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Effects of Anthropic Changes on the Propagation of the Gleno Dam Break Wave in the Valle Camonica Floodplain

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Abstract

The catastrophic flood following the Gleno dam break, which occurred in 1923, claimed the lives of at least 356 people. The event has been investigated in the literature considering the 20 km long steep alpine valley separating the dam location from the hamlet of Corna. In this contribution, we investigate the propagation of the flood wave from Corna, where the computed hydrograph from previous investigation provides the upstream boundary condition, as far as the Lake Iseo outlet in Sarnico. In the middle, the flood crossed 10 km of a wide pre-alpine floodplain that has been deeply modified over the last century and 23 km of a deep lake. The modeling of the last part of this event provides interesting insights on the effect of anthropic impact on the expected hydraulic hazard and is an interesting benchmark for the application of Shallow Water Equations in a deep lake.

Keywords: Dam break wave propagation; Case study; HEC-RAS; Shallow water; Numerical simulation.

1. INTRODUCTION

Due to the practical importance and the potential consequences of a dam break event, the study of the flood following real dam break events is always of great interest for land planning as well as the match between observed and numerically reproduced results can be key to the acceptance of the output of these models by laypersons when used for land planning and zonation. Accordingly, dam break events are often considered in the literature (e.g., Aureli et al., 2021). On the morning of December 1, 1923, the Gleno Dam located in Valle di Scalve (northern Italy) suddenly collapsed a few days after the first complete reservoir filling, releasing almost 4.5 million of m^3 of water. The consequent inundation caused havoc along the downstream valley and a death toll of at least 356 lives. This failure is historically important in Italy because it is the only case of dam break caused by structural reasons. The hydraulics of this event has been recently explored in a set of papers. A first work (Pilotti et al., 2011) focused on the reconstruction of the dynamics and timing of the failure of the dam, as well as the propagation of the dam break wave as far as the alluvial fan of Corna along a steep alpine valley. The wealth of data recovered for this case, provided a new complete data set for testing the effectiveness of De Saint Venant Equations in reproducing dam break waves in a setting where some of the fundamental hypotheses at the basis of the equations are challenged. In a following work Milanesi and Pilotti (2021) studied the propagation of the dam break wave on the highly populated alluvial fan around Corna, at the foothill of the alpine valley, to investigate a new approach to the study of fluid-building interactions, in a situation where collapsed buildings are dynamically removed from the computational domain.

Accordingly, in addition to its intrinsic interest, this historical test case gave the possibility to investigate methodological issues that have a more general scope for the community of hydraulics engineers. In this contribution we show that also the final part of the flood propagation has several reasons of interest for the community involved in the evaluation of risk and in the modeling of Shallow Water Equations. Actually, after devastating Corna, the flood wave, with a peak higher than 2 200 m^3/s (1.6 times the T_{500} discharge in the same location) and a volume of about 4 million m^3, swept a 10 km long stretch of floodplain in Valle Camonica before entering the deep prealpine Lake Iseo. Although strongly laminated due to its short duration and the flooding of the surrounding floodplain, the wave caused a swift increase of the lake level that was recorded by a limnograph at the lake outlet, in Sarnico, 23 km from the tributary entrance. Accordingly, considering that very few documents attest the extent of the flood in the Valle Camonica floodplain, the measured limnograph provides a way to cross-check the overall modeling of the propagation of the flood in the floodplain and in the lake.

This study completes the historical reconstruction of the propagation of the flood following the Gleno dam break. The reconstruction required a suitable pre-processing of the present LIDAR of the valley that underwent considerable modification in 100 years as a consequence of the growing anthropic pressure on the territory. The simulation was accomplished using the HEC-RAS 2D software, which was previously tested to verify its accuracy in reproducing dam break waves in mountain regions (e.g., Pilotti et al., 2020). HEC-RAS 2D was used also for the propagation of the wave through 23 km of the deep Lake Iseo, presenting an original, to our knowledge still undocumented, application of this software. Finally, considering that a similar event could happen in different historical times, possibly triggered by different reasons, it is of interest to see how the bathymetric changes between 1923 and present day changed the hydraulic hazard in Valle Camonica. The comparison highlights the effects of the hydraulic works and of roughness differences on the distribution of hazard, as a fundamental prerequisite for a future more comprehensive evaluation of changes in the hydraulic risk.

