Urban flood modelling using computational fluid dynamics

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The paper discusses the use of a code solving 2D shallow water equations in an urban area. Two application examples are described: a laboratory model representing low-density housing, and the city of Nîmes (France), which suffered a catastrophic flood in October 1988. From these examples, the paper shows that such 2D models can provide general flow dynamics. Moreover, they can integrate description of some details (such as obstacles and storage areas), which can contribute to an understanding of some flow features and thus provide accurate results locally. For engineering use, the limits are computational time and number of cells: the two examples described show that a grid adapted to urban topography features is a way to reduce these disadvantages while providing reliable results with a convenient numerical stability, even if the size of the cells varies considerably.

I. INTRODUCTION

The application of computational fluid dynamic methods to the propagation of a flood wave through an urban zone dates back to the pioneering work of Gallati and Braschi.1 A simplified form of the 2D depth-averaged equation and a rather coarse discretisation (grid size being of the order of hundreds of metres) were used to simulate the flood advance through the city centre of Florence (Italy).

Other methods have also been used (e.g. see references 2–4 for the more recent and complete ones). All these results have shown the promise that the emerging discipline of CFD holds in helping in the efforts to combat floods. A new computational tool was thus made available to urban planners to evaluate the impact of an urban development measure on future flood scenarios; crisis management personnel also stood to benefit from it, as they could devise their plans by taking into account a sample of likely flood events.

In the face of growing incidents of floods, and especially in inhabited areas, a need was felt to apply the latest flow computational methods to the problem of urban flooding in a more accurate form. Thanks to the progress in information technology, the computing power available has considerably increased. In order to use this computing ability to better effect, one way forward is to choose a more refined and complete description of the zone selected for modelling. Naturally, this leads to the choice of a 2D code, which carries many advantages.

First, building the model is much easier in 2D than in 1D for representing an essentially 2D situation. Typical examples are widening of a street (for instance, in a square) or a crossroads. In these situations, the use of a 1D model leads to the introduction of certain approximations not wholly consistent with the physical reality: horizontal water level and homogeneous velocity inside one cross-section as shown, for instance, in experiments on junctions or bifurcations of three rectangular channels.5–8 The results of some of these experiments9,10 have shown that, although the flow is essentially 3D near the crossings, 2D shallow water equations provide very accurate results for water levels and velocities. Similar results on a four-channel crossing have been obtained for subcritical flow in experiments recently performed in the Fluid Mechanics Laboratory of INSA (National Institute of Applied Sciences) in Lyon (France).11

The second principal advantage stems from the fact that a 2D model is equally efficient regardless of the structure of the urban zone: that is, whether it is a city centre characterised by a dense street network, or a suburban zone with low-density housing.

The third improvement that can be brought to the flood simulation computations by opting for a 2D code with a detailed topographical basis concerns the representation of the water storage and the obstacles. A 2D model can be effectively used to model large water storage areas, such as hospitals and lawns. Similarly, it is difficult to imagine a town centre without the presence of obstacles (vehicles) that hinder the flow and lead to slowing down. An accurate simulation of the effects...
created is much easier with a topography representing a lot of details such as that which can be taken into account by a 2D code.

Another feature that distinguishes the computations described in this paper is the use of the depth-averaged equations in their complete form. This is an important consideration because the simplified versions of these equations (diffusive or cinematic waves) cannot correctly represent the flow in the case of irregular topography and of a sudden change of the flow profile.12

Here, both subcritical and supercritical flows across complex topography are modelled, and in particular the change in the results due to the introduction of details is analysed. Two cases are considered. One corresponds to a laboratory model incorporating scattered obstacles. These obstacles represent villages in a floodplain submerged by a dam-break wave. The results of modelling with and without the obstacles are compared with the water depth measurements. The second case concerns the simulation of the 1988 flood in the southern French city of Nîmes. An area comprising 50 streets is chosen to create a very detailed computation grid. A sensitivity analysis is performed on two topics: introduction of storage areas and representation of parked cars.

