

Article

Flood Modeling of the June 2023 Flooding of Léogâne City by the Overflow of the Rouyonne River in Haiti

Rotchild Louis ^{1,2} , Yves Zech ², Adermus Joseph ¹, Nyankona Gonomy ¹ and Sandra Soares-Frazao ^{2,*} 

¹ Département de Génie Rural, Université d'Etat d'Haïti, Port-au-Prince HT 6122, Haiti; rotchild.louis@ueh.edu.ht (R.L.)

² Institute of Mechanics, Materials and Civil Engineering, UCLouvain, 1348 Louvain-la-Neuve, Belgium; yves.zech@uclouvain.be

* Correspondence: sandra.soares-frazao@uclouvain.be; Tel.: +32-10-472120

Abstract: Evaluating flood risk through numerical simulations in areas where hydrometric and bathymetric data are scarcely available is a challenge. This is, however, of paramount importance, particularly in urban areas, where huge losses of human life and extensive damage can occur. This paper focuses on the 2–3 June 2023 event at Léogâne in Haiti, where the Rouyonne River partly flooded the city. Water depths in the river have been recorded since April 2022, and a few discharges were measured manually, but these were not sufficient to produce a reliable rating curve. Using a uniform-flow assumption combined with the Bayesian rating curve (BaRatin) method, it was possible to extrapolate the existing data to higher discharges. From there, a rainfall–runoff relation was developed for the site using a distributed hydrological model, which allowed the discharge of the June 2023 event to be determined, which was estimated as twice the maximum conveying capacity of the river in the measurement section. Bathymetric data were obtained using drone-based photogrammetry, and two-dimensional simulations were carried out to represent the flooded area and the associated water depths. By comparing the water depths of 21 measured high-water marks with the simulation results, we obtained a Kling–Gupta Efficiency (KGE) and Nash–Sutcliffe Efficiency (NSE) values of 0.890 and 0.882, respectively. This allows us to conclude that even when only scarce official data are available, it is possible to use field data acquired by low-cost methodologies to build a model that is sufficiently accurate and that can be used by flood managers and decision makers to assess flood risk and vulnerability in Haiti.

Keywords: flood modeling; Rouyonne river; Haiti; hydrological modeling; rating curve; drone-based topography measurement



Citation: Louis, R.; Zech, Y.; Joseph, A.; Gonomy, N.; Soares-Frazao, S. Flood Modeling of the June 2023 Flooding of Léogâne City by the Overflow of the Rouyonne River in Haiti. *Water* **2024**, *16*, 2594. <https://doi.org/10.3390/w16182594>

Academic Editor: Chang Huang

Received: 22 July 2024

Revised: 1 September 2024

Accepted: 9 September 2024

Published: 13 September 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Urban flooding is a subject of major concern to both the scientific community and the public. To improve urban planning and to manage these risks, it is important to have digital tools capable of simulating flood events for better decision making. Hydraulic modeling tools can predict the spatial and temporal evolution of river behavior during a flood event and the resulting flood extent [1–3], provided that prior calibration of the model can be achieved. There are various approaches for modeling river flooding events, including simpler one-dimensional models [4,5], which require less data, and more detailed two-dimensional [6–8] models. The choice of approach must be consistent with the scale under study and with the risks involved [9]. Moreover, for accurate modeling, updated and good-quality topographic data are needed [10], as well as high-resolution water level and flow measurements to capture rapid flood variations [9]. For ungauged sites, hydrological models are often used to estimate flows based on precipitation data and watershed characteristics [11,12]. However, these models need to be calibrated for the specific site under study, and appropriate criteria, such as the KGE (Kling–Gupta Efficiency) and the NSE (Nash–Sutcliffe Efficiency), should be used to evaluate these models.

In the present case, the study site, namely the Léogâne City in Haiti, lies in a region where only scarce or inaccurate and incomplete data are available, resulting in additional modeling challenges. Indeed, the only official topographical data in the country dates back to 2014–2016, but since then, the country has undergone several natural hazards, such as Hurricane Matthew in 2016, which resulted in strong morphological changes in the rivers in the affected regions. Moreover, due to the complex political situation and the lack of means of the local authorities, many measurement devices have not been able to be maintained or replaced in the case of failure, resulting in important gaps in hydrological and hydraulic data.

The aim of this study is thus to develop hydraulic modeling combined with hydrologic tools to reconstruct the missing data in order to reproduce the June 2023 event in Léogâne, and from there, to initiate a methodology to characterize the flood risk in the region. Specifically, the proposed modeling strategy is based on the contribution of (i) low-cost drone-based photogrammetry to complement existing but inaccurate bathymetric data; (ii) the uniform-flow approach to construct a rating curve for poorly gauged rivers for which only scarce measurements are available; and (iii) hydrological modeling for the reconstruction of flood hydrographs corresponding to extreme events in weakly instrumented watersheds, as is often the case for Haitian watersheds.

Hydraulic modeling in such cases is usually performed by solving the two-dimensional shallow-water equations [7,13–19] on structured or unstructured grids constructed using available topographic and bathymetric data. While a wide range of software is available for such purposes (e.g., HEC-RAS, TUFLOW, MIKE-FLOOD, etc.), here, the WATLAB open-modeling environment developed by our research group “<https://sites.uclouvain.be/hydraulics-group/watlab/index.html>” (accessed on 11 June 2024) was used, which is based on reported developments, e.g., in [20–23], and widely validated by comparison with other existing tools. To validate the model in our study, measurements of water depth in the flooded zone were taken from the high-water marks shortly after the June 2023 event.

As regards stage–discharge relations, these are normally obtained from a series of direct measurements of the flow and water depth for a range of flows at a gauging station. During floods, it is easier to measure water depth than flow with reasonable accuracy, because water velocities and levels pose a safety problem. In such situations, extrapolation of the rating curve is often used [24,25] or alternatively, rating curves of similar rivers in the region are used for ungauged watersheds [26]. However, the uncertainty associated with any stage–discharge relations is often assessed [24,27–30], because extrapolating errors can be responsible for unrealistic river roughness estimates [31].

Finally, hydrological modeling allows flood hydrographs to be derived from rainfall data when discharge measurements are not available. Either lumped, semi-distributed or distributed models can be used (e.g., GR4J, GRSD, HEC-HMS, Mike-SHE, etc.) [32–35], all of which have different data requirements. Lumped models are easier to set up but need accurate discharge data for the calibration of the transfer functions as no physical transfer processes are considered. In the present case, the distributed model AtHyS (Atelier Hydrologique Spatialisé) was used [36], which takes into account the actual topographical data in a physically sound way for the transfer from runoff to the outlet of the catchment, considering evaporation and infiltration losses according to the curve number model [36].

The results of this modeling strategy are expected to provide critical insights for urban flood managers and policy makers to assess the flood risk in Haiti, and, ultimately, to contribute to the design of development and flood-risk management plans. The June 2023 event is expected to recur, especially in cyclonic periods. Depending on the data availability, synthetic extreme rainfall data with given return periods could be determined based on a statistical analysis of past events to construct corresponding design hydrographs and to design preventive risk management strategies in Haiti and hydro-climatically similar regions.

The paper is organized as follows: first, the study area and data collection are presented, including drone-based measurements for the bathymetry and hydrological mod-

eling to evaluate the discharges; then, a hydraulic model is constructed, and simulations of the June 2023 event are conducted. The results are compared to field measurements, and, finally, conclusions are drawn on the long-term perspective regarding possible flood forecasting systems for the city of Léogâne to predict what might happen when heavy rainfall is announced and to establish risk maps.

2. Materials and Methods

2.1. Study Area

This research study concerns a stretch of the Rouyonne River along the town of Léogâne in Haiti (Figure 1a,b). Fed by a mountainous upper watershed of 46.45 km² (Figure 1b), the river flows into the Caribbean Sea via an 8.2 km long channelized reach that begins at the upper watershed outlet (X = 754,280 m; Y = 2,044,471 m; coordinate system WGS 84/UTM zone 18N) and ends at the sea (X = 747,693 m; Y = 2,049,408 m). While the river is rather sinuous in the mountainous upper watershed, the downstream part of the Rouyonne River (the channel) is nearly straight, with an average slope of 0.62%. The lower course of the river was, in fact, artificially channelized and confined by embankments specifically to prevent inundations. The upper watershed is very hilly, with 75% of its surface area situated between 250 and 950 m above sea level (Figure 1c). The city of Léogâne lies in the flood plain zone, close to the channelized part of the river. Unfortunately, the embankments experience frequent overflows, which explains the recurrent flooding of the city.

