Checking a Culvert Suitability for Flood Wave Routing Within the Framework of the EU Flood Directive

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Abstract. Flooding is an international problem that represents the most common and destructive of all weather-related natural hazards. Moreover, man-made interventions such as deforestation, clearance of land and the poor design of hydraulic works such as bridges and culverts can often intensify that risk. This paper demonstrates a complete hydraulic study that was performed in a culvert located in Loforrema torrent (N. Greece) so as to examine its suitability for the flood wave routing of different discharges. The hydraulic model HEC-RAS was employed in order to compute the water surface level in the culvert location for flood events with probabilities of 10, 100 and 500 years. The results illustrated that, under all cases, the culvert overflowed putting in great danger the passing vehicles and citizens. Finally, the necessity of complete hydraulic studies is highlighted in order to support decisions in the dimensioning of a bridge in the same location, which it will be sufficient enough to deliver low probability flood events.

Keywords: Culvert, HEC-RAS, Flood Directive, Hydraulic Modeling, Loforrema torrent

1 Introduction

Floods have the potential to induce casualties, violent displacement of people, severe standstill of the economic development and undermining of all economic activities (E.U., 2007). These events are commonly associated with extreme precipitation events, which affect the outflow of the catchments and produce severe floods (Řezáčová et al., 2005, Máca and Torfs, 2009, Jarsjo et al., 2012), whilst it has also been observed the strong dependence between the flood regime and climatic changes (Notta and Price, 1999). Furthermore, sometimes the flood events are accompanied by strong debris flow activity (Stefanidis and Myronidis, 2006; Mitsopoulos and Myronidis, 2006), which maximizes the devastating phenomenon forces. Finally, water floods and water scarcity control ecosystem development and restoration measures (Mongil et. al., 2012).

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This situation has prompted EU to legislate a framework (the Flood Directive) for the reduction of risk to human health, the environment and economic activity associated with floods in the Community (E.U., 2007, Andersson et. al., 2012). The main points of this directive are the development of flood risk maps at a basin scale for flood events with different probabilities (10, 100 years and extreme events) (Myronidis et al., 2009). These maps will be further used to establish flood hazard management plans focused on prevention, protection and preparedness.

However, flood events are not only triggered by natural causes and the irregular hydrologic regime (Sofios et. al., 2008) but also by anthropogenic interventions such as the failures of hydraulic works e.g. dams (Dai et al., 2005) and the inappropriate design of bridges (Ural et al., 2008) and culverts (Stathis and Stefanidis, 2000). Additionally, Stathis and Stefanidis (2000) recorded the loss of human lives when people were trying to pass an overflowing culvert, while Stefanidis and Sapountzis (1999) highlighted the surrounding infrastructures irreversible damage from flood wave due to improper bridge design. A culvert may cause an increase in upstream water surface elevations due to its restrictive cross-section forcing the upstream flood levels to be several meters higher than they would be without the culvert and the embankment (Methods et al., 2003).

This paper summarizes an integrated hydraulic study that was carried out by employing the hydraulic model HEC-RAS (USACE 2010) in a culvert, which is located in the Loforrema stream, so as to check its suitability for flood wave routing of flood events with probabilities of 10, 100 and 500 years. HEC-RAS has been successfully utilized so as to analyze the influence of hydraulic structures on flood dynamics Hailemariam et. al., (2014), while the modeling results showed very good coincidence with the observed water surface levels (Ali et al., 2012). The simulations for theoretical flood waves are a valuable tool not only for avoiding the destruction of the hydraulic infrastructures but also for mitigating the associated flood risks.

2 Study Area

The Loforrema stream is located on the Pieria Mountain in Northern Greece and it intersects with the Serbion-Eginiou road before it outflows into the artificial Lake Polyfitou (Fig. 1). A culvert with 13 multiple identical circular barrels has been established there so to allow the runoff to move from upstream to downstream and to enable safe traffic. This 32.5 Km^2 torrent has repeatedly caused flood events in the past that disrupted road traffic and endangered human lives and it has already flooded twice during 2014. Basin's mean elevation is about 1,390m and it is situated in an inclined terrain with a mean slope of 43.1%, while the main stream length is 12.3km.

The bedrock of the catchment is mainly composed by granites (79%) and gneiss (10.3%). The Corine 2006 Level 3 classification revealed that the study area is well covered by a Coniferous forest (57%). The meteorological data (1977-2013) coming from the Lake Polyfitou dam station revealed that the mean annual precipitation was nearly 514 mm. Moreover, the data provided by a second Meteorological Station in

Velventos, which operated during 1978-1994, showed that the mean annual air temperature was 13.5 0C, while July was the warmest month of the year (24.6 0C).

