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HOW TO CHARACTERIZE THE RESILIENCE OF CITIES IN A DISADVANTAGED ENVIRONMENT? AN EXAMPLE IN HAITI

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ABSTRACT

Haiti is one of the poorest countries in the world, and prone to worst natural hazards. Among these hazards, inundations and mudflows, frequent in this hurricane zone with soils destroyed by intense deforestation, recurrently threaten people and goods. Technical approaches of event forecasting, flood modelling, risk mapping and alert organization, that are classical in developed countries become challenging in Haiti, where data are missing or incomplete and public administration is often ineffective and without adequate means. Moreover, even in case of improved technical tools, a large part of the difficulty relies in appropriation of the problem by the local population, who is often fatalistic. The paper describes a comprehensive process of technical study in link with sociological approach in a watershed severely affected by Hurricane Matthew in 2016: the watershed of Cavaillon River in the Southern Province of Haiti. The lack of hydrological data was circumvented by the use of conceptual model ATHYS and a smart use of the scarce data acquired immediately after the hurricane. A drone driven survey that appeared to be efficient, while cheap, addressed the lack of topographical and bathymetric information. Regarding the appropriation of the problem by the population, a vulnerability map was progressively built, using an Analytic Hierarchy Process and its transposition in terms of risk confronted with the perception by the local population.

Keywords: Lack of data; flood mitigation; flood modelling; drone survey, analytic Hierarchy Process.

1 INTRODUCTION

Haiti is particularly prone to natural threats and disasters. Its mountainous terrain (more than 75 % of the country area), where huge deforestation and subsequent soil erosion are observed, is subject to rapid propagation of floods in small coastal plains.

Haiti is also located on the route of major hurricanes, such as Hurricane Matthew that killed more than 500 people in October 2016, made more than 175,000 people homeless and affected 2 million Haitians. Moreover, it is one of the poorest countries in the world with a dramatically weak GDP per capita of 1200 US$ and limited government budget, resulting in poor infrastructures and disorganized administration, among others regarding hydrology and river management.

The strategy for risk reduction in Haiti relies on the effective implementation of the National Risk and Disaster Management Plan (NRDP), which considers interventions at the local level. In order to be effective, such a strategy requires not only local hydrological and hydraulic data but also the development of an adapted methodology for building such a database in a context of poor resources and for using this in a convenient way for the benefit of a population. Indeed, local people are in general not familiar with technical approaches and often fatalistic regarding natural hazards.

Within the frame of collaboration between the catholic University of Louvain (UCLouvain, Belgium) and the State University of Haiti (UEH), the present project aims at developing a methodology for constructing simple and efficient hydraulic models for Haitian rivers, without resorting to inaccessible or too expensive resources. Beyond hydraulic modelling of flood flows in rivers, the project also includes a thorough analysis of the vulnerability of the territories, to carry out a flood risk analysis of the zones situated in the flood corridors of the rivers. As an example, this strategy of modelling and analyzing flood risks was tested on the Cavaillon River and especially for the town of Cavaillon, located in the Southern department of Haiti (Figure 1). The Cavaillon River is approximately 50 km long. The studied reach has a length of 25 km, located between the Dory weir and the village of Grand Place. This reach includes the Cavaillon City that counts 45,000 inhabitants and is particularly prone to inundation as a large part of the town is built in the flood plain of the river.

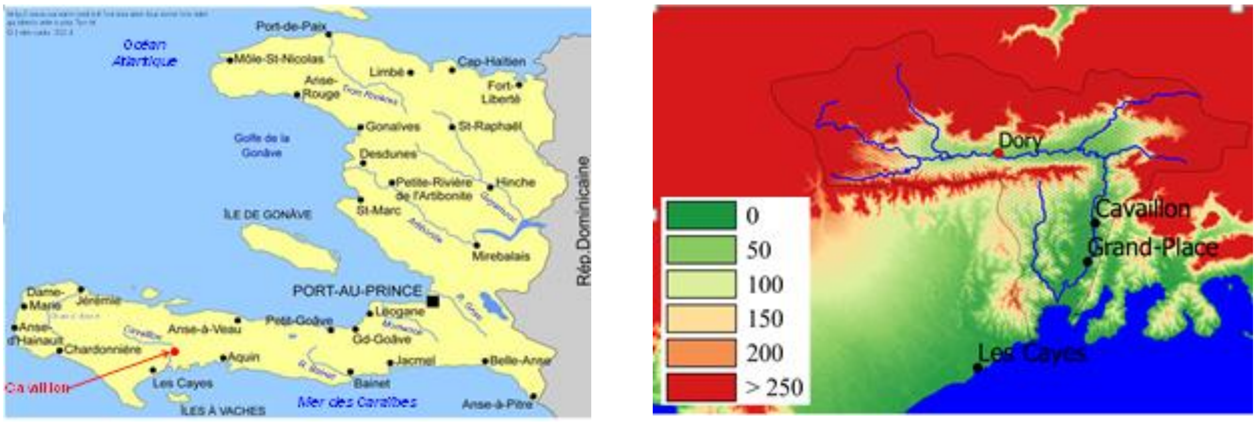
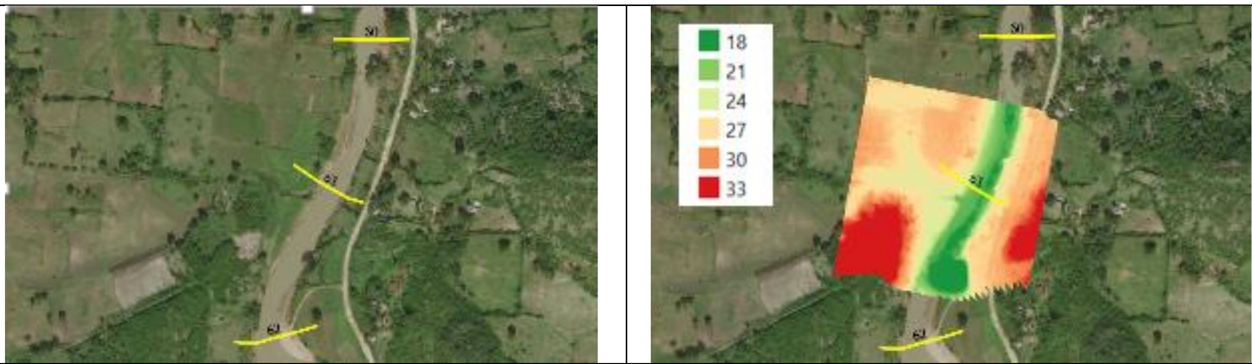