2. METHODS

2.1 Area affected by the flood in the floodplain of Valle Camonica

The sudden collapse of the Gleno dam generated a 21 000 m^3/s flood wave that in 45 minutes devastated 21 km of the steep Scalve valley (average slope of 0.06 m/m) down to the village of Corna di Darfo, located on an alluvial fan in correspondence of the junction of the Dezzo torrent with the Oglio river (see Figure 1a), causing about 400 victims, 100 in Corna di Darfo only. In this stretch the flood destroyed three villages, five hydroelectric plants and several isolated buildings. In spite of a strong peak reduction (the computed peak discharge at Corna was about 3 000 m^3/s), its peak was still four times greater than the corresponding millenary flood. After sweeping the alluvial fan of Corna, the flood entered the large and milder Valle Camonica valley (average slope along the river: 0.0025 m/m), with a peak discharge of 2 200 m^3/s that corresponds to a natural flood peak 1.6 times the T_{500} discharge at Corna di Darfo. Interestingly, the volume of the wave (about 4 million of m^3 in Corna) was much smaller than the volume of a natural T_{500} flood wave, which can be reckoned in the order of 30 million of m^3. The wave propagated for 10.4 km along Valle Camonica causing significant flooding of the surrounding riverbanks but with smaller damages with respect to the upstream reach. Eventually the flood entered Lake Iseo, with a peak discharge of 670 m^3/s that corresponds to a natural flood peak flow with a return period at the lake entrance between 2 years (386 m^3/s) and 20 years (810 m^3/s). The average depth of the lake is 130 m. Shortly after its entrance, a limnograph at the lake outlet registered a gradual increase of the lake level. This recording can now be used to calibrate the Shallow Water model that will be used in this contribution.

At the time of the event the floodplain of Valle Camonica was still weakly inhabited, in stark contrast with the present day situation. Accordingly, although the flood caused huge damages to agricultural activities, these were negligible with respect to the death toll and destruction caused upstream and they were only partly documented. The analysis of the historical information has provided very little quantitative results on the flood level in the floodplain: a water mark at the church of Bessimo is well documented (1.2 - 1.5 m above the ground, point A in Figure 1b). Moreover, journalistic account of the event document the flooding of about 3 km of the road between Pisogne and Ponte Barcotto (Line B in Figure 1b), the road between Corna and Bessimo was flooded and destroyed (Line C in Figure 1b) and the railroad between the Re di Gianico stream and Darfo was partially overtopped (Line D in Figure 1b). Similarly, from point E, where the railway station of Gianico is located, to the hamlet of Corna the cultivated areas were flooded on both sides of the river. The damage compensations deposited at the municipal hall of Costa Volpino document that the areas around points F and G were flooded.

