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ANALYSIS OF THE OPTIMAL BRIDGE PIERS NUMBER FOR REDUCING BACKWATER LEVELS

BY

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Abstract. Like much of the Vienne Valley, the area of Bouchard Island has a significant wealth in terms of environments and species. In the study area, 86 protected species are recorded, half of which are birds. The major areas of issue are located on the crossing of Vienne, along rivers and ponds and in the North sector of Bouchard Island. The presence of the *Margaritifera auricularia*, or *Spengler's freshwater mussel* is a major issue of the site because of its status as an invertebrate being one of the most threatened on the planet and its presence on the course of Vienne.

In order to quantify the damping of the backwater generated by the future crossing of the Vienne, we integrated into the hydraulic modelling software (InfoWorks ICM) the 2D model of the river and using 2 solutions (3 and 4 piers) to simulate the current flow conditions generated by the future bridge for each of the two floods studied as a function the width of the piles.

The hydraulic study of the Vienna crossing will be based on a two-dimensional (2D) modelling of flows because unlike conventional one-dimensional modelling, two-dimensional modeling allows to know precisely the speed in any point of the project area, to size the crossing structure and the piers

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and to assess more detailed the local impact of the project, in particular on the distribution of speeds in major beds.

Keywords: river; floods; discharge; hydrodynamic model; hydraulic model.

1. Introduction

As road infrastructure is constantly evolving, it is necessary to build bridges to connect localities and shorten road routes. In general, the vast majority of bridges are built over rivers and typically the force of water flow on the piers is calculated using specific methods in design codes. The flow rate of the flood will be rapidly influenced when the flow meets the piers (Abbas, 2014).

Due to the lack of space, most of the water will flow along the walls of the two sides of the piers, but some of the water will stop flowing or even flowing back due to the fact that it is obstructed by the piers (Lan, 2017).

By implementing hydraulic modelling, the specialists can predict phenomena related to quantitative and qualitative of water management (Wang, 2015). In this study, the impact of a high flow (1300 m^3/s) was investigated with a 2D numerical model to identify most optimum option between 3 and 4 piers. The focus was on the backwater effects and velocity fields in the nearby of piers. A digital terrain model (DEM) in the current state was based on the topographic data of the study area: Topographic and bathymetric data associated with the 2009 study (APS - Ingérop); Bathymetric profiles of Vienne collected by the Association for the Development of Higher Education in Val de Vienne (ADESVV) in summer 2005, as part of the development of the cartographic atlas of flood-prone areas of the Vienne in Indre et Loire.

Model construction was performed using InfoWorks ICM software. The software allows 2D modelling by solving the Barré de Saint-Venant equations in 2 dimensions of horizontal spaces. Its main results are, at each point of the resolution mesh, the water depth and the mean vertical speed. The modelled zone is represented by triangular elements whose ends are both the calculation points and the topographic data points. This tool is justified in rivers, to locally and very finally calculate major bed current fields on localized sectors or to finely represent flows at the right of singularity such as buildings or embankments. As part of the project, the grid is built taking into account the top and bottom of the banks as stress lines, a different roughness is applied in the major bed and minor bed.

2. Study Area

The case study is located in the Bouchard and Tavant, from the departmental road 760 east of Ile Bouchard to the West of Tavant. In this zone a new bridge is necessary from various reasons, among which main purposes are:

- strengthen security for the inhabitants of Ile Bouchard and Tavant;

- reduce nuisance to users in transit, when crossing L'Île-Bouchard and Tavant, particularly by heavy goods vehicles using the RD 760;
- reduce nuisance for the inhabitants of the towns of L'Île-Bouchard and Tavant unrelated to local economic activities.

The area planned for the development of the Ile Bouchard / Tavant diversion is part of the Vienne watershed, in an area where its alluvial plain extends over a width of about 2.5 km, at about twenty km approximately from its confluence with the Loire.

In the study area, the Vienne has a fairly straight east-to-west flow, the deviation project is located on the right bank of the Vienne, where several tributaries join it, the main ones being Le Manse, the Fausse Manse and the Ruau.

Le Manse is divided into 3 branches upstream of the Moulin de la Boussaye, by a flow distribution device. These arms are from east to west:

1. Le Ponceau stream, which flows from north west to south east, crosses the old SNCF line and the RD760 before emptying into Vienne in the town of Crouzilles,
2. Le Manse, the main tributary in the study area, is an artificial and slightly perched branch that crosses the village of Ile Bouchard (Saint Gilles) from the east before emptying into Vienne,
3. Le Fausse Manse, a tributary of the Ruau stream, which originates near Le Manse and runs along it in its upstream part (up to the right of the project) then joins the Ruau in an East-West flow.