Figure 1. Localization and level contours of the study area (elevations in meters).

2 GEOMETRY OF STUDY SITE

At the start of the study, neither topographic nor bathymetric data was available for the Cavaillon River, which is the case for most of Haitian rivers. Regarding the minor bed, 96 cross sections (Fig. 2a) were surveyed manually with a differential GPS device [Joseph et al., 2018]. Regarding the flood plains, the only available Digital Terrain Model (DTM) at that time was a 30-m mesh. This coarse density is usable for watershed hydrological modelling but not accurate enough for hydraulic modelling. Therefore, a high-resolution (0.15-m mesh) DTM of potentially flooded areas was built in May-June 2016 from a novel photogrammetry technique using an Unmanned Aerial Vehicle (UAV) [Fonstad et al., 2013; Carlier d'Odeigne et al., submitted]. This latter technique, while used in unusual and difficult conditions of accessibility and energy supply, revealed to be surprisingly accurate, despite its low cost (Fig. 2b). Details on the technique are available in Carlier d'Odeigne [2018].



(a) Satellite view around section 61 | (b) Dense DTM from UAV photogrammetry

Figure 2. Aerial view of surveyed area and corresponding DTM (elevations in meters).

At the end of the study, in 2016-2017, a new systematic survey of the country, using classical airborne laser scanning, yielded a 1.50-m resolution DTM, better than the former 30-m one but less accurate than the drone-driven DTM. It was thus interesting to compare the three data sets: the cross-sections surveyed manually by means of a differential Global Navigation Satellite System (GNSS), the drone-driven DTM over the river flood plain with a resolution of 0.15 m, and the "official" CNIGS (National Center of Geo-Spatial Information) DTM 2016-2017 with a resolution of 1.50 m.

Figure 3 shows such a comparison for one of the sections of Figure 2, where the water level does not exceed 25 m, even in case of major discharges. The agreement between the three approaches is rather satisfactory for the banks of the river. Some discrepancies can be observed between the drone-driven and CNIGS DTMs, especially on the plateau above the right bank. This may be explained by the presence of cultivated plots that cannot be removed easily by the drone-driven DTM process contrarily to a Lidar system. This constitutes one of the limitations of the drone technique. Another limitation is the loss of accuracy near the edges of the flown area, due, among others, to the fisheye effect of the drone camera. This latter limitation can be partially addressed by multiplying the number of flights to increase the overlap area between adjacent images. As the CNIGS DTM was not available during the study, these differences only appeared after the project completion. Anyhow, most of these discrepancies do not affect the hydraulic modelling, as they are often outside the inundation extent. In contrast, the differences observed in the minor bed are more significant. Unsurprisingly, the CNIGS DTM issued for airborne laser scanning misses the minor bed, yielding a quasi-horizontal level that is the water level at the time of the flight. In addition, discrepancies in the minor bed between the 2015 manual survey and the 2016 drone-driven DTM are significant. The drone flights were planned during the dry season in order to capture the major part of the minor bed. The differences in Figure 3 reflect the uneven transparency of the water, resulting in a detected level of the minor bed lying between the actual bed and the water elevation.

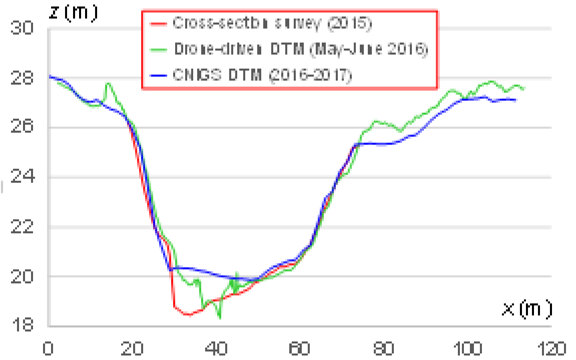


Figure 3. Cross-section 61: Comparison between DTMs.