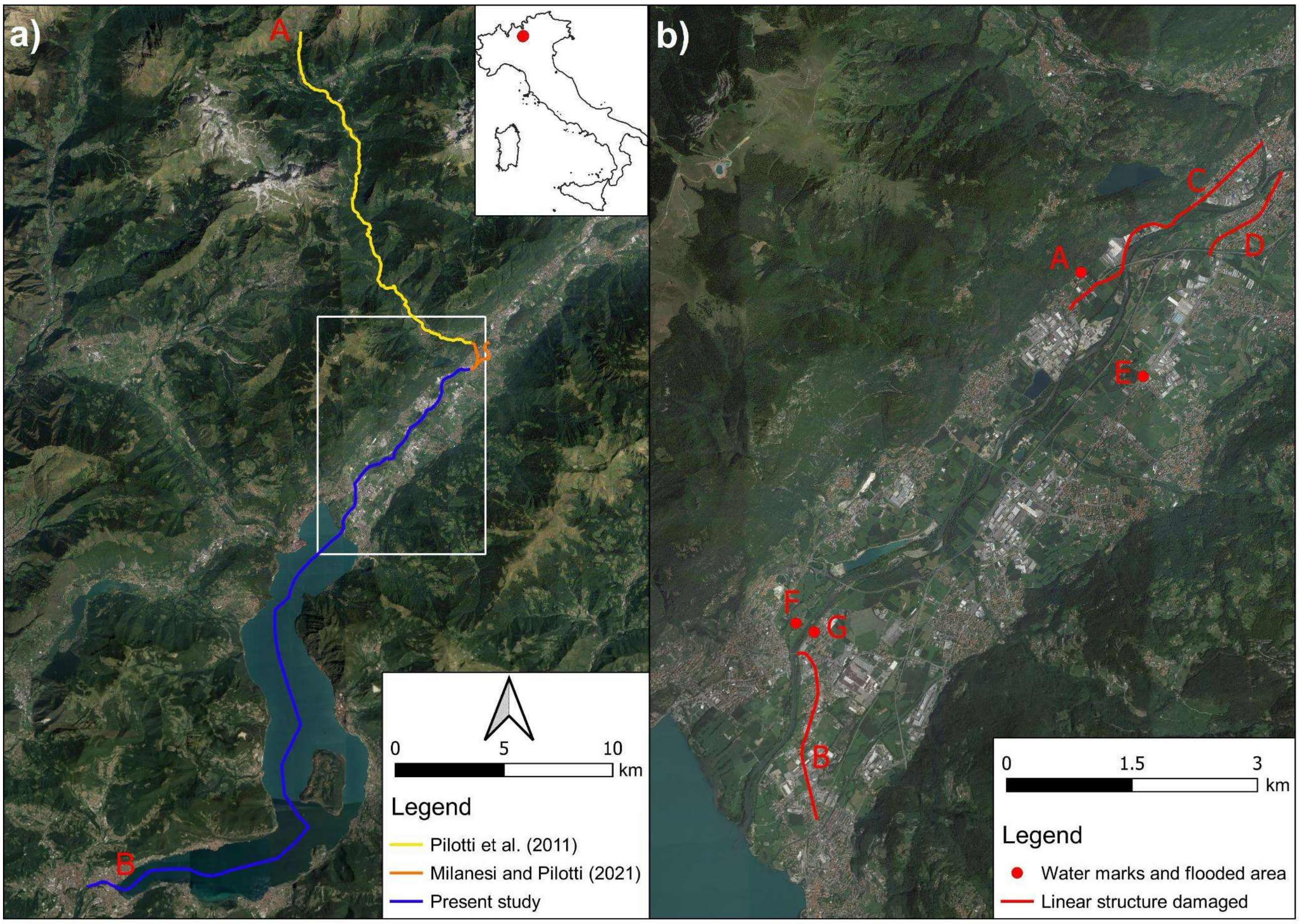

Figure 1. a) Satellite view of the study area highlighting the two reaches (respectively, yellow and orange lines) studied by Pilotti et al. (2011) and Milanesi and Pilotti (2021); the blue line shows the reach studied in this contribution. Points A and B show respectively, the location where the dam break occurred as well as the place where the limnograph was recorded. b) Satellite view of Valle Camonica, between the hamlet of Corna and the Iseo lake, highlighting the historical information derived from damage compensations and the description of the event from the newspapers.

2.2 The solver and the reconstruction of the 1923 bathymetry

The simulation of the flood propagation has been accomplished by using HEC-RAS 2D (Brunner, 2016) as a SWE solver with an unstructured computational mesh built using the so-called “high resolution subgrid model” (Casulli and Stelling, 2011). An adaptive time-step based on the Courant stability condition was adopted in order to advance in time the solution of the SWE in complete form using an implicit finite volume algorithm. The observation of the floodplain provided by a high-quality aerial synoptic photographic survey of 1944 compared to the present satellite view of the valley shows the transition from an agricultural based area to an industrial and heavy urbanized one. The analysis of the collected photogrammetric data has suggested the subdivision of the computational domain into different zones with an assigned roughness coefficient based on historical land use (see Table 1). Note that in some areas (e.g. main channel, banks) the roughness coefficient used has changed deeply over the years. Quite interestingly, most of the banks of the alpine river in 1944 (and presumably in 1923) were devoid of vegetation, as a consequence of an economy based on wood as burning material. This is in stark contrast with the present situation, where all the corridors surrounding the river bed are covered by bushes and trees. Considering the present bathymetry, thanks to the larger amount of data available on land use, a finer subdivision of the areas having different roughness coefficient was achieved.