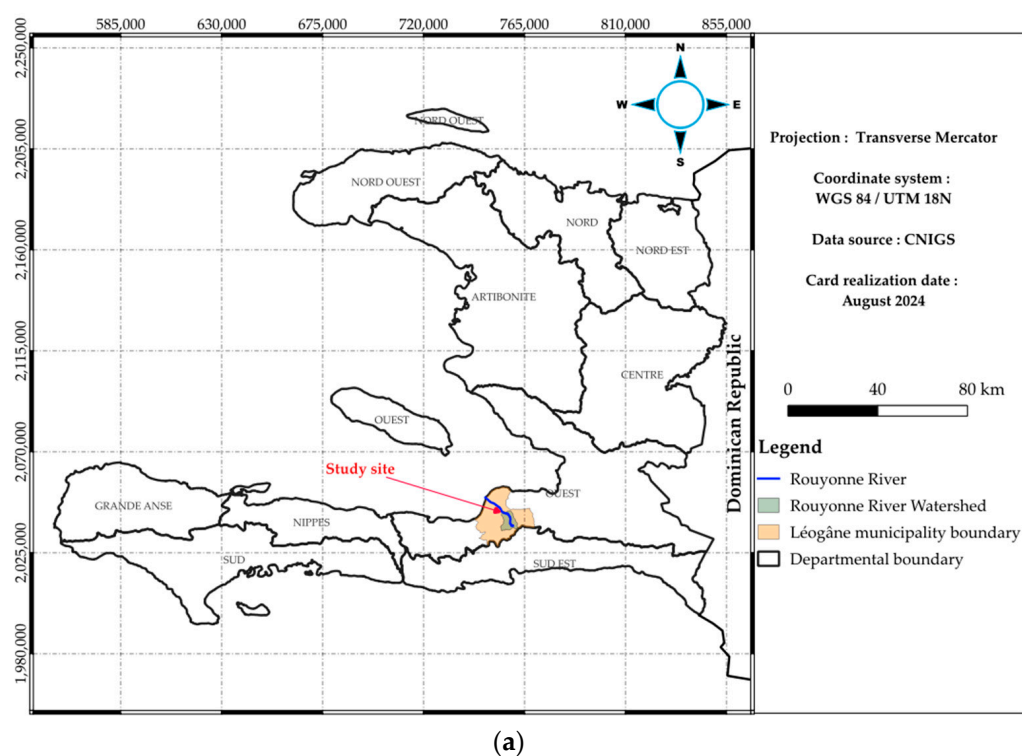


Figure 1. Cont.

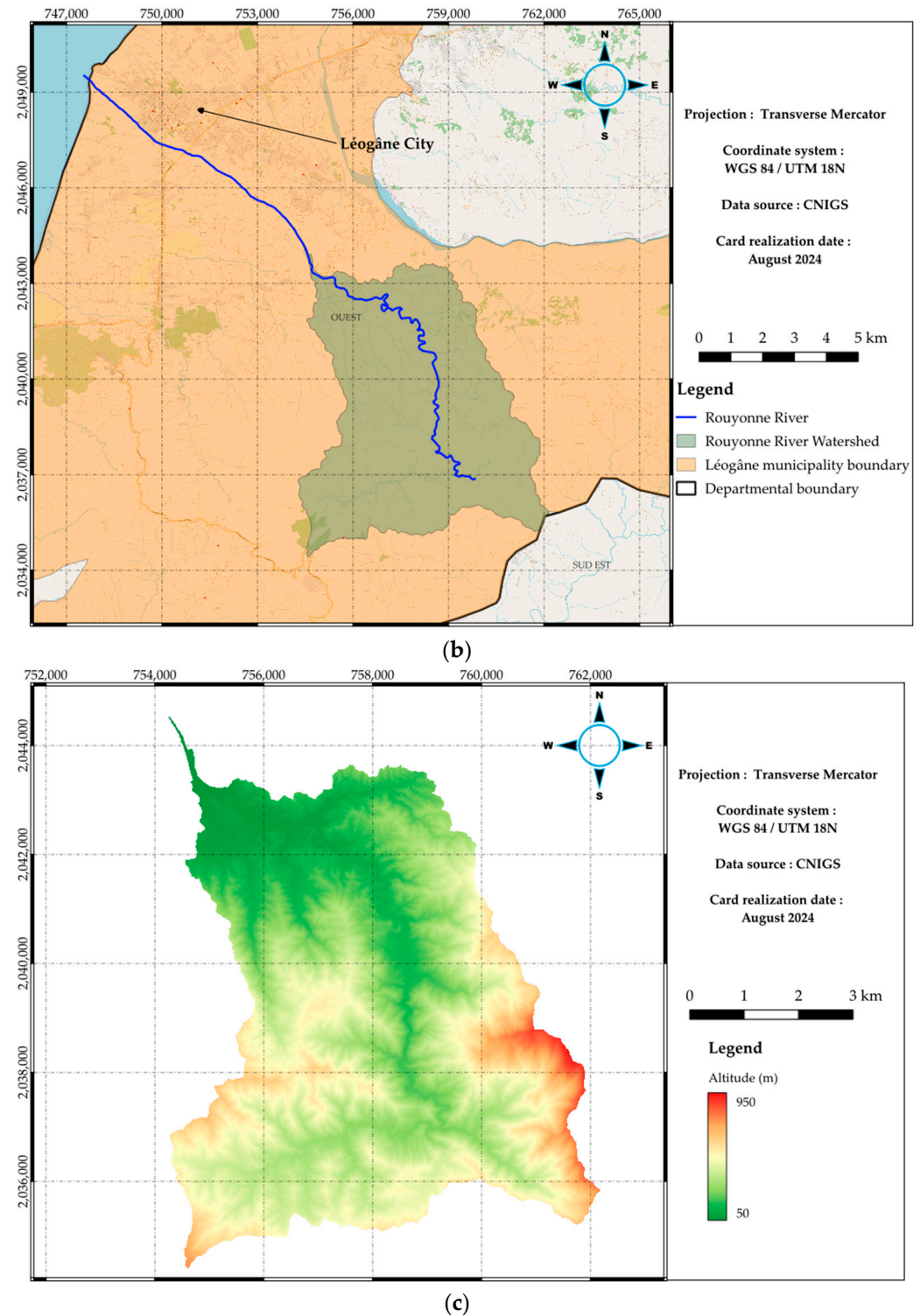


Figure 1. Study area: (a) Study site location in Haiti; (b) Rouyonne river channel and its upper watershed; (c) Altitude distribution in the upper watershed.

2.2. Data Acquisition

The topographical and bathymetric data available for the site were the official data from the National Center for Geospatial Information—Centre National des Informations Géospatiales (CNIGS) covering the entire country, which dated back to 2016 and were issued from a measurement campaign that was started in January 2014 by IGN France International (IGN FI), with funding from the World Bank. The 1.5 m resolution digital

terrain model (DTM) from the CNIGS was used for the hydrological modeling of the upper watershed. However, since the data acquisition, many major morphological changes were observed in the main rivers of Haiti, which were caused by extreme climatic events in the last years in the lower reach. This DTM has, thus, become too inaccurate for hydraulic modeling of the Rouyonne River reach. Therefore, a drone-based survey of the river was conducted during the dry season, when the river is empty (Figure 2a), to capture aerial images to measure the bathymetry and surrounding topography using photogrammetry through the image processing software “Agisoft Metashape pro version 1.8.0”. Aerial images were taken from a drone (DJI marvic Air 2) equipped with a GoPro Hero 4 camera (Figure 2b), which are all low-cost and easy-to-handle devices that are well suited to such field conditions.

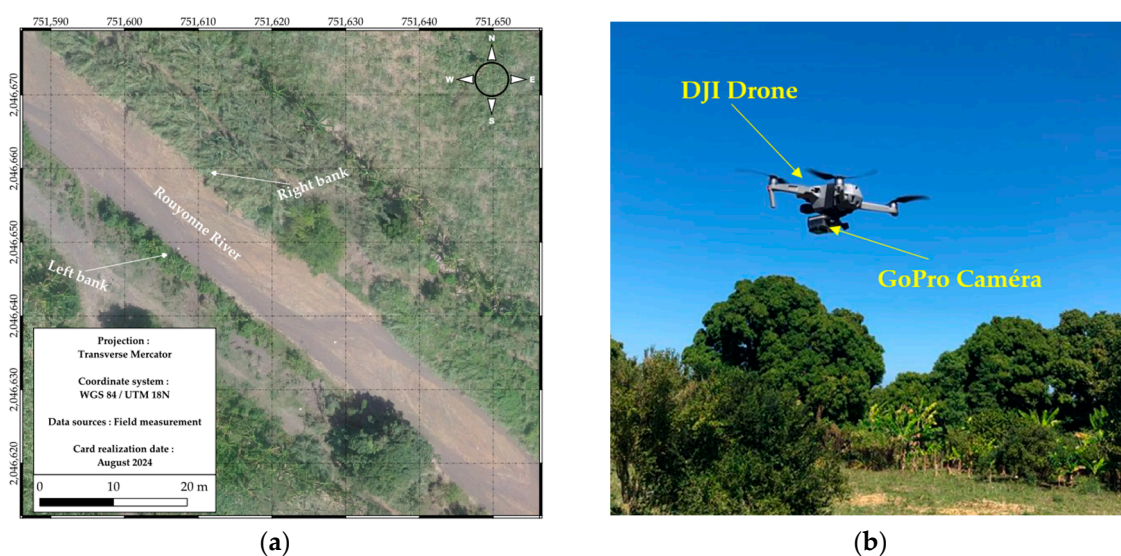
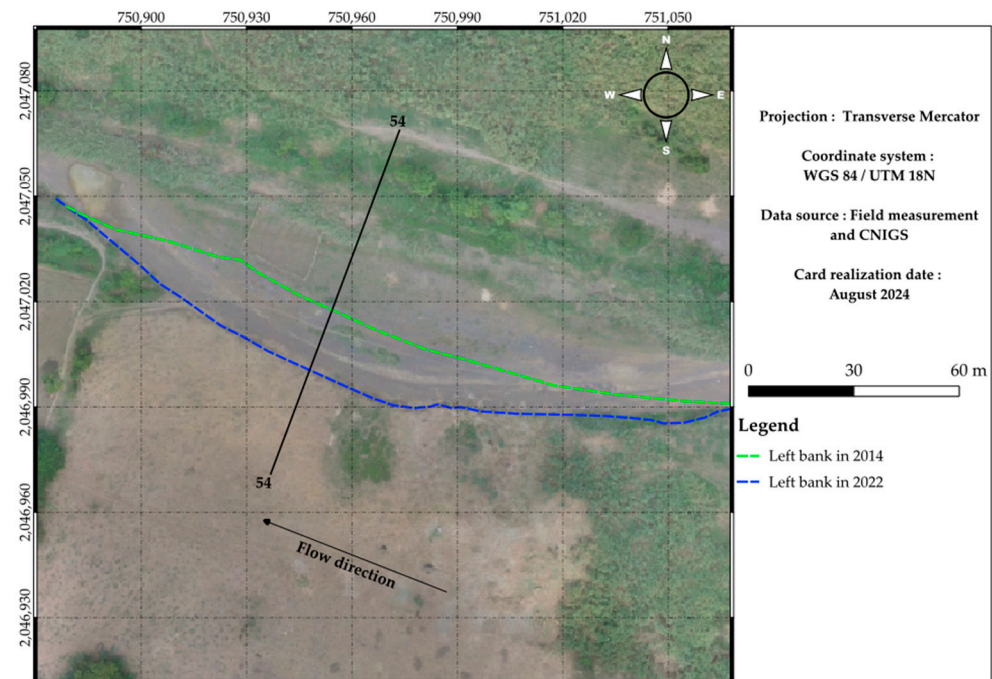