A key advantage of the drone-driven technique is its low cost and its flexibility, so allowing new surveys after any significant meteorological event. This was particularly the case after Hurricane Matthew (October 2016) that considerably affected the river landscape, mainly in the upstream reach of the river. The “official” CNIGS DTM was built before the hurricane and its update is practically impossible for a long time for lack of means. In contrast, the flexibility of the drone allowed capturing images in the months just after the catastrophe. Figure 4 shows orthophotos of a reach, respectively 6 months before and 6 months after the hurricane. In Figure 5, the cross-section before and after are compared, evidencing the dramatic upset of the river morphology, with, for example the erosion of the left bank of more than 20 m. More details about the drone-driven techniques and the characterization of the morphology consequences of the hurricane Mathew on Cavaillon River can be found in Carlier d’Odeigne et al. [2019].

(a) Before Hurricane Matthew	(b) After Hurricane Matthew

Figure 4. Orthophotos from drone flights before and after Hurricane Matthew

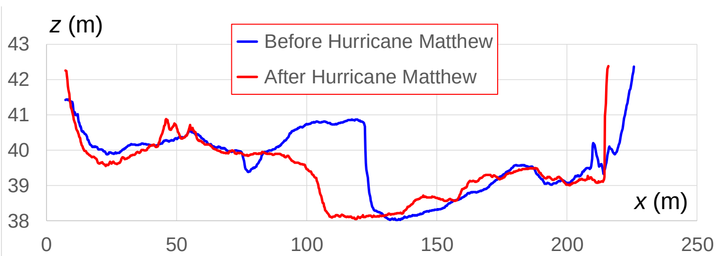


Figure 5. Evolution of cross-section of figure 4

3 DISCHARGES

3.1 Available data

Similarly to most of the Haitian rivers, no direct measurements of the discharge are available for the Cavaillon River. Moreover, only few data about rainfall are available and most of them suffer from data gaps in such a way that statistical analysis is generally impossible.

However, a weir exists at Dory for irrigation supply. The water level is measured for water supply regulation, but not exploited for discharge measurement. As Dory in the upstream section of our study reach, we tried to use the weir for a continuous measurement of the discharge. However, it rapidly appeared that the weir had been seriously damaged during past flood events and that no common head-discharge relationship was usable.

3.2 Head-discharge relationship at Dory

By means of manual surveys and drone-driven photogrammetry, it was possible to determine an accurate model of the weir geometry (Figure 6).

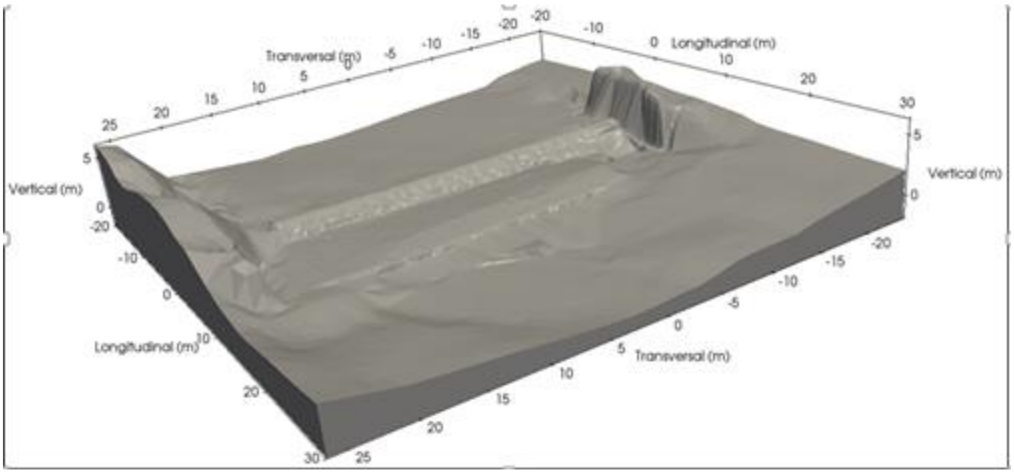


Figure 6. Geometry of the Dory weir.

Due to differential settlements and partial destruction of the downstream apron by wear and uplift pressure, the weir crest appeared to present level differences up to 20 cm (Figure 7) instead of being horizontal, making most of the common weir formulae unusable. Nevertheless, considering cross-sections of the weir, the profile can be approximated by a standard shape at least just after the crest (Figure 8), which is the most sensitive part of the weir regarding the discharge.

