OPTIMUM DESIGN OF LARGE FLOOD RELIEF CULVERTS UNDER THE A89 MOTORWAY IN THE DORDOGNE-ISLE CONFLUENCE PLAIN

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ABSTRACT

The planned A89 motorway will go through the Dordogne-Isle confluence plain which is regularly flooded under the effect of both river discharges and ocean tides. Hydraulic transparency of the motorway embankment was one of the prerequisites imposed by the French government. In order to optimise the cost/efficiency ratio of large culverts located under the motorway, their position and size had to be determined with great accuracy. This task has been fulfilled thanks to complementary sophisticated physical scale and 2D numerical models. The schematisation principles adopted in the 2D numerical model concerning bridge piers grouping were validated using the physical scale model.

The finite element Telemac-2D code was used to draw up the optimum design of this river engineering scheme. Telemac-2D solves the 2D shallow water equations on non structured grids in the presence of alternately dry and wet beds. 2D numerical modelling based on high quality topographic data allows considerable improvements to be made in the computation of flood flows in a flat valley as compared to traditional one-dimensional techniques. Near flood relief culverts in particular, the various physical effects contributing to the overall head loss can be distinguished: bottom roughness, medium size bed variations, strong curvature of the streamlines and vortices behind abutments.

The hydraulic impact of the optimum solution has been studied under different aspects (rise of maximum flood levels, increase in maximum velocity, changes in the water flow patterns, submersion time of flooded land, modification of flood routing characteristics) for a wide range of flood hydrological events.

Key words : river flood - 2D modelling - finite elements - flood culvert - motorway design

INTRODUCTION

In the south-west of France, the confluence of the rivers Garonne and Dordogne at Bec d’Ambès forms the Gironde estuary, which is the largest European estuary. In its downstream course, the river Dordogne meanders in a very flat valley before reaching the estuary. The city of Libourne is located on the right outer bank of a large meander of the river, the centre of which is only 6 metres above the lowest sea level of spring tides despite being located 100 kilometres from the Atlantic Ocean. The Isle, a tributary of Dordogne, also meanders in a flat valley.
oriented north-south which merges with the Dordogne valley immediately downstream of Libourne. Levels in the two rivers are subject to the influence of Atlantic semi-diurnal tides. This downstream influence is felt particularly at low river discharge values and, of course, during spring tides. This may lead to minor floods in the Dordogne-Isle confluence area occurring mainly at high tide. The water level in the valleys is even increased when a surge is generated in the Gironde estuary under the effect of storms over the Atlantic Ocean. Nevertheless, major floods are, for the most part, the result of simultaneous major peak discharges in the rivers Dordogne and Isle.

This situation led the inhabitants to long ago protect themselves by constructing dikes along both banks of the Dordogne meander. The river Isle’s banks are still mostly in their natural state. During the past few decades, roads and railways have been constructed in these valleys. They are generally located on embankments; some of them may be submerged by large floods. Insubmersible embankments are cut through regularly by wide culvert sections.

**The motorway development project**

The A89 motorway, linking Bordeaux with Clermont-Ferrand, will run through these valleys (fig. 1). The public usefulness of the motorway was pronounced by the French Government on January 10th, 1996. The project owner and operator of the future motorway is Autoroutes du Sud de la France (ASF), the first French toll highway operator. Scetauroute was responsible for the design of the motorway and supervision of construction works.

![Figure 1. Topography of the Dordogne and Isle valleys, and route followed by the A89 motorway](image-url)
Coming from Bordeaux, the A89 motorway will enter the Dordogne valley close to the town of Arveyres, south of Libourne. It will cross the Dordogne meander in a south-north direction. After the toll platform located south of the meander, a wide bridged section (1430 metres) will carry it across the train line located on the so-called “100 Arches bridge”, and the embanked RN 2089 road. Another function of this large bridge is, of course, to allow flood flows to pass. Two smaller culverts will be built in the Dordogne meander section. The motorway will cross the river Dordogne and enter the Isle valley on a large viaduct located at the foot of Fronsac hill. At the entrance to the Isle valley, the embanked RD 670 road perpendicular to the valley will be crossed by the same viaduct.
Continuing northwards, the motorway embankment will be interrupted by three bridges crossing meanders on the river Isle. It will then run in the centre part of the Isle valley and cross the insubmersible RD 18 road, which is again perpendicular to the valley at Les Billaux. Turning east, the motorway will leave the Isle valley south of Saint-Denis-de-Pile, more than 16 kilometres after the point at which it enters the Dordogne valley. Eight other culverts ranging in width from 12 to 250 metres are planned in the Isle valley section.