2. EQUATIONS AND NUMERICAL SCHEME
Code Rubar 20, developed by Cemagref, was used. Its explicit second-order finite volume scheme solves the following set of equations, which is one of the simplest ways to write 2D depth-averaged equations:

\[ \frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = 0 \]

\[ \frac{\partial (hu)}{\partial t} + \frac{\partial (hu^2 + gh^2)}{\partial x} + \frac{\partial (huv)}{\partial y} = -gh \frac{\partial Z}{\partial x} - g \frac{u}{K} \left( \frac{u^2 + v^2}{2} \right) + K \left( \frac{\partial u}{\partial x} \frac{\partial h}{\partial x} + \frac{\partial v}{\partial y} \frac{\partial h}{\partial y} \right) \]

\[ \frac{\partial (hv)}{\partial t} + \frac{\partial (huv)}{\partial x} + \frac{\partial (hv^2 + gh^2)}{\partial y} = -gh \frac{\partial Z}{\partial y} - g \frac{v}{K} \left( \frac{u^2 + v^2}{2} \right) + K \left( \frac{\partial u}{\partial x} \frac{\partial v}{\partial x} + \frac{\partial v}{\partial y} \frac{\partial v}{\partial y} \right) \]

in which \( u \) and \( v \) are the velocities along the \( x \)-axis and \( y \)-axis respectively, \( h \) is the water depth, \( Z \) is the bottom level, \( g \) is the gravitational acceleration, \( K \) is the Manning–Strickler coefficient, and \( K \) the viscosity coefficient, which is estimated as a constant.

The mesh is constituted of quadrilaterals or triangles that have 0 or 1 (full) common edge. The mixing of these two kinds of cell provides various possibilities for adapting to any detail of topography.

The Godunov-type scheme includes four steps:13

(a) Compute the slope of each one of the three variables \( h \) (or \( z \), water level), \( hu \) and \( hv \) in every cell on the \( x \)- and \( y \)-axes by the method of least squares and applying limitations of slopes following reference 14 in order to obtain a TVD (total variation diminishing) scheme.

(b) Compute the values of \( W = (h, hu, hv) \) at intermediate time \( t_{n+1/2} \) in the middle of the edge of cell \( M_i \) to obtain a second-order scheme.

(c) Solve a 1D Riemann problem in the direction normal to the edge at \( t_{n+1/2} \) in order to estimate the fluxes through edges for the conservative part of the equations. It is possible to use a Roe-type linearization,15 which provides an estimate of the fluxes directly.

(d) Integrate the terms of the second member of the set of equations (1)–(3) on the surface of the cell in order to add the corresponding contribution, and obtain the final value of the 3D variable \( W_{i+1/2}^{n+1} \) by adding a second member estimated at an intermediate time.

Gravity or slope terms \((-gh(\partial Z/\partial x)\) or \(-gh(\partial Z/\partial y)\)) are treated as fluxes in such a way that a horizontal water surface remains strictly horizontal. Bottom friction terms are more simply assessed at the centre of the cell; their computation uses an implicilation in time in order to avoid numerical instabilities when a rapid change in water depth or velocity occurs. Diffusion terms are treated as fluxes: first the derivatives are computed at the middle of the edges; then, these derivatives are treated in the same way as the original variables.

Rubar 20 was used because it easily enables modelling of hydraulic jump and any change from subcritical to supercritical flow.16 Moreover, drying and wetting of large areas are conveniently modelled.17 Consequently, in the examples selected here below, the initial conditions were simply constituted from a completely dry model.

3. PHYSICAL MODEL OF THE TOCE RIVER VALLEY
ENEL (Italian Agency for Electricity and Dams) constructed a physical model at its Milan hydraulic laboratory in order to reproduce a 5 km reach of the Toce river in the northern Alp. The model took into account houses, a reservoir, a dam and two bridges. The model was then subjected to flooding and depths of water measured at 28 selected points in the model.