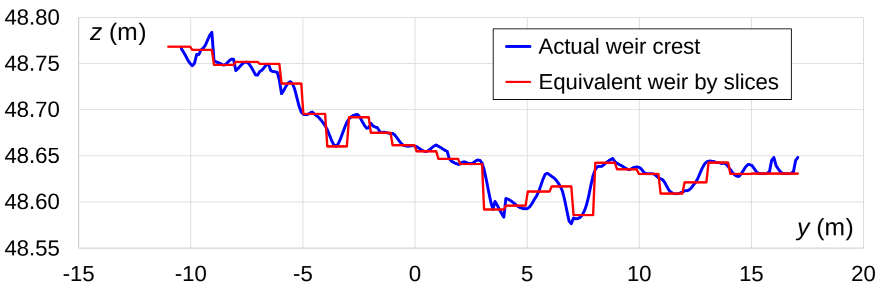


Figure 7. Weir crest elevation and equivalent weir by slices

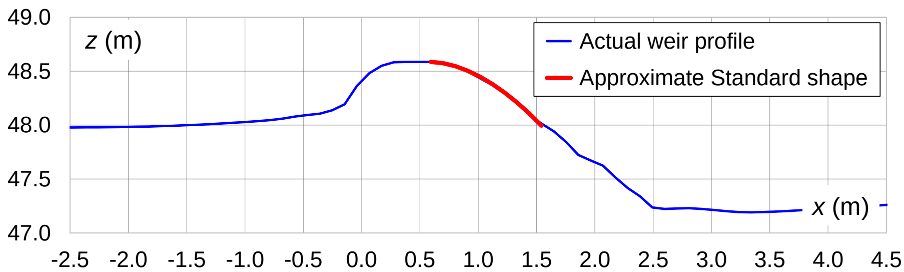


Figure 8. Longitudinal weir profile

For building a stage-discharge relationship, some measurements are required for calibration. Only few are available: before Hurricane Matthew, only small discharges were recorded and after the event most of the measurement devices were destroyed. The challenge was thus to use these few data and to extend these to flood discharges. In order to build such a relationship, four strategies were tested (Figure 9):

- a decomposition of the weir into 1-m wide slices, each with the corresponding averaged crest level (Figure 8), then summing the discharge calculated using OpenFoam software over each slice;
- a full 3D computation of the upstream head and the discharge using OpenFoam software, considering the actual weir shape;
- a simple classical Creager relationship with an assumed crest level at the average level of the actual crest;
- a simple classical USBR relationship with an assumed crest level at the average level of the actual crest..

The summation of elementary weirs is tedious but rather more accurate than expected, despite the fact that shear stresses between the slices in neglected in the calculations. The full 3D model is closer to the measurements but so demanding in computational time that only few discharges could be tested. Finally, the simple standard relationships considering an average value of the crest level revealed to be a useful compromise for low discharge but incorrect for higher discharge because of the increasing of the speed flow over the weir. For more details, see Carlier d'Odeigne [2018].

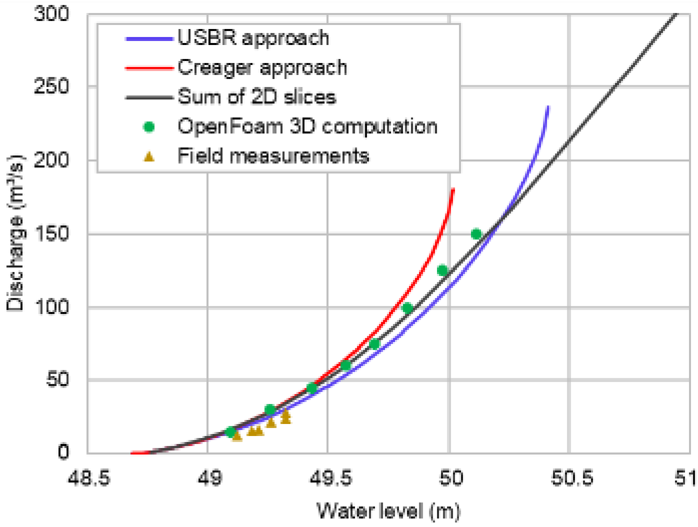


Figure 9. Dory weir: flow rate – discharge relationships

During the Hurricane Matthew, a rough estimation of the discharge at Dory was above 500 m^3/s, which represents a too large extrapolation for using accurately the above relationships. In order to circumvent this problem, a hydrological model of the upstream watershed was built to estimate the discharge from the available rainfall data.

3.3 Hydrological modelling of the catchment

The 30-m DTM available since the beginning of the study, although not refined enough for hydraulic modelling, is a satisfactory basis for hydrological modelling. It allows the delimitation of the contributive catchment and the evaluation of the ground slope and flow direction in each cell in such a way that a distributive model can be applied.

We adopted the ATHYS model developed by IRD-Montpellier [IRD, 2014], as only a few parameters need to be calibrated. The model relies on a production function developed by the SCS (US Soil Conservation Service, become the Natural Resources Conservation Service). This production function is applied to each cell, yielding the net contribution of the cell to the runoff discharge at each time step. In a second phase, this discharge is conveyed to the outlet by means of a transfer function between cells.

The SCS production function evaluates the part of the volume of total rainfall on a unit area during the time step that effectively contributes to the runoff after losses due to interception, depression storage and infiltration. The interception is represented by a rainfall reservoir with losses proportional to the cumulative rainfall, while infiltration is represented by another reservoir featuring the storage capacity of the soil. The part of the rainfall captured in this latter storage reservoir is partly returned to runoff as delayed interflow.