The Ruau is a tributary located in the commune of Panzoult and Vienne watershed covers an area of 20,300 km².

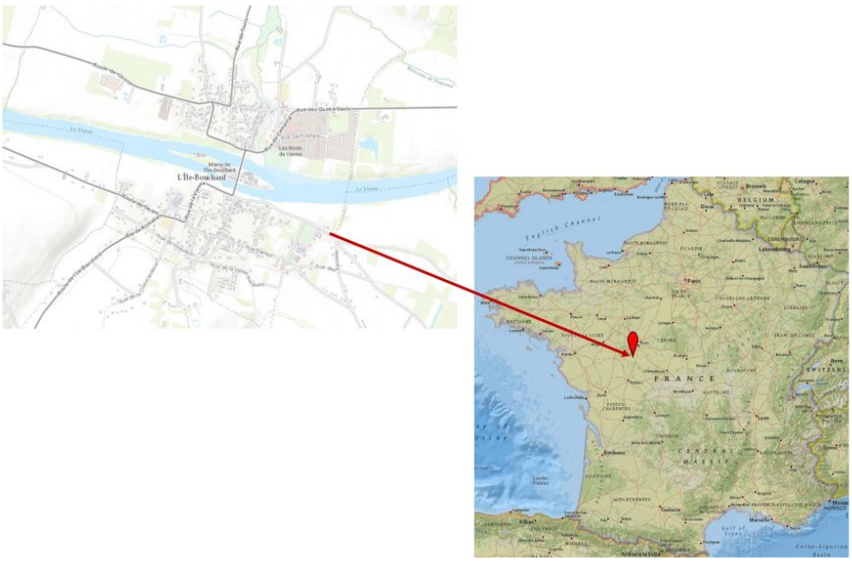


Fig. 1 – Location of the project.

3. Data and Methods

3.1. Data Processing

The input used for our study includes topographic, cartographic and hydrological data sets. From French Ministry of the Environment was collected a LIDAR aerial survey and projected in the Lambert 92 coordinate system (EPSG: 2154). The available LIDAR data set is including a Digital Elevation Model (DEM) at a resolution of 5 m. LIDAR DEM, which captures the characteristics of the land surface of the floodplain, excepting for the bathymetry of rivers and water bodies, was used to characterize the information about the bare earth needed to represent the topography of the floodplain.

The term Digital Terrain Model is used in this paper to distinguish the 5 meters processed data from the original LIDAR Digital Elevation Model. The measured cross-sections were obtained from a validated GPS set of river bathymetry surveillance, which covers the entire floodplain. The hydrology for the flood model was obtained from the water flood risk management plan. In particular, a flow rate of 1300 m^3/s was used as the designed inflow condition for the upstream node of the Vienne River.

The aerial images, collected from the ESRI database, were used mainly for visualization purposes, as a cartographic base that supports the analysis of flood modeling, but also for evaluating the analysis of the upper channel width implemented in the construction of the hydraulic model geometry. An input parameter of the configured 2D hydraulic model was collected from the flood risk management plan which included calibrated and validated topographic data, distributed roughness parameters and rating curves for bridges and sewers that characterized the floodplain domain. This 2D flood model, calibrated and validated in studies using real events, was used as a reference model for the research papers presented.

3.2. Hydraulic Model: FLO-2D

InfoWorks ICM is a 2D hydraulic modeling software based on flood volume conservation and hydraulic routing scheme that simulates changing the flood channel, attenuating flood values and changing flood dynamics due to artificial obstructions (dams, buildings, streets, etc.) on a grid topographic surface. The 2D engine that Infoworks ICM software uses is based on the procedures described by Alcrudo and Mulet-Marti (2005). The surface water equations (SWE), is the average version of the Navier-Stokes equation depth, are used for the mathematical representation of the 2D flow. SWE equations assumes the flow is predominantly horizontal. As respects the variation of speed over the vertical coordinate can be omitted.

In ICM are not currently modeled the turbulence contributions. It is considered that was included in the energy loss, which apperar due to the strength of the bed and it is modeled by the parameter Mannings n.

