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Impact of Structural Damage on Network Accessibility Following a Disaster:

the Case of the Seismically Damaged Port Au Prince Urban Road Network

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1 Introduction

When Haiti was hit by a magnitude 7.0 earthquake on January 12, 2010, very few georeferenced (GIS) datasets existed concerning this Caribbean island. In spite of this, and thanks to the voluntary effort of many individuals, governmental and non-governmental international agencies, it was possible to assemble a wide range of data sets that, even if not of use in the immediate aftermath of the disaster, could still be used in forthcoming reconstruction and aid programmes.

Closer to home in Europe it is worth considering how, when confronted with a disaster, we could use the much vaster wealth of knowledge available on critical European infrastructure networks, and how the physical failure of structural items in our networks could limit certain key functionalities. In this study we conduct a simple analysis of how the interruption of road networks caused by falling debris onto the roads, reduced the accessibility in the Port Au Prince area.

The low Gross Domestic Product of Haiti had, as expected, a dramatic role in the severity of the seismic consequences [1] because poorly built houses and the lack of anti-seismic design led to the collapse of many buildings. The low development index of Haiti presumably also contributed negatively to the lack of GIS information concerning housing and infrastructure.

However, with a view to supporting humanitarian organizations, a worldwide effort from the Internet community was soon to be seen on the WWW days after the seismic event, particularly by supplying geographical information that was to become crucial for emergency logistics. In particular, the open-source project Open Street Map (OSM) rapidly became the vital collecting point of the most up-to-date Haitian road network data. On the other hand, humanitarian organizations, such as the UN, started to compile damage assessments of the road infrastructures.

Just like travelling within a maze, the traditional blocked roads survey is not capable of fully capturing the impact of the disruptions on the urban blocks at a city-wide scale. Hence, starting from the publicly available data on the Haiti aftermath, this work combines graph theory and GIS spatial analysis to evaluate the reduced accessibility of the complete urban space in order to capture two aspects of the disruptions: the impossibility to freely travel along the urban road network, and the isolation of dwelling blocks that may not be easily reached by the emergency personnel.

Here we first show how the street vector data are converted into a graph network and how this is analyzed to identify roads isolated by the disruptions on the adjacent streets.

Secondly, through the use of raster-based techniques, we compute the accessibility of the urban space in the two cases of damaged and undamaged road network.

Finally, we combine the accessibility measures of the two networks —pre and post the hazard, in order to identify urban areas that can pose barriers to the emergency operations.

The case study focuses on the damaged Port Au Prince urban road network in order to analyze the effects of the disruptions of the 2010 seismic event on urban space accessibility.

2 Combining GIS and Graph Analysis

Graph theory has been successfully applied to many different systems [2]: from biological processes [3] to infrastructures [4][5][6], communications and social relationships [7]. An object, an ensemble of items, a process, relational matrices etc, can all be represented in terms of nodes and links called graphs or networks.

Network analysis was introduced into GIS systems to solve vehicle routing problems, to find shortest paths, or to perform origin destination and optimum route analysis [8]. Going beyond the most common interpretations of networks within GIS systems, graph theory analysis has also been implemented in order to capture new information that is usually not manageable by a GIS by itself. At the JRC, a number of topological analyses run on GIS platforms have been performed on electricity, gas and road networks [9][10][11] to investigate these network's vulnerability or resilience to attacks, failures and natural hazards. In particular, the analysis of urban streets carried out in [10] where the roads were converted into directed or undirected dual mode graph networks [12][13], allows us to convert the practical aspects of real road networks (one-way roads, road class, length etc), into graphs which can then be used to investigate their statistical and topological properties.

However, a combined approach that performs both network and GIS-spatial analysis is less common [14][15]. Moreover, when dealing with networks, GIS is more generally adopted only in the data pre-processing and to convert source spatial data into networks; i.e., it is simply used to prepare the data in such a form that it can be parsed into a graph. In this paper we try and go some way to generate a product that is, in a way, a fusion of GIS and basic graph theory concepts.

2.1 Urban Streets as a Graph Network

A graph or network is a collection of nodes or vertices *V(G)* and edges *E(G)* that make up the graph *G (V|E)*. Graphs can be undirected, if the links can be used in both directions, or directed (i.e., one-way streets in urban streets networks). Directed links are commonly defined as arcs.

In this analysis we choose to create an undirected road network. This is for two reasons: first, because the number of one-way streets in our study area (Port-au-Prince in Haiti) is a small percentage (less than 3%, according to the OSM data) of the total of the streets, and secondly because in an emergency situation the circulation of emergency vehicles is not necessarily limited by the traffic prescriptions. Therefore we have transformed all the streets into undirected edges (*E*) and the street junctions into nodes (*V*).

The importance of the network analysis in the case of a crisis scenario, where not all the urban streets are open to traffic, is strictly related to identifying which parts of the road network are still functional in order to reach urban areas affected by the event. For example, as a result of the disruptions, it is possible that some urban areas happen to be inaccessible because some, or all, of the connecting streets or paths to reach these areas are damaged. In network analysis terms, this corresponds to identifying the so-called *strong components* of a network, which we define below.

2.1.1 Network's components: definitions

A graph is *fully connected* if there is a path from every vertex to every other vertex in the network; hence all the nodes are mutually reachable. If the graph is not fully connected, it is fragmented into several independent connected components.

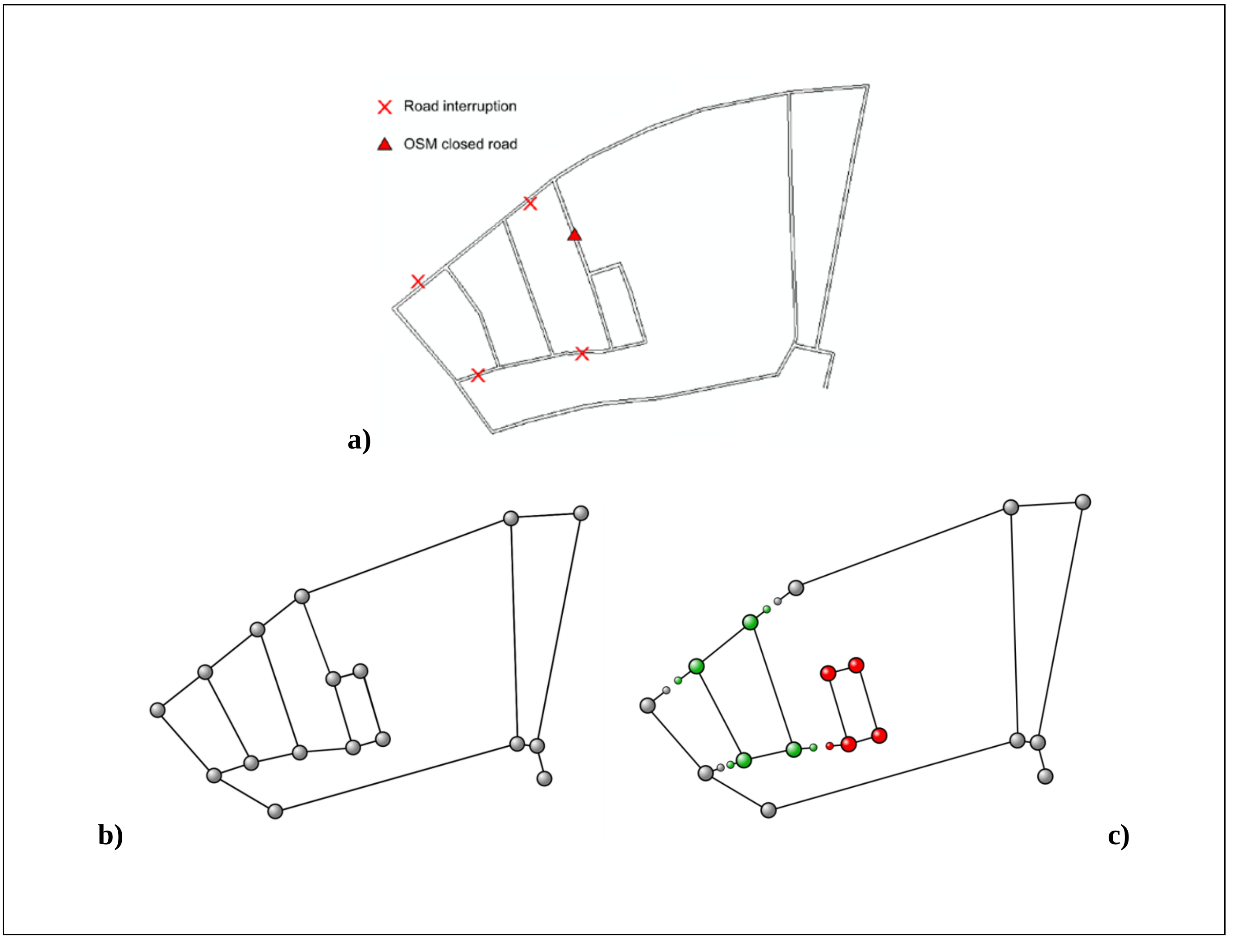


Figure 1 - Road network with located road blocks (a), correspondent graph network (b) and three components (green, gray and red vertices) resulting from the removal of blocked roads (red triangle) and splitting of road segments (X marks) in correspondence of debris' location (c)

In a road network, if links are missing (i.e., blocked or damaged roads), the contiguous nodes in the system may become unreachable and, as a result, the graph may be decomposed into several different components (see Figure 1).

Connectivity analysis through *strong components* identifies the isolated elements of the road network.

The *damaged* road network is then composed of all the roads that belong to the major component only; i.e., the streets that can still be driven through after the destructive event. All the damaged roads, as well as the edges that belong to minor components, are not part of the active network and therefore discarded.