The runoff volume generated by each cell at each time step has to travel to the outlet of the catchment by a transfer function. The propagation time from cell m to the outlet is computed as the sum of transfer times between cells along the path imposed by the direction of the steepest slope:

$$T_m = \sum_{m \to outlet} \left(\frac{l_k}{V_k} \right) \quad [1]$$

where l_k is the length of the path inside cell k and V_k the runoff velocity, which depends on the local slope $S_{0,k}$:

$$V_k(t) = V_0 \left(S_{0,k}\right)^{\alpha} \qquad [2]$$

Of course, a number of coefficients have to be estimated in this model. Two of them are the most sensitive: the soil storage capacity S and the transfer velocity parameter V_0 that are the most dependent on the watershed characteristics. These parameters are calibrated using a tool of the ATHYS software for automated exploration of possible values in order to optimize the fitting between observed and computed hydrographs.

This calibration was hazardous for the rather weak discharges measured before the Hurricane Matthew, since rainfall measurements were scarce and the discharge evaluation uncertain due to the small water head on the weir, which corresponds to the less accurate situation for the damaged crest of this weir. Paradoxically, Hurricane Matthew gave the opportunity for a better calibration. Only one rain gage, located at Dory, remained operational during the event and the stage gage used for the computation of the discharge over the Dory weir, was not immediately carried away by the flood, allowing to determine the discharge for the rising limb of the resulting hydrograph (blue curve of Figure 10). These few hours when rainfall and discharge were captured together allowed attempting a calibration of the main parameters. This yielded a soil storage S = 213 mm and a transfer velocity V_0 of 1.3 m/s. This was sufficient to extrapolate the hydrograph until the end of the rainfall event (red curve of Figure 10) although no more discharge measurements were available.

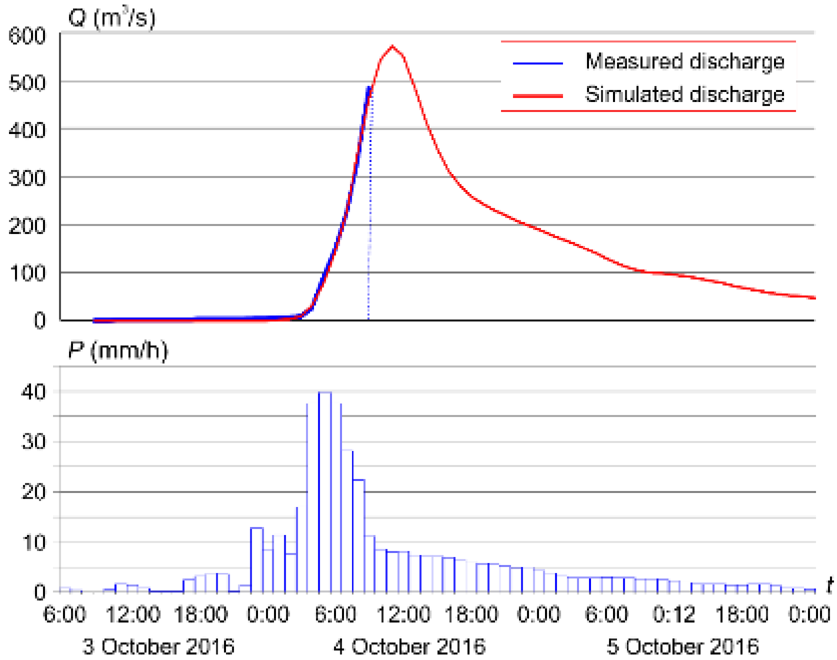
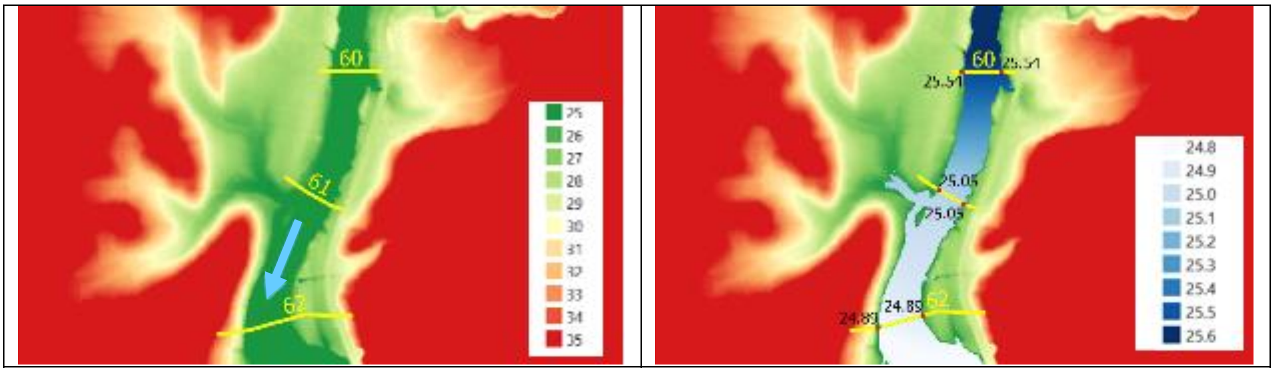


Figure 10. Measured rainfall, measured discharge, simulated discharge (Dory, Hurricane Matthew)

4 FLOOD EXTENT

Regarding the river and the flood plains geometry, we have three types of data: (1) cross-sections data, including minor bed but only usable for 1D description; (2) CNIGS “official” DTM, accurate enough (1.5 m mesh) for 2D computation but partly obsolete after Hurricane Matthew; and (3) drone-driven DTM, the most accurate, able to restore the situation before and after the hurricane but of course not during this event.