The conservative formulation of SWE preserve fundamental amounts of mass and momentum. This formulation type allows the representation of flow discontinuities and changes between the gradually and rapidly varied flow. Conservative SWE equations are discretized by using an explicit first-order limited volume scheme. Limited volume schemes use control volumes to represent the area of interest. With limited volume methods, the modeling range is divided into geometric shapes over which SWEs are integrated to give equations in terms of flows through the limits of the control volume (Giurma, 2009). The schema used to resolve SWE equations is based on the numerical schema of Gudunov, with the numerical flows through the control volume limits calculated using the standard Roe Riemann solver. Limited volume methods are in general considered to have a number of advantages as conservation, geometric flexibility and conceptual simplicity.

Wetting and cell exit management is performed using a threshold depth as a criterion to determine if a cell is wet and the speed is set to zero if the depth is below the threshold value (Speed threshold in default 2D parameters = 0.001 m). This avoids the formation of high artificial velocities in the wetting/drying areas.

Infoworks ICM is using an unstructured mesh to represent the 2D area, and this, together with the scheme used, allows a robust simulation of rapidly varying flows (shock capture), as well as super-critical and transcritical flows.

3.3. Topographic Data Processing and Floodplain Grid Resolution

The software's hydraulic model demands a grid of square cells to reproduce the topography of the floodplain. The size of the network cell defines the resolution of the hydraulic model. The 5 meters LIDAR Digital Terrain Model was used as a source of topographic information in the floodplain and an interpolation algorithm was implemented to produce a flooded DTM flood field model to be used as the input model of the hydraulic model. The nearest neighbor interpolation was selected for this study to interpolate the high resolution of 5 m DTM to the desired coarser resolution. It is observed that different interpolation methods (*e.g*. reverse distance weighting and regular kriging) would reproduce different DTMs. Here, we state that the selection of the sampling model does not influence the comparative analysis of the hydraulic modeling results, because the different resolution scenarios of the flood model are developed with the same interpolation model. Resampling was performed to test the effect of the process of expanding morphological information, smoothing the characteristics of the microtopographic floodplain on flood simulations.

Urban features, such as dams, bridges or streets, were also not represented in the DTM input, but were introduced as additional artificial elements of the geometry of the hydraulic model. The topographic model of the floodplain, represents empty land, while the impact of artificial obstacles and features on the surface propagation of flood waves was considered for the use of surface and width reduction factors. These reduction factors take into account the decrease in available storage, expressed by obstructions that change the width and area of the available network cell, in the direction of the surface water from the downstream cell.

River terrain processing to support large-scale flood patterns has been investigated in several papers that have tested optimal methods for DTM interpolation and cross-sections. These studies evaluate the impact of bathymetry processing in floodplains on the performance of hydraulic models. The problem of lack or uncertainty given to the fluvial cross section has been the subject of several attempts to replace the missing bathymetric information in hydraulic modeling. Investigations into the various performances of flood hazard studies with the changing resolution of floodable DTMs also highlighted the importance of identifying the optimal balance between the accuracy and efficiency of flood models. Resampling DTMs from high to low resolution has an impact on the spatial and vertical specification of simulated floodplain terrain, including mismatches between the location and height of canal banks and underestimation (or overestimation) of river and floodplain transport capacity.

3.4. Boundary Conditions and Roughness Parametrization

As upstream condition was using the 1300 m^3/s flow. The peak discharge was 1300 m^3/s and a duration of approximately 24 hours simulation corresponding to the hydrograph total duration. The downstream condition was characterized by the exiting of the flood wave in undisturbed conditions by assuming uniform flow conditions at the channel and floodplain outflow nodes. Manning’s roughness coefficient for channel cells was set constant to 0.05.

3.5. Method

The methods presented are integrated with the aim to develop the floodplain and the river bathymetry processing procedure that is implemented to produce a very coarse resolution riverbed model. The procedure had the scope to test the effect of the bridge piers to river biosphere. Like much of the Vienne Valley, the Ile Bouchard sector has significant wealth in terms of environments and species. In the study area, 86 protected species are recorded, half of which are birds. The major stake areas are located on the Vienne crossing, along waterways and ponds and in the hedged farmland area north of Ile Bouchard. The aspect of wetlands and flood expansion zones will also be essential, in a town subject to frequent flooding from the Vienne and the Manse. The original river model was used only as a reference because it was calibrated before and validated by including surveyed natural cross sections to represent the bathymetry of the channels.

The modeling implemented will be carried out with the Infoworks ICM software, making it possible to simulate two-dimensional flows. This software solves the Barre de Saint-Venant equations in 2 dimensions of horizontal spaces. Its main results are, at each point of the resolution mesh, the water depth and the mean vertical speed.