A Depth First Search (*DFS*) algorithm is implemented in SQL to loop across all the edges' adjacent vertices and so extract the connected components. Starting from one road segment, defined by its end-nodes (*FromID* and *ToID*), the procedure initiates the Partition counter and starts searching for all the streets sharing a node with that segment. The connected streets are then marked as visited and assigned with the same Partition number. The procedure loops recursively until all the connected streets are visited. If more streets are left unvisited, the Partition counter is incremented by 1 and the successive street is selected. The procedure ends when the entire network is visited.

Table 1 - Algorithm for network's component definition

Input: Undirected graph $G=(V,E)$
Output: Networks components

Set partition index $P_i = 1$

Set number of connected edges $E_{conn}=1$

Choose $e \in E$

Denote endnodes $V(e)$ by v_1, v_2

$E_{conn} \leftarrow$ all edges incident to e

while $e > 0$

set $N_{conn} = 1$

set $P_e = P_i$

while $N_{conn} > 0$

select $E_{conn} \mid V_{conn} \in V_{P_i}$; $P_{Econn} \neq P_i$

set edges' partition $P_{Econn} = P_i$

$N_{conn} \leftarrow$ **count**(E_{conn})

$e \leftarrow$get next unvisited edge

P_i += P_i

By thus performing the previously defined *DFS*, the main Partition (i.e., the main component) is extracted, i.e., the component with the highest number of streets. All the minor components (i.e., those having a Partition number different from that of the main component) are groups of streets disconnected from the main network and are therefore isolated. This means that, even if streets that belong to a disconnected (minor) component may remain undamaged and accessible from within the component itself, there is no access to and from the main network (Figure 1-c).

2.1.2 Disruptions and the damaged network

In the newly generated damaged network, the original undamaged strong component (i.e., a subgraph where every node can be reached from every other), is no longer fully connected. The identification of the network components in this —now fragmented— network is performed again in order to eliminate the disconnected street lines and the isolated part of the network.

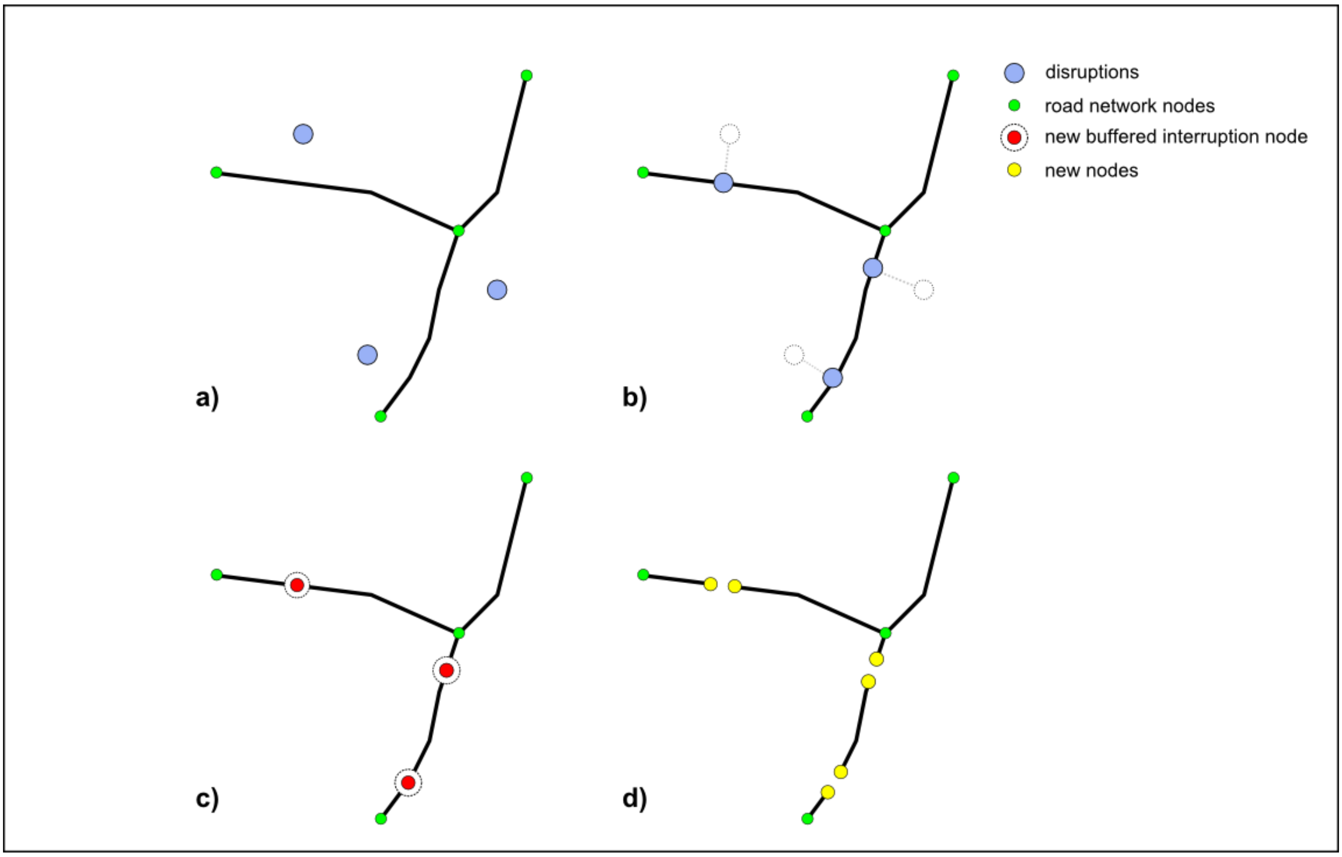


Figure 2 – Disruption points (a) are snapped to the nearest road lines (b), a debris buffer zone is created along the contiguous road segments (c) and then split at the intersections (d)

In order to split road lines in correspondence with the locations of damaged areas, points representing disruptions Figure 2 (a) are snapped to the closest street lines (b) and then buffered to represent the extent of debris on the road (c). Street lines are now trimmed by the buffered nodes, and multipart elements are broken into single parts (d).

2.2 Accessibility in Urban Areas

The term accessibility has been widely used in many fields and with different meanings to express different situations and purposes. In general, it refers to the ease of reaching a service, place or topographical item. As a consequence, different measures and approaches for the computation of accessibility have been defined [17]. Depending on the required type of analysis, accessibility in GIS can be performed to study the degree and type of disaggregation, the definition of origins and destinations, the measurement of travel impedance and the measurement of attractiveness.

Here we adopt the *travel impedance* approach as it is measured in units of distance (or time) and best expresses the consequences of disruptions on the network. Although more complex topological measures are available, *distance measures* are the simplest. Accessibility measures are commonly used when performing accessibility analysis to locate services in towns (e.g., stores, schools or emergency units) in order to fulfil specific requirements of proximity to the population.

Because we want to analyze how urban blocks are affected and, in particular, are isolated as a consequence of roads disruptions, here we consider the urban streets as the starting point to access urban blocks (i.e., the built up areas as detected on the basis of satellite imagery). Therefore, we measure the accessibility in terms of shortest time/distance from the road network to all the built-up urban areas. Based on this definition, the main transportation system (i.e., the road network) is to be considered as the origin where emergency service teams may depart from, and the built-up urban areas as the destination.

2.3 Cost Distance and the Least-Cost Algorithm

Cost distance is widely implemented in GIS; this concept is typically used to express the friction in geographical surfaces; meaning that the cost of a geographical unit implies a certain resistance. Different cost types can be associated to a geographical space, which are not solely related to physical distances (e.g., financial, time dependant, political, composite); these costs must be considered when dealing with paths and distances (e.g., a digital elevation model of an area may be considered when planning the path of a pipeline).

Cost distance in GIS terms is based on raster space data structures. Raster data can be associated to a matrix representation of space, with *cells* as the fundamental units of analysis. Each cell represents a location in tessellated space, and is associated to a numeric value: an integer to represent classes (e.g., soil type or land use) or a real number for continuously quantifiable items (e.g., terrain elevation or distances). Depending on the raster resolution and geographical projection, each cell covers a defined surface of given area, thus determining how coarse or fine the patterns or features in the raster are defined. Raster data are well suited to represent properties whose value varies across a surface, thus providing an effective method for storing the continuity as a surface. The cost raster can be either related to a single friction evaluation, or can be derived from the union of multiple cost surfaces (composite cost). In this last case, the merging operation may be dependent on the order of importance of all the raster datasets (grids) or from a map algebra operation.

When dealing with areas that cannot be included in the cost evaluation (i.e., barriers that prevent free movement), a *null value* is used.

The evaluation of the cost distance from a cell to an adjacent one is performed on the basis of the network representation of the raster grid (see Figure 3), and where each cell's centroid is a node [16]; edges are defined by the links connecting the adjacent eight nodes (four perpendicular to the cell's perimeter and four along the diagonals).

