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A new railway bridge on Gornalunga River: a flood modeling study.

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Abstract

In the present work, a 1D-2D-coupled model was used to perform hydraulic analysis of Gornalunga River (Sicily), in order to estimate and analyze the flood risk in correspondence of a crossing bridge. In the frame of the project “Speed up of the railway line Catania-Syracuse”, an existing bridge, crossing Gornalunga River, has to be enlarged and a configuration that mitigates the hydraulic risk on the surrounding area has to be found. At this aim, two different future configurations were considered and a flood modeling study in proximity of the railway crossing in existing and future configurations was conducted using MIKE FLOOD. Depths of flowing water through the bridge, as well as the maximum flood extent and maximum inundation depth have been evaluated for each scenario in order to identify the configuration that minimizes the hydraulic risk for the surrounding area. Finally, the effectiveness of this last solution is analyzed and discussed by comparison with the actual configuration. Simulation results demonstrate that in proximity of the railway bridge water level, as well the hazard risk of the surrounding area decrease passing from the actual configuration to the future one.

1 Introduction

Nowadays institutions dealing with the hydraulic territory government pay particular attention to river crossings, because their safety can be deeply compromised by flooding events and devastating impact can be generated on the surrounding areas. River flood analysis and risk prediction on existing and proposed bridges are compulsory and required by authorities in order to guarantee the safety of structures, environment and people. In the past few years, various researchers have used the hydrodynamic modelling approach to simulate flood inundation in the floodplains (Werner, 2004). In order to delineate the floodplain zones bordering the rivers and calculate the risk associated to floods of different return periods, various numerical models have been developed: these models are classified into one-dimensional (1D) models, two-dimensional (2D), and one-dimensional river flow models coupled with two-dimensional floodplain flow (1D-2D) models (Biscarini et al., 2010) (Manciola et al, 2009). Though simple to use, 1D models provide information on bulk flow characteristics but result

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inaccurate in hydraulic discontinuities, meandering reaches or large-scale scenarios where the flow is at least 2D and more detailed mathematical models are required (Di Francesco et al., 2016) (Alcrudo et al, 1993) (Brunner, 2015). Different models, based on shallow water equations, can be used to compute the 2D nature of floodplain, but since they require substantial computer time, attempts have been made to couple 1D river flow models with 2D floodplain flow models (Biscarini et al, 2016): Dhondia and Stelling (2002) describe the 1D-2D model SOBEK (Rural/Urban), the Danish Hydraulic Institute developed the MIKE FLOOD package that dynamically link 1D (MIKE 11) and 2D models (MIKE21) (Kadam, & Sen, 2012) (Kjelds & Rungo, 2002) (DHI, 2007).

In this paper, MIKE FLOOD is used to simulate the flood inundation for Gornalunga River in East Sicily (Italy) in proximity of a railway bridge. In the frame of the project “Speed up of the railway line Catania-Syracuse”, whose aim is to double the railway line, this existing bridge will experience enlargement as well as modifications in shape. Different geometric configurations were suggested, determining deep modifications with respect to the actual planar and altimetric configuration of the river network and consequently altering the entire hydraulic set-up of the system. In order to identify, among the proposed future configurations, which one minimizes the hazard risk for the surrounding area, a flood modelling study was carried out using MIKE FLOOD considering rainfall events of different magnitude. Hydraulic simulations for each proposed solution were performed and depths of flowing water through the bridge, as well as the maximum flood extent and inundation depth in the surrounding area have been evaluated. By analyzing and comparing simulation results obtained for each future solution with respect to the actual one, a configuration that after the enlargement guarantees not only maintenance but also decrease of the hydraulic risk of the area was found.

The aim of the work is to analyze and discuss the effectiveness of this last solution, referred to as “Post-Operam configuration (P.O.).” with respect to the existing one, referred to as “Ante-Operam configuration (A.O.).”

2 Study area

The study area covers the ending part of Gornalunga watershed: a river reach of about 12 km, ending at the confluence of Gornalunga River with Simeto River (Figure 1) is analysed.