For small discharges, the most frequent situation, a mix of 1D modelling for water profile computation and 2D DTM for the representation of the flood extension appeared as the best approach (Figure 11) [Joseph, 2019].



(a) CNIGS DTM missing the minor bed	(b) Spline surface based on 1D water profile

Figure 11. Flood extent from 1D water profile computation (elevations in meters)

The water profile computation yields the water level at each cross section (for example, 25.05 m at section 61). The intersection between this level and the cross-section profile gives the extent of flooding at the section. A spline surface based on these points represents the water table, whose the intersection with the appropriate DTM give the flood extent.

For larger discharges and in areas where flood plains are wide, the minor bed flow description is less significant and a 2D approach is preferred (Figure 12). For the flood induced by Hurricane Matthew, a comparison is possible with floods marks (the blue line) and testimony of some riverine people (the red circles). Discrepancies mainly appear in the downstream part of the modelled area that can be explained by an uncertain downstream boundary condition in the model. Other discrepancies affect areas where the water depth is rather small, maybe too small to be considered as really inundated by people during the interviews.

Figure 12. Flood extent during Hurricane Matthew (water depths in m)

5 PEOPLE AND PERCEPTION OF RISK

5.1 Hazards, vulnerability and risk

Technical modelling approaches result in maps of inundation hazard with potential water depths and velocities. Ideally, a probability of occurrence should be associated to different scenarios of flood phenomena but in the present case, data are too scares for characterizing this probability and people are not prepared to such an approach. In that sense, a reference as Hurricane Matthew is more telling for the population, and as far as hydraulic models yield results close to their own observation, flood mapping may be convincing.

Actually, vulnerability mapping and crossing hazard and vulnerability to characterize risk associated to each territory in order to optimize alert and protection measures is not a usual procedure for them. Therefore, a large part of the work was to involve people, not only decision makers, in the process of constructing risk maps.

5.2 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process, developed by Saaty in the 1970s [Saaty,1980; Saaty, 2001] provides a rational framework for structuring complex group decisions. It is based on a mix of mathematics and psychology.

For example, the problem to prioritize protection actions in Cavaillon city against flood threat may be decomposed into a hierarchy of sub-problems that can be analyzed separately (Figure 13).

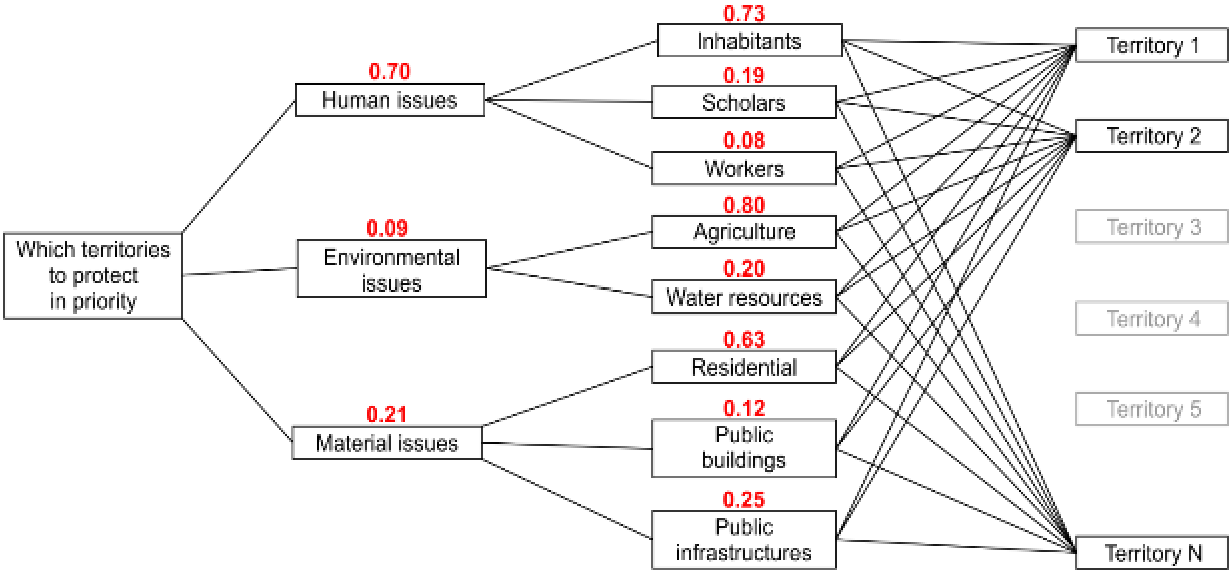


Figure 13. Analytic Hierarchy Process applied to Cavaillon City.

The hierarchy between issues is determined by pairwise comparisons, weighting the differences using the intensity scale of Table 1, so yielding a matrix of issue hierarchy.

