Three-dimensional CFD modelling of urban flood forces on buildings: a case study

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Abstract. Italy is among the countries most likely to be exposed to high hydrogeological risk. The recent 2018 Hydrogeological Disruption Report by ISPRA (Higher Institute for Environmental Protection and Research) states that about 90% of Italian municipalities fall within areas with hydrogeological risk, that is where the probability of floods/landslides is high (level P3) or very high (P4) or the hydraulic hazard is of medium level. Floods are the most severe and frequent phenomena affecting landscapes, mainly if they occur in urban contexts. Urban development, if nature-based solutions are not taken into account, determines an increase in the impermeable surface, with the effect of reducing the infiltration and water evaporation, and consequently with an increase in runoff peaks and decrease of the concentration times. In this framework, the work here presented numerically analyses the effect of floods in an urban basin, in term of their three-dimensional interaction with buildings. The site under study is Cervinara, a municipality in the Campania region, Italy, hit by severe floods in 1999. Flow peaks were calculated using the VAPI procedure, a regional methodology based on two-component extreme value (TCEV) distribution. The results show that the level of exposure of the buildings, evaluated by calculating the thrust of the interacting water on the exterior walls, is influenced by the local three-dimensional kinematics.

1. Introduction

The presence of water in different forms is responsible for various processes on Earth, consisting of dynamic interactions between the water itself, in the form of rainfall, evapotranspiration and runouts, landforms and landscapes. The leading actor in the water cycle is the solar energy, spatially and temporally distributed in the atmosphere and Earth surface, producing continuous exchanges of thermal energy. Precipitation is one of the most important and frequent processes between the atmosphere and the inlands and oceans. With respect to the ground, its contribution can be basically divided into two components: one contributes to surface runoffs, the other evaporates or infiltrates, contributing to the deep runoff, the quality of which should be preserved [1]. The distribution of these components depends on the climatic area, soil features, vegetation and anthropic activities [2-3]. Mediterranean regions are characterized by mild and humid winters and hot and dry summers [4]. The Mediterranean Sea has the particularity to be nearly closed, with the evaporation that exceeds the contribution of precipitation and rivers: the Atlantic Ocean supplies the Mediterranean with water through the Strait of Gibraltar. Humidity formation, together with the ongoing increasing temperature trends, promote extreme precipitations [5-7], defined as meteoric events characterized by high intensity and a short duration, capable of triggering paroxysmal events [8-13] with devastating effects on the territory, both in economic terms of damage to infrastructures and buildings, and in terms of loss of human life. Among severe induced phenomena are floods, large masses of water quickly covering commonly dry areas. They may be catastrophic [14-17], caused by rivers embankment failures, lakes dam breaks, etc. [18-20]. Damages may be even more catastrophic if floods take place in urban environments. With generally increasing impermeable surfaces, urban development alters the
basin hydrological response, reducing infiltration and evaporation [21-26]. Alteration is enhanced due to the fact that urban regions have a higher temperature than rural regions, with buildings facades and other anthropic infrastructure absorbing most of the incident radiation (yielding the so-called urban heat island effect), storing it and then releasing it in the form of thermal radiation overnight [27,28]. Consequently, the outflow and peak volume increases and the concentration time decreases [21, 29].

Nature-based solutions, defined by the European Commission as “solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience” [30], consist of solution strategies briefly defined as blu-green infrastructure (BGI), declined for cities specifically as Sustainable Urban drainage Systems (SUDS) for pluvial/river flood risk management [31-36]. Green roofs [37-39], rain gardens [40,41] and permeable pavement [42,43] are among possible solutions to mitigate urban flooding. Current technologies advances, such as light detection and ranging (LiDAR) systems and Unmanned Aerial Vehicles (UAVs) help tackling with flooding phenomena [44] as well as for other geomorphological processes [45].

In this paper, urban flooding is investigated in terms of its three-dimensional (3D) interaction with buildings. The city of Cervinara, Southern Italy, has been chosen as case of study, owning the tragic fast flow slide events occurred in 1999. The procedure, next described in the Material and methods section, is however generally applicable, knowing urban topography and input hydrographs. The literature on the application of porous Shallow Water Equations, two-dimensional (2D) Finite Volume/Difference methods is huge, see for instance [46-49], to name a few. Significant insights on 3D Fluid-Structure Interaction (FSI) analysis can be however noticed, as recently proved by [50-55].

