Impact of relief accuracy on flood simulations and road network vulnerability analysis

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The increased availability and accuracy of multi-sources data enhance the simulation quality of natural disasters (hazard). Moreover, it enables a better prediction of their impact on the territory (vulnerability). Numerical representation of relief (DTM) is a prime necessity in risk simulation, in particular in flood study. Integrating 2D objects into a DTM significantly improves the relief representation around each object. The aim of this paper is first to enrich the relief accuracy with the altimetric attributes of 2D vector objects, and then to assess the impact of these modifications within the context of a rise in the water level and its consequences on the road network vulnerability.

The first part focuses on the integration of 2D vector data (e.g. roads) on a 2.5D digital terrain model. The integration of 2D vector data on a DTM usually raises data consistance issues. These data often stem from different acquisition modes ; moreover, their scale and their dimension (2D, 2.5D, 3D) vary according to their nature and the data capture. In order to overcome these problems, our approach consists in converting 2D vector data in 2.5D vector data by assigning them a width and computing their elevation. Then, these latter are integrated into the DTM and make it sharper, especially on the former interpolated areas.

In a second part, we analyze the floods effects on the running of the road network in Orléans (France). In addition to the direct damages caused by the physical action of the water, the flood also leads to functional disruptions on the road network by forcing users to take detours. In a risk preventive viewpoint, the network administrator has first to consider a given flood scenario and consequently to identify the network components to be protected as a priority, in order to reduce to the minimum the costs induced by the detours. On account of both levels of precision considered in the original DTM and in the enriched DTM, we have to compare two damaging scenarios of the road network for a given flood hazard. To that end, we quantify the functionality of the network components with centrality measures and we compare the efficiency of the different configurations of damaged network with accessibility measures. The results of this study prove how much the flood of the road network, the induced functional disruptions and the associated preventive actions depend on the adopted precision in the representation of the terrain.

Context

The increasing importance of natural and technological catastrophs have lead societies to take an interest in the risks prevention and prediction (see e.g. Gleyze (2002) for an overview on risks). For this purpose, many research projects aim to simulate the events and to assess their impact on the territory. In this context, the need in accurate geographic data is topical, on the one hand to simulate the events in a realistic way, and on the other hand to identify the elements at risk.
In this article, we experience the importance of the data accuracy in the flood prevention. We first study the impact of the Digital Terrain Modelling (DTM) accuracy level on the quality of the flood simulation. On that account, we consider ways to enrich the DTM by integrating relevant geographical data and then to forecast the flood at best. As an application case, we study in a second part the damaging of the road network caused by the simulated flood, according to the DTM accuracy level. The whole process is implemented all through the article on the french town of Orléans, whose configuration is particularly interesting in consideration of the variety of its protective engineering works against floods and the heterogeneous structure of its road network. At this juncture, the results of this study help us to draw up an appropriate preventive plan for the town.

Presentation of the study area

Before analyzing in detail the role of the DTM in floods simulations and its impact on the road networks planning, let us quickly introduce the area on which we apply our process.
The area in question is the french town of Orléans, located in the middle of France, 120 km away from Paris in the Région Centre. The Loire river crosses the city from east to west : the north part of the town is built on a small hill, whereas the south one is lower and more putted in danger (cf Figure 1).

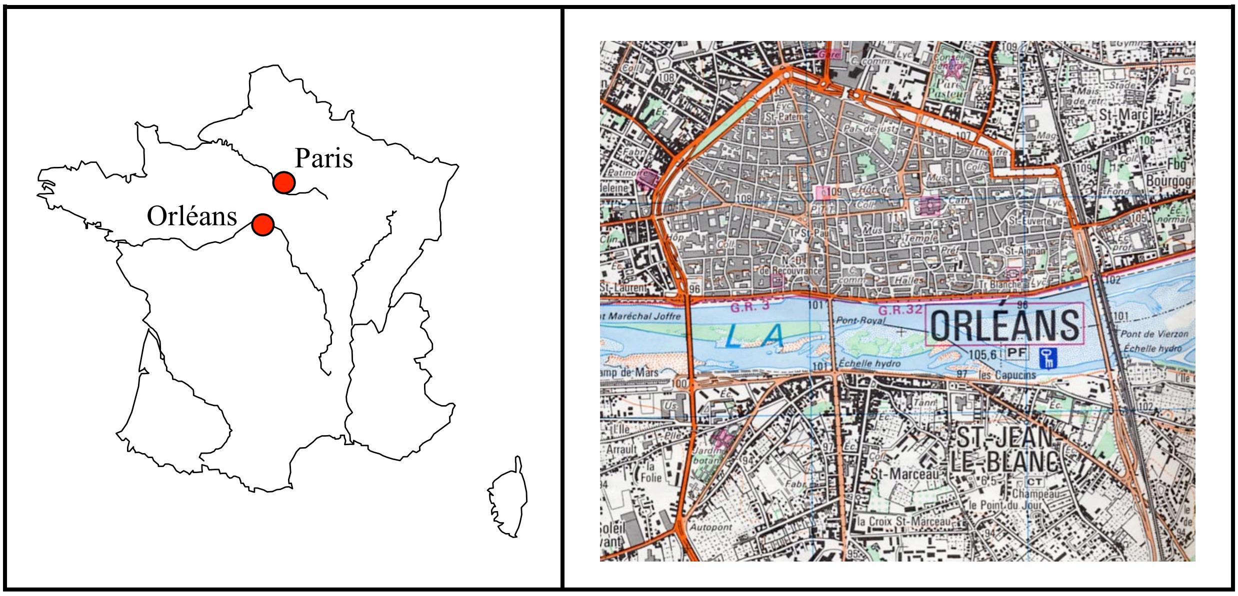

Figure 1 : location of Orléans in France and map of the town at the 1/25k scale (source : Institut Géographique National)

This Loire is the longest river of the country and is known to be the wildest too. Three important centennial floods have completely inundated the valley during the XIXth century (precisely in 1846, 1856 and 1866) : the last centennial flood dated more than 130 years ! Since that time, this area has continually and strongly grown up : more and more people and companies have settled in the valley. And in spite of several town and country plannings, this area is always subject to a high flood hazard (for further details, see Gautheron & Pignol (2001)).