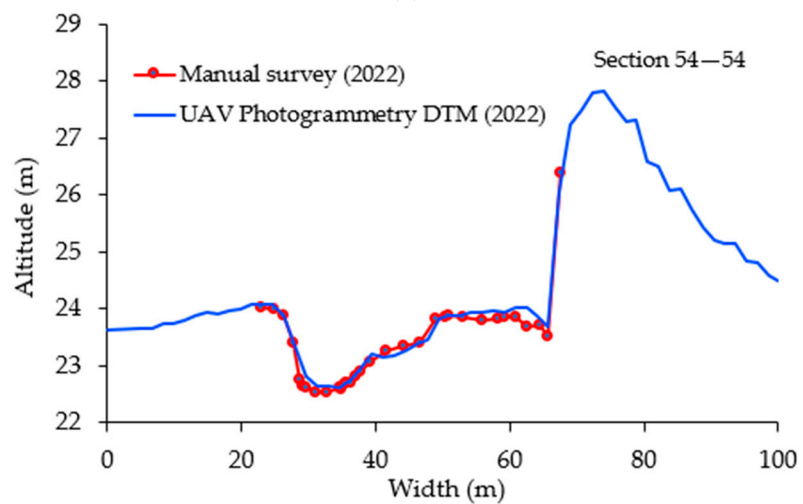
Figure 2. Illustration of image acquisition: (a) Aerial image of the river during the dry season; (b) DJI drone equipped with a GoPro camera (sensor type: 1/2.3" CMOS; camera type: sport/action camera; equivalent focal length: 16.41 mm; lens type: wide angle; aperture: f/2.8).

Each drone flight had a duration of about 10 min, depending on the battery autonomy, with a speed of 5 m/s and a capture frequency of one image every two seconds. The image overlap between successive flights is 80% at the front and 60% at the side [37]. These overlaps provide sufficient information for the spatial reconstruction of the scenes studied, with a total of 300 images, on average, for a flight plan. The accurate georeferencing of the imagery was performed by the global navigation satellite system (GNSS) positioning of at least 15 ground control points (GCPs) for each flight plan, which were used for image georeferencing during the photogrammetric processing. For more information on the processing procedure and assessment of this method at sites in Haiti, see [38–43].

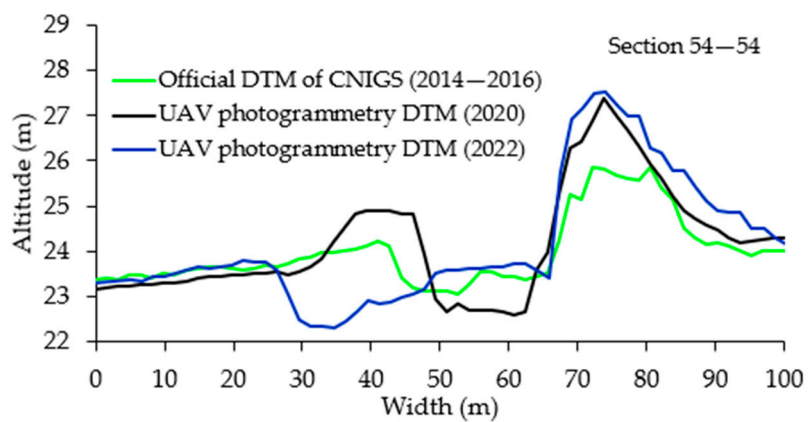
Two drone-based surveys were conducted in 2020 and 2022, respectively. The drone-based technique was found to be very accurate, with a root mean square error (RMSE) of 0.18 m at 80 verification points. A comparison between a manual survey of cross-section 54–54 and the photogrammetric data is illustrated in Figure 3a,b. The marked morphological evolution of the river at this cross-section is illustrated in Figure 3c, where the official DTM (2014–2016) is compared to that from the 2020 and 2022 surveys. It can be observed that the left bank, which was destroyed during Hurricane Matthew in 2016 and then reconstructed, was again completely eroded between 2020 and 2022.



(a)



(b)



(c)

Figure 3. Illustration of the morphological changes in the Rouyonne river channel: (a) Cross-section 54—54 of the Rouyonne River; (b) Bathymetric data comparison between UAV photogrammetry DTM (2022) and the manual survey (2022); (c) Evolution of morphological changes between 2014 and 2022 in cross-section 54—54.

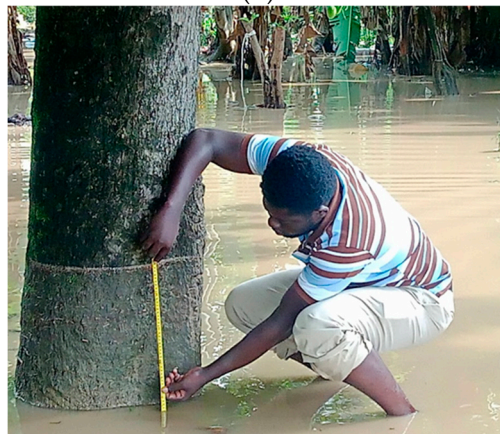
The 3 June 2023 event resulted in the death of almost twenty people in the city of Léogâne, a lot of injuries and considerable damage (Figure 4a,b). In just 32 h and 30 min, the average rainfall recorded in the watershed amounted to 142.1 mm. This value exceeds the monthly average rainfall of around 100 mm for the month of June in the municipality of Léogâne. Consequently, significant overflows were observed during this event, inundating the flood plains and, finally, a part of the city. One day after the June 2023 event, 21 high-water marks were measured in the city and along the river, as illustrated in Figure 4c,d. These were subsequently used to validate the hydraulic model.



(a)



(b)



(c)

Figure 4. *Cont.*

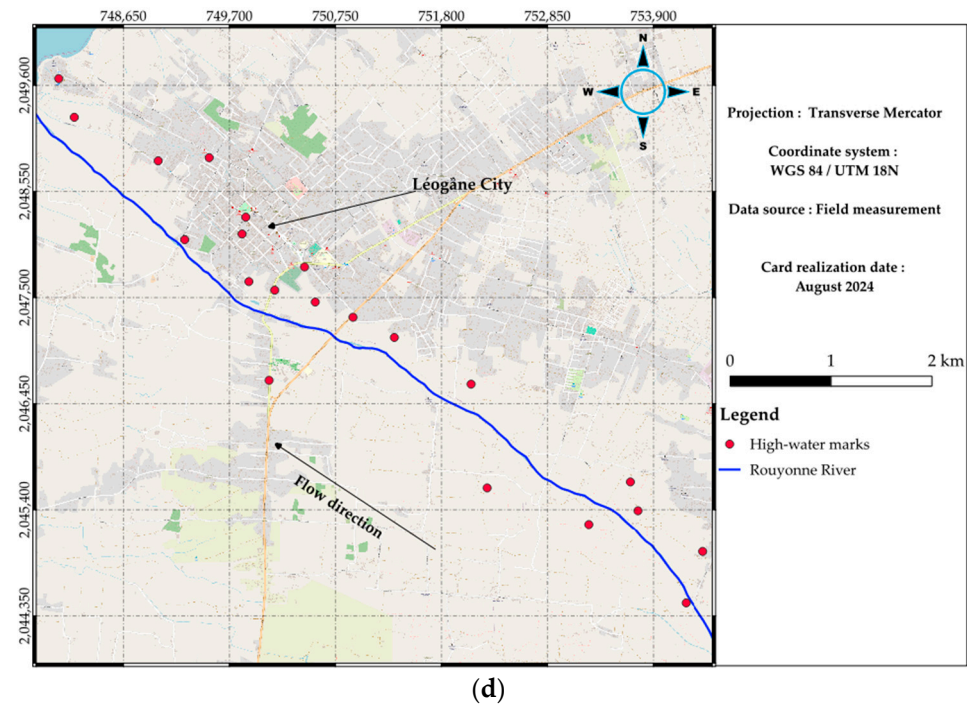


Figure 4. Illustration of the damage caused by the 3 June 2023 event: (a) Buildings destroyed by the flood in the town of Léogâne; (b) Pressure sensor broken by flood at the measuring section; (c) High-water mark measurement; (d) Spatial distribution of high-water marks measured for the 2–3 June 2023 event.

