies investigated, adaptation required upgrade of roads, such as the addition of a lane to maintain acceptable levels of service. Changes in signal timing and phasing may be required at intersections with high V/C ratios. To ensure that public infrastructure can safely provide essential services, continual adaptation is deemed necessary and the proposed adaptive measures should be seen in the wider context.

The results show that full-scale research is viable and necessary. There is a strong need to conduct a comprehensive investigation on this subject in the eThekwini context. Improvement may be realised by:

- Involving key stakeholders in the initial stages of vulnerability assessment
- Ensuring that Emme/2 input data adequately caters for recent development and changing traffic patterns, by conducting surveys and updating data regularly
- Developing a wider vulnerability methodology for transportation in the eThekwini context, which includes other factors like river flooding, increase in temperature, increase in intense precipitation events and storm intensity
- Conducting more case studies so that each may be compared to the other.

Studies such as this one are important for long-term transportation network planning and the preparedness to respond locally to climate change. However, adaptation will be achieved only if sound and coordinated long-term planning takes place, and appropriate programmes are developed. For this to occur, multi-disciplinary collaboration regarding transportation planning is essential. The National Department of Transport (2005a) acknowledges that there has been a lack of long-term planning for the road network. They note that "a comprehensive road needs study is considered necessary". It is suggested that such a study should include climate change impacts. This paper is a first step in that direction.

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REFERENCES

Banks, J H 1998. *Introduction to transportation engineering*. Boston, US: McGraw-Hill.

Bell, M G H & Cassir, C (Eds) 2000. *Reliability of transport networks*. Baldock, Herts, UK: Research Studies Press.

Belton, V & Stewart, T 2002. *Multiple criteria decision analysis: An integrated approach*. Dordrecht, Netherlands: Kluwer Academic Publishers.

Bredica, K 2002. An introduction to road vulnerability: What has been done, is done and should be done. *Transport Policy*, 9(2): 117–127.

CSIR (Council for Scientific and Industrial Research, South Africa) 2006. Climatic future for Durban. Available online at: http://www.csir.co.za (accessed in August 2008).

Dasgupta, S, Laplante, B, Meisner, C, Wheeler, D & Yan, J 2007. The impact of sea level rise on developing countries: A comparative analysis. Policy Research Working Paper WPS 4136, Washington DC, US: World Bank.

ESRI Economic and Social Research Institute, Dublin, Ireland) 2008. ESRI website: http://www.esri.com (accessed in November 2008).

eThekwini Municipality, South Africa. 2005, Integrated Development Plan (IDP) for the eThekwini Municipality. Available at: http://www.durban.gov.za/durban/government/munadmin/policy/idp (accessed in November 2008).

Gordon-McKenzie, L 2008. (Officer, eThekwini Municipality Records Department), Personal communication.

Iida, Y, & Bell, M G H (Eds) 2003. *The network reliability of transport* Oxford, UK: Pergamon-Elsevier.

INRO (software) 2009. INRO website: http://www.inro.ca/en/index.php (accessed in June 2009).

Jacob, K H, Gornitz, V, & Rosenzweig C 2007. Vulnerability of the New York City metropolitan area to coastal hazards, including sea level rise: Inferences for urban coastal risk management and adaptation policies. In: McFaden L, Nicholls R, & Penning-Rowsell, E (Eds), *Managing coastal vulnerability*, Oxford, UK: Elsevier.

Jenelius E, Peterson T, & Mattson, L-G 2006. Importance and exposure in road network vulnerability analysis. *Transportation Research Part A*, 40(7): 537–560.

Jenelius, E 2008. Network structure and travel patterns: Explaining the geographical disparities of road network vulnerability. *Journal of Transport Geography*, 17(3): 234–244.

Koetse, M J & Rietveld P 2009. The impact of climate change and weather on transport: An overview of empirical findings. *Transportation Research Part D*, 14(3): 205–221.

Lam, W H K (Ed) 1999. Special issue on network reliability and transport modelling, *Journal of Advanced Transportation*, 33: 121–251.

Mather, A 2008. (Project Executive, eThekwini Municipality Coastal Management Division), Personal communication.

Mehdi, B (Ed) 2006. Adapting to climate change: An introduction for Canadian municipalities. Canadian Climate Impacts and Adaptation Research Network (C-CIARN). Available at: http://www.laurentian.ca/NR/rdonlyres/BCB0CDD1-4E30-4204-9A95-045E063FFF93/0/CCIARNAdaptation.pdf (accessed in January 2009).

National Department of Transport (South Africa) 2005a. Road Infrastructure Strategic Framework for South Africa: A discussion document, Chapter 3. Available at: http://www.transport.gov.za/library/docs/rifsa/road.html (accessed in January 2009).

National Department of Transport (South Africa) 2005b. Road Infrastructure Strategic Framework for South Africa: A discussion document, Chapter 4. Available at: http://www.transport.gov.za/library/docs/rifsa/infor.html (accessed in February 2010).

Schmidt, N 2008. Climate change and transportation: Challenges and opportunities. MEng dissertation, Atlanta, Georgia, US: Georgia Institute of Technology.

Suarez, P, Anderson, W, Mahal, V & Lakshmanan, T R 2005. Impact of flooding and climate change on urban transportation: A system-wide performance assessment of the Boston Metro Area, *Transportation Research Part D*, 10(3): 231–244.

Taylor, M A P & D'Este, G M 2004. Critical infrastructure and transport network vulnerability: Developing a method for diagnosis and assessment. In: Nicholson, A & Dantas, A (Eds), *Proceedings*, Second International Symposium on Transportation Network Reliability (INSTR), Christchurch, New Zealand, 20–24 August, pp 96–102.