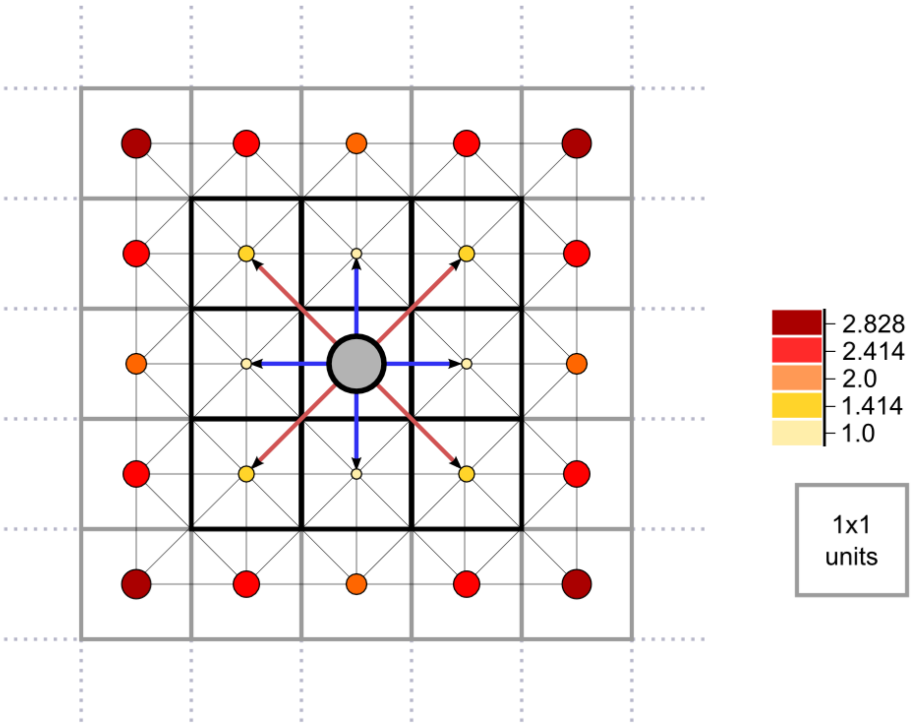


Figure 3 - Cost function: how the cost distance is computed in a raster set (size and colour of centroids according to the cost distance relative to the centre)

Having defined the composite cost of an area, the cost distance is then computed as the distance from each single cell previously defined as a source, to all the others on the basis of the defined impedance of each link. The impedance is defined by the costs (from the cost surface) associated with the origin and destination cells of each path considered, and the direction of movement through the cells.

For this reason the orthogonal paths among adjacent cells are computed as the average of the two cells' costs. For diagonal movements the cost is computed as the average of the two cells' costs times $\sqrt{2}$ so as to compensate for the longer distance.

a) Orthogonal cost $c_o = (cost_1 + cost_2)/2$

b) Diagonal cost $c_d = \sqrt{2}(cost_1 + cost_2)/2$

The *cumulative cost* is then calculated as the cost to reach cell n_i plus the average cost to move through cell n_i and n_i+1. The *cost distance* can be then computed from any cell to a source cell as the cumulative cost of all the links along the least-cost path from each cell to all the sources.

2.4 Cost-distance Analysis

Considering an urban area, we select one source layer and a friction layer. The source layer is the raster dataset converted from a road network vector feature set (Figure 4a) from which the accessibility is computed. The friction layer is defined by the cost surface of the urban built-up area considering a travelling speed of 6 *km/h* (walking speed), assuming that this land use type can be travelled at a minimum human speed only.

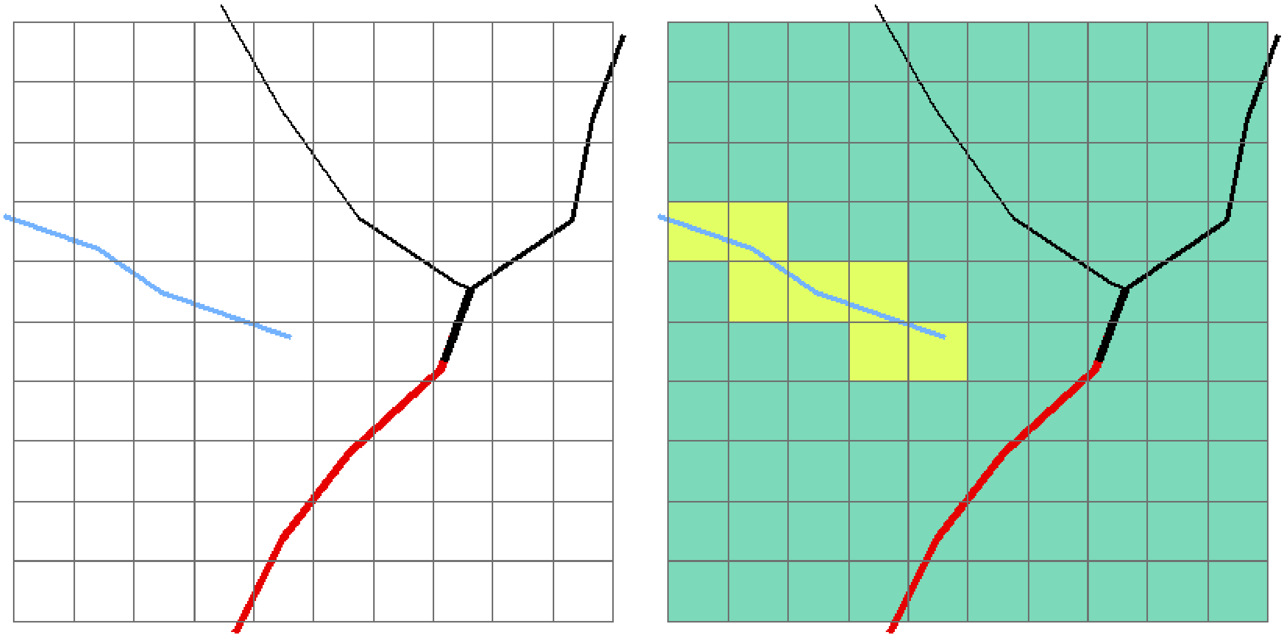
The cost surface is then merged with a river raster dataset with a fictitious constant cell cost; the merged raster is then reclassified (Figure 4b) so that the cells in correspondence with waterways are defined as *No Data* (i.e., these empty cells will not be accounted in the computation of the cost distance).

The calculation of the least cumulative cost from each cell to specified source locations over a cost raster is performed in the cases of undamaged (Figure 5a) and damaged networks (Figure 5b).

Depending on the method used to build the damaged network (e.g., removing all the street lines or splitting roads in correspondence of detected damaged areas), a different source raster set is generated; thus affecting the computation of the cost distance.

In the examples of Figure 5, cell colours are related to the cost distance; dots are the cell centroids with size proportional to the cell value.

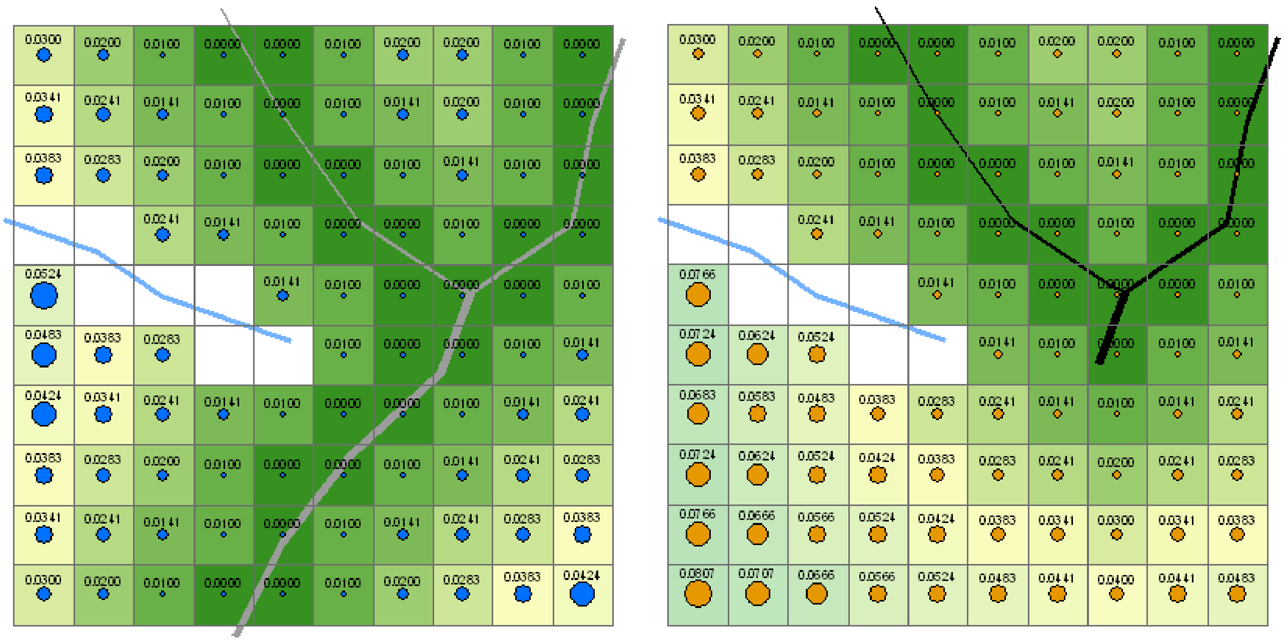
Damage to a road network affects the path travelled; in particular, damaged roads may result in the complete isolation of some areas. Considering the example of Figure 5, it can be seen how the removal of the damaged street (red line in Figure 4) changes the original cost distance values of the undamaged case (Figure 5a) by reducing the number of greenish cells (i.e., areas contiguous to street lines) in the lower part of the raster area (Figure 5b).



(a) Road network (black lines), damaged road (in red) and waterways (in cyan)

(b) Cost surface (*NoData* in yellow); roads are the sources for the cumulative cost analysis

Figure 4 – Vector feature sets and computed cost surface (with overlay of vectors)



(a) Cost distance (Undamaged Network)

(b) Cost distance (Damaged Network)

Figure 5 – Accessibility analysis example

The *reduced accessibility* (or the level of isolation) of the urban environment (Figure 6) is the result of the difference of the two cumulative costs (Figure 5) computed for the *damaged* and *undamaged* network. Cells unaffected by the disruptions are reached with unchanged effort (white cells in Figure 6), whereas the increased cost is due to the missing parts of the network affecting the distance from the defined sources (undamaged roads).