The modeled zone is represented by triangular meshes whose ends are both the calculation points and the topographic data points. The advantage of two-dimensional modeling with the software used (finite element) is the flexibility in the construction of the mesh: the size of the meshes can vary and adapt to the constraints.

Model construction and setting

The objective of the hydraulic modeling implemented as part of this study is to determine the hydraulic impacts of the crossing structures on the flows of the Vienne and its tributaries in a flood situation.

Two-dimensional modeling makes it possible to quantify these impacts in terms of water depth and flow velocity near the project.

The construction of the hydraulic model will be carried out in 2 main stages:

• Discretization of space (mesh) on the basis of the topographic data obtained;

• Definition of the boundary conditions of the model;

The modeling will extend from upstream of Bouchard Island to a place called Chézelet in the town of Tavant (downstream of the crossing project).

4. Results

The differences which appear in the water levels with and without the bridge piers for a flow of 1300 m^3/s were obtained by using GIS tools to subtract the water levels when there are no piers from the water levels when piers are used.

In the below figures is presented the distribution of computed velocity near the piers and the locations of the piers. From Fig. 2 it can be clearly seen that there was a clear effect of the water due to the presence of bridge piers upstream of the bridge, and the maximum increase in water level was about 1 m.

Flow-velocity fields during floods are also important, as high-speed flow will cause riverbeds to erode and banks and bridges to be destroyed.

Quantitative analysis has indicated the maximum flow velocities near to the bridge to be 1.74 m/s and 2.58 m/s without and with piers, which means an increase of 1.44%. The highest depth in the situation without piles reach a value of 4.97 m, while in the case of the 4 piers this value decreases to 4.93 m.

The maximum flow was reduced with 0.99% which leads to sediment deposition in this river section.

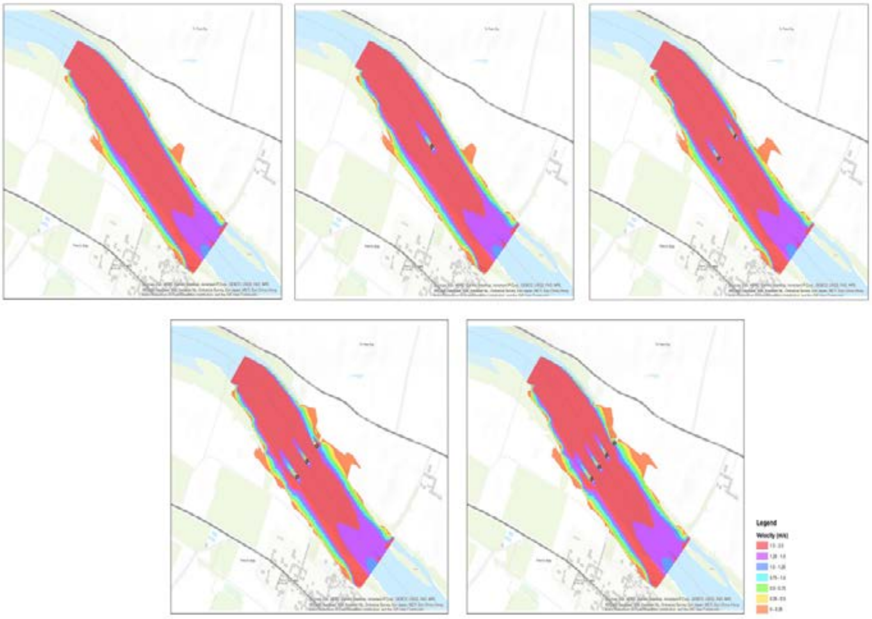


Fig. 2 – Flow 1300 m^3/s – a) no piles; b) 1 pile; c) 2 piles; d) 3 piles; e) 4 piles.