Table 1. Scale for pairwise comparison matrix according to Saaty [1980]

Intensity	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favor one activity over another
5	Strong importance	Experience and judgement strongly favor one activity over another
7	Demonstrated importance	A dominance of one activity over another is demonstrated in practice
9	Extreme importance	Highest order of evidence favoring one activity over another

An example of weighting matrix is given in Table 2 for the sub-criteria regarding human issues (Figure 13). The comparison is made between inhabitants, scholars and workers. Issues related to inhabitants are judged slightly more important (factor 3) than issues related to scholars and much more important (factor 7) than issues related to workers, while scholars' issues are considered as strongly more important (factor 5) than workers' one. This does not mean that a child at school is less important than a person at home. This means that in case of major flood risk, people will not send their child to school or go to their work place in such a way that habitation protection is the priority. This latter example shows that building a weighting matrix is delicate and requires appropriate guidance and a very good knowledge of local features.

Then, from the vulnerability matrix C_{ij} of dimension $n \times n$ the weight of each issue (the line i of the matrix) can be deduced:

$$W_i = \left(\prod_{j=1}^{n} C_{ij}\right)^{1/n} \qquad [3]$$

and then normalized:

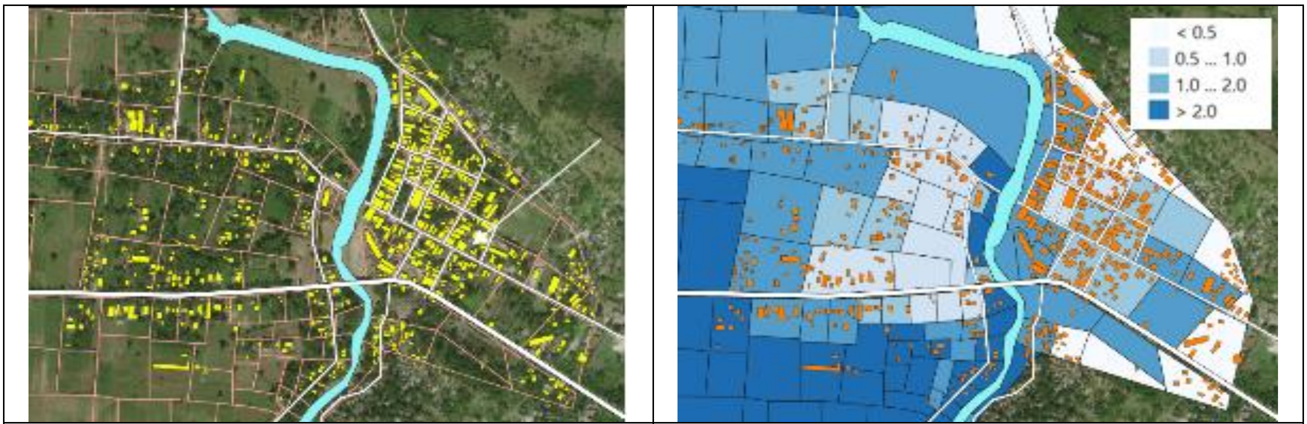
$$T_i = \frac{W_i}{\sum_k W_k} \qquad [4]$$

yielding the red numbers of Figure 13, hierarchizing the weight associated to each issue.

Table 2. Weighting matrix for human issues

	Workers	Scholars	Inhabitants	W_i	T_i
Workers	1.000	0.333	0.143	0.362	0.081
Scholars	3.000	1.000	0.200	0.843	0.188
Inhabitants	7.000	5.000	1.000	3.271	0.731

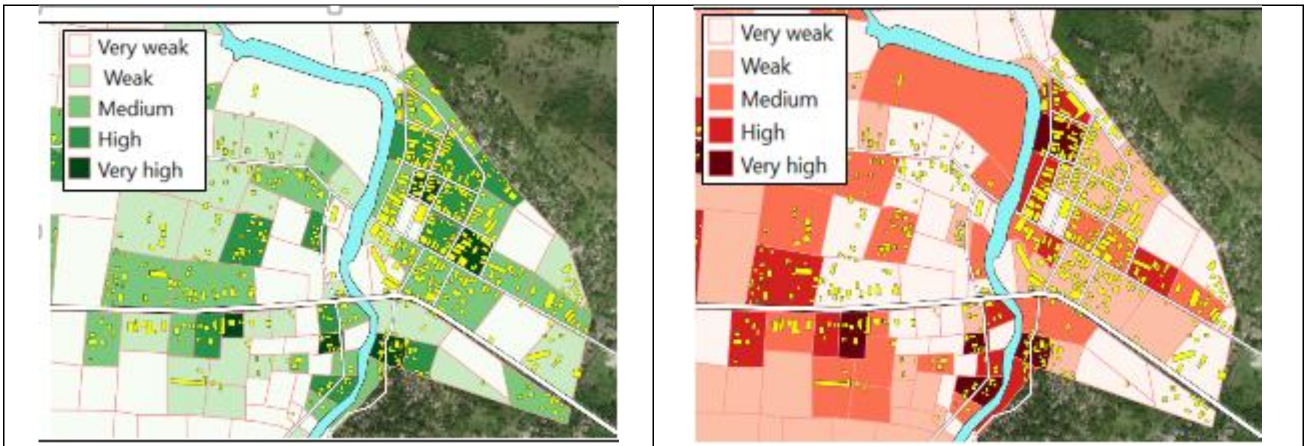
The second step consists in characterizing the vulnerability of the various areas prone to inundation. The city of Cavaillon was divided in 431 zones homogeneous in terms of land use and associated issues (Figure 14a), some more residential, some more devoted to services, industry or agriculture. In each zone, the computed mean water depth corresponding to Hurricane Matthew represents the hazard affecting the zone (Figure 14b).