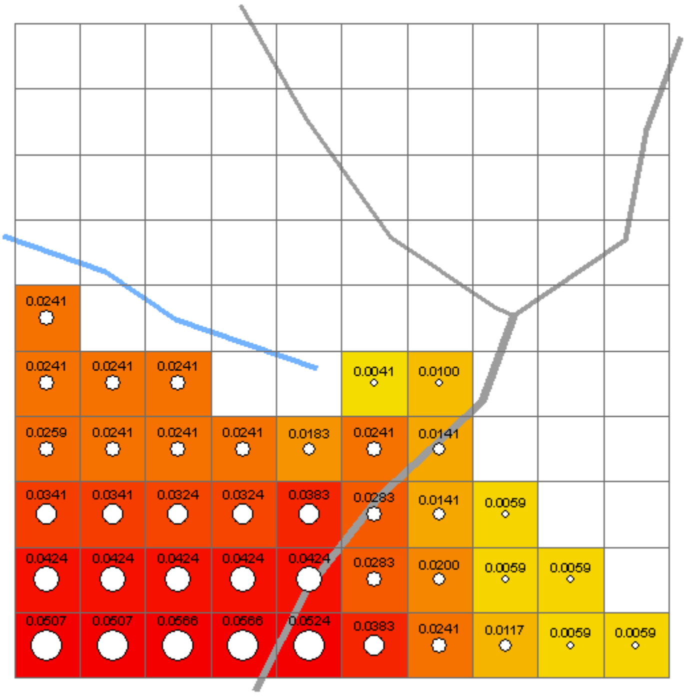


Figure 6 – Example of Reduced Accessibility result

3 The 2010 Haiti Earthquake

Haiti was severely affected by a magnitude 7.0 earthquake on January 12, 2010. The capital (and largest city), Port-au-Prince, has a metropolitan population estimated to be between 2.5 and 3 million people, and is located 25 km east-northeast of the epicentre. The earthquake caused extensive damage to buildings throughout the Port-au-Prince region, including the Presidential Palace, the main seaport and the UN mission. Infrastructures were also severely affected, either directly or by the collapse of adjacent structures (see Figure 7).

Figure 7 – The collapse of buildings caused the interruptions of several urban streets, in particular in the downtown of Port Au Prince (photo F.Taucer, JRC-IPSC)

3.1 Reported Damage

Humanitarian and international organizations performed surveys in the aftermath to assess the damage caused to both housing and infrastructures. The U.S. Geological Survey (USGS) shortly after the event performed investigations in Port-au-Prince and the heavily damaged communities to the west [18]. As reported, from a survey of 107 buildings in downtown Port-au-Prince, 28 of them had collapsed and another 33 were damaged enough to require repairs. Damage to buildings was mainly due to the lack of earthquake-resistant design, not only in non-engineered housing but also in more recent modern multi-storey buildings.

Several institutional buildings were severely damaged; in particular, many hospitals (e.g., the main hospital in the hillside suburb of Pétionville) were reported as collapsed, all of which was compounded by the severe damage to the buildings housing the international medical aid organization *Doctors Without Borders* all of which further reduced the country's medical assistance capacity.

The port docks suffered major damage, including one which completely collapsed, and a second which suffered a partial collapse (presumably as a consequence of liquefaction-induced lateral spreading). Furthermore, damage to the electricity system was reported, and two power plants were left un-operational due to failures in the transmission lines and adjacent structures.

3.2 How the Urban Road Network Was Affected

From other international agency reports [18][19][20], it appears that the infrastructure network in Haiti was severely affected by the seismic event. Many large landslides along Highway 204 were reported, as well as in the foothills of the La Selle Mountains between downtown Port-au-Prince and Pétionville.

Because they are usually well-engineered designed structures, most of the bridges resisted the seismic forces, though some of them suffered damage to the shear keys at the supports due to insufficient or inadequate steel reinforcements detailing.

Several streets of the urban areas, in particular the Port-au-Prince downtown area and the Leogane and Carrefour districts, were blocked as a consequence of the collapse of buildings and by the presence of debris (Figure 8 and Figure 9).

Figure 8 – Port Au Prince: debris on street (photo F.Taucer, JRC-IPSC)

Figure 9 - Port Au Prince: street with damaged buildings (photo F.Taucer, JRC-IPSC)

4 Data sources

The GIS model was implemented using *ArcGIS 9.2* software by *ESRI*, including *Spatial Analyst* for raster analysis and *ModelBuilder* for structured model development. The data repository is a Microsoft SQL-based geospatial database that offers the possibility to develop complex data processing with stored procedures.

For the analysis of the Port-au-Prince road network, Open Street Map (OSM) data [21] were processed and converted into a shapefile dataset (see *Appendix A – OSM Data Processing into a Network* for details). OSM contains the most complete and up-to-date data on the Haitian roads, thanks to the contribution of many individuals and organizations who volunteered after the seismic event. In addition to road data, waterways are also available from OSM and were included in the analysis.

Table 2 - GIS source datasets

Dataset	Type	Source
Road Network	polyline	Open Street Map
Road interruptions	point	UNOSAT and JRC
Administrative Boundaries	polyline	GeoFabrik
JRC PANTEX Built-up mask for Port-au-Prince from SPOT imagery	polygon	JRC

OSM road vectors are presented in aggregated lines that belong to each single named street. The road vectors are then divided into the single elements comprised between junctions. A point vector dataset is created from all the vertices of the streets and two fields *FromID* and *ToID*, corresponding to the origin-destination (OD) pairs, are created and updated with the unique identifiers of the end-nodes of each single street. Functional Road Classes (FRC) indices are created for each street on the basis of the OSM description (see Table 3).

UNOSAT, the UN Institute for Training and Research Operational Satellite Applications Programme, compiled a point dataset reporting road disruptions; this is converted into a shapefile from the original *km*l dataset available online [22]. The points defining the observed disruption or the location of the debris on the roads are first spatially joined to the closest street segment; streets are then assigned with the correspondent *Unosat* damage state (0-no damage, 1- partially blocked, 2- blocked).

The detailed mapping of built-up areas was compiled by the GLOBESEC Unit of the IPSC Joint Research Centre [23] with an automatic procedure that extracts automatically those areas using high or very high spatial resolution satellite data. The polygon dataset is used to clip the raster results to the urban extent only.

Table 3 - OSM road types and correspondent defined FRC

OSM type definition	FRC
Primary	9
Primary_link	9
Secondary , Secondary_link	8
Residential, residential, Unc Residential, Uncl Tertiary,Tertiary_link	7
Living_street , Unclassified, Unclassified;	6

4.1 Road Disruptions Surveys and the Road Network

Damage surveys were conducted by different groups in order to release prompt evaluation of the post-event situation —mainly in support of the humanitarian and emergency organizations. The analyses were performed on the basis of the available satellite images and the detection of damages was performed either manually or automatically. For our analysis the UNOSAT dataset of the road disruptions was considered as the basic generating set/data. The original *kml* file was converted into a shapefile and loaded into the GIS. The dataset contains the interruption points with two severity levels (road partially interrupted or fully blocked). The disruption dataset was integrated with new findings observed during the evaluation of the UNOSAT dataset; new disruption points were created in Google Earth and a *kml* dataset was generated (see Figure 10).

Figure 10 – Examples of new findings in *GeoEye* Satellite Images during the evaluation of the *UNOSAT* road disruptions dataset

5 Spatial Analysis of the Urban Area of Port Au Prince

5.1 Selection of the Analysis Area

The selected area for the analysis is derived from the urban built areas as defined by the IPSC-GLOBESEC dataset derived from the *Quickbird* satellite imagery [23].

In order to avoid border effects in the components identification (where roads on the area's limits may be disconnected due to the cut-out operation), a 5 km buffer was initially considered, thus considerably reducing the dimensionality (especially in graph terms) of the whole network. After the components were identified, the road network is clipped to the desired extent (red rectangle in Figure 11).