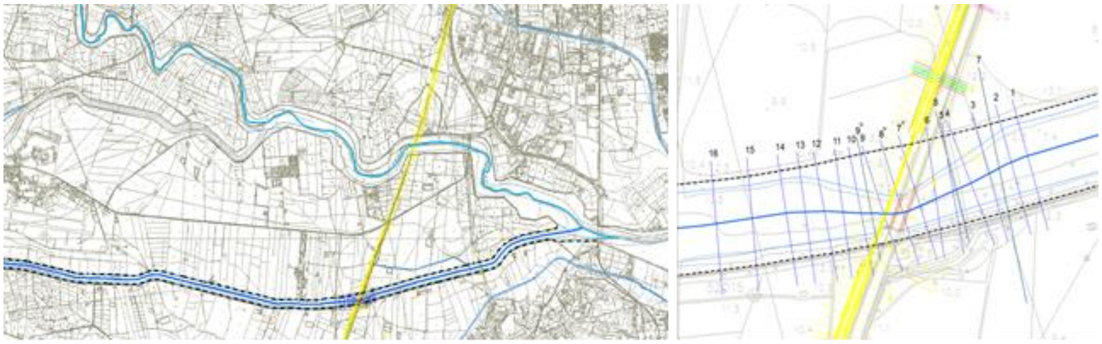


Figure 1: Gornalunga river network on the background topography (left side): the black dashed lines represent the levees, the yellow line stands for the crossing railway bridge that is expected to be doubled in the P.O. configuration. A zoom of the planar configuration nearby the railway bridge is provided on the right side, in which both measured and DEM-derived cross sections are represented and identified.

In the Hydrogeological Basin Extraction Plan (P.A.I) (Regione Sicilia, 2013), a 1D study is reported for this area, conducted considering rainfall events related to return periods T of 50, 100 and 300 years, corresponding respectively to P3, P2 and P1 hazardous areas. According to this study, the study area mostly falls into a P3 hazardous area. In the actual configuration, in correspondence of the railway bridge, an obstruction to the natural outflow of water on the left side of Gornalunga River occurs for a longitudinal length of 130 m: such configuration is expected to be eliminated by adapting to new structures and extending the river network's cross sections. Modifications on the railway infrastructure and expected reliability improvements imply deep river network's planar and altimetric variations whose impact on the surrounding area has to be carefully evaluated.

3 Materials and Methods

The 1D model setup in all the considered configurations was prepared to present the entire river system in the study-area. The river network has been retrieved from a 2m resolution DEM, using GIS Hydraulic tools: as very few measured river cross sections were available, DEM extracted cross-sections were used along with the measured ones. Details of the cross-sections extraction and refinement procedure used in the model are provided in Patro et al.(2009).

River cross sections, as build for the actual configuration, have been modified in the proposed configurations to take into account riverbed and levees' elevation modifications as well as river cross-sections enlargement and introduction of new structures (figure 2). Adaptation of the cross sections was identical for all the proposed solutions, differentiated by the arrangement of master levees.

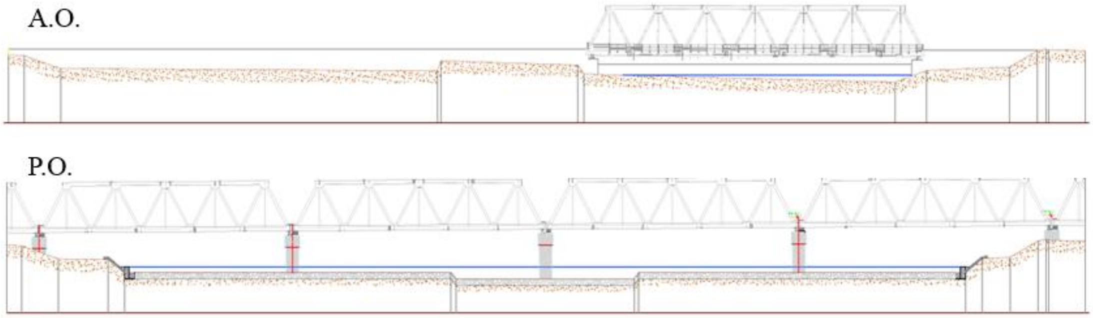


Figure 2: Bridge cross-section in the actual (A.O.) and in the future configuration (P.O.)