The reconstruction of the river channel bathymetry is challenging in the absence of ancient cross-section surveys. The planimetric path of the Oglio river is mainly unchanged as shown by qualitative comparison between historical cadastral or geographic maps and present satellite view. Local differences in the channel morphology were found upstream the Barcotto Bridge (see point F in Figure 1b) and at the inlet of the lake. Only the last difference was considered in the reconstruction of the 1923 bathymetry.

Table 1. Manning coefficients adopted in the simulation

	1923 ($s/m^{1/3}$)	**2009** ($s/m^{1/3}$)
River channel	0.05	0.033
Bushes and trees	0.1	0.1
Roads	-	0.015
Agricultural areas	0.067	0.067
Urban areas	-	0.05

A computational mesh was built with an average grid size of 10 m aligned in correspondence of levees and other singularities using a modified bathymetric reconstruction of 1923 Valle Camonica (in the following DEM_B), obtained by modification of the LIDAR DTM (Italian Ministry for the Environment, Land and Sea) surveyed in 2008-2009 (denoted DEM_A) with a planimetric and vertical accuracy of +/- 0.30 m and +/- 0.15 m respectively. Accordingly, important structures, such as levees and road embankments (e.g., the current 510 highway), that locally changed the bathymetry in a way capable of limiting the flooded areas, were removed in order to fully replicate the historical topography. The chosen approach to accomplish the task was the "top down method" (van der Meulen et al., 2020) in which a high resolution modern digital elevation model (DEM_B) is considered as a starting point and, one by one, each recently built element is removed from the DEM and the void cells are interpolated based on the surrounding elevations.
In particular the accomplished task can be summarized in the following steps:

- A variable width buffer (see Table 2) of the anthropogenic change was built and possible inconsistencies in the buffer polygon (e.g., not complete overlapping between polygon and footprint in the DEM were manually corrected). The polygon buffers of each element were merged into a single vector of the structures considered, like levees, roads, quarries and building footprints;
- The cells in DEM_A intersected by the vector obtained from variable buffer in step 1 were removed from the original digital elevation model;
- The cell elevations on the boundary of the buffer area were extracted and interpolated in order to obtain a new surface to be swapped with the original points.

Table 2. Anthropogenic element, source and buffer width used in step 1

	Source	**Type**	**Buffer width (m)**
Building footprint	Geoportale Regione Lombardia	Polygon	10
Roads	Openstreetmap	Linear	Variable width (5 - 25)
Quarries and Levees	Manually defined	Polygon	-

3. RESULTS

3.1 The propagation of the wave along the river and in the floodplain

The upstream boundary condition for the flood propagation is provided by the numerical study of Milanesi and Pilotti (2021) and is the time-referenced flood hydrograph at the foothill of Corna. This hydrograph was superimposed to a reasonable baseflow (180 m^3/s) suggested by historical recordings in the days before the event. The downstream boundary conditions at the river entrance into the lake is provided by the lake level, set constant to 185.15 m.a.s.l. This level is the elevation currently used as a reference in the regulation of the lake. Difference in water elevation (+ 0.5 m) of the boundary condition provided almost similar results in terms of flow hydrograph at the inlet of the lake and flooding extension. Figure 2 shows the maximum extent of the flooding using the bathymetry provided by DEM_A (2009) and by DEM_B (1923). The computed map for the 1923 event matches the only documented water mark in the flooded area (computed depth of 1.14 m and documented depth of 1.2 - 1.5 m) and is in qualitative agreement with the flooded areas identified in Figure 1b, superimposed as black lines on the right map. As one can observe comparing the two maps, 100 years of river training have strongly reduced the extent of the flooding in the upper part of the domain, mostly due to the highway levee on the river left side and to an additional levee built on the first river bend on the right side. In the lower part of the domain, upstream of the lake, the reduction of the hazard is smaller. However, everywhere in the domain the 2009 flood extent is smaller than the 1923 one, whereas, as one could expect, the hydraulic risk has followed an opposite dramatic increase.