DETAILED HYDRAULIC STUDIES OF THE A89 MOTORWAY

According to the French Law on Water voted on January 3rd, 1992, any large civil engineering project must be submitted to a public inquiry after a complete file has been compiled presenting the project, its hydraulic impact on surface and ground waters from all points of view, and justifying the technical solutions adopted.
Before the A89 motorway was declared to be of public usefulness, preliminary design studies had been performed to locate and size flood relief structures that would minimise the related hydraulic impacts. They were based in particular on a refined one-dimensional mathematical model representing flood plains by a meshed network of storage cells linked together and with the river beds.
When the declaration of public usefulness was made, the French government specified that the flood relief culverts should be designed to produce a rise in maximum water levels of less than 2 centimetres in sensitive parts of the valleys (i.e. inhabited areas with serious flood risks) and less than 5 centimetres in all other inundated areas. This is a stringent requirement for the motorway designer. It also calls for a high level of accuracy in estimating possible impacts. Sensitive areas were defined by government services on the bases of the potential damage (urban or industrial areas are more sensitive than rural ones) and natural factors (maximum water depths and velocities produced by floods on the basis of the results from the 2D numerical model).
In order to satisfy government requirements concerning the project, and also to give the inhabitants of the valleys accurate and complete information on the hydraulic impacts of the future motorway for all types of floods, with a high level of confidence, Autoroutes du Sud de la France decided to carry out detailed hydraulic studies based on refined physical and 2D numerical models. A group consisting of Sogreah Ingénierie, Laboratoire d’Hydraulique de France and Sogelerg-Sogreah Sud was selected to carry out these studies.
METHODOLOGY

The detailed hydraulic studies of the A89 motorway were performed in three stages:

- optimum design of the hydraulic structures for the motorway,
- detailed description of the hydraulic impacts of the motorway,
- preparation of the public inquiry file.

Optimum design of the hydraulic structures for the motorway

On the basis of the preliminary design study, the number, locations and sizes of flood relief culverts under the motorway were refined by adopting a progressive approach aimed at (1) minimising the hydraulic impacts of the project for a representative range of past and projected floods and (2) minimising the cost for motorway construction. The cost of a culvert section under a motorway is indeed higher than the cost of an embanked section by a factor of 5 to 8, which means that it is advisable to define these sections accurately. Accompanying measures such as culverts under neighbouring roads or bed levelling in the motorway area were also defined as part of this optimum design phase.

Detailed description of the hydraulic impacts of the motorway

The hydraulic impacts of the motorway were then studied for a wide range of hydrological events, in relation to the following aspects:

- distribution of the rise in maximum water levels resulting from the project;
- flood duration, i.e. the submersion time of flooded land;
- modification of the flow distribution in the valleys resulting from the project;
- distribution of the increase in flow velocity due to the project;
- determination of the transformation in flood routing due to the motorway, in order to ensure no increase in risk for people living downstream of the motorway in the Dordogne valley;
- impact of the motorway on scenarios concerning the creation of breaches in the Dordogne dikes during floods.

Finally, the hydraulic impact of constructing the motorway was also studied in detail.

Preparation of the public inquiry file

The recent French Law on Water aims at preserving aquatic ecosystems and landscapes, in the framework of sustainable environmental management. Development projects should be designed to respect the balance between different water uses (potable water supply, energy, agriculture, transport, tourism, etc.), public health and safety. As shown in the previous section, the impacts of the motorway on flood disposal were studied in great detail. The public inquiry file also presented the impacts of the motorway from the following points of view:

- behaviour of the surface water network, as designed after motorway construction, during normal and low water periods;
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- groundwater flows;
- quality of surface and ground waters, in particular with regard to the entrainment during rainfall events of hydrocarbons deposited on the motorway or possible pollution resulting from traffic accidents;
- respect of ecosystems and landscapes in the aquatic environments and wetlands surrounding the motorway.

Two complementary models

The hydraulic study programme was conducted using two high-performance models: a two-dimensional mathematical model for computing transient flows throughout the study area (the model grid is shown on fig. 2) and a large physical scale model simulating steady flows in the Libourne meander of the river Dordogne and downstream part of the river Isle (fig. 3).

These two models were used in close conjunction at all stages. They also allowed mutual enhancement. For instance, early in the calibration phase, comparisons between the results of the mathematical and physical models showed up minor topography errors introduced at the construction phase: a section of the RN 2089 road embankment in the scale model was 3 millimetres too high (i.e. 15 centimetres in reality, taking into account the 1:50 scale of the model) thus producing an area in which flow would not take place. This was detected by comparison with the flow patterns of the mathematical model. Conversely, the numerical model initially featured an unrealistic bump in the river Isle upstream of the confluence with the river Dordogne, producing a local head loss which was not observed on the physical model. These localised errors would have been undetectable by simple comparison with available in-situ observations.