In the framework of the European CADAM (Concerted Action for Dam Break wave), these experiments were used to evaluate the performance of the computer simulation methods. The calculated water depths at these 28 stations were compared with the measured values in order to assess the amount of confidence that can be put on the predictive capacity of the simulation methods.17

3.1. Model details and information supplied
The scale of the model was 1:100, and the total dimensions of the experimental facility were 55 m by 13 m.

Two floods were modelled, corresponding respectively to the upstream discharge hydrographs A and B. Hydrograph B was greater in intensity, with a peak of 0.356 m$^3$/s, which overtopped the reservoir embankment (Fig. 1), whereas hydrograph A was of lesser intensity (peak of 0.21 m$^3$/s) and did not overtop the embankment. Discharges and water depths were provided at the upstream cross-section with a time step of 1 s during a period of 180 s, which included rise and fall of the
water levels. The results detailed here below concern hydrograph B only, but the behaviour of hydrograph A is quite similar.

The topographic data was supplied in two forms:

(a) a digital terrain model that divided the projected surface area of the model into a 5 cm² mesh and gave the altitude—that is, coordinate z—of each node. Finally the three coordinates (x, y and z) of 140 985 points were given.

(b) 67 cross-sections, containing 14 433 points.

In addition, topographical data concerning the dam and bridges were also supplied.

3.2. Representation of the houses in the model

The Toce model contained 173 houses, spread over the model area. These are concrete blocks of varying height designed to represent the real houses in the valley. Some blocks are grouped (interval between them smaller than their own dimension) whereas other ones are isolated and scattered.

When 'houses' are grouped, it was decided to merge the individual houses into a large house, of which the perimeter is the periphery of the group. Starting from 173 houses, 17 groups of houses were obtained.

The coordinates of the vertices of these house groups were then matched with the coordinates of the nodes of the grid, and as the space discretisation left a finite number of points, the node nearest to a vertex in the (x, y) plane was selected. This node then replaced the corresponding vertex. Thus two types of approximation arise in the houses representation:

(a) The merger into groups served to represent the collective influence of the houses on the flow, but the detail regarding the individual units was lost.

(b) We were unable to represent the exact points in the horizontal plane corresponding to the vertices of the house groups. Note that this constraint could be overcome by opting for a finer mesh, so that the size of a rectangle making up the mesh was of the order of the smallest house, but the computation time would be greatly increased.

3.3. Computation and results

The initial computation was performed with a maximum space step of 30 cm, a total of 8400 cells, zero diffusion, and a Manning’s value of 0.0162 m²/s (Strickler coefficient of 60 m¹/³/s) recommended by the ENEL. This last value—corresponding to the concrete from which the model was made—was kept constant through all the computations because tests from the CADAM project proved it was a convenient value. A second computation was conducted with a refined mesh defined by a maximum space step of 15 cm comprising 15 800 cells (Fig. 1). Each of the two computations considered two cases, namely with and without houses.

The inclusion of the houses led to an increase of water depth only at those measuring stations that were situated close to a large group of houses. In fact, only three groups of houses (G1, G2 and G3 in Fig. 1) exercised any influence on the results at the stations in their vicinity. One explanation is the strong supercritical flow in the model, which precluded any transmission of waves carrying information upstream from the obstacles. Fig. 2 shows that the representation of the houses by
their description as topography provides more ‘realistic’ results than a representation by increased friction (Manning’s value of 0.04 m$^{-1/3}$ s), although neither representation shows the same variations of water level as the experimental measurements.