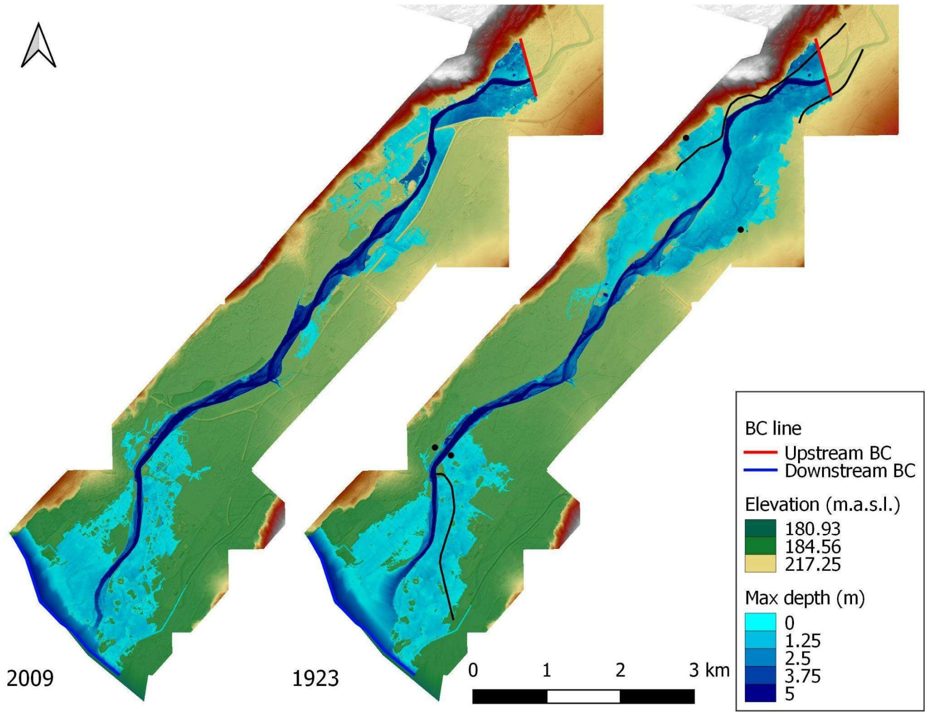

Figure 2. HEC-RAS inundation maps: DEM_A (left), DEM_B (right). The solid black lines reported on the right map show the location in which the presence of the water is documented as shown in Figure 1b.

Figure 3 shows the Computed flow hydrograph of the downstream end of the domain shown in Figure 2, where the Oglio river enters Lake Iseo. In the same figure also the hydrograph at the upstream end of the domain (Corna) is shown, underlining the strong peak reduction occurred during the propagation. The flood takes approximately 50 min to travel the 10.4 km of the floodplain, with an average velocity of 3.5 m/s. The strong peak reduction can be explained also due to the small volume of the flood wave.

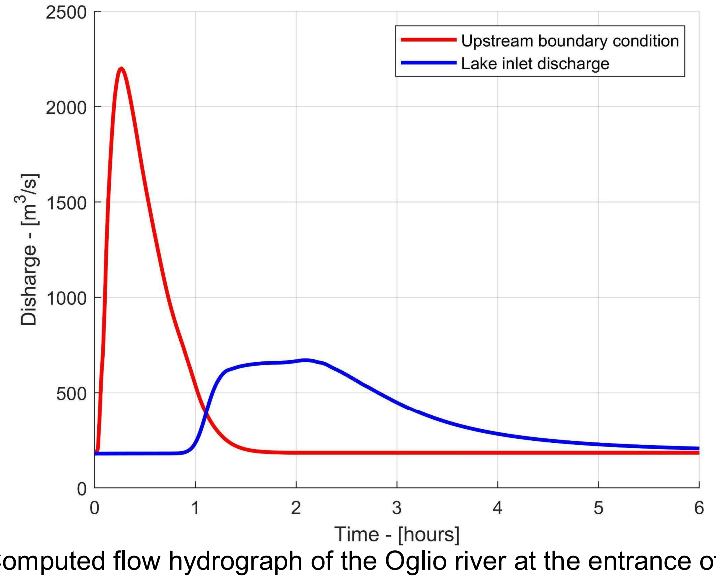

Figure 3. Computed flow hydrograph of the Oglio river at the entrance of Lake Iseo.