More importantly, the piers of the 100 Arches railway bridge had to be represented schematically on the mathematical model in order to avoid having an excessively large number of computational nodes. This was done by grouping neighbouring piers into a hydraulically equivalent larger pier. This simplification was validated by comparison with the results of the physical model. In the exploitation phase, the same schematisation principle was then extended to the motorway culverts in the Dordogne and Isle valleys.

On the other hand, one of the roles of the mathematical model was to supply boundary conditions to the physical model. In this respect, one complete tide cycle was computed with the mathematical model for each hydrological event studied. Three instants were identified in the run, corresponding respectively to maximum water levels, maximum velocities in the Dordogne meander and maximum velocities in the lower Isle valley. As inertia effects are moderate, variations in computed discharges and water levels in the valley cross-sections were used at the boundaries of the physical model for simulating the three associated typical steady states.

Finally, during the calibration and exploitation phases, a high level of confidence in the conclusions of the optimisation study was achieved by comparing the results produced by these two models. In the Dordogne meander, in case of any small discrepancy between the mathematical model and the physical scale model, the physical model was considered as the reference and the mathematical model was adjusted accordingly. In the Isle
valley, optimum design and hydraulic impact of the motorway were performed thanks to the mathematical model only.

Inhabitants of the Dordogne and Isle valleys were tightly associated to the data collection phase through enquiries carried out at the beginning of the project. They were also consulted for the validation of model results due to their very good knowledge of local hydraulic phenomena, even if not scientifically based. Their confidence in the models was therefore reinforced.

The mathematical model was used extensively to produce the comprehensive maps presenting the results of the study, especially those illustrating the various aspects of the motorway’s impacts. On the other hand, the physical model was a powerful communication tool for explaining flow processes. The association of these two models revealed useful for the presentation of flood processes to the members of the project Steering Committee and to the inhabitants of the valleys. It allowed their efficient involvement in the design of the motorway project.

**The 2D mathematical model**

The two-dimensional mathematical model computing transient flood flows in the Dordogne and Isle valleys was constructed on the basis of the Telemac software system, developed by EDF-DER and distributed by LHF. Within this system, Telemac-2D is based on finite-element numerical schemes solving the two-dimensional shallow water equations on triangular unstructured grids (Hervouet and Van Haren, 1996). In Telemac-2D, particular attention is paid to the treatment of alternatively dry and wet elements, the software being used in particular to compute dam-break waves (Hervouet, 1997) and flood flows (Bates et al., 1996). Other scientific programs embedded in the system enables the computation of 3D flows in natural domains, the dispersion of contaminants or thermal plumes in these waters, the transport of sand or mud, the transformation of wave characteristics, etc. Around the different scientific programs in the Telemac system, a set of user-friendly modules enables computational grids to be designed and boundary conditions and model steering files to be prepared. Enhanced analysis of model results and the preparation of graphical outputs are also possible. A complete presentation of the system can be found in the Telemac presentation document (LHF, 1997).

**Domain and grid characteristics**

The upstream limit of the model in the Isle valley is located at Guîtres. 15 kilometres of the valley were represented, i.e. a linear distance of 28 kilometres along the meanders of the river Isle. A 23 km reach of the river Dordogne, representing three meanders, was modelled together with its flood plain. The non-structured grid consisted of some 60000 triangular elements of varying sizes and shapes and 30000 nodes. The triangular elements ranged in size from 2 metres under culverts to 150 metres in very flat flood plains.
Boundary conditions

The boundary conditions imposed in the upstream sections of the river Dordogne and river Isle were the dynamic changes in discharge during flood events. Variations in water level were prescribed at the downstream boundary of the river Dordogne. This water level is assumed to be constant in the downstream cross-section. Although this assumption is not perfectly true when the valley is flooded, it has no effect on the Libourne meander, which is located far from the downstream boundary: possible small errors on the downstream boundary are damped along the backwater line.

The boundary conditions of the two-dimensional mathematical model were obtained from an extensive one-dimensional flood model representing the river Garonne and river Dordogne under tidal influence and the Gironde estuary down to the sea.

Numerical aspects and physical parameters adopted

A first-order approximation of time derivatives with a semi-implicit approximation of other terms is used in Telemac-2D. No numerical constraint is therefore imposed on the time step; however, as a rule of thumb, the cell Courant number should not reach values higher than 3 over most of the computational domain during the simulation. In order to satisfy this criterion on the one hand and to limit the number of iterations per time step on the other hand, a constant 6 second time step was used. With regard to space discretisation, the F.E. quasi-
bubble triangular element option was selected. Telemac-2D solves the system of discretised equations at each time step using Iterative Preconditioned Conjugate Gradient (IPCG) type methods associated with Element By Element (EBE) storage techniques in order to save core memory (Hervouet, 1991). On average, 5 iterations were necessary at each time step to achieve $10^{-5}$ m accuracy for overall water levels. These characteristics led to a ratio between computation time and real time of approximately 2:1 on a modern workstation (i.e. the model computes a 5-day flood within about 10 days).