At gauge P21, situated about 50 cm from a large group of houses (Fig. 1), various computations yielded intersecting results. The relative proximity of this measurement point allowed us to assess the effect of various changes in the mesh on the results. Fig. 3 shows that one clear tendency witnessed with both types of mesh after the introduction of the houses in the model was the rise in the water level, which is understandable as such a change leads to a reduction of the section available for the flow. The refined mesh computation with houses overestimates the water level, whereas the coarse mesh with houses agrees quite closely with the measurements. It seems that, whereas the introduction of the houses led to improved results, the refinement contributes to no further improvement except the capability to simulate the slight decrease of water level just after the initial quick rise. One reason might be that even the refined mesh is not sufficiently refined to describe every house individually, and consequently the flow between the houses is not taken into account: the higher water level with the refined mesh is then only a consequence of the narrowing of the valley because, in that precise place, refining the mesh had the consequence of increasing the area of houses slightly. Further tests were performed locally including cells of average size 5 cm by 5 cm, which makes possible the description of the topography of individual blocks; the conclusion was similar at gauge P21.

Nevertheless, generally, the introduction of the houses provided water levels closer to the experimental measurements. Similarly, the wave arrival time for certain stations increased after the introduction of the house data, resulting nearer from measurements. Although it is difficult to generalise, the tests show that the effect of an obstacle or a group of obstacles depends on its location in the flow, and thus even a detailed topographical description is not enough to model local variations of hydraulic variables.

Fig. 3. Toce model: water levels at gauge P21

4. THE 1988 FLOOD IN THE CITY OF NIMES

4.1. General features of the model

On 3 October 1988 an extreme flood occurred in the southern French city of Nîmes. It was caused by a generalised storm that poured down about 150 mm of rain in 3 h and 250 mm in 6 h. Modelling the event in part of the city was undertaken. First, a database of the zone concerned, comprising around 50 streets, was built from varied data (urban database and field surveys). The zone measured about 1 km along the north–south axis, which is also the principal flow direction. Structurally, the zone is varied, characterised by a rather steep upper part followed by a middle part where the width attains its minimum value, and a third southern zone of narrow, straight streets crossing at right angles.

The primary building block for the database was the street cross-sectional profiles (about 200). As no other topographical or geometrical information was available concerning the street intersections, they were interpolated from the street profiles. A simplified typical street profile contained seven points (coordinates $x$, $y$, $z$ for each point) and corresponded to two sidewalls (four points), the two gutters (two points), and the mid point of the road section. Each sidewalk was slightly inclined so that the coordinates of the top and bottom of a wall had different coordinates in the horizontal plan. This operation is necessary in the case of Rubar 20 to distinguish two points located on the same vertical that, otherwise, will be projected as the same point on the horizontal plane. This configuration divided the width of the street into four computation cells if walls were excluded (Fig. 4).

From the seven-point profiles, a mesh was created by linear interpolation along the streets. The mesh at the intersections (Fig. 4) followed from the selected street profile, and represented the intersection points of the two sets of curves emanating from the crossing streets. The minimum space step in the crossroads is 0.2 m, whereas the average space step along the streets is about 50 m. Such a mesh includes 9093 cells, but only about half of them are flooded.

Thus, by using this mesh, the representation of the city is simplified to a network of streets. By contrast, the Toce example shows the case of isolated obstacles. It can be hoped that, by joining the two methods, the complexity of the flow through the city could be modelled.

One of the difficulties of modelling part of the flooded area only is the definition of suitable boundary conditions. In the present case, upstream inputs were perfectly located because a railway embankment closes the two upstream valleys and thus...
narrow streets. The total length of this street is 517 m and it has a width of 5.5 m; the part in which the obstacle was simulated measured 95 m. The row of cars was simulated by raising the $z$ coordinate of the point between the mid point of the road and the bottom point of the adjacent wall by 1.25 m (see Fig. 6) in the streets, whereas no change was effected in the $z$ coordinate value at the intersections on the two extremities of the street part. The objective was to model a volume similar to that occupied by parked cars, without introducing a change in friction or diffusion coefficients, because such changes are difficult to define from field observations.