Boundary conditions of given runoff hydrograph and rating curve were assigned (Figure 3), respectively for the inlet section and the confluence section between Gornalunga and Simeto River. The MIKE URBAN Time-Area rainfall-runoff model was used to derive the runoff hydrograph based on a given excess rainfall hyetograph.

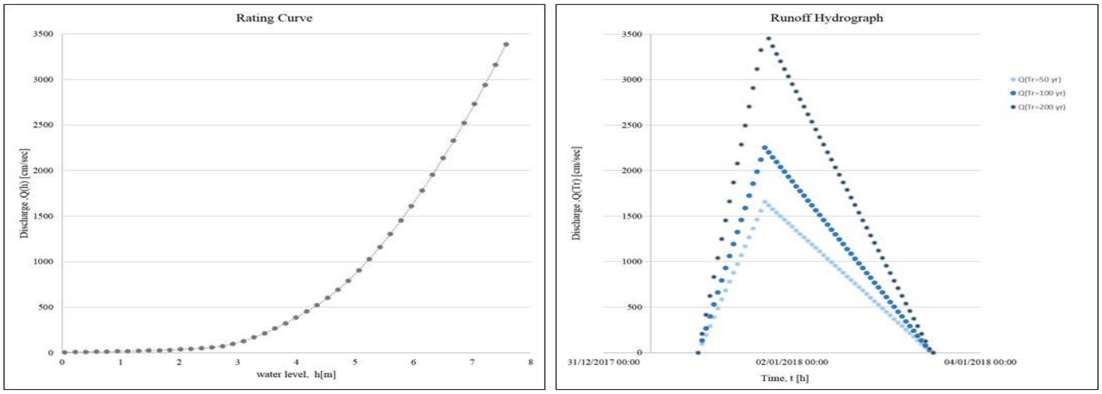


Figure 3: Rating Curve Q(h) [cm/sec] and Runoff Hydrograph Q(T, t) [cm/sec].

The 1D model was coupled with the bathymetry of the 2D model using the lateral link option available in the MIKE-FLOOD. The spatial resolution of the simulation domain has been defined after a grid sensitivity analysis, performed considering a structured squared mesh with a resolution ranging from 1 m to 10 m: a spatial step of 6 m was chosen, the study area is therefore discretized in 2.636 x 1.449 (3.819.564 elements). Land-use maps, reported in the Hydrogeological Basin Extraction Plan (PAI) were used to retrieve Manning's values for the floodplain.

For the 2D model, boundaries were initially considered to be closed (i.e. no flow) except at the outlet, where the Gornalunga River flows out of the model domain. A water level boundary condition was used at the downstream end where the reference water level was obtained from a 1D model for the flood events object of this study. The river-bank has been dynamically linked with the 2D grid using a cell-by-cell approach.

The simulation period for both 1D and 2D models was of 70 hours and model computational time step was brought to a value of 10 seconds in order to keep the Courant number (CR) less than or equal to 1 so as to achieve stable simulation run without any errors.

4 Results

Result simulations obtained inserting the doubled railway infrastructure into the existing configuration demonstrated that embankments' overtopping would occur even for a 50 years return period rainfall event. Overtopping would take place starting from river sections in correspondence of the crossing (sections 9^u and 7^u) and propagating for all the upstream river reach. For rainfall events with return period T = 50, 100 and 300 years, simulated water levels were respectively 0.27, 0.31 and 0.33 meters over the embankments at river sections 9^u and 7^u, but upstream sections experienced water levels up to 1.7 m higher than embankments' elevation. Moreover, for the heaviest rainfall event (T = 300) also the area downstream from the railway crossing experienced flooding, being water level from 0.56 up to 0.80 meters over the downstream embankments.