(a) Division in homogeneous zones	(b) Hazard level: mean water depth (m)

Figure **14**. Cavaillon City (partial): hazard mapping [Joseph, 2019]

The determination of the index of vulnerability for a given issue is based on this issue's density (Figure 15a). For example, the human issue "Inhabitants" was distributed in five density classes (more than 70 inhabitants/km^2, 39 to 70, 12 to 39, 5 to 12 and less than 5). A weight was attributed to each class of inhabitant's density by means of a weighting matrix similar to the example of Table 2, finally yielding normalized weights T_i of each density class. Let us consider the area pointed by the white arrow in Figure 14a. The human issues are predominant as this zone is completely urbanized. The workers, scholar and residential population densities are respectively 70, 787 and 116 persons/km^2, so corresponding to the highest class (T_i = 0.238) for workers, the highest class for scholars (T_i = 0.584) and also the highest class (T_i = 0.634) for residential inhabitants. Using the weights of Table 2, this yields to a vulnerability of $0.081 \times 0.238 + 0.188 \times 0.584 + 0.731 \times 0.634 = 0.593$, this latter value corresponding to the highest vulnerability class (Figure 15a). However, since the average water depth is less than 1 m in this area (Figure 14b), the risk level (Figure 15b), which is the product of the hazard by the vulnerability is only "medium". More details can be found in Joseph [2019].



(a) Global vulnerability level	(b) Risk level

Figure 15. Cavaillon City (partial): vulnerability and risk mapping [Joseph, 2019]

5.3 Perception of risk

The above methodology yields maps that can be easily understood by engineers and by most of the decision makers. However, their power of conviction towards the concerned population is not evident. Two types of work were carried out for improving the acceptance of the population: a survey conducted among the population and a workshop of restitution of the study with local decision-makers.

The survey concerned more than 1800 persons in the Cavaillon River watershed and revealed some surprising statistics. Only 8 % of concerned people (30 % in the city) have some knowledge about the numbers characterizing a cyclone's magnitude, with the consequence that most of them cannot interpret warnings from the radio when such numbers are given. The results is that 37 % (73 % in the City) have reported that they have been flooded. On the other hand, many people are conscious of what to do for protecting their houses. Some have raised the level of foundations but their home is gradually sinking into the ground that is eroded by runoff. The cost of material to strengthen their house is generally beyond people economical resources. The highest concern is about evacuation planning: they know that they have to leave their house if inundated, but they do not have any clear idea of adequate shelter to take refuge. Often the church or the public buildings where they go happen to be more flooded than the house they have left because, for example, they lie closer to the river.

Following this survey a workshop was organized for some decision-makers of the City of Cavaillon in order to explain the methodology and to confront our risk mapping with their pragmatic perception (Figure 16). The main benefit of this confrontation is the perspective of an improved organization for alerts and shelter design.

Figure 16. Workshop with decision makers (5 January 2019, City of Cavaillon)

6 CONCLUSION

Starting from very limited topographical, hydrological and hydrographical data, a methodology was developed to circumvent these limitations by means of adapted and rather cheap solutions.

The geometry of the Cavaillon River, selected as study site, was acquired by a mix of classical in-situ survey for the minor bed and an innovative drone-driven photogrammetry for the flood plains. This demonstrated that this latter technique was usable even in a context of a rather inaccessible land and without easy energy supply.

Despite a very poor data availability regarding the local hydrology, the discharge could be evaluated thanks to the existence of a weir designed for irrigation. This weir was seriously damaged by former floods and a tentative relationship between head and discharge required a combined approach mixing approximate evaluations by classical formulae and validation by CFD techniques. As only small discharges were observed before Hurricane Matthew, a direct extrapolation to the huge discharges induced by this event was impossible. Fortunately, the ATHYS distributed hydrological model, based on SCS production formula, could be successfully calibrated during the major part of the rising limb of Matthew hydrograph, until measurements devices failed and the weir was bypassed by the flood.

The water depth during the flood event could be modelled by a mix of 1D computation with an extrapolation of the water table by spline surfaces, and also by 2D computations. The latter approach, while more accurate in principle, was limited by the fact that the 2D digital terrain model does not account for the minor bed bottom.

Moreover, the technical approach was completed by an important social component in order to include local people knowledge and experience in the evaluation of the vulnerability of properties and infrastructures. The Analytical Hierarchy Process (AHP) of Saaty allowed ranking the different issues, by a translation of subjective feelings into weighting matrices. As an example, the City of Cavaillon was divided in 431 zones considered as homogeneous regarding land use and population. From the AHP, it was possible to characterize the vulnerability of each zone, and crossing this information with hazard distribution, to determine risk mapping.

This approach was then confronted to population's perception by conducting surveys and organizing workshops with decision makers.

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