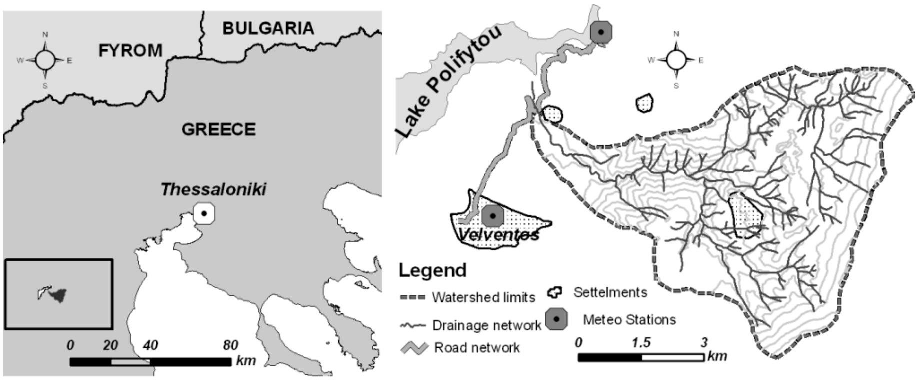


Fig. 1 Study area location map

3 Hydraulic Modeling Methods

HEC-RAS hydraulic software is designed to perform one-dimensional (1-D) steady and unsteady flow calculations to determine water-surface profiles for both natural and prismatic channels (USACE, 2010). The hydraulic modeling process within the HEC-RAS it can be divided in three major phases. Firstly, the input of the channel Geometric Data (river system schematic, the cross-section geometry, the placement of the cross sections, and the culvert/bridges information) were performed. Secondly, the available Flow data (type of flow, peak discharge and boundary conditions) have to be entered while in the last step, the model performs all the necessary computations and several graphical and tabular data are generated.

The River System Schematic is a diagram of how the stream network is connected together. Cross section data represent the geometric boundary of the stream and the cross sections are located at relatively short intervals along the stream to characterize the flow carrying capacity of the stream and its adjacent floodplain (USACE 2010). Once all the necessary cross-section data have been entered, the users can then add any bridges or culverts while HEC-RAS computes energy losses caused by structures in three parts:

a) losses that occur in the reach immediately downstream from the structure where flow expansion takes place

b) losses at the structure itself, which can be modelled with several different methods

c) losses that occur in the reach immediately upstream of the structure where the flow is contracting to get through the opening

The culvert hydraulics routine in HEC-RAS includes the ability to model every type of culvert and is based on the Federal Highway Administrations (FHWA) standard equations (FHWA, 2012). Finally, the cross-section interpolation can be automated extracted from the DEM (Digital Elevation Model) or it could be surveyed on the field.

Moreover, the type of flow (Steady or Unsteady) must be specified. The Steady flow represent a flow in which the velocity of the fluid at a particular fixed point does not change with time while if at any point the conditions change with time, then the flow is characterized as Unsteady. Once the type of flow is determined and peak flow value has been imported in the model, the Boundary Conditions must be provided. Boundary conditions are necessary to establish the starting water surface at the ends of the river system, while for a subcritical flow regime, boundary conditions are only necessary at the downstream ends of the river system. If a supercritical flow regime is going to be calculated, boundary conditions are only necessary at the upstream ends of the river system. Additionally, If a mixed flow regime calculation is going to be made, then boundary conditions must be entered at both ends of the river system (USACE, 2010).

Finally, once all Geometry and flow data have been entered the program performs all the necessary hydraulic calculations and computes various parameters such as: the water surface profiles for each cross-section, a plot of the water surface elevation versus flow rate for the profiles that were computed, velocity distribution output from the cross section, and others.+

4 Hydraulic Modeling Results

HEC-RAS enable hydraulic engineers to simulate and analyze open channel flow for a reach or a river (Methods et al., 2003). Initially, the reach was defined for a total length of 30m while the culvert was located approximately in the middle of this length (Fig. 2). This was achieved in the field by using a tape measure, a Meridian universal compass MG-3101, which is a foldable combination of Clinometer with Compass, and stadia. Two more cross sections are needed to model properly a culvert: on at the beginning of the contraction into the culvert and a second at the end of the expansion out of the culvert (Methods et al., 2003). These two cross-sections, upstream and downstream of the culvert, were similarly surveyed in the field and were not interpolated from the DEM because the detail relief variation could not be captured.