2. Materials and methods

2.1. The urban area under study: Cervinara, Italy

Cervinara (Fig. 1) is located at 284 m. a.s.l., and it is among the largest municipalities in the province of Avellino, Campania Region, Italy, covering nearly 30 km². It borders the municipalities of Rotondi, Avella and San Martino Valle Caudina. It is part of the Parthenio Regional Park, a protected natural area. The territorial limits fall within the jurisdiction of the Liri-Garigliano and Volturno River Basin Authority. It is bordered to the north by the Caudina Valley and to the south by the Parthenio massif. The inhabited area is located in the inner flat part, surrounded by woods and crossed by several torrential water courses.

Figure 1. The area under study: Cervinara Municipality, Avellino Province, Italy.

The area is prone to fast flow slides induced by precipitation due to the presence of steep hill slopes and unsaturated soil conditions. In December 1999 severe flow masses from the near hillslopes caused
five victims and several damaged and destroyed buildings [56]. The territory of Cervinara falls within the hydrographic basin of the Volturno river, among the most extended watercourses in Southern Italy. Specifically, the surrounding hydrographic network falls within the catchment area of the Isclero river, a left tributary of the Volturno river. Five main streams cross the municipal area: the Castello stream, the Loffredo stream, the San Gennaro stream, the Remescuso stream, the Conca stream and the Pirozza stream [57, 58].

2.2. Generation of the model in the CAD environment
The first phase involved the generation of the urban model in the CAD (Computer Aided Design) Autodesk AutoCAD ® environment, through the definition in plain of NURBS (Non-Uniform Rational Basis-Splines), commonly used in computer graphics for representing simple to complex curves and surfaces, which can be modified using their control points. NURBS are mathematically defined by a polynomial of degree one less than the order of the curve, e.g. second-order curves are represented by linear polynomials. The urban plan extension was deduced by the CTR (Regional Technical Cartography, 1:5000 scale) sheets (Fig. 2.a) of Campania Region [59], while the ground elevation was obtained from Google Earth. Urban works like buildings, sheds, shelters were then obtained by vertically extruding the NURBS (Fig. 2.b).

The need to first pre-process the urban fabric in a CAD software derives from the fact that the used CFD program Flow-3D [60] needs the STL (Standard Triangulation Language) as input format, specifically for complex geometries, numerically representing the surfaces of 3D bodies as a mosaic of triangles.

![Figure 2](image_url)

**Figure 2.** a. CTR sheets covering the area under study. b. Geometric model generated in a CAD environment.

2.3. The VAPI procedure
The survey area (Fig.3) covers 13 (first 13 rows in Table 1) of the 17 basins that underlie the municipal area of Cervinara. The northern limit is represented by the railway line that delimits most of the inhabited center. The first 6 basins on the South consist of vegetated mountainous, the rest are nearly flat. For each of the mountain basins (1-6), the maximum average flow rate peaks Q were calculated using the VAPI procedure for a return period T=20 years.

The VAPI procedure [61, 62] is a hierarchical regional frequency analysis for the assessment of the flood peak for different return periods. It is based on the use of the TCEV (Two Component Extreme Value) probability distribution.
The procedure interprets the annual maximum events as a result of the combination of two distinct populations: the first concerns the ordinary maximum events, which are more frequent but less intense, the second, the extraordinary maximum events, which are less frequent but more intense. The probability of occurrence of extreme events is generally very low, but it becomes not negligible in a wider context (regional or national). Extreme phenomena are treated on a regional statistical basis to reduce the uncertainty of estimation in the measurement points and for the assessment of risk even in areas without measurement.
2.4. The CFD solver

Flow-3D® software [60, 63] numerically solves the Reynolds-Averaged Navier-Stokes equations (RANS), consisting of non-linear second order differential equations, ruling the motion of a free surface fluid. RANS are here coupled with the k-ε turbulence model [18, 20, 64], based on the transport equations for kinetic turbulent energy (k) and the dissipation rate (ε). The finite volume approximation is used for spatial discretization. The free surface is modelled with the VOF (Volume of fluid or Volume fraction) method [65]. VOF is a specific algorithm that treats the free surface as a cutting interface moving through a computational grid, and as a means of applying boundary conditions to the surface. Physical space is discretized into computational cells of parallelepiped shape. Sixteen cell meshes were used for spatial discretization (Fig. 4.a). Adaptive cell meshing was adopted to cover areas that need a higher resolution with a finer mesh, e.g. see Fig. 4.b.