Impact of DTM accuracy level on flood simulations

Altitude and multi-source data are more and more numerous and accurate. They help to modelise in a more coherent way simulations of natural or industrial hazards on the one hand, and to predict the impact of the hazards on the terrain (vulnerability) on the other hand. For example, when simulating a rise in the water level, the boundaries of the underwater area need to be very accurate. Overlaying different sources of data is a way to reach such a level of knowledge and to determinate which elements at risk are likely to be exposed to the hazard.

In this first part, we focus our research on a coherent and realistic 2D linear vector data integration on a DTM. For this purpose, we propose to use roads layer in a 2D representation, for which the altimetric information is stored as an attribute in the database. By integrating roads, we aim to account for the role of the main protective engineering works, ie the embankments. The information provided by the road layers and the DTM in its 2.5D representation are extracted from the same database : the BDTOPO®. This latter is a one-meter resolution database provided by the french national mapping agency (IGN), and contains 2D and Z attribute vector information with metric accuracy and altimetric information stored as contour lines (see the specifications of IGN (2001)).

The problem of integration

2D vector data integration on a Digital Terrain Model generally raises important problems of coherence between layers. If vector data are simply placed on the TIN (Triangulated Irregular Network – ie the irregular setpoints on which the DTM is computed), several problems appear (see the example on Figure 2).

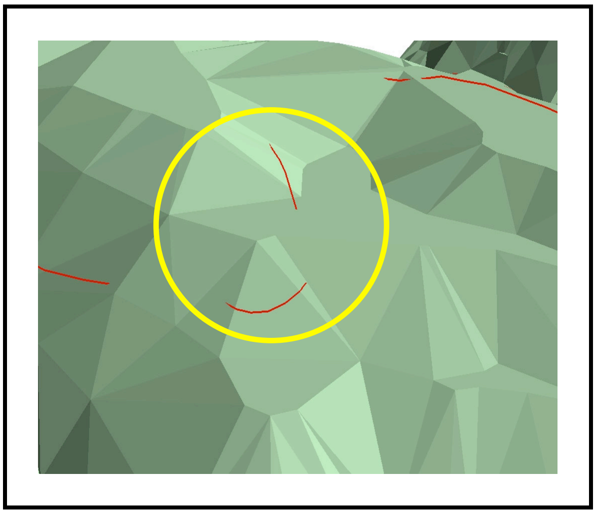

Figure 2 : example of incoherence between a TIN and a road layer : the road runs above and below the terrain

This incoherence arises from multiscale capture data (see Rognant (2000)). For example, a road is captured with a higher precision than a contour line. The capture accuracy depends on the nature of the object and on the difficutly to capture this object. It is easier for the stereoplotter to follow a road, which is more visible than a mind construction such as a contour line. If the DTM has a lower resolution than vector data, interpolated areas of the DTM have a good chance to be different in Z altitude. In order to increase the realism of the result of our integration, roads are computed with a witdh. The information related to the witdh is stored as an attribute in the database. Thanks to the integration of more accurate data, we improve the quality of the geometric information in altitude. Such a realistic integration deeply enrichs the ground description by comparison with a simple interpolated area (the whole process is described in Rousseaux (2003)).

Towards a coherent integration of vector data on a DTM

In a first step, the DTM is naturally computed as a TIN (Triangulated Irregular Network) from the nodes extracted from the contour lines. However, the TIN computed from this method contains « bad triangles » such as flat triangles or triangles computed from more than two consecutives contour lines (these drawbacks are detailed in Julien (1991)). For this purpose, we exclude well-known artefacts on the computed TIN thanks to an algorithm which detects flat triangles (triangle with a 0% slope, created with three points of the same contour line). In order to delete them, we re-create contruction lines such as talwegs and ridges. With this end of view, a point is added to each triangle on the middle of its base – the Z dimension of this added point is calculated by a linear interpolation from its position and the position of the two nearest contour lines. Then, our contour lines are resampled in order to densify points on each line according to the distance to other lines. This ensures that the distance between two points of a same contour line is always shorter than the distance between two points of different contours lines. In this way, this algorithm helps to obtain a more realistic ground. Henceforth, linear objects can be integrated in the Triangulated Irregular Network.

In a second step, we transform 2D linear road data into 2D surfacic roads by assigning them a horizontal width. The width depends on the road type and on its number of lanes (both features are stored as attributes in the database). In practice, the altitude of roads is computed along their length from the Z attribute stored in the database. After checking the slope and regularity constraints, these data are lastly integrated into a new set of points with Z information. This new set of points is added to the set of points originating from the TIN. This representation enables us to integrate anthropic slope breaklines, such as dams, dikes, or steep roads.

Due to different data capture procedure modes, contour lines have a lower accuracy than 2D vector geographical objects. As altimetric 2D objects are more accurate than contour lines, they are prefered to contour lines in case of conflict. An additional algorithm to delete points from the contour lines located on the roads is launched. Thus, the roads are obtained with no artefact. At last, the set of points (TIN + roads) is triangulated with a Delaunay algorithm. Roads are clearly visible on the resulting TIN (see Figure 3). Besides, the different operations leading to the enriched DTM are summarized in the Figure 4.