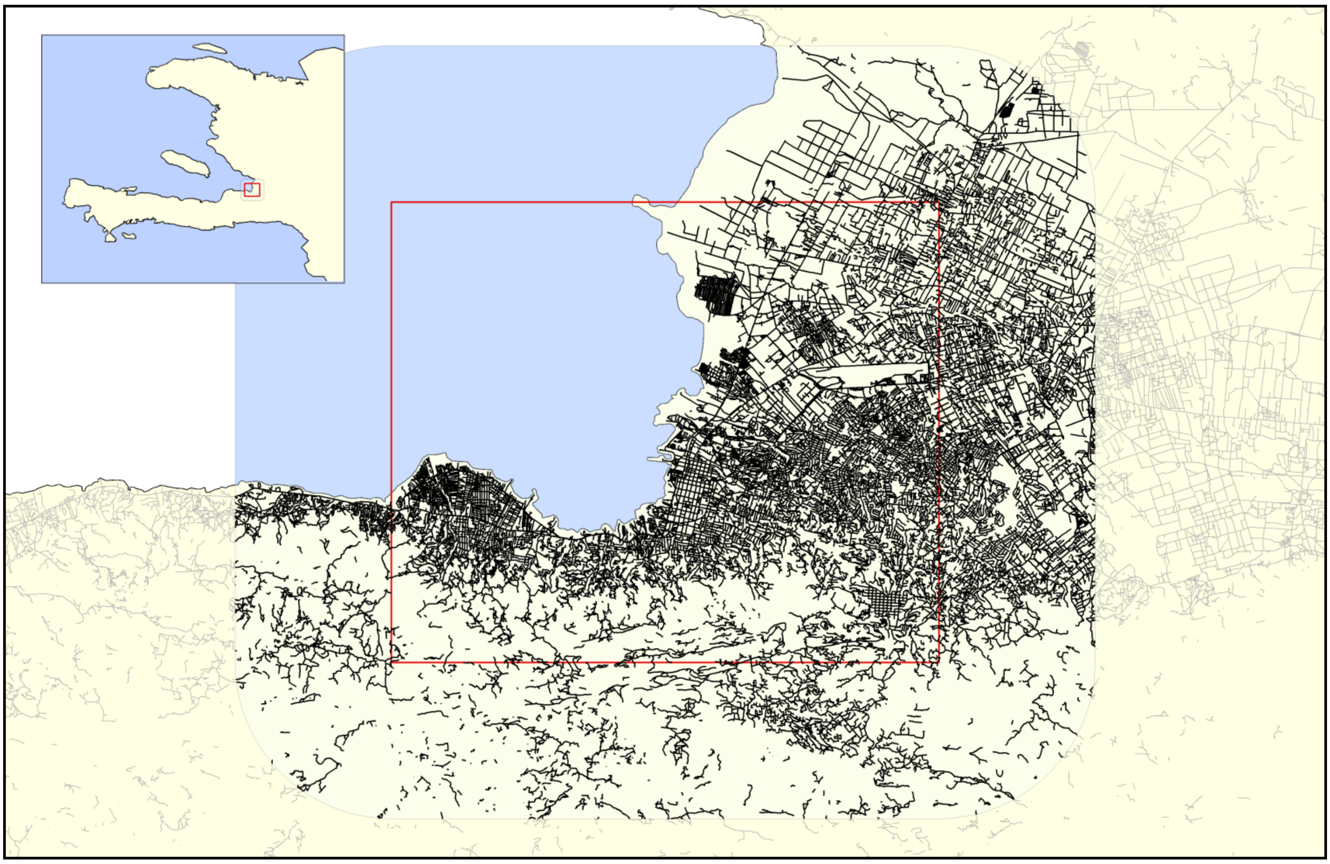


Figure 11 - Selected area for the network analysis (red rectangle)

5.2 The Damaged Road Network

The damaged road network is derived from the original —undamaged— one by splitting the street lines at their intersections with the disruption-points dataset (previously snapped to the closest lines, see 2.1.2).

The disruption points were snapped onto the closest street lines (see Figure 2) with a sufficiently precise snap tolerance to allow all the interruption points to be snapped to the lines, whilst ensuring a one-to-one relation between an interruption and the closest street; these were then divided at the intersection of the snapped damage points with a 2 *m* buffer, creating the new dataset of the *damaged network*. This operation creates two new nodes assigned with a unique ID, thus ensuring that the network analysis will consider the two newly created nodes as independent and not connected.

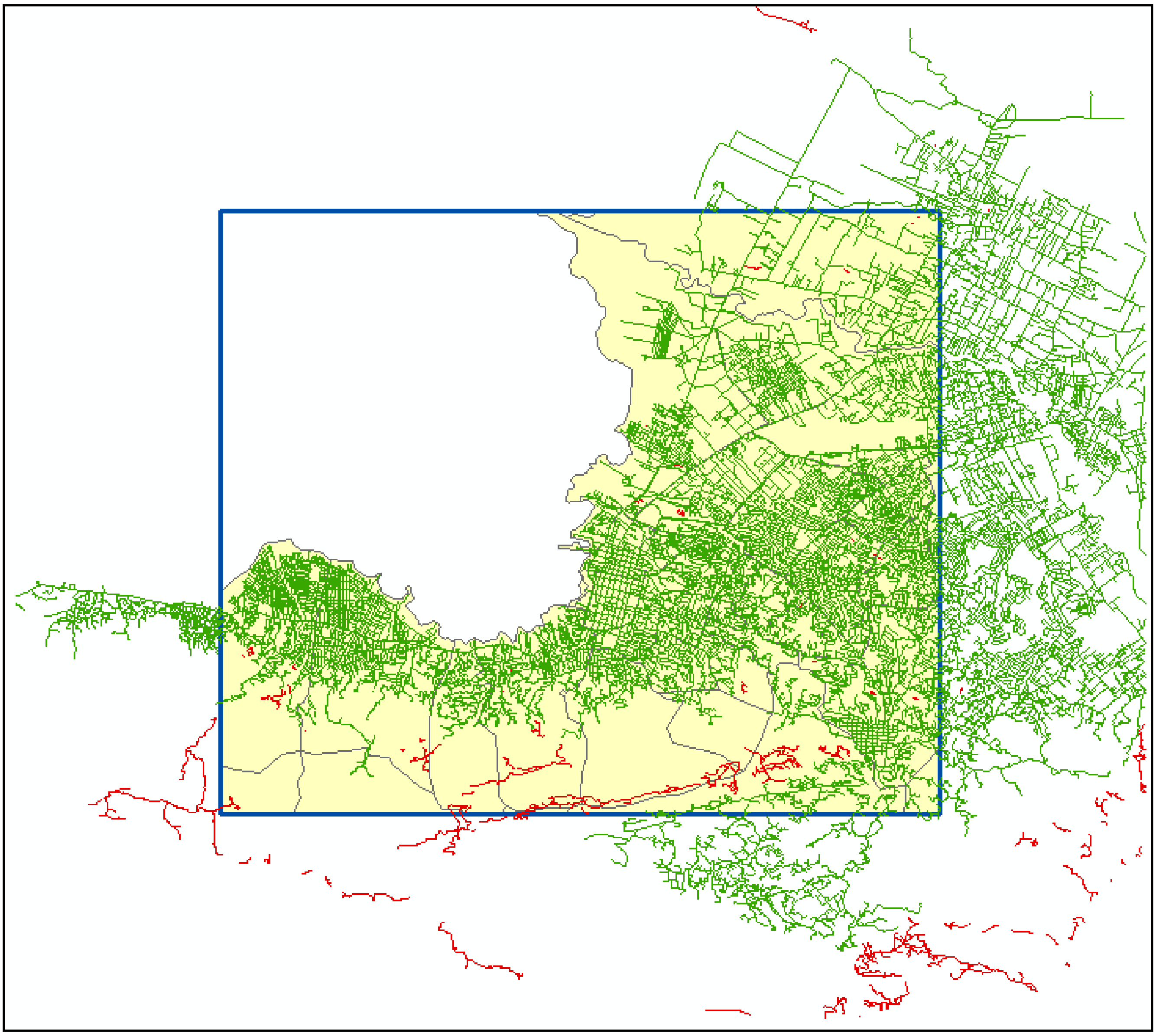


Figure 12 - The Port Au Prince damaged road network. Some roads (in red) are isolated from the network even if undamaged.

The disruptions dataset is composed of a total of 280 locations, which split the network causing the total number of edges to increase from 27855 to 28131.

The nodes created by the line-splitting operation are numbered sequentially, starting from the higher node ID. Two new table fields are created (*IDfrom2* and *IDto2*) and updated with the nodes' IDs based on the geographical coordinates. The identification of the network's *connected components* is now performed on the basis of the new connectivity relations.

5.3 Network Statistics

The undamaged network is composed of 27855 streets; by splitting them at the disruption-point intersections; a final damaged network of 28131 road segments is obtained. The total number of segments composing the damaged network is increased because splitting the lines at the intersections with reported disruptions generates two distinct separate lines.

When considering the main component only, in the damaged and undamaged network it can be observed that the total number of streets is increased. Therefore, in order to compare the level of connectivity, the total length of the street network must be compared (see Table 5).

Figure 13 - Damaged Network's isolated components
(circles' size proportional to the number of streets of each single component)

It can be observed how the main component of the street network after the earthquake is still significantly connected. The network does not break up by bisection, but rather through the erosion of many small-component islands as shown in Figure 13; thus, 22 minor components are induced by the seismic event ranging from groups of 2 to a maximum of 8 streets (Table 4). Moreover, many single streets are disconnected (59) because terminal (or dead end) streets are more prone to be isolated, given that one single disruption is sufficient to disconnect from the network. Conversely, multiply connected streets must be severely affected by disruptions to cancel out the redundancy of multiple paths and links.

Table 4 – Damaged Network's detected components

Number of components	Number of street segments
1	28000
1	8
2	5
3	4
10	3
6	2
59	1

The difference between the undamaged and damaged networks clearly shows the decrease of performances induced by the earthquake event. The loss in terms of total street length for the main component is about 9 km; i.e, 0.36% of the whole network (N.B. this is the number of isolated streets and not of the detected disruption locations). The induced isolated street components affect the accessibility of a 87.84 *ha* surface (computed from the reduced accessibility raster having cells with value >0).

Table 5 – Undamaged and Damaged networks statistics

	Damaged D	Undamaged U	Difference (U-D)
Street segments	28131	27855	276
Number of nodes	22771	22227	544
Total length of main component (*km*)	2435,56	2444.48	-8.92
Components	82	1	81
Number of streets in Main Component	28000	27855	145

6 Accessibility in the Damaged Port Au Prince

The computed *accessibility* of the urban areas, following disruptions to the road network, shows a significant decrease in different areas of the urban land in Port-au-Prince. The city's downtown suffered major damage, as evidenced by the number of disconnected roads (e.g., Figure 14).