2.3. Discharge Estimation

To run the hydraulic model, we needed the flood hydrograph at the system inlet for the 2–3 June 2023 event. Ideally, the discharge should have been obtained from a hydrometric station, which was, unfortunately, not the case at Léogâne. Only data from a limnimeter (OTT PLS probe: pressure sensor) installed at the measurement section (at the channel inlet) since April 2022 were available. At this location, an OTT “MF Pro” magnetic induction current meter was used to take a range of flow measurements at shallow water depths of below 40 cm. Beyond this depth, measurements become dangerous; therefore, the number of stage–discharge points available to construct a rating curve were not sufficient. It was thus necessary to extrapolate the few points of the rating curve for greater water depths. The construction of the rating curve was based on the assumption of uniform flow in the measurement section and was complemented by the Bayesian rating curve (BaRatin) method [44,45] developed by the National Research Institute for Agriculture, Food and the Environment (INRAE) in 2010, which allowed the uncertainty associated with this approach to be assessed.

However, it is also important to be able to predict the flow from rainfall measurements when the water-level station is dysfunctional, as was indeed the case during the 2–3 June 2023 event as the probe was destroyed. To achieve this, the rainfall data recorded at three rain gauges on the Rouyonne river catchment were used to establish a rainfall–discharge relationship for this watershed using version 6.0 of the AtHyS software developed at the Research Institute for Development (IRD), Montpellier, France [36]. This distributed hydrological model was used because of its physical basis in terms of water propagation and infiltration modeling, and it has provided good-quality results in previous studies in similar poorly gauged environments [46–48]. The key parameters of this hydrological model are the following: V_0 (m/s), which can be estimated as the velocity of flood wave propagation; S (mm), the total ground reservoir capacity, which depends on soil characteristics; ds (day^{−1}), the proportionality coefficient between the reservoir level and the emptying intensity; ω (dimensionless), the fraction of the underground reservoir emptying that participates in

hypodermic flow; and K_0 (dimensionless), a proportionality constant between the diffusion time and the transfer time. These parameters were calibrated and validated using two other events that occurred before the June 2023 event. The performance of the hydrological model was assessed using the classic criteria most widely used in hydrology studies [49–52], i.e., the Nash–Sutcliffe Efficiency (NSE) proposed by [53] and the Kling–Gupta Efficiency (KGE) [54], used in other hydrological studies [55,56]. The KGE criterion was used to select the best parameter set during the calibration and to assess the hydrological model performance. Once validated, the rainfall–discharge relationship can be used to predict flows resulting from given rainfall events.

2.4. Hydraulic Model and Simulation Tool

Based on the DTM, a hydraulic model was built using a triangular mesh (Figure 5), with the advantage that different mesh resolutions could be used for the computational cells: (1) the riverbed with a 1 m resolution; (2) the floodplain with a 40 m resolution; and (3) the transition zone between the Rouyonne riverbed and the floodplain, where the dikes can be identified, with an intermediate 3 m resolution. This mesh was then used for numerical simulations within the WATLAB environment developed at UCLouvain/iMMC “<https://sites.uclouvain.be/hydraulics-group/watlab/index.html> (accessed on 11 June 2024)”, solving the two-dimensional shallow-water equations using a finite-volume scheme for unstructured meshes:

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \quad (1)$$

$$\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x} \left(\frac{q_x^2}{h} + g \frac{h^2}{2} \right) + \frac{\partial}{\partial y} \left(\frac{q_x q_y}{h} \right) = gh \left(S_{0,x} - S_{f,x} \right) \quad (2)$$

$$\frac{\partial q_y}{\partial t} + \frac{\partial}{\partial x} \left(\frac{q_x q_y}{h} \right) + \frac{\partial}{\partial y} \left(\frac{q_y^2}{h} + g \frac{h^2}{2} \right) = gh \left(S_{0,y} - S_{f,y} \right) \quad (3)$$

where h is the water depth; q_x and q_y are the unit discharge in the x and y directions; $S_{0,x}$, $S_{0,y}$, $S_{f,x}$, and $S_{f,y}$ are the x and y components of the bed slope S_0 and of the friction slope S_f that is calculated using the Manning equation. The WATLAB modeling environment is based on previous works, e.g., [20–23], and provides an open-source environment that allows the creation of a computational mesh using GIS tools and the version 4.8.4 of the GMSH software in a unified Python framework, while the core computational code is run in C++ with a parallel implementation. The advantage of this open-source environment is that it can be easily adapted to the user needs or to specific features of the studied environment.

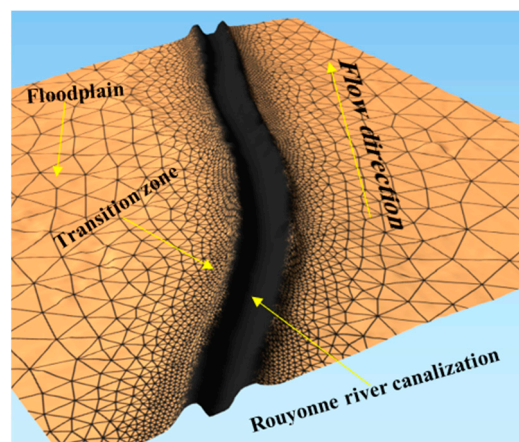


Figure 5. Illustration of the unstructured mesh of the study area.

The hydraulic model roughness was characterized through two different values of Manning’s coefficient: $n_c = 0.048 \text{ sm}^{-1/3}$ for the main channel, and $n_f = 0.05 \text{ sm}^{-1/3}$ for the

floodplain. As regards the upstream boundary conditions, the flood hydrograph generated using AtHyS was used, because no complete hydrograph could be established from the limnometric data recording as this had stopped at the time when the probe cable broke.

2.5. Summary of Data Used in This Study

All the data used in this study are summarized in Table 1, which describes the origin of the data and the time or space resolution applied in the simulations. It is worth noting that the drone-based topography has a finer resolution than the official DTM from CNIGS.

Table 1. Data used in this study.

Data	Sources	Resolution	Explanations
Terrain data	DTM of CNIGS	1.5 m	Official data based on a LiDAR survey in 2014–2016 by IGN FI. Data were constructed during this study to update the bathymetry of the Rouyonne River.
	Drone photogrammetry	0.1 m	
Rainfall data	3 rain gauges	1 min	Calibration of the hydrological model (21–22 August 2022), validation (20 September 2022), and application to the flood event (2–3 June 2023).
Hydrometric data	OTT PLS pressure sensor;	1 min	Three sets of water-level data for the same dates at the measuring station.
	magnetic induction current meter “MF Pro”		
Inundation data	Field measurement		Maximum water depth sampled for construction of the water depth–discharge relationship: 0.40 m. 21 water-level measurement points were collected (24 h after the 2–3 June 2023 event) from high-water marks.

3. Results

3.1. Rating Curve for the Rouyonne River

The cross-section of the Rouyonne River at the location of the limnometric station is illustrated in Figure 6. It has an almost regular trapezoidal shape, and based on the uniform-flow assumption, a stage–discharge relation could be constructed using Manning’s equations, after calibrating the roughness using the eight manually measured stage–discharge values for water depths of up to 0.40 m. As the maximum discharge that was manually measured was well below the probable discharge that occurred during the June 2023 event, it was necessary to assess the quality of the rating curve established using the uniform-flow assumption. Therefore, the BaRatin method [44,45], combining all the sources of uncertainties related to the rating curves, was used.

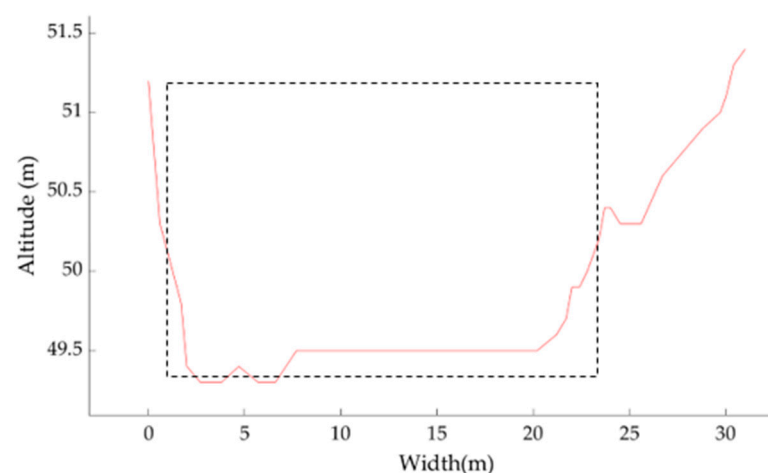


Figure 6. Cross-section at the limnometric station with the equivalent rectangle (discontinuous black line) used in the BaRatin method.