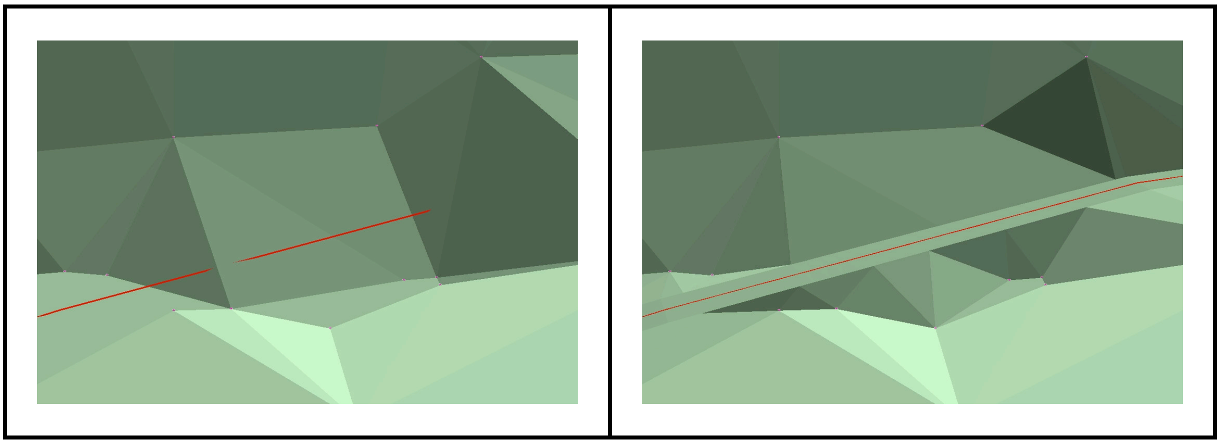

Figure 3 : relief modelling before (left) and after (right) integration of roads on the TIN

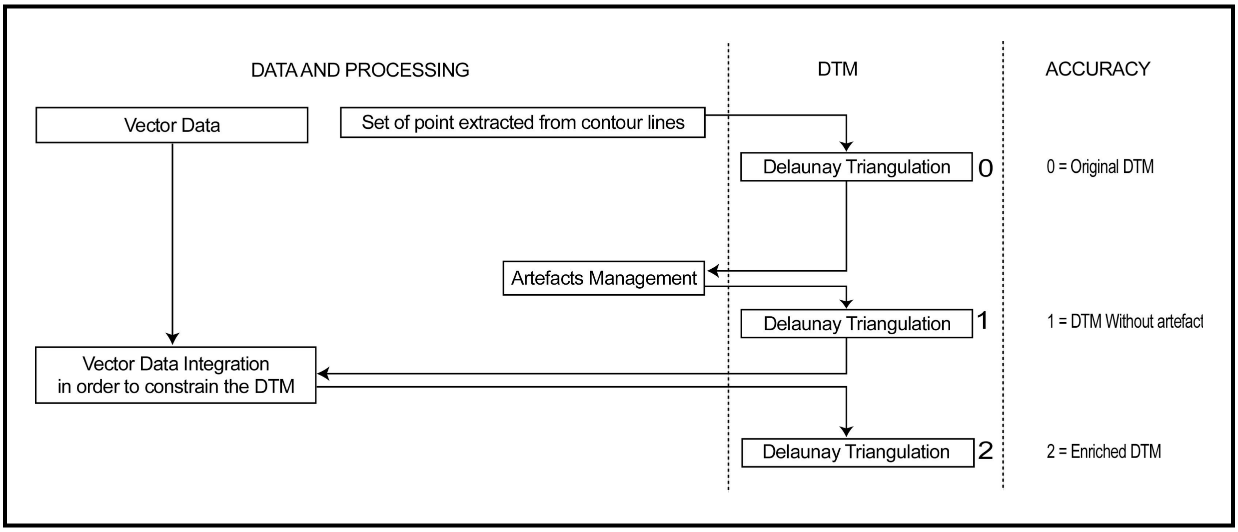

Figure 4 : construction diagram of the enriched DTM and accuracy degrees of the intermediate DTM

Thanks to the enrichment of the DTM, the coherent combination of the original altimetric layer and the additional vector data layer (ie a kind of semantic layer integrating relevant geographical objects such a embankments) helps the user to identify the nature of the potential damaged features. In this paper, we particularly focus on the road network and its vulnerability. Therefore, the study of the road networks running in a flood context is the subject of the last part of the paper.

Methodology

Flood scenarios

As mentioned above, we experience the impact of the DTM enrichment through flood simulations. For this purpose, we consider two flood scenarios simulated on the original DTM and on the enriched one. Actually, the word « scenario » formally refers to the hazard – the flood – whose extents depends on its frequency. In our application case, the variable is not the frequency, but the accuracy level of the DTM, and both flood simulations are two different forecasts of a same event : a centennial flood. For this reason, we use the term « scenario » by a misuse of language to designate these simulations.

Simulation process

In practice, we implement both simulations by inundating the original DTM and the enriched DTM on the Orléans area. Note that the underlying process is not based on an hydraulic modelling from usual parameters such as speed and flow, but on the intersection of a water surface and the considered DTM (a similar study is presented in Puydebois (2003)). The DTM accuracy level has naturally an impact on the distribution of the emerged areas. As we will see in the next part, the enriched DTM takes into account the embankments and shows in a realistic way that the raised roads are not flooded.

In detail, the above-mentioned water surface for the flood simulation is computed from a Z_polygon. For the Orléans area, this polygon has been computed by the DIREN Centre (the regional department of environment concerning Orléans) from the « PHEC map », that is the highest known water level map at the 1/25k scale (PHEC maps are available on the website of DIREN (2003)). As for the Z_polygon, the altitude is computed by a linear interpolation. In order to improve the interpolation, other altimetric information is extracted from flood levels of the PHEC map. The Figure 5 sums up the different objects used in our simulation process and the Figure 6 presents the visual results obtained for Orléans.