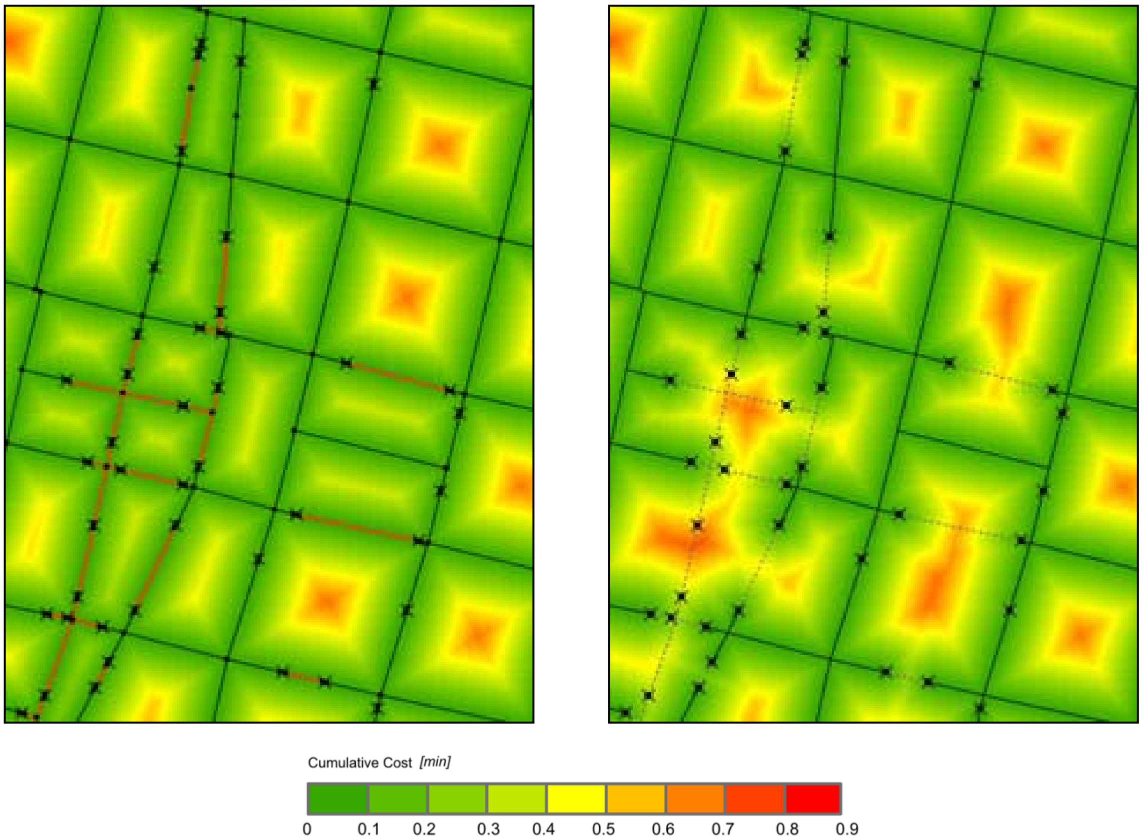


Figure 14 – Cost surface in minutes. For the undamaged (left) and damaged (right) urban road network (central PaP detail)

The central town of Port Au Prince shows isolation not immediately quantifiable with the usual representations of damage: traditional damage maps represent the road network either with the location of damage or by differentiating between damaged and undamaged streets.

Therefore, when trying to identify a path on the basis of the aforementioned road network damage assessment, it is not straightforward to discern how to travel along the streets, whilst accounting at the same time for the degree of isolation of certain areas, due to the modified topological connectivity. Introducing the reduced accessibility index may help understand the town's transport capacity.

Thus, if the surface costs in both cases (damaged and undamaged) is compared, it is possible to quantify how road isolation affects the ease of getting to areas close to the removed components (e.g., in the right upper corner of Figure 15).

It can be seen from Figure 15 (right) that the reduced accessibility of the urban area is not directly proportional to the damages of the buildings: it is not necessarily true that the distribution of building damages will affect transit on the adjacent streets. Moreover, peripheral zones may result in over-ranked accessibility indices as they are served by a limited number of roads (i.e., peripheral areas are even more easily isolated because they start off as being badly connected in the first place).

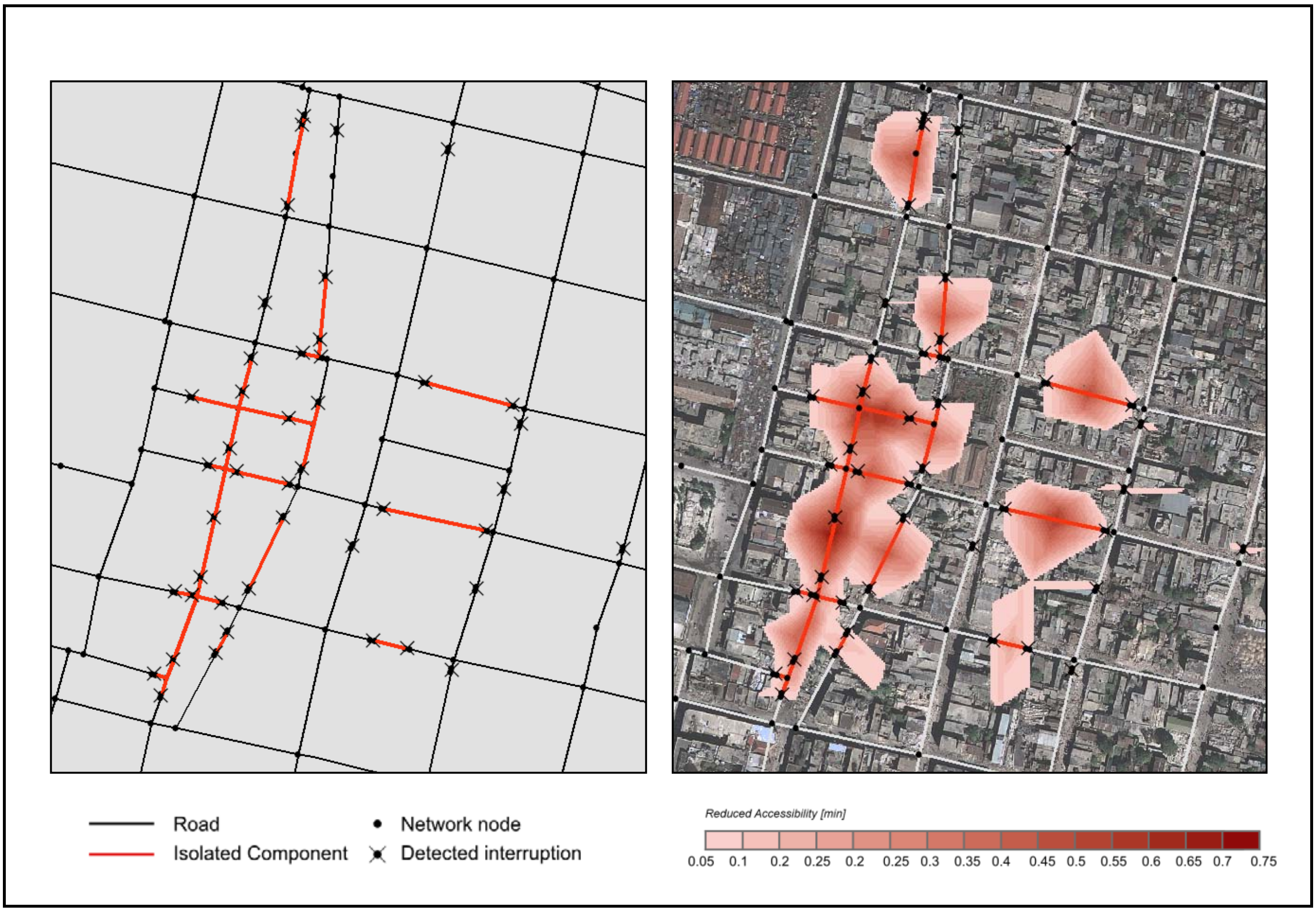


Figure 15 – Damaged Network with isolated roads (left) and Reduced Accessibility index (right)

The reduced accessibility (Figure 15 right and Figure 16) shows how some areas of Port Au Prince became completely inaccessible to vehicles after the earthquake, with a higher concentration in the central part of the town. Whereas most of the isolated areas are relatively small, disruptions on the road network also generated a few large inaccessible areas.

It must be noted that the present *reduced accessibility* accounts only for the elimination of disconnected components. However, whenever a single road is blocked but still connected at both ends to the major network component, the disruption does not affect —in this case— the accessibility as the two halves of the street can be accessed (even if with the disadvantage of travelling along, what is technically, a dead end street).

Figure 16 – Reduced Accessibility Raster overlay on *Google Earth*

7 Conclusions

A method that integrates spatial and network analysis was implemented to assess the degree of isolation of urban blocks as a consequence of major disruptions to the urban road network due to collapsed buildings and debris. This method was applied to the Port Au Prince urban area in Haiti by parsing the reported disruptions of the 12 January 2010 earthquake into a *before and after* connectivity network.

The analysis of the reduced accessibility/level of isolation in Port Au Prince shows, what appears to be, a moderate level of isolation after the earthquake. Only 0.36% of the total length of the urban road network, or approximately 9 *km* of streets, was completely inaccessible. However, as the street "islands" (or disconnected components) are mainly located in the most affected areas, the difficulties for emergency operation could only have been further complicated.

The method would appear to be effective in showing isolated urban areas, and for analysing the accessibility from the road network. The preliminary analysis, performed by graph deletion and erosion corresponding to all those streets where disruptions were reported, lead to a more severe reduced accessibility result and the present method proved to be more precise in assessing the degree of isolation. Further improvements would involve network measures to account for disruptions that, although do not isolate parts of the road network, can still contribute to decrease the transport capacity whenever these do not allow optimal flow conditions.

8 Appendix A – OSM Data Processing into a Network

Nowadays there are a considerable number of web sites offering pre-compiled world areas from original Open Street Map data. A variety of formats are also available, including the ESRI shapefile format suitable for the *ArcGIS* program.

Although it is advantageous to have ready-to-use street data for the GIS, there is, however, a major issue that prevents the adoption of these data sets for network analysis. OSM data are xml data types, where roads and streets are grouped by street names with no discontinuities (Figure 17a). Although this format is efficient for map drawing applications, this structuring of roads leads to the more simple straight conversion into different formats, which, unfortunately makes compiling networks difficult or impossible because the interconnection information is missing.