Figure 7 shows the rating curve obtained with the uniform-flow assumption calibrated using the few measured points and the rating curve calculated with the Baratin method, as well as the associated uncertainties. Parametric uncertainty expresses the uncertainty related only to the estimation of the curve parameters, while the total uncertainty is the combination of the parametric uncertainty and the uncertainty induced by the remnant error.

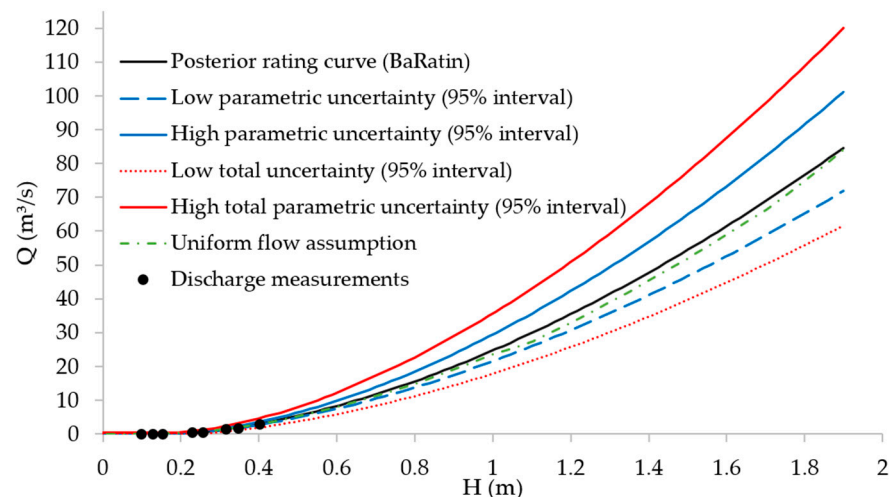


Figure 7. Relationships between water depth and discharge at the measurement section: comparison of the Bayesian rating curve with uncertainties and the uniform-flow assumption.

Unfortunately, the water-level gauge failed during the June 2023 event when the water level reached 2.43 m, making it impossible to use the rating curve to calculate the corresponding hydrograph. Therefore, a rainfall–discharge relation is required.

3.2. Rainfall–Discharge Relationship

The AtHyS hydrological model was run on one event that occurred in August 2022 to calibrate the model parameters and then applied to an event in September 2022 for validation. The comparisons between the estimated flows using the rating curve of Figure 7 and the hydrological model results are shown in Figure 8. The values of the calibrated parameters are given in Table 2, as well as the KGE and NSE scores.

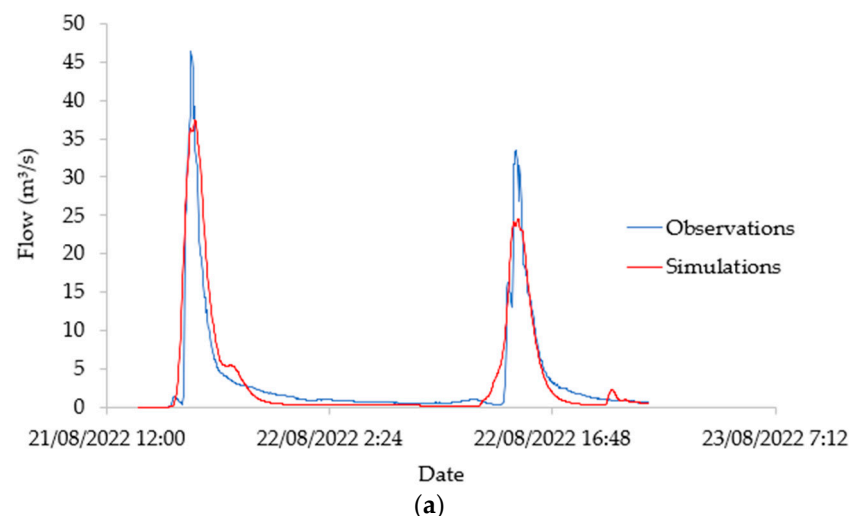


Figure 8. Cont.

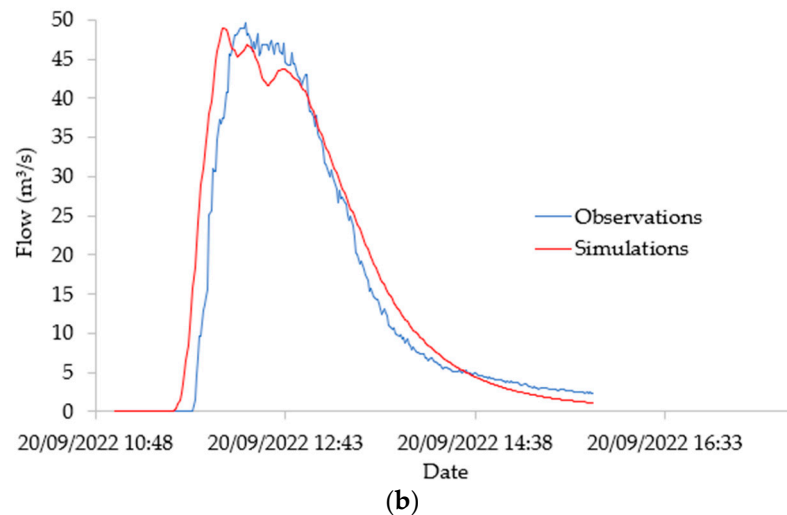


Figure 8. Hydrological modeling: (a) Calibration (August 2022); (b) Validation (September 2022).

Table 2. Hydrological model assessment.

Calibrated Parameters				
$S = 82.44 \text{ mm}$	$V_0 = 5.43 \text{ m/s}$	$ds = 1$	$\omega = 0.02$	$K_0 = 0.73$
Statistical scores: calibration				
KGE = 0.923				
NSE = 0.878				
Statistical scores: validation				
KGE = 0.906				
NSE = 0.925				

Using this validated model, the complete hydrograph of the 2–3 June 2023 event was built, and the results are illustrated in Figure 9. It can already be observed that the agreement between the observations and the model is very good during the period when the limnimetric station was working properly. The simulated maximum flow ($Q = 168 \text{ m}^3/\text{s}$) at the measuring section for this event is two times larger than the maximum flow ($Q = 84 \text{ m}^3/\text{s}$) that the river can convey without overflowing at this section.

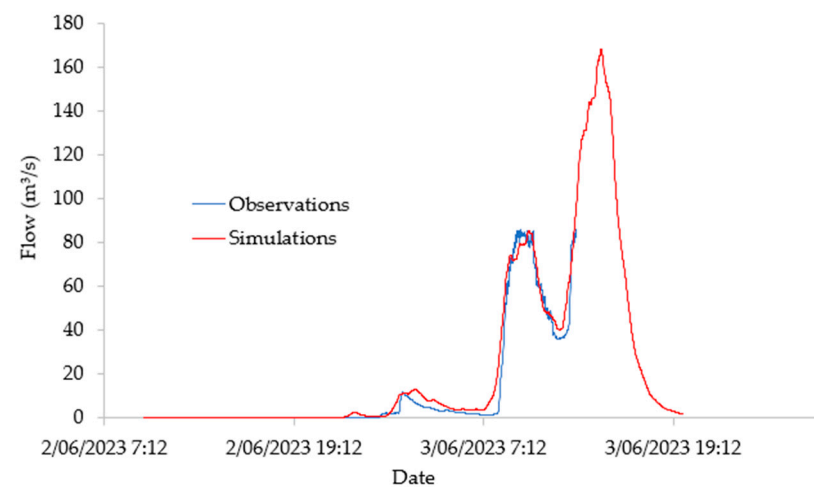


Figure 9. Hydrological modeling applied to the event of 2–3 June 2023.

3.3. Hydraulic Modeling of the 3 June 2023 Flood Hydrograph

The simulation results are illustrated in Figure 10. It can be observed that the Rouyonne River indeed overflows the dikes and induces severe flooding of the surrounding

areas, including the city of Léogâne. The extent of the inundated area appears to be well reproduced by the model, as the points where high-water marks were recorded are indeed located in the inundated area (red points in Figure 10).