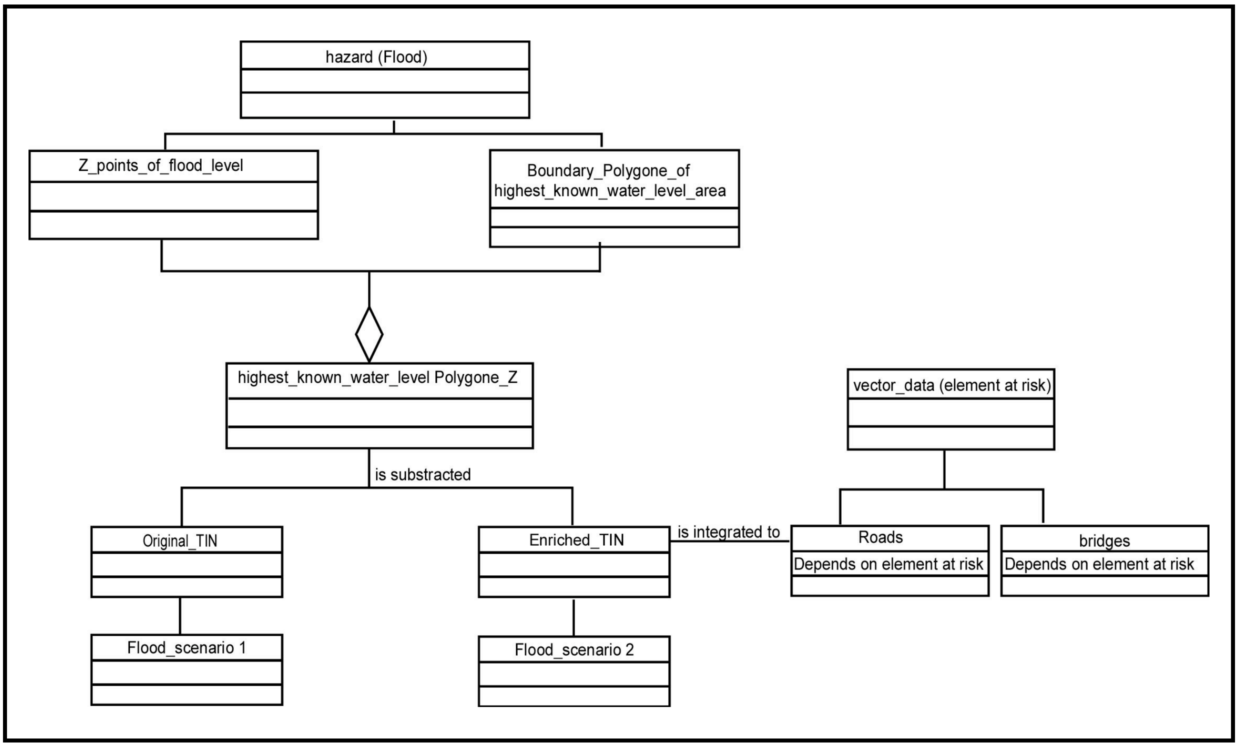

Figure 5 : modelling of hazard and elements at risk

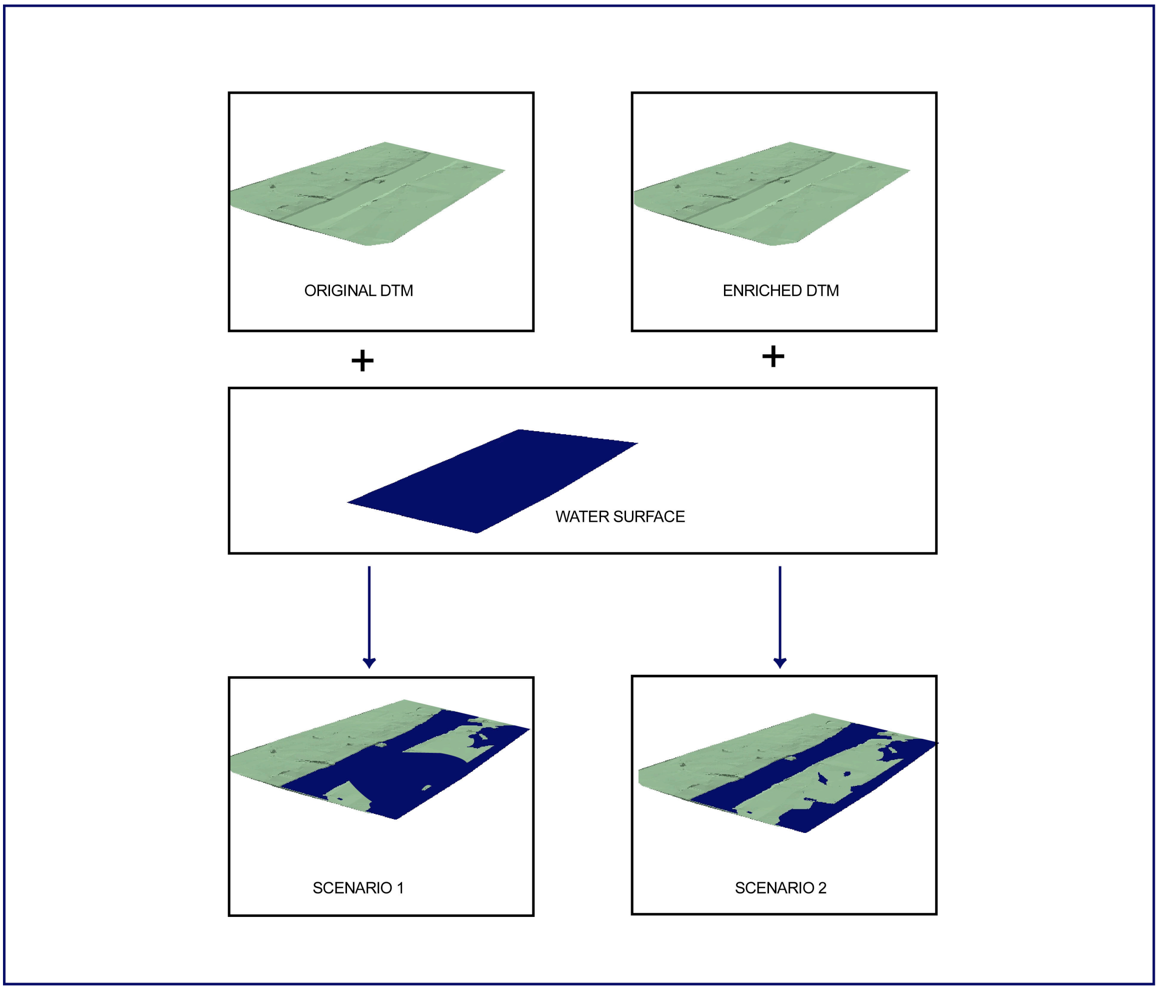

Figure 6 : illustration of the simulation process on Orléans

Note that the flooded areas are exclusively determined by the direct overflowing of the Loire. The non-connected areas (ie areas only threatened by the ascent of sheets of water) have been deleted (anyway, their total surface is unsignificant).

Identification of the road networks damaging

In order to map the damaging on the road network, we identify the broken roads thanks a SQL request between the flooded area and the road layer. The breaking points on the network are precisely located thanks to the road setpoints which we already used to integrate the road layer. We shall no longer repeat the request on the road section object, but on the setpoints which forms the road networks. As the distance between two successive points is about one meter, the location of the breaking points on the roadway is accurate to within about one meter.

In the application case dedicated to the road network analysis, each road section is considered as an elementary component whose state is either in good working order or out of order. The users does not actually take a road section which is known to be totally or partially flooded.

Application : flood impacts on the road network

As an application case, we study in this part the effects of a centennial flood on the Orléans road network. This work implies to select a DTM on which we simulate the flood. At this juncture, we aim both to analyze the impact of the DTM accuracy level on the flood simulation and to analyze the real risk and its consequences on the road networks running. For this reason, our approach is divided in three steps as decribed below.