In Telemac-2D, no simplification is made in the general shallow water equations when semi-covered elements are encountered. At very shallow depths, the pressure gradient term is roughly balanced by the bottom shear stress. Therefore, the free surface gradient must be computed accurately even though the free surface presents a discontinuous slope on semi-covered elements. In order to give precedence to the computation of velocities on these elements, the free surface gradient is considered to be equal to that in the wet part of the element.

Bed roughness was represented by using the Strickler law. After calibration, a space-dependent Strickler coefficient was adopted, ranging from 70 in the river Dordogne to 10 in flood plains covered with trees. Vortices and streamline curvature are generated downstream of obstacles, in particular bridge piers and culvert abutments. Accurate representation of these turbulent features is possible only thanks to sophisticated higher-order turbulence models and very small mesh sizes, at least in areas with vortices. With such turbulence models, the overall number of points is increased and a small time step value must be adopted. As a consequence, the computational time is increased. However, such higher-order turbulence models are not necessary to obtain precise information on the effect of turbulent features on the overall head loss produced by the obstacle. This could be verified by comparing the results obtained by both turbulence modelling approaches on test models. Therefore, for the present flood study, a turbulence model based on a constant eddy viscosity equal to 1 m$^2$s$^{-1}$ was adopted.

**The physical scale model**

The physical scale model constructed for the detailed hydraulic studies of the A89 is very large: its horizontal dimensions are 75 x 35 metres.

The Libourne meander of the river Dordogne was represented in its entirety, as well as the downstream 2 kilometres of the lower Isle valley. The model was distorted with a horizontal scale of 1:100 and a vertical scale of 1:50. Distortion allows for sufficient water depth with respect to the height of roughness, and it avoids the unacceptable model plane dimensions of a 1:50 horizontal scale. The adopted vertical scale also allows for the development of turbulent flow. It was chosen to respect the Froude similarity law. The horizontal velocity scale is therefore close to 1:7.

The vertical scale of 1:50 is also the lower limit for acceptable measurement errors: in the best conditions, the water level is read to within 0.1 mm, i.e. 5 millimetres in nature, which gives a 2x0.5 = 1 centimetre reading error in terms of impact (difference between two simulations performed on the scale model). This value may be compared with the maximum authorised rise in water level due to the motorway (2 centimetres in sensitive areas and 5 centimetres elsewhere).
The water surface elevation was measured at 35 points distributed over the model. Velocity fields were obtained by trajecto-videography; spot velocity values were measured with a current-meter.

![Figure 3. Physical scale model - Map and photographs of the model](image)

**NUMERICAL MODELLING TECHNIQUES ADOPTED**

First of all, it should be stressed that a considerable amount of data is needed to construct a highly accurate numerical model of a river. It is also a long process, especially the mesh generation phase. When constructing the mesh, the modeller has to keep in mind two contradictory constraints at all times: namely, the model should agree as much as possible with the available topographic data, and the number of computational nodes should be reasonable in order to keep the model operational during the exploitation phase. At present, no F.E. mesh generator is able to generate an optimised mesh in a “press-button” mode, which satisfies all the topographical, hydraulic and numerical constraints of a river plain. This is still a difficult task, that must be undertaken only with the guidance of a skilled modeller.

The following sections describe the characteristics of the 2D mathematical model of the Isle/Dordogne confluence area.
Flood plains

Photogrammetric maps with a scale of 1:1000 and altimetric accuracy of 15 centimetres were available for the Dordogne and Isle valleys. It was thus possible to take into account small variations of topography in these very flat valleys. Singularities in the topography, such as river banks, dredging basins, artificial hills of dredged sediments, embankments, etc. could also be located. Longitudinal profiles of potentially flooded linear embankments were also available with an altimetric accuracy of 2 centimetres. In flat flood plains, the grid was kept as regular and isotropic as possible, with typical mesh sizes of 100 metres. The Strickler coefficient ranged between 10 and 20.

It should be noted that value adopted for the roughness coefficient in a two-dimensional model depends on the refinement of the grid. This is particularly sensitive in flood plains, where the water is shallow and roughness plays an important role. Indeed, a refined grid with only slight topographic variations from node to node presents a “shape” roughness which must not be included in the overall roughness coefficient. In contrast, when the grid is relatively course, the roughness coefficient includes both skin roughness and small topographic features.

River beds

The bathymetry in the rivers Dordogne and Isle was available in the form of recently measured cross-sections spaced every 500 metres. The grid in the rivers was constructed with quadrangles elongated in the direction of flow, with maximum distortion ratio 1:10, and split into two triangles. The spacing between cross-sections containing nodes depended on the curvature of the river bends, the average value being 70 metres. Each cross-section was described by 8 points for the Isle and 10 points for the Dordogne, so that assymmetric flow could be simulated in the river bends.