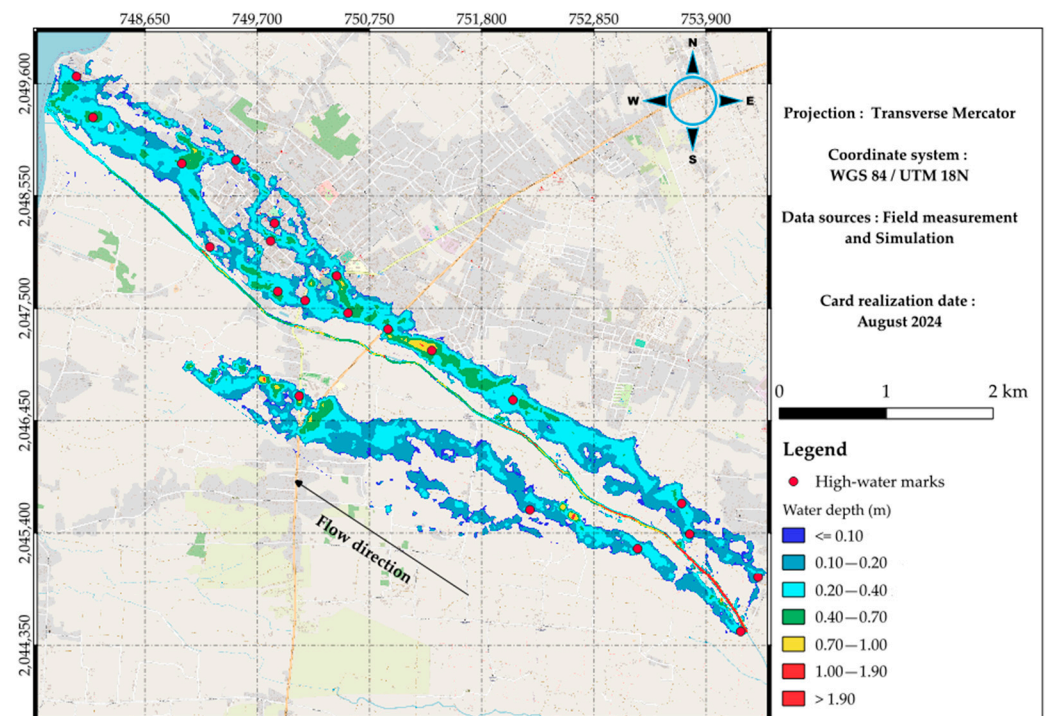


Figure 10. Illustration of the 2–3 June 2023 event simulation.

The comparison of the simulated and measured water depths at the 21 high-water marks (Figure 11) shows that the model provides a good estimate of the water depth in the study area. With KGE and NSE values of 0.890 and 0.882, respectively, based on these 21 comparison points, the model is considered satisfactory.

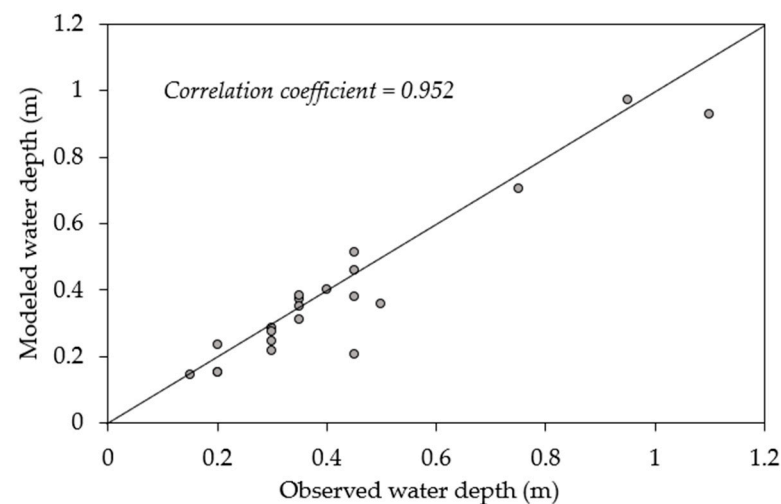


Figure 11. Model evaluation: Comparison between the observed and modeled water depths.

4. Discussion

The rating curve was established using a few measured points and considering a uniform-flow assumption, which is a questionable assumption as the flow is highly unsteady, especially during rapid floods. Nonetheless, the validity of the curve was confirmed

by the use of Baratin method, which allowed the related uncertainty to be estimated, especially considering the limited number of gauging points. A similar situation was observed in [57], where the authors verified the beginning of their rating curve with water depths of no more than 0.50 m for a total section height of around 1.20 m.

This rating curve was then successfully applied to determine the parameters of the AtHyS hydrological model. The optimal parameters (Table 2) allow for a very good reproduction of both the validation case and the beginning of the June 2023 hydrograph. However, the very high value of the velocity V_0 , equal to 5.43 m/s, is questionable. It could be explained by the very steep slopes in the upper catchment, as well as by significant deforestation that prevents the slowing down of runoff water by vegetation. The calibrated value of $S = 82.44$ mm corresponds to a CN of close to 75, which is in agreement with classical values for the type of soil and vegetation cover in the catchment, where the hydrological conditions of the cultivated surfaces are medium. However, it can be observed that the model underestimates the peak discharge in the calibration stage; nonetheless, it reflects well the hydrological behavior of the Rouyonne river watershed, as the curves are very close, and the statistical scores are very good (Table 2). The same situation was described in [46,58], where the peaks of the hydrographs were also underestimated while the curves followed each other in the rising and falling limbs of the hydrographs. As the extent of the inundated area is more related to the volume of the hydrograph than to the peak discharge, the calibration with the parameters found as providing the highest KGE and NSE was retained. In the validation case presented in Figure 8b, the peak discharge is better estimated, but a time lag appears in the hydrograph. This can be related to the velocity parameter V_0 , which could also depend on the initial conditions of the watershed, which were not considered here. However, considering the high KGE and NSE values, and the good fit with the measured data in Figure 9, it was decided to keep the calibrated parameters to reconstruct the missing part of the 23 June 2023 hydrograph.

The hydraulic simulation based on this hydrograph identified three major overflow points on the Rouyonne river, which are highlighted in Figure 12: two points on the right bank (Figure 12a), responsible for flooding the town center, and one point on the left bank (Figure 12b), upstream of and close to the gauging station. This last overflow point explains why the probe was torn off, interrupting the water-depth recording at the measuring section.

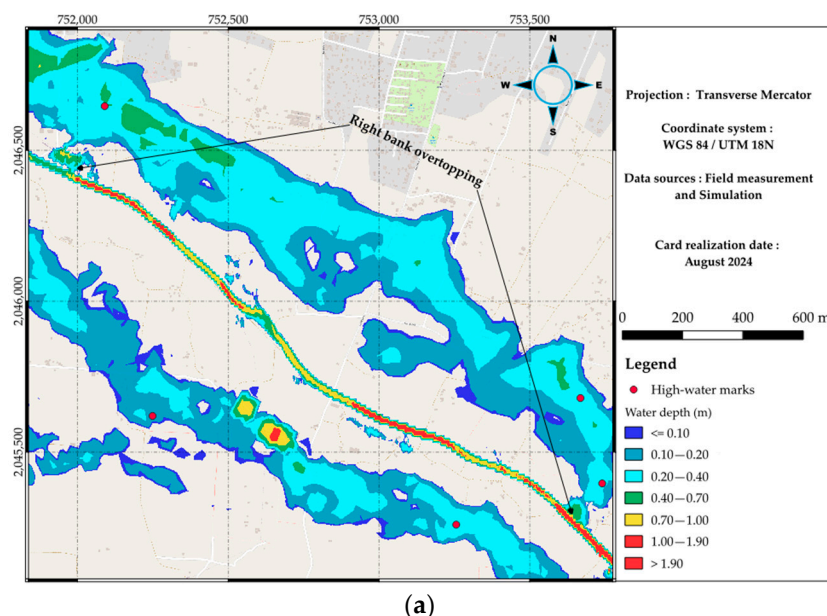


Figure 12. Cont.

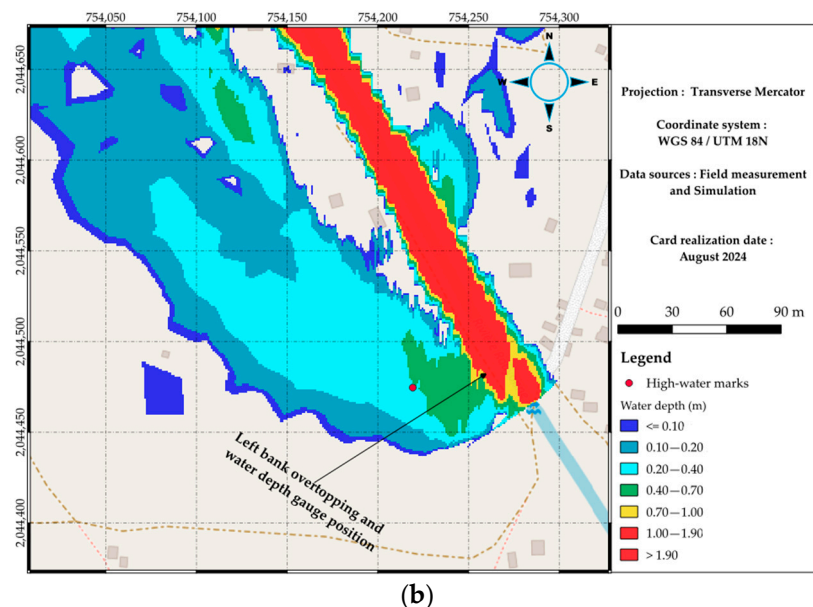


Figure 12. Identification of the overflow points on the Rouyonne river: (a) Right bank overtopping to downtown Léogâne; (b) Left bank overtopping where the probe was installed.