In the first step, we simply simulate the centennial flood on the Orléans road network according to the original DTM on the one hand and to the enriched one on the other hand. On that account, each simulation will be afterwards considered as a flood scenario, and we will go on with the comparison between the DTM modellings through the functional analysis of both of them. From this point of view, we preliminarily study in a second step the road networks functionality in its usual configuration. Thanks to this overview, we complete in a last step the comparison of both scenarios by analyzing for each of them the networks perturbations, and we show how the enriched DTM helps finally to draw up the main outlines of an appropriate preventive plan for the Orléans road network.

Simulation of a centennial flood in Orléans according to the DTM accuracy level

As established in the first part of this paper, simulating floods with the original DTM does not take into account some protective engineering works and gives one to think wrongly that a set of road sections are under the water level. The Figures 7 and 8 below display the differences between the edge removals in the network for both DTM modellings.

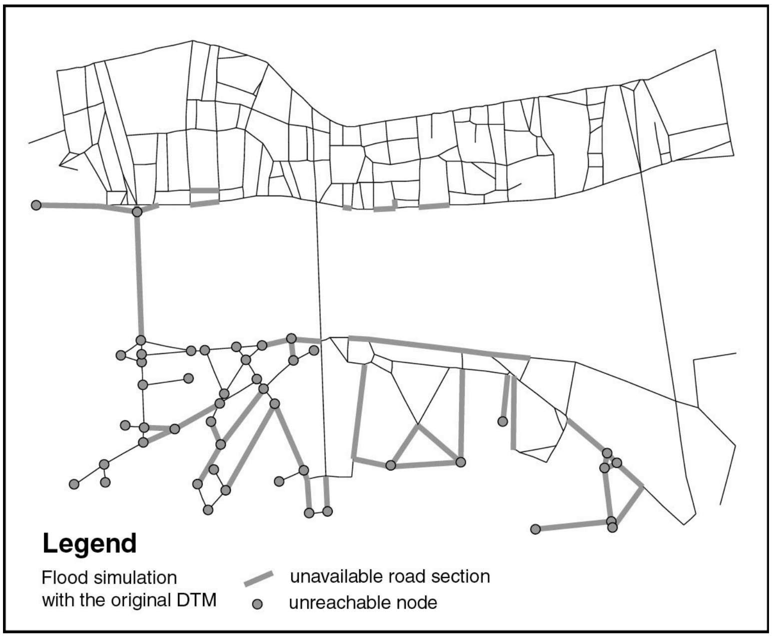

Figure 7 : simulation of centennial flood effects on the original DTM

The inaccuracy of the original DTM leads us to catastrophism in the prediction of the flooded areas. In the associated scenario, the access to the west bridge is removed and the embankments are partly unavailable on both sides of the Loire.

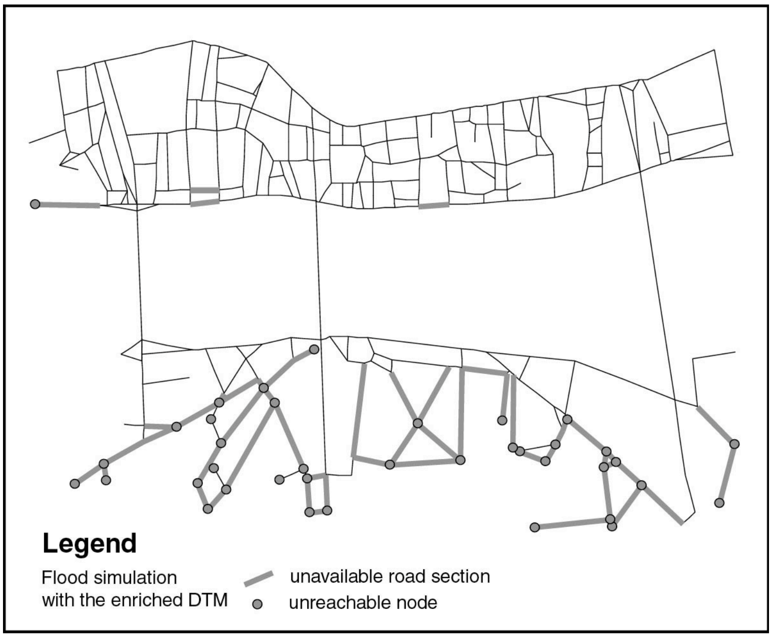

Figure 8 : simulation of centennial flood effects on the enriched DTM

The enriched DTM scenario is less alarmist, because it considers the protective engineering works in the relief modelling. As the result, neither the bridges nor the south embankment are damaged by the flood. However, the protective engineering works induce flood transfers inside the south bank where almost half the road sections are broken. From this point of view, we will be afterwards attentive to the road networks running and to the consequences of edge removals around the bridges, the embankments and the areas which are not easily accessible.