In the bed of a river, a two-dimensional model has a higher grid resolution than a one-dimensional model. This again explains partly the difference between the roughness coefficient used in a two-dimensional model and a one-dimensional model representing the same reach of river: in the one-dimensional model, the effects of small and medium bed variations are included in the roughness coefficient whereas this is not the case in the two-dimensional model. The Strickler coefficient was set at 70 in the river Dordogne, where the bottom is covered by a layer of mud, and between 35 and 50 in the Isle.

Obstacles to flow: river dikes and embanked roads and railways

Water flowing over dikes generally produces strong curvature of the streamlines. Supercritical flow and hydraulic jumps are likely to occur downstream of the dike when the downstream water level is low.

In one-dimensional models, the flood plain is represented by interconnected storage cells. This type of representation makes the transfer of momentum from the river to the flood plain over the dikes of reduced importance, and overflowing is generally modelled by weir formulae taken from channel flow hydraulics.

Although such a formulation can be prescribed in Telemac-2D on a line symbolising the dike, this is not a satisfactory solution because the momentum component parallel to the river axis is taken to be zero downstream of the dike. Therefore, it was decided to model the dikes along the Dordogne by using variations in topography
and a refined grid, without any specific treatment of the shallow water equations. This was possible because Telemac is able to handle semi-covered elements as well as supercritical flow and regime transitions.

The grid on the dikes is elongated along the dike axis and the grid was constructed in the same way as in the rivers (see the previous section). Tests were performed with increasingly refined dike slopes. They showed that the velocity field was better close to the dike when the grid was refined, but no difference in water levels could be detected. It was therefore decided to represent the Dordogne dikes schematically as shown on fig. 4. Submerged road embankments were modelled according to the same principles. Embankments which are not submerged in any flood conditions were represented by islands with solid boundaries: this is the case of the A89 motorway embankment.

Bridges and flood relief culverts

Bridge and culvert sections are strategic places were water flows must be computed accurately. The computational grid was therefore extremely refined in these places, with meshes having a characteristic length as little as 2 metres (the smaller culvert having a width of 6 metres). It is more likely that there will be convergence difficulties and a consequent overall limitation of the time step in these places, where the velocity is generally higher and more variable than in the flood plain or ordinary river sections. The grid around culverts and bridges was therefore designed almost completely by hand with user-friendly tools in order to monitor the probable streamline curvature as much as possible and to elongate the meshes in the direction of the current.

In one-dimensional models, culverts are modelled in the form of an overall head loss coefficient. This coefficient includes many physical phenomena, the major ones being (a) the bed and shape roughness in the immediate vicinity of the culvert, (b) differential advection, (c) reorientation of the streamlines on approaching the culvert and (d) the turbulent structures created downstream of the culvert abutments. A two-dimensional model makes a distinction between these different physical phenomena. They are computed individually and with much greater accuracy.

Since roughness stress varies quadratically with unit discharge, flow is sensitive to the local roughness value adopted for the model since the velocities are relatively high under culverts. It is therefore important to note that vegetation is not able to grow below the motorway because sunlight is rare. This locally reduces the roughness considerably in this location. This is the reason why a Strickler coefficient in the range 22-25 was adopted in the culvert sections whereas a value in the range 10-20 was generally taken in the flood plain. A consequence for the

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motorway’s owner is that regular maintenance of the culverts and their surroundings is necessary in order to prevent refuse from accumulating, either naturally or through dumping. If not, the efficiency of the culvert will be significantly reduced.

As was stated in a previous section, bridge and culvert piers were grouped together in order to limit grid refinement. Concerning the 100 Arches railway bridge for instance, 4 piers were grouped into one obstacle (2 piers on each side of one arch). The equivalent obstacle was sized to comply with the hydraulic opening of the bridge or culvert. Streamline direction with respect to the opening was taken into account. This schematisation was validated by the physical scale model.

**HYDROLOGICAL EVENTS CONSIDERED**

The main factors generating floods in the Dordogne/Isle confluence plain are the peak discharges in the rivers Dordogne and Isle respectively. Since their catchments are of similar lengths and subject to similar climatic events (major rainfall events originate in the Atlantic), there is generally a very short time lag between peak discharges on the two rivers. This explains the enormous amount of inundation produced by major floods. But the water level in the river Dordogne also depends on the influence of the downstream tide, and spring tide high water levels will increase the amount of flooding. Finally, low pressure areas and winds blowing from the Bay of Biscay may produce storm surges in the Gironde estuary which reinforce tidal effects.