Hence we decided to process the original OSM data in order to define a proper structure suitable for the needs of network analysis (Figure 17b). We retrieved the data connecting to the *www.informationfreeway.org* server and retrieved the selected area of interest with the *wget* utility.

```
wget http://www.informationfreeway.org/api/0.6/map?bbox=-
72.5437,18.3947,-72.0826,18.7228 -O portauprince.osm
```

As we were dealing with a large area, we processed the *.osm* downloaded dataset by removing the unnecessary elements and attributes by means of an XSLT transform (see Appendix B - XSLT Transformation To Extract and Reduce the Original *.osm* Data).

The OSM original data we are interested in are composed of the data primitives' *ways, nodes and relations* as in the following examples (Table 6 and Table 7).

Node elements are the basic elements for the definition of ways and contain the *lat/lon* coordinates.

Table 6 – Node xml element in the .osm dataset

```
<node id="9827074" version="59" timestamp="2009-03-23T20:55:05Z"
uid="79857" user="RDSantiago" changeset="848602" lat="19.7755913"
lon="-70.4558514"/>
```

Each *way* element contains the set of nodes that is composed of; these nodes are specified by the *ref* attribute (equivalent to the node id) in the *<nd>* tags. The tag *k="highway"* defines the road elements, and its attribute *v* the type of road (primary, secondary, service ...); we process this information to define the functional road classes *FRC*. All the other *way* elements (e.g., waterways) are ignored.

Table 7 – Way xml element in the *.osm* dataset

```
  <way  id="50824581"  version="3"  timestamp="2010-03-07T18:38:27Z"
uid="149876" user="dbusse" changeset="4064707">
    <nd ref="330910421"/>
    <nd ref="662441765"/>
    <nd ref="648200422"/>
    <nd ref="648200421"/>
    <nd ref="648200425"/>
    <nd ref="330942238"/>
    ...
    <tag k="highway" v="secondary"/>
    <tag k="name" v="Avenue Hailé Sélassié"/>
    <tag k="oneway" v="yes"/>
    <tag k="source" v="Google, 2010-01-21"/>
  </way>
```

The Open Street Map source *.osm* file was then processed by a stored procedure in the MS SQL database and converted into a *.gml* file. All the *way* elements are split into the constitutive segments; as the topology of the road network is defined by how edges (ways) are connected, *ways'* end-nodes coordinates are retrieved and stored for each single street (Figure 18). The generated *.gml* file is converted into a shapefile suitable for the ArcGIS with the FWtools [26] utilities.

Table 8 – Output to the .gml file

```
    <nd ref="330910421"/>
    <nd ref="662441765"/>
    <nd ref="648200422"/>
    <nd ref="648200421"/>
```

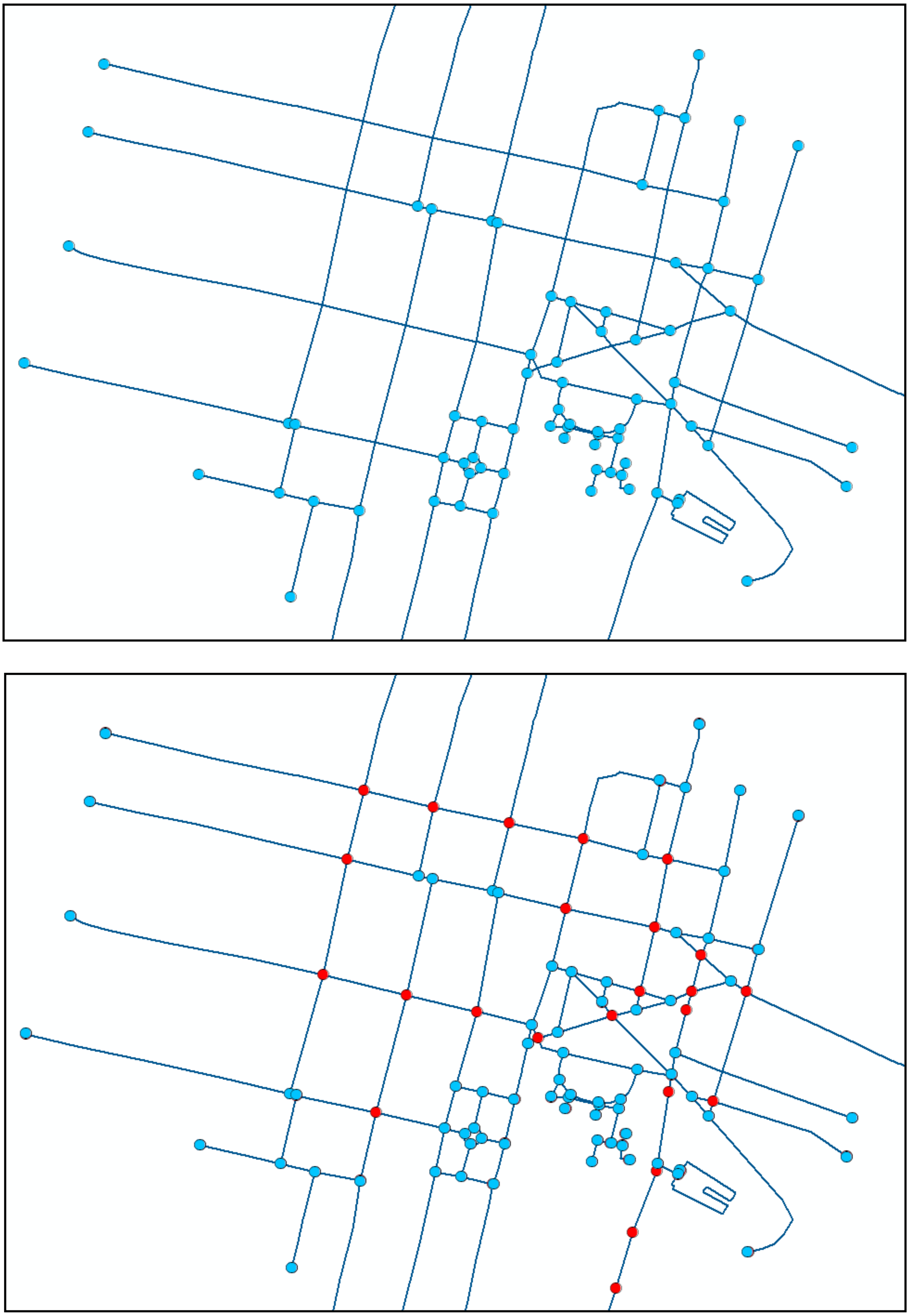


Figure 17 – (a) OSM extract plain road network nodes in the GIS and (b) network processed intersections (red nodes)

Attributes of HaitiJOSM

FID	Shape	id	FRCtype	FromID	ToID	Xfrom	Xto	Yfrom	Yto
0	Polyline	30047692	secondary	330871283	330871281	-72.264419	-72.264268	18.637309	18.637734
1	Polyline	30047692	secondary	330871285	330871283	-72.264814	-72.264419	18.636623	18.637309
2	Polyline	30047692	secondary	330871287	330871285	-72.26497	-72.264814	18.636309	18.636623
3	Polyline	30047692	secondary	330871289	613001575	-72.265071	-72.26497	18.635969	18.63619
4	Polyline	30047692	secondary	330871290	613002778	-72.265346	-72.265305	18.635314	18.635412
5	Polyline	30047692	secondary	330871292	619273093	-72.265533	-72.265517	18.634893	18.634929
6	Polyline	30047692	secondary	330871294	330871292	-72.265769	-72.265533	18.634354	18.634893
7	Polyline	30047692	secondary	330871301	613002774	-72.266355	-72.266143	18.633261	18.633681
8	Polyline	30047692	secondary	330871304	617809891	-72.266803	-72.266566	18.632482	18.632894
9	Polyline	30047692	secondary	330871306	330871304	-72.267202	-72.266803	18.63182	18.632482
10	Polyline	30047692	secondary	330871308	330871306	-72.267308	-72.267202	18.631677	18.63182
11	Polyline	30047692	secondary	330871311	330871308	-72.267428	-72.267308	18.631517	18.631677
12	Polyline	30047692	secondary	330871315	330871311	-72.267666	-72.267428	18.631203	18.631517
13	Polyline	30047692	secondary	613001575	330871287	-72.26497	-72.26497	18.63619	18.636309
14	Polyline	30047692	secondary	613002773	330871294	-72.265992	-72.265769	18.633969	18.634354
15	Polyline	30047692	secondary	613002774	613002773	-72.266143	-72.265992	18.633681	18.633969
16	Polyline	30047692	secondary	613002778	619273096	-72.265305	-72.265205	18.635412	18.635649
17	Polyline	30047692	secondary	617809891	330871301	-72.266566	-72.266355	18.632894	18.633261
18	Polyline	30047692	secondary	619273093	330871290	-72.265517	-72.265346	18.634929	18.635314
19	Polyline	30047692	secondary	619273096	330871289	-72.265205	-72.265071	18.635649	18.635969
20	Polyline	30047738	tertiary	330876300	617824408	-72.219135	-72.219591	18.602581	18.602433

Record: 1 Show: All Selected Records (0 out of 19605 Selected) Options

Figure 18 - Attribute table from the converted shapefile

Having defined the end-nodes for each street element, we can extract the network with the same approach used in [10] for the network analysis. The advantage of transforming spatial datasets into graph networks relies on the possibility to easily identify the connectivity of the original dataset (identification of disconnected streets islands within the network), and to assess the isolated streets due to the seismic damages.