In short, the results of these simulations directly show how the DTM accuracy level has a great influence on the prediction of the flooded area. In the following, we analyze the flood impact on the road networks running while going on the comparison between both simulations.

Preliminary study of the Orléans road networks functionality

Before tackling the networks functionality analysis in a risk context, we propose preliminarly to study the networks running in its usual configuration in order to know how the trips are distributed and what are the strategic nodes and edges on the network.
In that respect, we decide to consider the network in its ability to serve the space on which it is located. In pratice, the origin-destination relations have to correspond to a uniform demand on the territory, that is representative of trips whose origin and destination would be selected according to a uniform random law on the space and associated with the nearest nodes of the network[1] (such a process has already been implemented by Gleyze (2003)).
Thus, we notice that :

- the origin-destination trips demand does not correspond to a real use but represents the sum of spatially uniform interactions on the space,
- the flow which is consequently observed on each component of the network corresponds to the probability for a random trip to pass through the component in question for a uniform service of the space.

For such a trip logic, we have computed the betweeness index on the edges of the network (see Freeman (1978) for the definition of the betweeness index and Brandes (2000) for a computation algorithm). This index corresponds to the total weight of the relations passing through each edge. For our origin-destination trips demand, the betweeness index also equals the probability to pass through the considered edge during a trip whose origin and destination would be choosen at random on the territory. Therefore, this index provides information about the functionality of the edges for a uniform service of the space. The Figure 9 shows the results of this index for the Orléans road network in its usual configuration.

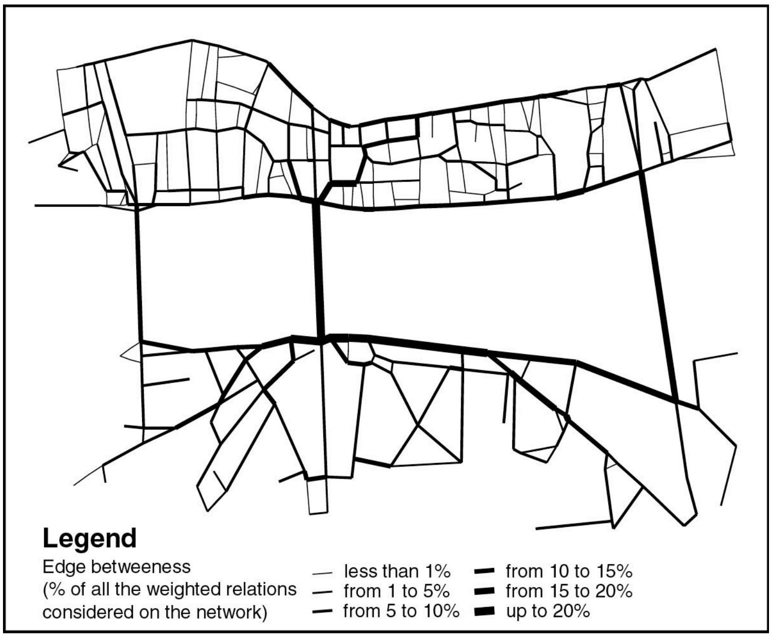

Figure 9 : betweeness index of the edges for a spatially uniform origin-destination trips demand

As we would expect, the betweeness index emphasizes the importance of the bridges, but this latter is unbalanced since 62% of the relations getting across the river (i.e. half of all the relations) take the central bridge (respectively 18% and 21% for the side bridges). Besides, the figure highlights on both banks preferential ways converging on the central bridge : these ways partially

[1] In mathematical terms, we associate each node i with a weight p_i representing the surface of the Voronoï cell on the set of all nodes, then we weight each relation between two nodes i and j with a standardized weight p_{ij} proportional to the product $p_i.p_j$.

take the embankments and some local service road sections, especially on the south bank where the low density of the network concentrates the trips on a limited number of edges.

As a result, it turns out that sensitive functional components of the network are localted around the central bridge and the embankments, particularly the south ones. We have finally completed this preliminary study by computing a vulnerability measure of the edges (see Holme (2002) for further details on the vulnerability notion and evaluation tools). For a given edge *i*, we define its vulnerability level as the ratio between the weighted average length of the relations on the damaged network from which the edge *i* has been removed, and the same variable measured on the network in its usual configuration. In other words, the vulnerability index corresponds to the average detour caused by the removal of the considered edge. The results for this index are given on Figure 10 :