Two possible solutions for adapting river cross-sections and mitigating the hazard risk for the entire area were studied: at first simulations were conducted by setting for all the sections upstream from section 9^u levees elevation 2 m higher than in the actual configuration and raising the embankment elevation downstream from the crossing. Considering the potential increment in transient discharge due to the enlargement, downstream embankments were set 1 m higher than in the actual configuration.

Simulation results demonstrated that for all the considered rainfall events, water depth definitely stayed under the railway path and that this solution would assure no flooding for the upstream river reach.

Anyway, even for rainfall events with return period of 100 years flooding would occur downstream from the railway crossing, being water level more than 0.32 m higher with respect to the existing configuration. This would certainly determine a remarkable stress increment for the embankments that, a part from overtopping could fall into dangerous collapse.

In order to assure that no overtopping takes place for the entire downstream reach, and to guarantee the stability of embankments, more stressed due to the increment of transient discharge induced by section enlargement, a different solution was studied.

Since embankments' raising up at river sections downstream from the crossing were supposed to determine water level's increment, for the entire river reach the existing configuration was kept unchanged. By keeping upstream embankments 2 m higher than in the existing configuration and by inserting hydraulic transparency structures that allow water passage a solution that assures both stability of embankments and efficiency of the railway bridge was found.

Right and left levees' elevations in this configuration, referred to as P.O. configuration, are reported in Table 1 for river sections nearby the river crossing, respectively section 9^u and 7^u.

	A.O.		***P.O.***	
Section ID	Left Levee	Right Levee	Left Levee	Right Levee
9^u	13.30	12.82	15.30	14.82
7^u	12.58	15.09	12.58	15.09

Table 1: Left and right levee elevation [m] at river cross-sections 9^u and 7^u.

Simulated water levels in this configuration turned to be even lower than in the existing configuration for sections in correspondence of the crossing (Table 2).

	A.O.			***P.O.***		
Section ID	T=50	T=100	T=300	T=50	T=100	T=300
9^u	13.357	13.398	13.424	11.551	11.968	12.390
7^u	11.817	11.839	11.854	11.524	11.891	11.923

Table 2: Water level [m] in proximity of the railway bridge (river cross sections 9u and 7u).

In accordance with the existing configuration, water level in this last configuration definitely stays under the railway path. In contrast with results obtained in the actual configuration (A.O.), a part from case with T=300, no flooding takes place in any section upstream from the river crossing. This would clearly imply for this area a reduction of the hydraulic risk, passing from a P3 to a P1 hazardous area. Furthermore, also the area downstream from the railway crossing will experience a reduction in the hydraulic risk: in fact only for T=300 an increase of 0.19 over the levees was worked out at a section 800 m downstream from the railway crossing. This overtopping was supposed to be acceptable since it does not alter in any way the safety of the bridge. Water level established at the downstream reach are always lower than in the existing configuration: this will assure that embankment will not experience an extra effort that could threaten their stability.

Maps of maximum flooding depth as well as maximum surface elevation are very similar in the existing and future configurations, as depicted in Figures 4 and 5, showing that the proposed solution will not alter the hydraulic asset of the entire area. Statistics for maximum flooding depth are reported in Table 3, showing that the proposed configuration will maintain flooding depth at least unchanged with respect to the actual configuration.