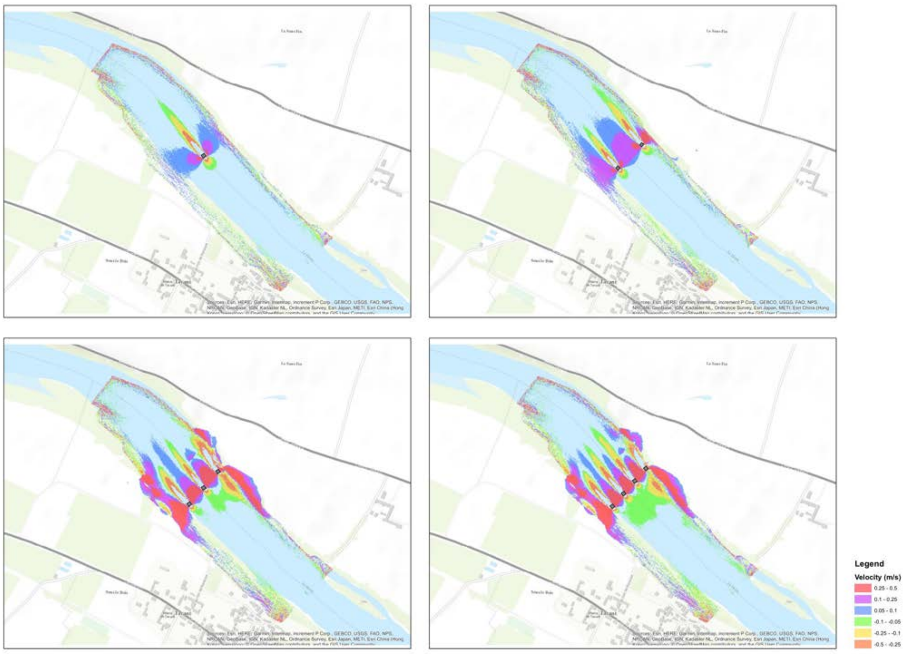
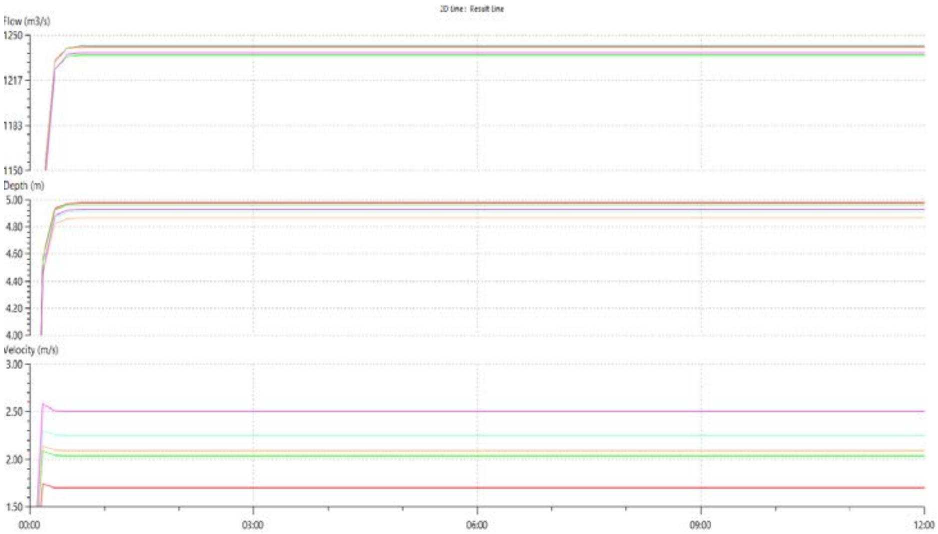


Fig. 3 – Flow 1300 m^3/s – a) Difference between 1 pile and no piles; b) Difference between 2 piles and no piles; c) Difference between 3 piles and no piles; d) Difference between 4 piles and no piles.

Results with the comparison between the current situation and construction of the bridge with 4 different scenarios are presented in the Fig. 3. By building a bridge with one pile, the flow velocity is reduced from 0.5 m/s to 0.25 m/s in the axis line of the river. In the scenario with 4 piles, in the calculation section the flow velocity is reduced from an entire lane with the same velocity (0.5 m/s) to smaller speed areas which reach this speed only at the impact with the bridge piles. In all scenarios can be seen the piles situated in the center part will carry more pressure compared with piles closed to bank lines.

Figure 4 lists the comparison between all piles solutions together with their performance. Graphs with the performance regarding flow, depth and volume are displayed for each design solution. Although the stress level increases, these solutions are in an acceptable range. The four different design solutions for bridge construction reach nearly the same flexibility to lateral displacements and stress level in the pile head. The maximum flow is reached in the case without no piles and has a value of 1242 m^3/s. Although the design with 4 piles has a much higher reduction in the flow speed, its construction is more difficult. For the solution with no piles, less work is necessary. However, the maintenance and durability of the bridge with 4 piles is long lasting.