3.2 The propagation of the wave through the lake

Although the flow field in a lake is three-dimensional, it is also a situation where the horizontal length scale is much greater than the vertical length scale, so the use of vertically averaged Navier Stokes equations, i.e., the Shallow Water Equations, to study the propagation of a long wave is justified, provided that the wavelength of the wave is much larger than the depth of the lake. Considering that the maximum depth of Lake Iseo is 256 m, this condition is true for the hydrograph shown in Figure 3. Accordingly, we modeled the propagation of the flood wave of Figure 3 throughout the lake, cross-checking the result with the historical lake water level in Sarnico (see Figure 4) recorded on December 1, 1923. To this purpose, the downstream boundary condition was provided by the stage-discharge curve that in Sarnico governs the outflow discharge from the lake as a function of the level of the lake.

To this purpose we used a bathymetry of the lake which was obtained by a sonar survey of the lake bed in the form of raster DEM on a regular 5x5 m grid. An unstructured grid was built with average mesh size of 30 m aligned with the lake shoreline. A sensitivity on the Manning's coefficient, set to 0.011 s/m$^{1/3}$, proved that its role in the propagation is practically negligible in the range of physically meaningful values. Figure 4 shows the comparison between computed and measured lake water level in Sarnico as a function of time: the very good match between the two limnographs demonstrates the validity of the overall simulation chain. To our knowledge, this example is the first case of application of HEC-RAS 2D to the problem of flood propagation through a lake.

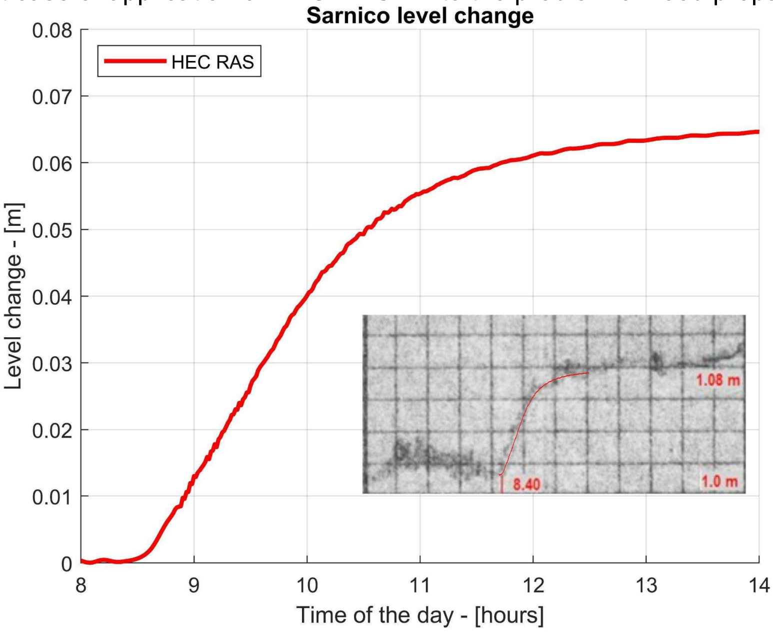

Figure 4 Comparison between the computed water level change at Sarnico and measured limnograph.

4. CONCLUSIONS

The study of the propagation of the flood following the Gleno dam break in Valle Camonica provides the opportunity of observing the effects of a flood with relatively small volume but high return period peak. It also provides the opportunity to study the effects of 100 years of anthropic changes on the flood extent: the comparison of the flood extent on the two bathymetries highlights the consequences of systematic hydraulic works on the hazard distribution for the same event. In spite of the significative reduction of the hazard, the present situation of Valle Camonica paradoxically suggests that the residual risk is now much higher than 100 years ago due to the increase in exposure on the flooded areas. Finally, it provides a successful and relatively rare example of application of a Shallow Water Equation solver, usually applied for flood propagation on a floodplain, to the problem of flood propagation through a lake.

5. ACKNOWLEDGEMENTS

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