Probably only once in the 20th century, in December 1944, has the Dordogne totally overflowed the dikes along the meander. The return period of this event is approximately 40 years. In January 1994, however, a 10-year flood occurring during average tidal range conditions inundated the entire Isle valley over a distance of several kilometres. In February 1996, a storm with strong winds blowing over the Gironde estuary and Dordogne valley generated a flood featuring typical downstream conditions in the Isle valley. The flood of December 1981 also led to flooding in the Isle valley and isolated spills over the Dordogne dikes.

These known historical hydrological events are fortunately not severe enough to be used as project flood for designing flood relief culverts along the motorway. A fictitious 100-year flood discharge in the two rivers, with an exceptional tidal range and severe storm surge conditions in the Gironde estuary was therefore considered. Corresponding level and discharge variations in the Libourne area were computed by means of the comprehensive one-dimensional mathematical model. This was the design flood. Finally, an even larger flood, the so-called “security flood”, was simulated in order to see if this would lead to different hydraulic conditions in the valleys due to pressurised flow under a culvert or bridge, for instance. The security flood was obtained by increasing discharges in the rivers by 25% as compared to the design flood.

All these hydrological events were studied with mathematical and physical scale models. They encompass a complete range of real and extreme floods likely to occur in the valleys. Hydro-climatological conditions are summarised in the following table.

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<td><strong>Dordogne peak discharge</strong></td>
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### MODEL CALIBRATION AND REFERENCE STATE

The first step in the mathematical model calibration process was to obtain good agreement between model results and observations of the water surface profiles just as the dikes or banks begin to overflow.

As far as the flood plains are concerned, the January 1994 flood was used to calibrate the model in the Isle valley. Good quality observations of the maximum water level were available for this recent flood. The only flood maximum water level observations available in the Dordogne meander are those of the December 1944 flood. However, the topography of the plain has changed since then: the RN 2089 road embankment has been constructed and the Dordogne dikes were reinforced after this disastrous flood. Only approximate calibration was possible in this area.

The results of the physical scale model and two-dimensional numerical model were compared. The average difference in maximum water level between the physical model and the numerical model was 3 centimetres with an isolated maximum value of 6. The two models are therefore consistent. The velocity fields supplied by the mathematical and physical models were also qualitatively in agreement.

After the two models had been calibrated, their absolute accuracy in relation to flood maximum water levels was estimated to be in the range of 5-10 centimetres: this is the discrepancy between one model and field observations. As far as accuracy is concerned, it should be borne in mind that the main error to be considered in the study results is that concerning the impact of the motorway. The impact is the difference between two simulations of a given flood event: one simulation including the motorway project minus the other simulation on the reference state model. The error relating to the impact is of course much lower than the absolute accuracy of the model.

After calibration, the mathematical model was slightly modified in order to represent very recent changes in the valleys (essentially the extension of a rowing basin located in the lower part of the Isle valley and its surrounding banks). The result is the so-called reference state model. All the different floods were again simulated with this reference state model before going to the exploitation phase.

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| Isle peak discharge (m$^3$s$^{-1}$) | 1000 | 850 | 150 | 455 | 1200 | 1500 |
| Tidal coefficient | 51 | 71 | 87 | 99 | 110 | 110 |
| Surge (m) | 0.40 | 0.62 | 1.72 * | 0.76 | 1.62 | 1.62 |
| Wind (km/h) | - | - | 170 | - | - | - |

*The storm surge value is the one observed at the entrance of the Gironde estuary (Le Verdon harbour). The tidal coefficient is a measure of the tide amplitude: it ranges from 20 (extreme neap tide) to 120 (extreme spring tide).

* This surge value is the one observed in Bordeaux since it was generated mainly by winds blowing over the Gironde estuary, the surge at the entrance of the estuary being only 0.48 m
FLOOD FLOWS BEFORE MOTORWAY CONSTRUCTION

Isle River valley

The distribution of maximum water depths reached in the Isle valley during the 1994 flood is shown on fig. 5. The flow pattern at flood maximum and main water fluxes expressed in m$^3$.s$^{-1}$ are superimposed.

It can be seen that almost the entire valley cross-section is inundated by this flood with return period of 10 years. A large part of the total discharge flows in the flood plain and perturbs flow in the meandering river Isle, especially when the river axis is not aligned with the valley. This is even amplified in the case of higher floods.

Road embankments perpendicular to the valley are obstacles through which water can only pass by means of a bridge across the river and culverts in the valley. Along the axis of the valley, head loss is localised mainly in these places, whereas water accumulates upstream the roads, producing backwater effects. This is the case with the RD 670 road, which follows the right bank of the Dordogne (where the head loss is about 25 centimetres at high water) and the RD 18 road (where it is more than 50 centimetres during large floods). Downstream in the valley, a 2000 metres long, 7.5 metres deep rowing basin drains water from the western part of the valley to its eastern part. It should be noted that sensitive urban areas are mainly located along the eastern border of the Isle valley as shown on fig. 5.