![Figure 4](image1)

**Figure 4.** a. Spatial discretization of Cervinara municipality into 16 cell meshes. Cell mesh 6 was adopted for the inflow boundary condition. b. Different spatial resolution to accurately detect flow hydrodynamics.

3. Results

3.1. Data extrapolation

The VAPI procedure returns the highest flow rate peak $Q=30\text{m}^3/\text{s}$ for basin 6 (Castello basin). Mesh cell 6 (bottom right corner in Fig. 4.a), located at the downstream end of the watershed, was therefore used for the inflow boundary condition. Three simulations were considered, corresponding to the flow rates $Q$, $2Q$, $3Q$. To evaluate the flow impact produced by each simulation, three buildings (with upfront red vertical walls in Fig. 5.a) were considered in mesh 8, 9, 12, respectively. Buildings (Fig. 5.b) were chosen according to their spatial location, which was expected along the fluid path trajectory. The instant considered for the data extrapolation of the local interacting pressures $p$ and velocities components $v_x$ and $v_y$ (see global reference system in Fig. 4.a) corresponds to that in which the highest interacting pressure value was detected. Specifically, the following parameters were evaluated for each simulation: pressures $p$ in correspondence with each vertical cell that intercepts the building’s red surface and the consequent spatial weighted average pressure $\bar{p}$; the fraction of liquid that fills each vertical cell, to evaluate the whole wet area; the components $v_x$ and $v_y$ along the coordinate $x$ and $y$ directions of the velocity to reconstruct on each vertical cell the velocity...
component orthogonal to the impacted surface, and ultimately the average velocity $\bar{V}$. The above-mentioned hydrodynamic quantities allow the definition of static and dynamic thrusts components (RHS of Eq.1).

3.2. Thrust calculation
The literature on evaluating the total thrust $S$ on surfaces due to a water impact is huge, see e.g. Pugliese Carratelli et al. [63]. Basically, the impact force can be assumed either to be proportional to the mean pressure $\bar{p}$ or to the square of the mean velocity $\bar{V}$ of the impacting mass. Other models consider a combination of the previous approaches. Therefore, three macro-group models can be identified: hydrostatic, hydrodynamic and mixed models. In this study we referred to the mixed model, in which $S$ is given by the sum of the hydrostatic contribution $S_{\text{stat}}$ and the hydrodynamic contribution $S_{\text{dyn}}$:

$$S = S_{\text{stat}} + S_{\text{dyn}} = \bar{p}A_{\text{wet}} + \rho A_{\text{wet}} \bar{V}^2$$  \hspace{1cm} (1)

![Figure 5](image)

**Figure 5.** a. The buildings (numbered as “1”, “2” and “3”), chosen to assess the flood impact (red coloured). b. Mesh definition on the upfront wall surfaces for pressure and velocity data extraction.

where $\bar{p}$ is the average pressure acting on the wet area, $\rho$ is the density of the water fluid (1000 kg/m$^3$), $\bar{V}$ is the averaged orthogonal component of water velocity respect the impacted wet surface. The results are shown in the Table 2:

| Water discharge Q at mesh cell 6 | Building # | $A_{\text{wet}}$ [m$^2$] | $S_{\text{stat}}$ [kN] | $S_{\text{dyn}}$ [kN] | $S$ [kN] | $S / A_{\text{wet}}$ [kN] |
|---------------------------------|------------|--------------------------|---------------------|-----------------------|----------|---------------------------|
| Q = 30 m$^3$/s                  | 1          | 4.36                     | 16.22               | 1.59                  | 17.81    | 4.08                      |
| Q = 30 m$^3$/s                  | 2          | 8.35                     | 32.01               | 67.42                 | 99.43    | 11.91                     |
| Q = 30 m$^3$/s                  | 3          | 8.52                     | 70.04               | 2.79                  | 72.83    | 8.55                      |
| Q = 60 m$^3$/s                  | 1          | 35.02                    | 182.86              | 10.57                 | 193.43   | 5.52                      |
| Q = 60 m$^3$/s                  | 2          | 16.71                    | 87.95               | 81.17                 | 169.12   | 10.12                     |
| Q = 60 m$^3$/s                  | 3          | 12.06                    | 62.06               | 13.16                 | 75.22    | 6.24                      |
| Q = 90 m$^3$/s                  | 1          | 20.4                     | 203.42              | 8.04                  | 211.46   | 10.37                     |
| Q = 90 m$^3$/s                  | 2          | 23.28                    | 146.09              | 74.25                 | 220.344  | 9.46                      |
| Q = 90 m$^3$/s                  | 3          | 10.3                     | 49.51               | 1.95                  | 51.46    | 5.00                      |
3.3. Discussion
Total thrust $S$ is generally increasing with the water discharge $Q$ except for Building “3”. This is basically due to the fact that above $Q=60 \text{ m}^3/\text{s}$ the flooding mass tends to remain on its main course toward Building 3, hence lower flooding volumes deviate to its direction. This evidence is confirmed by the fact that most of the thrust at Building 3 is given by the hydrostatic component $S_{\text{stat}}$, that is $S_{\text{dyn}}/S_{\text{stat}} = 21\%$ and $S_{\text{dyn}}/S_{\text{stat}} = 4\%$, for $Q=60 \text{ m}^3/\text{s}$ and $Q=90 \text{ m}^3/\text{s}$, respectively. Besides climatic factors (temperature, rainfall regime) and drainage characteristics (sewer capacity, lamination tanks), the influence of urban topography has been already enlightened in literature, as to be among the most influencing drivers in flooding evolution and related consequences, see for instance [66, 67]. Likewise, interesting is the behaviour of the specific thrust $S/A_{\text{wet}}$: a monotonic trend is exhibited by Building 1, which is the one directly invested by the upcoming flooding. On the contrary, Buildings 2 and 3 exhibit the opposite behaviour. Building 3 exhibits the lowest values of $S/A_{\text{wet}}$, confirming that it is the less exposed among the buildings taken into account.

4. Conclusions
In this paper, a numerical modelling of flood forces on urban buildings is performed and discussed in a case study in Southern Italy. The Flow-3D VOF-based software was used for the solution of the Navier-Stokes ruling equations. The urban fabric was first created in a CAD environment as a collection of 2D splines representing building contours and other urban objects such as tree trunks, then converted as a 3D geometric model, lastly given to Flow-3D as stereolithography input file. Upstream flow rates peaks, for a twenty-year return period, were calculated with the VAPI procedure, based on the TCEV probabilistic distribution. Obtained maximum flow rate was then given as inflow boundary condition in Flow-3D. Flow-3D results obtained, consisting of velocity components and pressures at the mesh cells, were post-processed to get the mean hydrostatic pressure $\bar{p}$ and to the square of the mean velocity $\bar{V}$ of the approaching mass near three buildings exterior facades. The analysis let us drove the following conclusions:
- The nearest Buildings “1” and “2” to the inlet flow condition suffered the highest impacting forces.
- The longer was the free path toward the Building the higher was the dynamic thrust $S_{\text{dyn}}$ onto it, as it can be seen in Table 2, comparing $S_{\text{dyn}}$ for Buildings “1” and “2”.
- Conversely, Building “3” exhibit the lowest $S_{\text{dyn}}$ values, proving that upstream Buildings and other urban works act as barriers, making them at a higher hydraulic risk.
This study proves the strong dependence of urban flooding on topography. More reliable results can be obtained considering 3D pressure and velocity fields at the buildings front facades, from which average $\bar{p}$ and $\bar{V}$ values can be obtained for the application of Eq. 1. More in general 3D flooding simulations allow taking into account 3D water deviation effects and building obstruction.

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