9 Appendix B - XSLT Transformation To Extract and Reduce the Original *.osm* Data

```
<?xml version="1.0" encoding="ISO-8859-1"?>
  <xsl:stylesheet
    xmlns:xsl="http://www.w3.org/1999/XSL/Transform"
    version="1.0">

  <xsl:output method="xml"/>
  <xsl:output indent="yes"/>

  <xsl:template match="/">
    <osm>
      <xsl:for-each select="/osm/node">
        <xsl:call-template name="node"/>
      </xsl:for-each>

      <xsl:for-each select="/osm/way/tag[@k='highway']/parent::way">
        <xsl:call-template name="way"/>
      </xsl:for-each>
    </osm>
  </xsl:template>

  <xsl:template match="/osm/node" name="node">
         <xsl:choose>
      <xsl:when  test="tag[k='Operational_status']/@v='closed' or
                       tag[@k='type']/@v='roadblock' or
                       tag[@k='access']/@v='no' or
                       tag[@k='type']/@v='bridge_damage' or
                       tag[@k='type']/@v='road_damage'">
        <node id="{@id}" vis="{@visible}" lat="{@lat}" lon="{@lon}" dm="1" />
      </xsl:when>
          <xsl:otherwise>
            <node id="{@id}" vis="{@visible}" lat="{@lat}" lon="{@lon}" dm="0" />
          </xsl:otherwise>
    </xsl:choose>
  </xsl:template>

  <xsl:template match="/osm/way" name="way">
    <way id="{@id}" vis="{@visible}">
      <xsl:for-each select="./nd">
```

```
        <nd ref="{@ref}"/>
        <xsl:variable name='nodeid' select="@ref"/>
      </xsl:for-each>
      <tag k="highway" v="{tag[@k='highway']/@v}"/>
      <tag k="name" v="{tag[@k='name']/@v}"/>
         <tag k='brg' v="{tag[@k='bridge']/@v}"/>
         <xsl:variable name='dam' select="tag[k='impassable']/@v"/>
         <xsl:choose>
              <xsl:when test="$dam='yes'">
                 <tag k='dm' v="1"/>
              </xsl:when>
              <xsl:otherwise>
                <tag k='dm' v="0"/>
              </xsl:otherwise>
         </xsl:choose>
    </way>
  </xsl:template>
</xsl:stylesheet>
```

10 Appendix C – OSM Roads Classification

n.	Number of elements	OSM Road Type	Excluded from road network	n.	Number of elements	OSM Road Type	Excluded from road network
1	1	blocke		19	1	residential;track;tr	
2	1	Entree du plan		20	1	residential;track;un	
3	1986	footway	X	21	34	residential;unclassi	
4	1	footway;unclassified	X	22	5	residentiel	
5	3	ford		23	8	road	
6	5	living_street		24	2102	secondary	
7	2	no service	X	25	7	secondary_link	
8	3582	path	X	26	2591	service	
9	1	path;residential	X	27	13	steps	X
10	205	pedestrian	X	28	38	tertiaire	
11	847	primary		29	6	tertiaire;tertiaire;	
12	1	primary_link		30	10507	tertiary	
13	10	raceway		31	13	tertiary;track	
14	9526	residential		32	8	tertiary;unclassifie	
15	1	residential;resident		33	1	tertiary_link	
16	2	residential;service		34	5527	track	X
17	16	residential;tertiary		35	3466	unclassified	
18	1	residential;track		36	11	unspecified	

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12 Data Sources and Tools

[21] OSM streets data (http://www.openstreetmap.org/)

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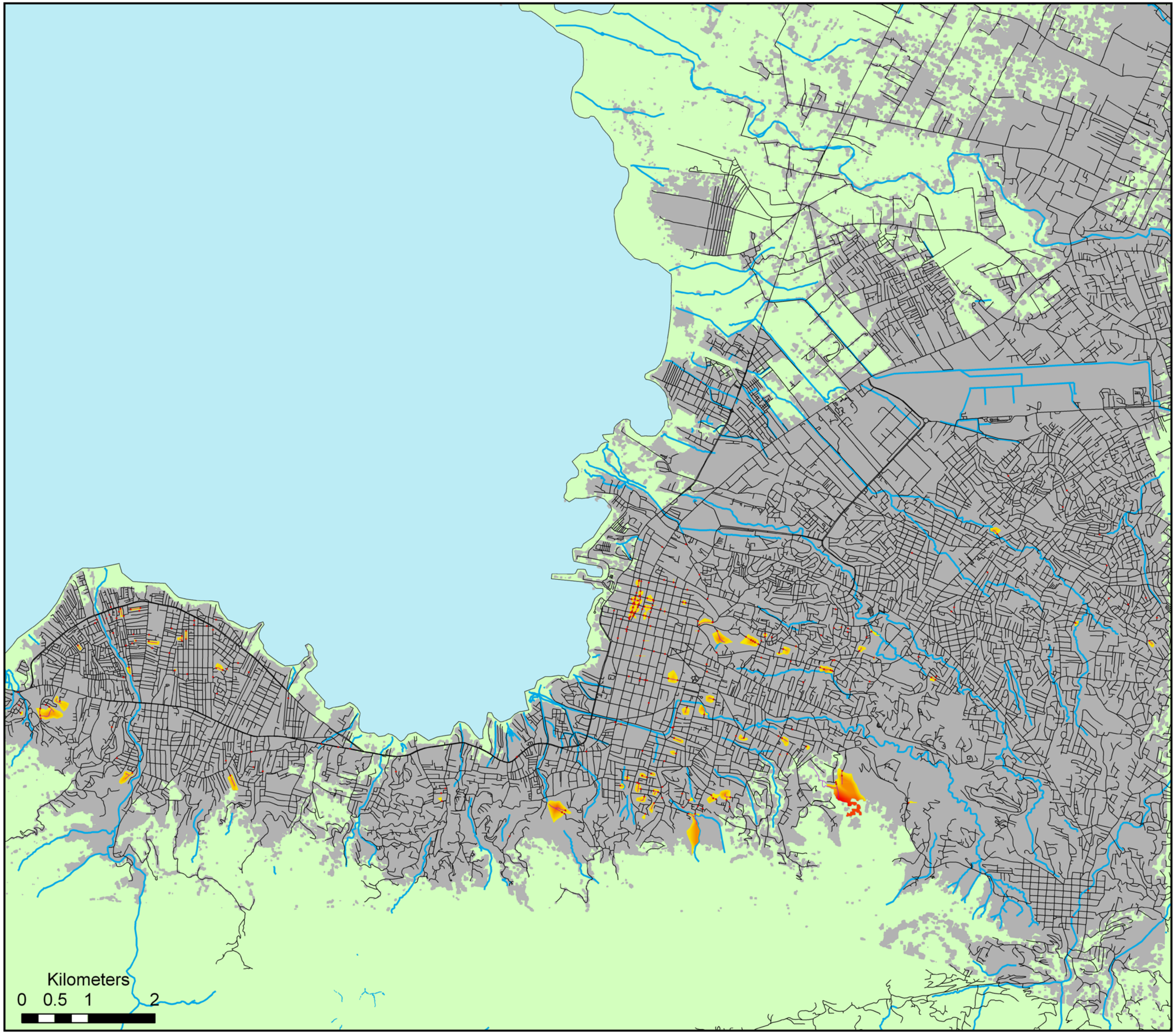
[26] FWtools (http://fwtools.maptools.org/)

Port Au Prince
HAITI
Accessibility Analysis

Revision: 2.0 Date: 19 November 2010

WGS 1984 PDC Mercator Projection



Legend

- Road
- Removed Isolated Road
- Waterways
- Detected interruption
- Urban built up area

Reduced Accessibility

[min]

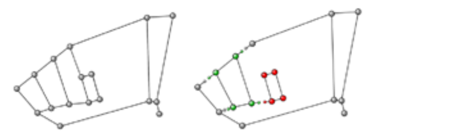
0. 0.5 1.0 1.5 2.0 2.5

Data Sources

Dataset	Type	Source
Road Network	polyline	Open Street Map
Road interruptions	point	UNOSAT and JRC
Administrative Boundaries	polyline	GeoFabrik
JRC PANTEX Built-up mask for Port-au-Prince from SPOT imagery	polygon	JRC

How reduced Accessibility is computed

Reduced accessibility is computed by means of spatial analysis onthe basis of the damaged (D) and undamaged (U) graph network (*fig. a*) where isolated roads are identified by means of network analysis.



Waterways are considered as barriers to the free movement (*fig. b*); two cost surfaces *Cu* and *Cd* are defined (*fig. c* and *fig.d*) and the reduced accessibility is computed from their combination.

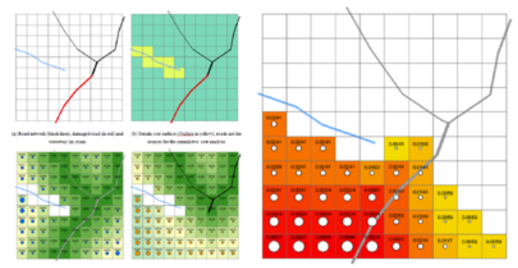


Figure 4 – Example of Reduced Accessibility result

European Commission

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Abstract

The catastrophic seismic event that struck Haiti in January 2010 led to an unprecedented effort in collecting and providing geographical information in support of the humanitarian aid. Although most of the compiled datasets and generated maps try to provide specific and detailed information on the location of damage and road interruptions, little or no information was available in terms of accessibility of the urban space. Here we try to offer an alternative method in defining the urban aftermath damage, coupling graph theory and GIS-based spatial analysis to assess how the urban space accessibility decreases when the road network is damaged. We believe there could be important lessons to be learnt from this exercise in the event of the physical failure of critical elements of European infrastructure.

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