For floods with return periods of 10 years and above, the tide progressing up the Isle valley is almost stopped at the level of the RD 18 road. For these large floods, flow never reverses in the Isle, even though the water level

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fluctuates with time downstream of the RD 18 road. In the case of smaller floods that are influenced by
downstream tidal effects, as in February 1996, the Isle valley is flooded at high tide up as far as the wetlands
located upstream of the RD 18, and slowly re-empties during the ebb (fig. 6).

**Dordogne meander**

The distribution of maximum water depths reached in the Dordogne meander during the 1944 flood is shown on
fig. 7. The flow pattern at flood maximum and main water fluxes expressed in m$^3$s$^{-1}$ are superimposed.

Fortunately, the Dordogne meander rarely floods thanks to the dikes running along the entire length of the river.
The overall hydraulic behaviour of the Dordogne valley during flood periods is governed mainly by the
pronounced Ω shape of the meander. Indeed, the distance along the river is about 8 kilometres, whereas it is only
2.1 kilometres for water flowing through the plain. Therefore, at high water during major floods, the average free
surface slope in the plain is twice the value reached along the river. This explains why discharge flowing through
the valley is a relatively high percentage (about 35%) of the total flow. In this respect, it is worth noting that the
height of the Dordogne left-bank dike is almost constant: in these conditions, as soon as water flows over the
upstream dike section, the plain fills up, like a large basin. The downstream dike prevents the formation of a steep
free surface gradient and strong velocities in the plain, which would be the case if the downstream dike section
were lower, especially at low tide. Apart from the upstream and downstream dikes two major obstacles produce
significant head losses in the plain: these are the openings of the 100 Arches bridge, which concentrate flows in
the valley, and the submersible embankment of the RN 2089 road. The free surface difference produced by each of
these obstacles does not, however, exceed 10 centimetres.

After the flood, water flows from the plain over the dikes to the river and then slowly leaves the meander through
the drainage network.

Tidal influence never disappears in the river Dordogne, although high floods have a strong damping effect.
Figure 6. Inundated areas at high and low tide in the Isle valley during the Feb. 1996 tidal flood

Figure 7. Maximum water depth and velocity pattern in the Dordogne valley for the 1944 flood
EXPLORATION OF THE MATHEMATICAL MODEL

Progressive improvement of flood relief culverts

In the first part of the exploitation phase, the hydraulic impact of the motorway embankment was progressively reduced by improving the position and size of each flood relief culvert. In order to do so, the distribution of maximum rise in water level in the valleys was taken as a means of comparison. In order to speed up convergence towards a solution, this optimisation work was carried out by simulating the design flood peak over a few tide cycles only. Regular checks were performed using other types of floods and over longer simulation periods.

As observed previously, the bed roughness in the surroundings of a culvert plays an important role in its ability to dispose of the flow. Therefore, in some strategic places where flows concentrate, the efficiency was further improved by simulating bed levelling and a roughness coefficient corresponding to low vegetation (K = 22 to 25). In a situation where flow is mostly parallel to the motorway and a culvert allows it to pass from one side of the embankment to the other side, bed levelling and low vegetation conditions increase the culvert’s conveyance capacity. They also accentuate the curvature of streamlines upstream of the culvert, which are more perpendicular to the motorway in the culvert section. The overall hydraulic efficiency of the culvert is therefore improved.

Figure 8. Illustration of the improvement in culvert efficiency by bed levelling and low vegetation conditions

This effect is clearly shown on fig. 8: on the left side of the figure, the velocity field is obtained for a wide culvert opening (675 metres) and surroundings that are uneven and covered with bushes (K = 15), as in the initial state.
The velocity field shown on the picture in the middle of the figure is obtained for a smaller culvert opening (300 metres), but the area included inside the dotted line has been levelled and covered with low vegetation in the model \((K = 25)\). The right side of the figure shows that the difference in water level between both sides of the culvert is approximately the same in the two cases.

As a practical consequence, a cheaper and more cost-efficient solution will be obtained by levelling the ground and maintaining low vegetation in the culvert surroundings. It should be stressed, however, that such low friction conditions must be guaranteed permanently: this led the motorway's owner to buy the fields surrounding the culvert and to undertake to maintain these low friction conditions in the future.

**Optimum hydraulic solution for the A89 motorway**

The principles of the optimum solution that was finally adopted for the Isle valley and Dordogne meander respectively are briefly described below.

Fig. 9 shows the impact of the motorway on maximum water levels with the design flood: it can be seen that the objective (less than 5 centimetres everywhere and less than 2 centimetres in sensitive areas) is achieved. Furthermore, maximum water levels are generally decreased after motorway construction along the inhabited eastern edge of the Isle valley.