The computations performed showed that the presence of the obstacle caused a rise in the water level in the street section in question but had nearly no effect elsewhere, which is consistent with the hydraulics of the problem as the obstacle created is of quite small proportions. A curve of water depth against time at point P1 situated in the Bons Enfants street compared the cases before and after raising the $z$ coordinate: it shows an increase of peak of about 10 cm and a faster water rise (Fig. 7). Thus, because of the balancing of the water levels, even locally, the influence is limited.

4.3. Introduction of a water storage area

The flooding in an urban environment is a complex phenomenon owing to the availability of storage areas for the invading waters. Therefore any modelling of the flood propagation should be able to simulate this behaviour with a reasonable degree of ease and accuracy. This effect was modelled for the case of flooding in Nîmes.

The storage area is situated in the upper reaches of the modelled zone at the site of the hospital (Fig. 8). It is surrounded on the eastern, western and northern sides by streets that are bordered by walls: thus the water previously did not flood this part. As several doors exist to enter the hospital, three openings were created, one for each street, in order to allow water to enter this area. Whereas the previous situation with no opening at all was unrealistic, this hypothesis certainly increases the exchanges between the streets and the storage area by too much.

4.2. Representation of a row of cars

In order to simulate a row of cars, one part of the Bons Enfants street was selected. This street is aligned from west to east, and the part concerned is the centre of the southern area with
The slope of the area is adjusted to conform to the general slope—that is, inclining from north to south and from west to east. The area serves to store about 47,000 m³ (about 10% of the volume of the flood), with an average water depth of about 1 m. Fig. 9 shows the evolution of the depth of water at point P2 located in the southern part in which the water depth is higher: it reveals the difficulty for stored water to evacuate because no opening was modelled in the southern side of the storage area.

In order to examine the beneficial effects of the creation of the storage in the upstream part in terms of reduction in the flood peak, the peak water depths are compared at the same 82 points with and without storage. The results show a noticeable decrease, as summarised in Table 1.

The mean maximum water level is decreased by 0.32 m resulting in a level that is 0.29 m too low, which means that, if the input discharges are not underestimated, this storage is by far too important (which is the impression from the observations although they did not result in measurements as the water depths were low). However, it seems that the reduction of the flood downstream of this storage area improved the results in some places, particularly, as it resulted in a larger proportion of the water going to the western part of the southern flooded area. This point is well observed by the standard deviation of maximum water depths, which reduced from 0.93 m to 0.79 m. So, although the global result of the introduction of the storage area is a higher deviation, it proves that consideration of some local or complementary flow may improve the results, or at least improve our knowledge of the uncertainty about these results.

5. CONCLUSIONS
Two situations of floods in urbanised milieu have been analysed: one with low-density housing, the other one with dense housing. In both cases the velocities are very high (often higher than 2 m/s) owing to longitudinal slopes above 1%: consequently, flow becomes supercritical in some areas.

Using Rubar 20, which solves 2D shallow water equations by an explicit second-order finite volume scheme, provides water levels close to measurements. The tests pre-
sented in this paper proved the capability of 2D codes to simulate flow around or through various obstacles simply represented by their shape. One limit is the size of the cells, as too fine a discretisation may lead to such a high number of cells that it becomes practically impossible to compute (too long a computing time) and difficult to define all the details. One other limit is the interaction between obstacles close together that creates waves and, more generally, essentially 3D processes that cannot be directly represented by a 2D model.

In the Toce case, unless an appropriate or detailed enough way of representing houses is selected, a finer mesh will not necessarily provide average water levels closer to measurements anywhere, although the details of the hydrographs are generally modelled in a more accurate way.

In the Nième case, although the complexity of the processes and the uncertainty of the data hinder a precise comparison between observations and calculation results, it seems that the representation of specific features (such as cars and water storage areas) may be used to create local changes in water levels and thus to simulate such observed or possible discrepancies.

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