	Flow (m3/s)			Highest depth (m)		Highest speed (m/s)	
	Min	Max	Volume (m3)	Min	Max	Min	Max
No Piles	0.000	1242.045	53209491.797	0.000	4.978	0.000	1.746
1 Pile	0.000	1235.530	52931440.503	0.000	4.965	0.000	2.086
2 Piles	0.000	1241.145	53170843.030	0.000	4.863	0.000	2.143
3 Piles	0.000	1242.430	53218722.144	0.000	4.914	0.000	2.304
4 Piles	0.000	1237.267	52998023.767	0.000	4.931	0.000	2.585

Fig. 4 – Flow 1300 m^3/s – Comparison between all solutions.

5. Conclusions

In this study an 1D model was created in order to assign the optimal bridge piers number for reducing backwater levels. The backwater effects and the flow velocity value due to the presence of piers in the river body were analysed in detail.

The following conclusions can be derived from the comparative analysis:

Flood flow velocity in the calculation section can be significantly reduced by using more piles in the design of the bridge.

The results show that the flow field around the piles is considerably influenced by the construction of the piles.

The analysis shows a competitive approach to the design of bridge because it can show the real pile response.

The flow structure near to the piers are very important, as long as the resulting sediment erosion are critical to the safety of bridges. These represent an issue of interest to engineers, and thus this subject deserves further study. Maximum flows, flow velocities and volumes with different probabilities are the most important elements used in dimensioning and usage of hydrotechnical constructions. Their safety and economic efficiency depends on the accuracy of these values. Optimal design of the flood modelling leads to increase the performance of the flood prevention structures.

REFERENCES

Abbas M.J., *Bridge Pile Foundation: Simulation and Analysis*, Journal of Earth Sciences and Geotechnical Engineering, **4**, *1*, 131 (2014).

Lan C., Briseghella B., Fenu L., Xue J., Zordan Tobia, *The Optimal Shapes of Piles in Integral Abutment Bridges*, Journal of Traffic and Transportation Engineering (English Edition) **4**, *6*, 577 (2017).

Giurma I., Hrăniciuc T., Cercel P., *Flood Monitoring Through Hydrological and Hydraulic Parameters Modeling Using Modern Software*, The VIth Int. Conf. on the Manag. of Technol. Changes (MTC 2009), Alexandroupolis, Greece, vol. **I**, 630.

Wang Y., Zou Y., Xu L., Luo Z., Lan C., *Analysis of Water Flow Pressure on Bridge Piers Considering the Impact Effect*, Mathematical Problems in Engineering, Volume 2015, https://doi.org/10.1155/2015/687535, 2015.

ANALIZA NUMĂRULUI OPTIM DE PILE DE POD PENTRU REDUCEREA EFECTULUI DE REMUU

(Rezumat)

Precum multe dintre văile râului Vienne, arealul insulei Bouchard înglobează bogății semnificative în ceea ce privește mediile și speciile. În zona de studiu sunt înregistrate 86 de specii protejate, dintre care jumătate sunt păsări. Principalele zone în pericol sunt situate în zona traversării râului Vienne, de-a lungul râurilor și iazurilor și în

sectorul de nord al Insulei Bouchard. Prezența *auriculariei Margaritifera*, sau a *midiilor de apă dulce ale lui Spengler*, este o problemă majoră a zonei de studiu datorită statutului său de nevertebrat fiind una dintre cele mai amenințate de pe planetă. Aceste specii pot fi puse în pericol dacă se realizează lucrări de infrastructură care modifică regimul natural al râului. Acest studiu s-a efectuat pentru a evalua numărul optim de pile de pod care nu modifică substanțial regimul de curgere al râului. Pentru a cuantifica amortizarea apei din efectul de remuu generat de viitoarea trecere peste râul Vienne, am integrat în software-ul de modelare hidraulică (InfoWorks ICM) modelul 2D al râului și utilizând diverse soluții (1, 2, 3 și 4 pile) pentru a simula condițiile de curgere curente generate de viitorul pod pentru fiecare dintre cele două inundații studiate ca funcție dată de lățimea pilelor. Studiul hidraulic al traversării râului se va baza pe o modelare bidimensională (2D) a debitului, deoarece, spre deosebire de modelarea unidimensională convențională, modelarea bidimensională permite localizarea exactă a vitezei în orice punct al zonei proiectului, dimensionarea structurii de traversare și a pilelor și evaluarea mai detaliată a impactului local al proiectului, în special asupra distribuției vitezelor în albia majoră a râului.