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**Figure 9. Impact of the motorway on rise in maximum water levels for the design flood**

Fig. 10 shows the impact on maximum velocities with the design flood: although flow is significantly redirected in the vicinity of the motorway (it is of course parallel to the embankment), velocity increases significantly only...
close to the river bridges and flood relief culverts. Along the left bank of the river Dordogne downstream of the motorway viaduct, this velocity increase means that it is necessary to protect the river bank.

Figure 10. Impact of the motorway on the increase in maximum velocities for design flood

Isle River valley

In the Isle valley, the motorway is mostly parallel to the valley and to the average flood flow. It became apparent that the creation of openings in the eastern part of the RD 18 embankment rapidly created a major rise in water level along the eastern inhabited edge of the valley downstream of the RD 18. Therefore, less flow was provided for in the eastern part of the valley located north of the RD 18. This is ensured by small culverts. The volume stored in this swampy area is, however, preserved.

In order to avoid backwater effects upstream of the RD 18 in the western part of the valley, two new culverts were added under this road (their impact is combined with those of the Isle river bridge and the existing 120 metres culvert).

Downstream of the RD 18, flows must be redirected from the west side to the east side of the motorway embankment. Two large culverts achieve this objective. They are located in relatively low points of the topography in order to provide direct supplies to the rowing basin in the eastern part of the Isle valley. Their efficiency is improved by bed levelling and maintenance of low vegetation conditions. The transfer of water flows
to the eastern part of the valley was, however, kept at a lower level than before construction of the motorway in order to obtain lower maximum water levels along the inhabited part of the valley.

As a consequence, flow in the western part is slightly higher than before construction of the motorway. To ensure efficient disposal of water to the river Dordogne, a new culvert was added below the RD670 road west of the motorway. The efficiency of this culvert during floods is enhanced by a shallow channel linking the last meander of the Isle with the culvert. This channel will normally be dry and covered with grass. In this way it was possible to maintain small rise in the maximum water level in the western part of the Isle valley.

**River Dordogne meander**

Both the physical scale and mathematical models were used to optimise the culverts in the Dordogne meander. The concentration of overflows by the 100 Arches railway bridge in the present state and the angle between the motorway and the railway meant that it was necessary to provide for a very wide (1430 m) bridge in the middle of the meander. Because of serious backwater effects produced upstream of the contraction formed by the 100 Arches bridge, two other culverts were added in the meander on either side of this central bridge in order to protect the sensitive areas located in the Dordogne meander. Again, the angle between the southern section of the 100 Arches bridge and the motorway embankment was considered to be levelled and covered with low vegetation in order to dispose of flows in the southern part of the meander and to feed the 100 Arches bridge properly.

Finally, the formation of breaches in the Dordogne dikes in the upstream part of the meander was simulated on the mathematical model. The results produced for a particular scenario are illustrated on Fig. 11. They showed that the impact of the motorway in the event of such dike destruction would be slight. An increase in maximum velocity on the northern abutment of the 100 Arches bridge meant that the protection of this abutment had to be improved.

**CONCLUSION**

2D numerical modelling of flood flows proved to be extremely efficient in this optimisation and hydraulic impact study. The major advantages offered by this approach, as compared to the traditional 1D modelling technique, are the great accuracy of the results produced and the realism guaranteed by enhanced graphical post-treatment of these results. 2D modelling also gives access to detailed knowledge of the flow field, particularly in the flood plains, which is not possible with 1D modelling. In fact, a 2D model lies on much less empirical coefficients than a 1D model of the same area, such as for modelling the exchanges between the main river course and the flood plain for instance. As a consequence, tuning of the 2D model is reduced in the calibration phase: it consists mainly in refining the knowledge we have of the domain geometry. This gives a higher degree of confidence to the 2D model. The accurate representation of alternately flooded and exposed areas in a river valley is also an important advantage of the 2D model.

Of course, refined DTM (Digital Terrain Mapping) is necessary to obtain this gain in accuracy and confidency, but finite elements are adapted to treat a high level of complexity in the topography.
This study and others carried out by the authors show that 2D flow modelling of inland waters is now an operational technique which can be used in an industrial context. In the case of the A89 motorway, the advantage of using this technique obviously lies in the savings it provided in the design of optimum flood relief culverts. It also provided a very detailed description of the hydraulic impact of the motorway project.

Figure 11. Scenario concerning the formation of a breach in the Dordogne dike. Water depths and velocity pattern.

ACKNOWLEDGEMENTS

The A89 hydraulic optimisation study was funded by Autoroutes du Sud de la France and managed by Scetauroute. Both are thanked for the ambitious optimisation program they launched and for using state-of-the-art modelling tools for this engineering application. The Project Steering Committee, which analysed the progress of the project throughout the 2-year period, is also thanked for the useful recommendations made to the project team.
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