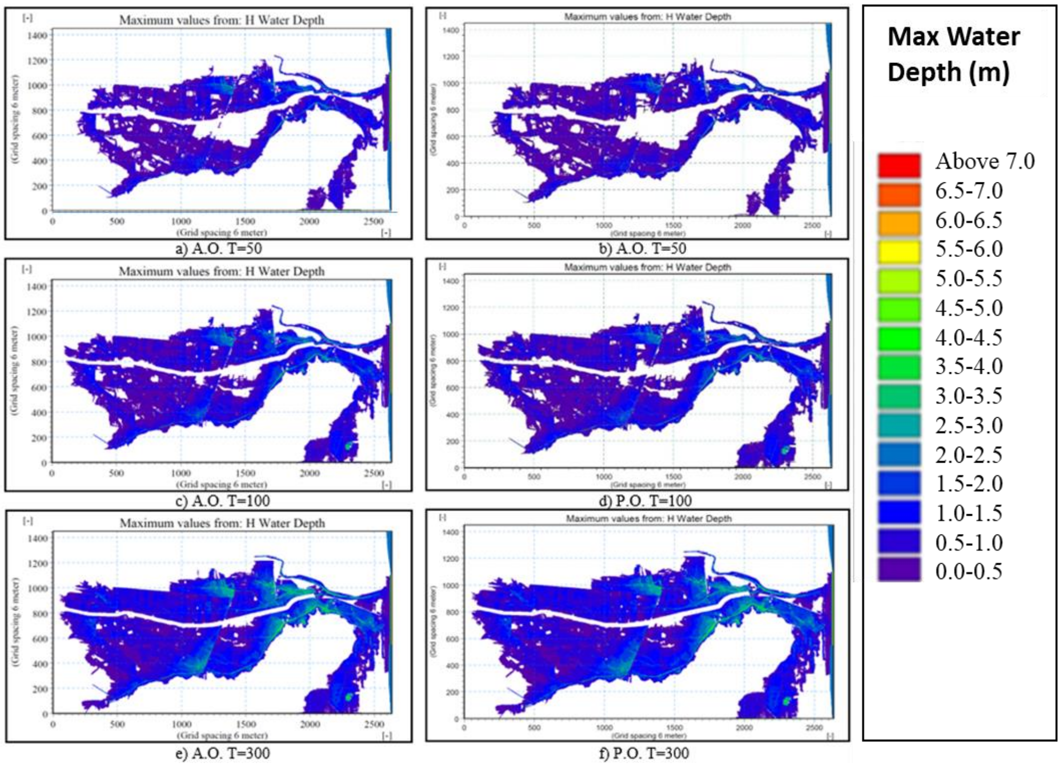
	A.O.			***P.O.***		
H [m]	T=50	T=100	T=300	T=50	T=100	T=300
Max.	7.396	7.403	7.412	7.376	7.402	7.397
Med.	0.614	0.762	1.012	0.599	0.746	0.995
St. Dev.	0.637	0.646	0.724	0.639	0.637	0.712

Table 3: Statistics of Water Depth in A.O. and P.O. configurations for different return periods.

For all the considered return periods, calculated flooding extent values demonstrate that in the P.O. configuration the area interested by flooding results to be smaller than in A.O. (Table 4).

	$A_{A.O.}$ [m^2]	$A_{P.O.}$ [m^2]	$A_{P.O.}$ / $A_{A.O.}$
T=50	105’225	103’631	98.5 %
T=100	122’910	109’992	89.5 %
T=300	131’093	116’786	89.1 %

Table 4: Flooding extent in A.O. and P.O. configurations for different return periods.