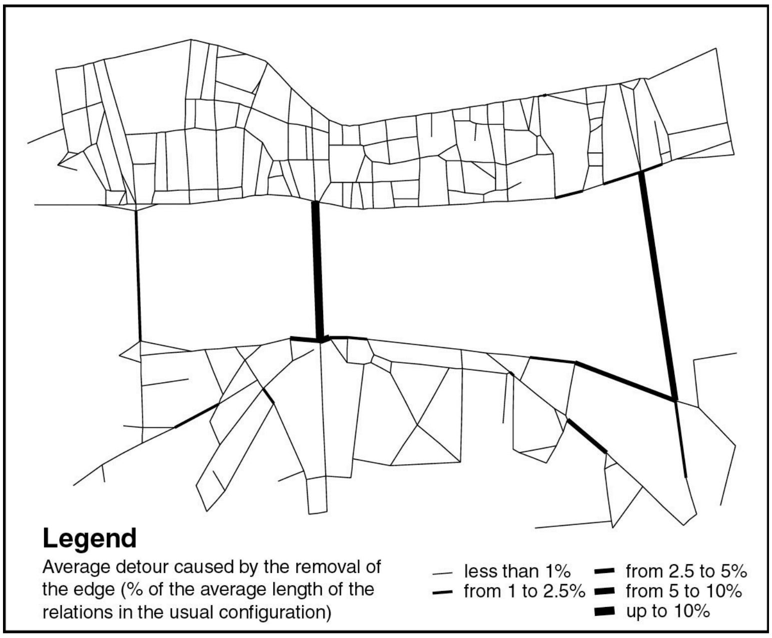

Figure 10 : vulnerability index of the edges for a spatially uniform origin-destination trips demand

The above-mentioned trends are confirmed here with much more pronounced contrasts. The central bridge is shown to be the vital component of the network. To a less extent, the east bridge plays a significant role. At last, the west bridge as well as some road sections on the south bank play minor role – the rest of the network is little sensitive to edge removals because of the networkings density. Nonetheless, it is important not to forget that these results are related to a single edge removal and that the combined effects of several single component removals may cause bigger functional damages.

Damages caused to the road networks running

Impact on the DTM accuracy level on the prediction of road networks perturbations

From this short overview of the networks running, we consider now the flood scenarios related to both DTM modellings. In this way, we want to show how an appropriate DTM modelling leads to relativize the damages on the territory and provides information to draw up a suitable preventive plan.
In the first place, we have measured the betweeness transfers following upon the flooded edges removals in each scenario. In this respect, we have computed for each edge the betweeness difference between the considered scenario and the network in its usual configuration. The results of this operation are shown on Figures 11 and 12.

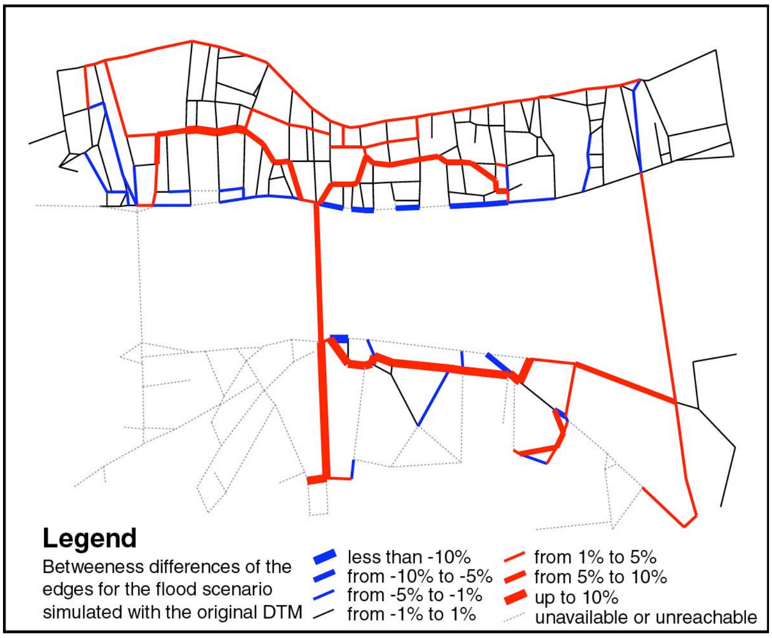

Figure 11 : betweeness differences of the edges between the scenario simulated on the original DTM and the network in its usual configuration

The removal of the west bridge in the original DTM scenario involves significant transfers on the other bridges. These transfers become apparent on the banks through east-west routes which are especially loaded because of partial removals on the embankments.

Figure 12 : betweeness differences of the edges between the scenario simulated on the enriched DTM and the network in its usual configuration

The continuous running of the bridges in the enriched DTM modelling considerably reduces the transfers in the associated scenario. Considering the layout of the available road sections, this scenario gives a realistic view of the consequences of the partial embankments removals. In this connection, we observe local overloads on some road sections of the south bank because of the significant damage of the service in this part of the town.

While the betweeness deficits helped us to measure the functional evolution of the network, the assessment of the accessibility deficits on the territory gives information on the networks efficiency variations. In this respect, we have computed for each node the average closeness difference between the considered scenario and the network in its usual configuration (see e.g. Freeman (1978) for the average closeness notion). The average closeness of a node corresponds to the weighted average of the network distances to all the other nodes of the network. Figures 13 and 14 display the results of this computation and highlights the areas penalized by the flood for each simulation.

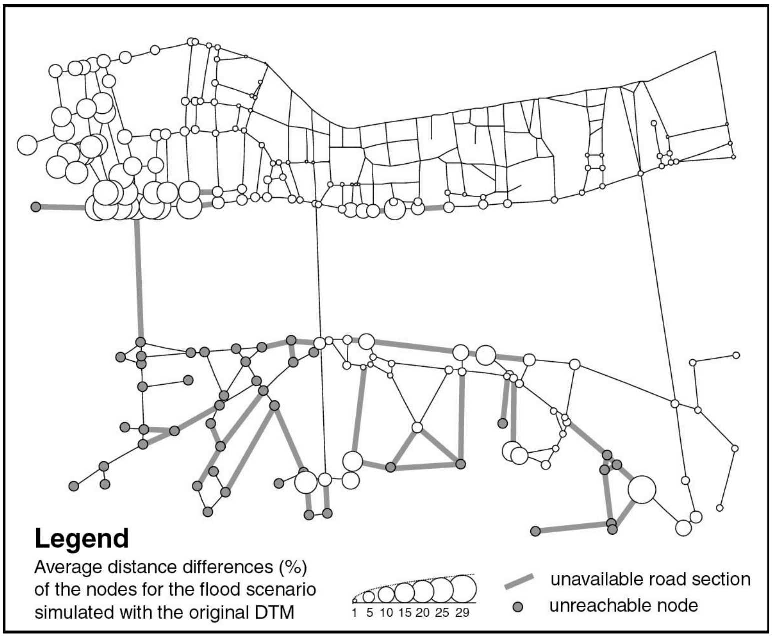

Figure 13 : average closeness differences of the nodes between the scenario simulated on the original DTM and the network in its usual configuration

The alarming forecast for the first scenario heavily penalizes the north-west nodes because of the removal of the west bridge. In less proportion, the networks difficulties in serving the south bank are easily perceived through the important accessibility deficits in this area.