From the good agreement between the simulated and measured water depths (Figure 11), the hydraulic model can be considered as satisfactory. However, the accuracy of the results could be further improved by using a more refined mesh (for example, by reducing the size of the cells in the floodplain); however, this would come at the cost of a great increase in calculation time. Also, the buildings in the city of Léogâne are not properly accounted for. As shown in the work of [6,7], various local aspects can influence the modeled water height, such as spatialized roughness in the floodplain and the effect of buildings in the city. Consequently, our results may underestimate the water depth in some places. This is a prospect for further studies in Haiti.

5. Conclusions

By combining different sources of data and low-cost field measurement techniques, it was possible to develop a hydraulic model for the Rouyonne catchment that reproduced well the inundation of the city following the June 2023 event. This shows that the model could be used to draw up flood zone maps for the city of Léogâne. By using rainfall events or synthetic rainfalls with given return periods, it will be possible to derive corresponding hydrographs and to characterize the possible flooded area for different return periods. Such rainfall data with known return periods are not available at the moment but could be used in the future.

Author Contributions: Conceptualization, methodology and validation, R.L., S.S.-F. and Y.Z.; software and investigation, R.L., A.J., Y.Z., S.S.-F. and N.G.; formal analysis, resources and data curation, R.L., S.S.-F. and Y.Z.; writing—original draft preparation, R.L.; writing—review and editing, S.S.-F. and Y.Z.; visualization and supervision, N.G. and A.J.; project administration and funding acquisition, N.G., Y.Z. and S.S.-F. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the ARES (Académie de Recherche et d’Enseignement Supérieur) RISRUE project (grant number COOP-CONV-22-190).

Data Availability Statement: Data supporting the results of this study are available from the authors upon reasonable request.

Acknowledgments: The authors would like to thank ARES-CCD for funding this study through the RISRUE research project in Haiti and also thank Dauphin Géthro, Asie Louis Raymond, Jacky Dolciné and Lamour Frantz for their assistance in the data collection in the field, the team at the Civil

and Environmental Engineering Department of UCLouvain and the team at the Rural Engineering Department of the State University of Haiti for their help in the realization of this study.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Lhomme, J. Modélisation des Inondations en Milieu Urbain: Approches Unidimensionnelle, Bidimensionnelle et Macroscopique. Ph.D. Thesis, Université de Montpellier II, Sciences et Techniques du Languedoc, Montpellier, France, December 2006.
2. Mathieu, G. Développement d'une Méthodologie Pour la Cartographie du Risque D'inondation: Application à la Rivière de Cavaillon en Haïti. Ph.D. Thesis, Université Catholique de Louvain, Ottignies-Louvain-la-Neuve, Belgium, January 2023.
3. Joseph, A.; Gonomy, N.; Zech, Y.; Soares-Frazão, S. Modelling and analysis of the flood risk at Cavaillon City, Haiti. *Houille Blanche* **2018**, *104*, 68–75. [\[CrossRef\]](#)
4. Crispino, G.; Gissoni, C.; Iervolino, M. Flood hazard assessment: Comparison of 1D and 2D hydraulic models. *Int. J. River Basin Manag.* **2015**, *13*, 153–166. [\[CrossRef\]](#)
5. Horritt, M.S.; Bates, P.D. Evaluation of 1D and 2D numerical models for predicting river flood inundation. *J. Hydrol.* **2002**, *268*, 87–99. [\[CrossRef\]](#)
6. Lhomme, J.; Soares-Frazão, S.; Guinot, V.; Zech, Y. Large scale modelling of urban floods and 2D shallow-water model with porosity. *Houille Blanche* **2007**, *93*, 104–110. [\[CrossRef\]](#)
7. Van Emelen, S.; Soares Frazao, S.; Riahi-Nezhad, C.; Chaudhry, M.H.; Imran, J.; Zech, Y. Simulations of the New Orleans 17th Street Canal breach flood. *J. Hydraul. Res.* **2012**, *50*, 70–81. [\[CrossRef\]](#)
8. Pinos, J.; Timbe, L. Performance assessment of two-dimensional hydraulic models for generation of flood inundation maps in mountain river basins. *Water Sci. Eng.* **2019**, *12*, 11–18. [\[CrossRef\]](#)
9. Apel, H.; Aronica, G.T.; Kreibich, H.; Thieken, A. Flood risk analyses—How detailed do we need to be? *Nat. Hazards* **2009**, *49*, 79–98. [\[CrossRef\]](#)
10. Dewals, B.J.; Detrembleur, S.; Archambeau, P.; Erpicum, S.; Ernst, J.; Pirotton, M. Caractérisation micro-échelle du risque d'inondation: Modélisation hydraulique détaillée et quantification des impacts socio-économiques. *Houille Blanche* **2011**, *97*, 28–34. [\[CrossRef\]](#)
11. Hrachowitz, M.; Savenije, H.H.G.; Blöschl, G.; McDonnell, J.J.; Sivapalan, M.; Pomeroy, J.W.; Arheimer, B.; Blume, T.; Clark, M.P.; Ehret, U.; et al. A decade of Predictions in Ungauged Basins (PUB)—A review. *Hydrol. Sci. J.* **2013**, *58*, 1198–1255. [\[CrossRef\]](#)
12. Blöschl, G.; Bierkens, M.F.P.; Chambel, A.; Cudennec, C.; Destouni, G.; Fiori, A.; Kirchner, J.W.; McDonnell, J.J.; Savenije, H.H.; Sivapalan, M.; et al. Twenty-three Unsolved Problems in Hydrology (UPH)—A Community Perspective. *Hydrol. Sci. J.* **2019**, *64*, 1141–1158. [\[CrossRef\]](#)
13. Buwalda, F.J.L.; De Goede, E.; Kneplé, M.; Vuik, C. Comparison of an Explicit and Implicit Time Integration Method on GPUs for Shallow Water Flows on Structured Grids. *Water* **2023**, *15*, 1165. [\[CrossRef\]](#)
14. Mitsopoulos, G.; Panagiotatou, E.; Sant, V.; Baltas, E.; Diakakis, M.; Lekkas, E.; Stamou, A. Optimizing the Performance of Coupled 1D/2D Hydrodynamic Models for Early Warning of Flash Floods. *Water* **2022**, *14*, 2356. [\[CrossRef\]](#)
15. Guo, W.; Zhai, M.; Lei, X.; Huang, H.; Long, Y.; Li, S. Two-Dimensional Hydrodynamic Simulation of the Effect of Stormwater Inlet Blockage on Urban Waterlogging. *Water* **2024**, *16*, 2029. [\[CrossRef\]](#)
16. Martínez-Aranda, S.; Meurice, R.; Soares-Frazão, S.; García-Navarro, P. Comparative Analysis of HLLC- and Roe-Based Models for the Simulation of a Dam-Break Flow in an Erodible Channel with a 90° Bend. *Water* **2021**, *13*, 1840. [\[CrossRef\]](#)
17. Guan, M.; Guo, K.; Yan, H.; Wright, N. Bottom-up multilevel flood hazard mapping by integrated inundation modelling in data scarce cities. *J. Hydrol.* **2023**, *617*, 129114. [\[CrossRef\]](#)
18. Yang, Q.; Ma, Z.; Zhang, S. Urban Pluvial Flood Modeling by Coupling Raster-Based Two-Dimensional Hydrodynamic Model and SWMM. *Water* **2022**, *14*, 1760. [\[CrossRef\]](#)
19. Delis, A.I.; Nikolos, I.K. Shallow Water Equations in Hydraulics: Modeling, Numerics and Applications. *Water* **2021**, *13*, 3598. [\[CrossRef\]](#)
20. Soares-Frazão, S.; Zech, Y. HLLC scheme with novel wave-speed estimators appropriate for two-dimensional shallow-water flow on erodible bed. *Int. J. Numer. Methods Fluids* **2010**, *66*, 1019–1036. [\[CrossRef\]](#)
21. Meurice, R.; Soares-Frazão, S. A 2D HLL-based weakly coupled model for transient flows on mobile beds. *J. Hydroinform.* **2020**, *22*, 1351–1369. [\[CrossRef\]](#)
22. Sandra, S.F.; Yves, Z. Dam break in channels with 90 degrees bend. *J. Hydraul. Eng.* **2002**, *128*, 956–968.
23. Soares-Frazao, S.; Zech, Y. Dam-break flow through an idealized city. *J. Hydraul. Res.* **2008**, *46*, 648–658. [\[CrossRef\]](#)
24. Westerberg, I.K.; Sikorska-Senoner, A.E.; Viviroli, D.; Vis, M.; Seibert, J. Hydrological model calibration with uncertain discharge data. *Hydrol. Sci. J.* **2020**, *67*, 2441–2456. [\[CrossRef\]](#)
25. Lee, M.; Yoo, Y.; Joo, H.; Kim, K.T.; Kim, H.S.; Kim, S. Construction of rating curve at high water level considering rainfall effect in a tidal river. *J. Hydrol.* **2021**, *37*, 100907. [\[CrossRef\]](#)
26. Jafarzadegan, K.; Moradkhani, H. Regionalization of stage-discharge rating curves for hydrodynamic modeling in ungauged basins. *J. Hydrol.* **2020**, *589*, 125165. [\[CrossRef\]](#)