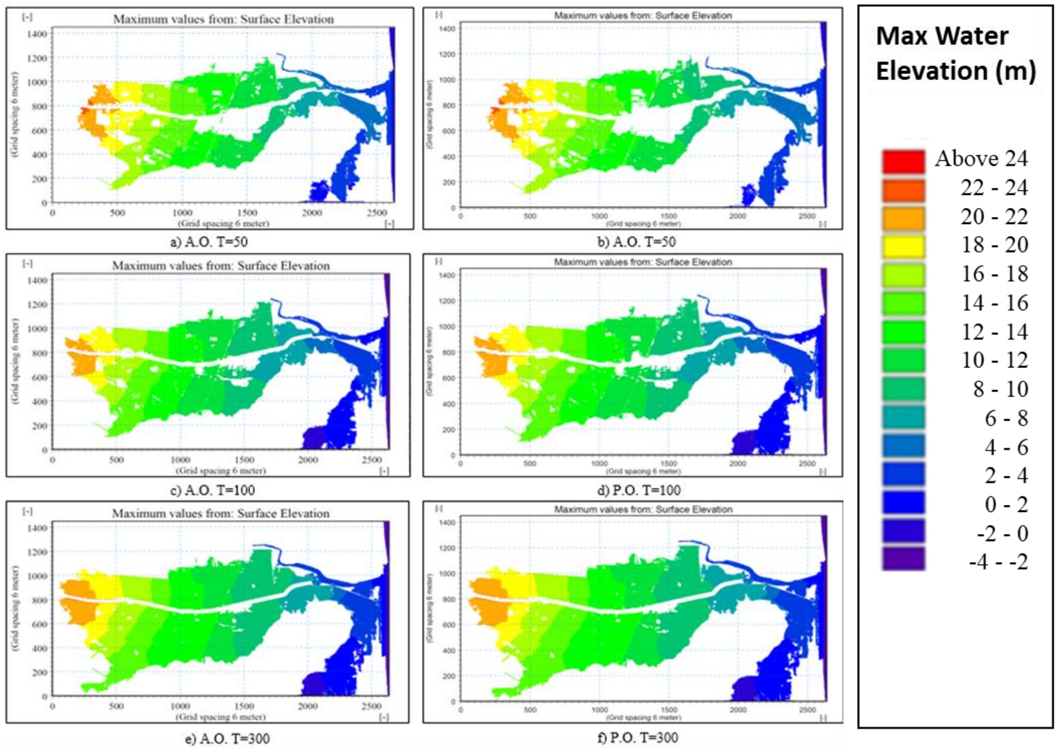


a) A.O. T=50 b) A.O. T=50

c) A.O. T=100 d) P.O. T=100

e) A.O. T=300 f) P.O. T=300

Figure 4: Maximum values of Water Depth [m] in A.O. and P.O. configuration for different T.



a) A.O. T=50 b) A.O. T=50

c) A.O. T=100 d) P.O. T=100

e) A.O. T=300 f) P.O. T=300

Figure 5: Maximum values of Surface Elevation [m] in A.O. and P.O. configurations for different Tr.

5 Conclusions

The present study aimed at evaluating the effects of the project “Speed up of the railway line Catania-Syracuse”, in terms of hydraulic hazard for the area currently affected by the flooding of the Gornalunga River. Two different future configurations for the doubled railway crossing were studied and a coupled 1D-2D hydrodynamic model was used for simulating the flood inundation extent and flooding depth as well the water level established nearby the river crossing. Simulations were at first conducted in the existing configuration and a solution that guarantees the maintenance of hazard risk for the entire area was attempted. Modifications on the network were suggested by simulation results obtained by inserting the doubled structure into the existing configuration. Considerations on stability of embankments and safety of the railway structure induced to choose a configuration in which only embankments situated upstream from the railway crossing will experience modifications. This would assure no overtopping for the entire upstream river reach. Hydraulic transparency structures were inserted in the P.O. configuration that allow water passage and attenuate the water level raising up at sections downstream from the crossing.

Water levels calculated in the Post-Operam scenario showed the maintenance of the flood levels within the banks, for all the considered rainfall events. This is in accordance with results obtained in the existing configuration.

Maps of maximum flooding depth as well as maximum surface elevation resulted very similar in the two different configurations, demonstrating that the future configuration will not alter the hazard risk of the interested area. Moreover, for all the considered return periods, in the future configuration flooding would no longer take place in the portion of area situated upstream the railway bridge, and consequently the hydraulic hazard will decrease. With respect to the portion of territory downstream of the bridge, it can be stated that no flooding of Gornalunga River will occur for rainfall events with return periods of 50 and 100 years, despite the mapping of P.A.I. shows that the territory is entirely affected by the P3 hydraulic hazard. This difference could be due to the presence of the Simeto River, whose flooding in not taken into account in the present work, as reported in past studies reported in P.A.I (Regione Sicilia, 2013). Finally, for all the considered return periods, calculated flooding extent values in correspondence of the railway crossing demonstrate that in the P.O. configuration the area interested by flooding results to be smaller than in A.O.

Acknowledgments

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