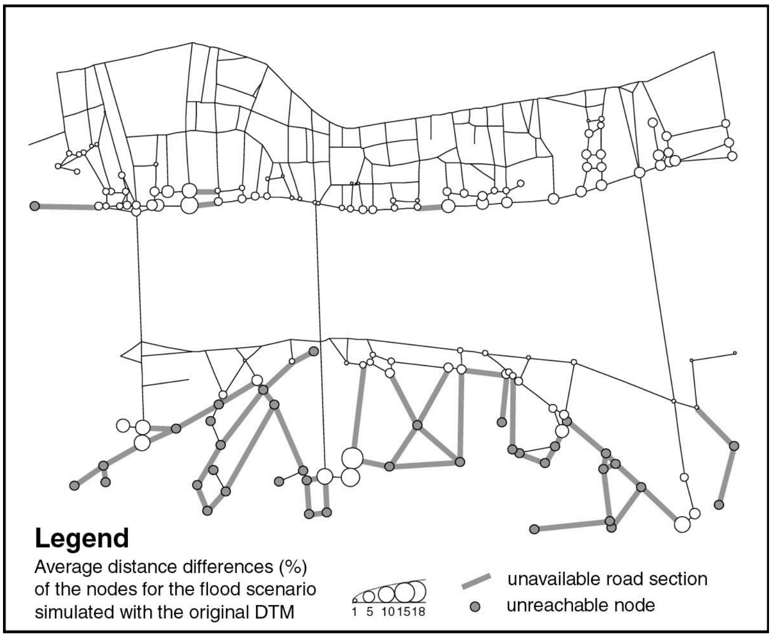

Figure 14 : average closeness differences of the nodes between the scenario simulated on the enriched DTM and the network in its usual configuration

Enriching the DTM limits the estimated flooded area to some road sections of the north embankment and to sparse road sections inside the south bank. On that account, it appears that the flood actually causes less damages than in the scenario outlined with the original DTM. The disruptions on the north embankment are locally limited because the dense networking of the north bank offers a lot of substitution ways. The edges removals on the south bank take place at local level too : in this scenario, the south-east embankment is intact and only service itineraries are actually concerned by the flood.

Synthesis – Elements for a suitable preventive plan of the Orléans road network

The comparative study of both flood scenarios makes the most of the DTM accuracy for the forecast of the flooded area. In the present case, using the original DTM does not take into account the roads altitude – especially the altitude of the embankments and of the bridges access – and wrongly foresees the flooding of the south embankment and the closing of the west bridge. In view of the analysis of the networks functionality in its usual configuration, this inaccuracy is far from being insignificant, because it concerns some components whose role is proved to be important in the networks running. Simulating the flood with the original DTM lets suppose that the central bridge as well as secondary itineraries on the south bank will be strongly loaded in case of flood. In practice, the results obtained with the enriched DTM show that (fortunately) the damages caused by the flood are less serious and mainly concern the local service of the south bank – the associated trips cause slight overloads on some east-west substitution itineraries. However, the information provided by the scenario based on the original DTM may be useful because it indicates by comparison where the preventive actions should be transfered.
As regards preventing from floods, it is relevant to take into account both the networks running in its usual configuration and the set of the damaged road sections which are foreseen thanks to the flood simulation with the enriched DTM. Obviously, the protection of the bridges has priority, but it seems that these latter are not threatened by a centennial flood. Conversely, the networks manager has to make a point of saving transversal itineraries near the river : such routes are usually guaranteed by the embankments for which the protective engineering works seem to be efficient (only three road sections of the north embankment would be threatened by a centennial flood, according to the Figure 8). Furthermore, additional protection efforts have to be provided on the south bank in order to guarantee continuous long range itineraries on the one hand, and to improve the local service on the other hand.

Conclusion

In this paper, we have highlighted the important role of the MNT in flood simulations. In the application case on the Orléans area, using the original DTM lets wrongly suppose that some areas are located under the water level. The DTM enrichment corrects these mistakes thanks to the integration of relevant altimetric information to the relief, in the sense that it involves structuring elements as embankments, dikes, etc.
As an application case in risk analysis, we have choosen to study the flood impacts on the road network. In practice, both DTM accuracy levels (obtained with the original DTM and the enriched one) lead us to consider two flood scenarios, whose comparison confirms the interest to enrich the DTM with structuring features of the landscape. The combined analysis of the road networks running in its usual configuration on the one hand and in the damaged configurations for both scenarios on the other hand gives a subtle overview of the networks vulnerability to flood hazards. The synthesis of several functional networks index helps us to draw up priorities in the prevention and in the protection of the network.
However, such a process, from the flood simulation to the analysis of the impact on the road network, is based on simplified modelling assumptions. Among other, note that the DTM enrichment does not take into account other structuring elements of the landscape such as the houses. Moreover, the role of the road network is only considered in a spatial service way inside a limited area ruling out the surrounding network.
The implementation of an exhaustive study is often long and costly and needs a knowledge of the terrain and an expertise in hydrology which concerns more accurate analysis fields. From this point of view, the process described in this paper will never stand in for the hydrologists works, such as

the ones lead by DIREN (2003). Notwithstanding it should become a compromise for any preliminary large scale study.

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