27. Kumar, V.; Sen, S. Rating curve development and uncertainty analysis in mountainous watersheds for informed hydrology and resource management. *Front. Water* **2024**, *5*, 1323139. [\[CrossRef\]](#)
28. Ocio, D.; Le Vine, N.; Westerberg, I.; Pappenberger, F.; Buytaert, W. The role of rating curve uncertainty in real-time flood forecasting. *Water Resour. Res.* **2017**, *53*, 4197–4213. [\[CrossRef\]](#)
29. Garcia, R.; Costa, V.; Silva, F. Bayesian Rating Curve Modeling: Alternative Error Model to Improve Low-Flow Uncertainty Estimation. *J. Hydrol. Eng.* **2020**, *25*, 04020012. [\[CrossRef\]](#)
30. Qiu, J.; Liu, B.; Yu, X.; Yang, Z. Combining a segmentation procedure and the BaRatin stationary model to estimate nonstationary rating curves and the associated uncertainties. *J. Hydrol.* **2021**, *597*, 126168. [\[CrossRef\]](#)
31. Domeneghetti, A.; Castellarin, A.; Brath, A. Assessing rating-curve uncertainty and its effects on hydraulic model calibration. *Hydrol. Earth Syst. Sci.* **2012**, *16*, 1191–1202. [\[CrossRef\]](#)
32. Reed, S.; Schaake, J.; Zhang, Z. A distributed hydrologic model and threshold frequency-based method for flash flood forecasting at ungauged locations. *J. Hydrol.* **2007**, *337*, 402–420. [\[CrossRef\]](#)
33. Montaldo, N.; Mancini, M.; Rosso, R. Flood hydrograph attenuation induced by a reservoir system: Analysis with a distributed rainfall-runoff model. *Hydrol. Process.* **2004**, *18*, 545–563. [\[CrossRef\]](#)
34. Peredo, D.; Ramos, M.H.; Andréassian, V.; Oudin, L. Investigating hydrological model versatility to simulate extreme flood events. *Hydrol. Sci. J.* **2022**, *67*, 628–645. [\[CrossRef\]](#)
35. Azizi, S.; Ilderomi, A.R.; Noori, H. Investigating the effects of land use change on flood hydrograph using HEC-HMS hydrologic model (case study: Ekbatan Dam). *Nat. Hazards* **2021**, *109*, 145–160. [\[CrossRef\]](#)
36. Bourvier, C.; Delclaux, F. ATHYS: A hydrological environment for spatial modelling and coupling with GIS. In *HydroGIS 96: Application of Geographic Information Systems in Hydrology and Water Resources Management (Proceedings of the Vienna Conference, April 1996)*; IAHS Publication: Wallingford, UK, 1996; Volume 235, pp. 19–28.
37. Agisoft Metashape. Available online: https://www.agisoft.com/pdf/metashape-pro_1_8_en.pdf (accessed on 14 March 2023).
38. Louis, R.; Dauphin, G.; Zech, Y.; Joseph, A.; Gonomy, N.; Soares-Frazão, S. Assessment of UAV-Based Photogrammetry for Bathymetry Measurements in Haiti: Comparison with Manual Surveys and Official Data. In *Proceedings of the 39th IAHR World Congress from Snow to Sea, Granada, Spain, 19–24 June 2022*; pp. 565–574, ISBN 978-90-832612-1-8.
39. Verhoeven, G. Taking computer vision aloft—Archaeological three-dimensional reconstructions from aerial photographs with photostan. *Archaeol. Prospect.* **2011**, *18*, 67–73. [\[CrossRef\]](#)
40. Lowe, D.G. Distinctive Image Features from Scale-Invariant Keypoints. *Int. J. Comput. Vis.* **2004**, *60*, 91–110. [\[CrossRef\]](#)
41. Snavely, N.; Seitz, S.M.; Szeliski, R. Photo Tourism: Exploring Photo Collections in 3D. *ACM Trans. Graph.* **2006**, *25*, 835–846. [\[CrossRef\]](#)
42. Snavely, N.; Seitz, S.M.; Szeliski, R. Modeling the World from Internet Photo Collections. *Int. J. Comput. Vis.* **2008**, *80*, 189–210. [\[CrossRef\]](#)
43. Westoby, M.J.; Brasington, J.; Glasser, N.F.; Hambrey, M.J.; Reynolds, J.M. ‘Structure-from-Motion’ photogrammetry: A low-cost, effective tool for geoscience applications. *Geomorphology* **2012**, *179*, 300–314. [\[CrossRef\]](#)
44. Le Coz, J.; Renard, B.; Bonnifait, L.; Branger, F.; Le Boursicaud, R. Combining hydraulic knowledge and uncertain gaugings in the estimation of hydrometric rating curves: A Bayesian approach. *J. Hydrol.* **2014**, *509*, 573–587. [\[CrossRef\]](#)
45. Horner, I.; Renard, B.; Le Coz, J.; Branger, F.; McMillan, H.K.; Pierrefeu, G. Impact of stage measurement errors on streamflow uncertainty. *Water Resour. Res.* **2018**, *54*, 1952–1976.
46. Bouadila, A.; Bouizrou, I.; Aqnouy, M.; En-nagré, K.; El Yousfi, Y.; Khafouri, A.; Hilal, I.; Abdelrahman, K.; Benaabidate, L.; Abu-Alam, T.; et al. Streamflow Simulation in Semiarid Data-Scarce Regions: A Comparative Study of Distributed and Lumped Models at Aguenza Watershed (Morocco). *Water* **2023**, *15*, 1602. [\[CrossRef\]](#)
47. Nguyen, S.; Bouvier, C. Flood modelling using the distributed event-based SCS-LR model in the Mediterranean Real Collobrier catchment. *Hydrol. Sci. J.* **2019**, *64*, 1351–1369. [\[CrossRef\]](#)
48. Mourad, A.; El Messari, J.E.S.; Bouadila, A.; Morabbi, A.; Benaabidate, L.; Al-Djazouli, M.O. Modeling of Continuous and Extreme Hydrological Processes Using Spatially Distributed Models MERCEDES, VICAIR and VISHYR in a Mediterranean Watershed. *Ecol. Eng. Environ. Tech.* **2021**, *22*, 9–23. [\[CrossRef\]](#)
49. Mathevet, T.; Gupta, H.; Perrin, C.; Andréassian, V.; Le Moine, N. Assessing the performance and robustness of two conceptual rainfall-runoff models on a worldwide sample of watersheds. *J. Hydrol.* **2020**, *585*, 124698. [\[CrossRef\]](#)
50. Orth, R.; Staudinger, M.; Seneviratne, S.I.; Seibert, J.; Zappa, M. Does model performance improve with complexity? A case study with three hydrological models. *J. Hydrol.* **2015**, *523*, 147–159. [\[CrossRef\]](#)
51. Worqlul, A.W.; Ayana, E.K.; Maathuis, B.H.P.; MacAlister, C.; Philpot, W.D.; Osorio Leyton, J.M.; Steenhuis, T.S. Performance of bias corrected MPEG rainfall estimate for rainfall-runoff simulation in the upper Blue Nile Basin, Ethiopia. *J. Hydrol.* **2018**, *556*, 1182–1191. [\[CrossRef\]](#)
52. Tegegne, G.; Park, D.K.; Kim, Y.O. Comparison of hydrological models for the assessment of water resources in a data-scarce region, the Upper Blue Nile River Basin. *J. Hydrol.* **2017**, *14*, 49–66. [\[CrossRef\]](#)
53. Nash, J.E.; Sutcliffe, J.V. River flow forecasting through conceptual models part I—A discussion of principles. *J. Hydrol.* **1970**, *10*, 282–290. [\[CrossRef\]](#)
54. Gupta, H.V.; Kling, H.; Yilmaz, K.K.; Martinez, G.F. Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *J. Hydrol.* **2009**, *377*, 80–91. [\[CrossRef\]](#)

55. Reis, A.A.; Weerts, A.; Ramos, M.H.; Wetterhall, F.; Fernandes, W.S. Hydrological data and modeling to combine and validate precipitation datasets relevant to hydrological applications. *J. Hydrol.* **2022**, *44*, 101–200. [[CrossRef](#)]
56. de Lavenne, A.; Lindström, G.; Strömqvist, J.; Pers, C.; Bartosova, A.; Arheimer, B. Evaluation of overland flow modelling hypotheses with a multi-objective calibration using discharge and sediment data. *Hydrol. Process.* **2022**, *36*, e14767. [[CrossRef](#)] [[PubMed](#)]
57. Langhammer, J.; Bernsteinová, J.; Miřijovský, J. Building a High-Precision 2D Hydrodynamic Flood Model Using UAV Photogrammetry and Sensor Network Monitoring. *Water* **2017**, *9*, 861. [[CrossRef](#)]
58. Bouizrou, I.; Chahinian, N.; Perrin, J.L.; Müller, R.; Rais, N. Network Representation in Hydrological Modelling on Urban Catchments in Data-Scarce Contexts: A Case Study on the Oued Fez Catchment (Morocco). *J. Hydrol. Reg. Stud.* **2021**, *34*, 100800. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.