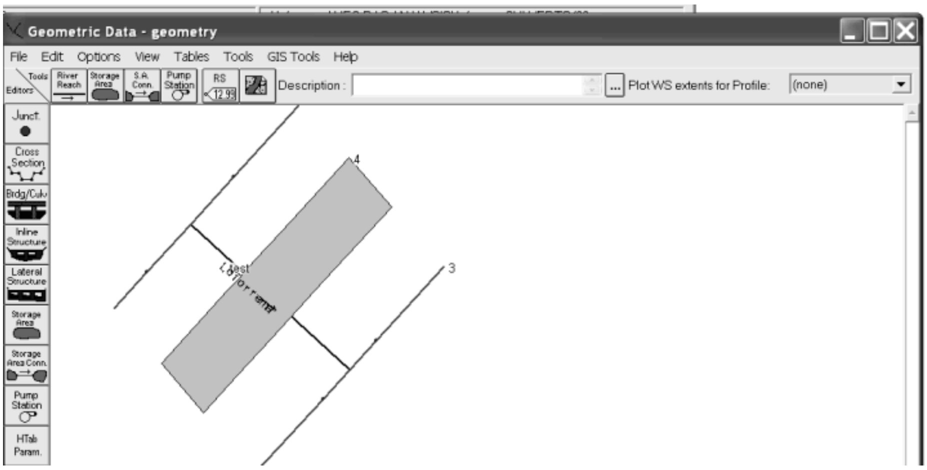
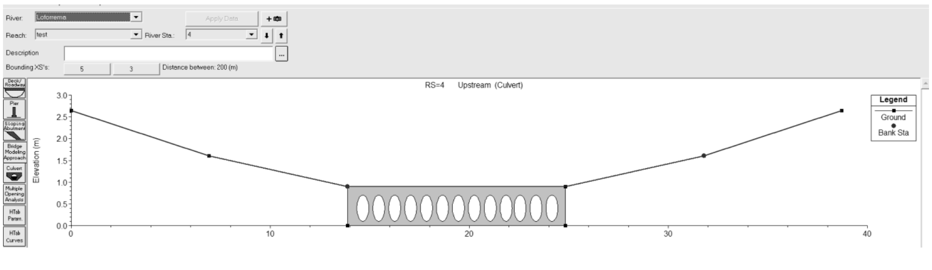


Fig. 2. Stream schematic and culvert location

Each cross-section and the structural details of the culvert where first designed in Autocad 2006 so as to acquire the relative x-y coordinates and then were entered in HEC-RAS. There, the distance from the first cross-section to the next downstream section was entered as 30m for the main channel the left and right over bank locations (Fig. 2). Furthermore, the Manning's n values were entered for the main channel and the overbank locations equal to 0.035 and 0.06 respectively (Linsley et. al., 1988).

The roadway surface elevation was defined from field data as +0.90m from the river bed while the width of the roadway (9m) and the distance to the upstream cross sections (15m) were also defined (Fig. 3). Furthermore, the length of the culvert (9m), its shape (Circular), the number of identical barrels (13), their position in the cross-section, the Manning’s n values for Top and Bottom along where also determined. Additionally, the contraction and expansion coefficients of the culvert were assigned values of 0.3 and 0.5 respectively (Methods et al., 2003). Finally, when flow over the roadway approaching the culvert a weir coefficient was calculated using the standard weir equation.



River: Loforrema

Reach: test River Sta.: 4

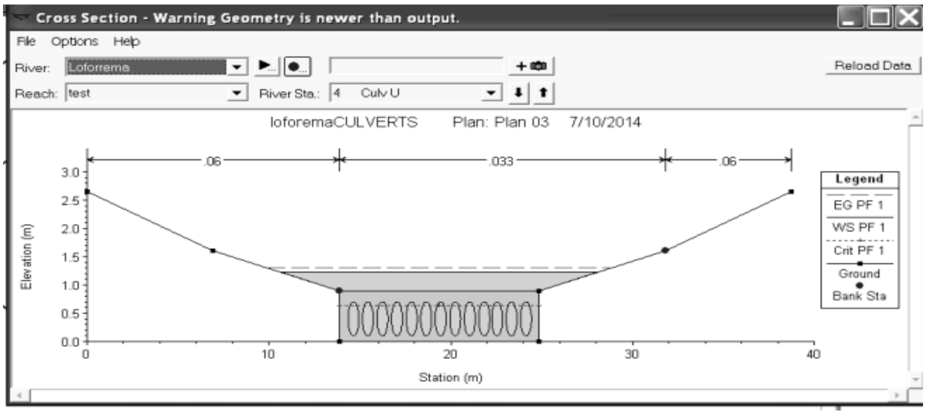
Description

Bounding XS's: 5 3 Distance between: 200 (m)

Fig. 3. Culvert data geometry on HEC-RAS

Since the reach is short and uncomplicated the type of flow were determined as steady uniform flow while this assumption suggests that the channel invert slope and the energy grade line slope are equal that rarely describes a real-world situation. However, the latter is sufficient to design and analyze many small-scale flood management systems, such as storm sewers and highway drainage (Methods et al., 2003). Next, from a recent study of peak discharge computations (Sgouropoulou and Myronidis, 2014) peak discharge data for Loforrema stream of 16.0, 23.1 and 29.9 m3/sec were inputted to HEC-RAS which corresponded for flood events with probabilities 10, 100 and 500 year respectively. Additionally, this flow analysis was performed using a subcritical flow regime which suggests that only the Downstream Hydraulic Conditions were entered. For this type of boundary condition the slope of the channel bottom (3.6%) were used in calculating normal depth (Manning's equation) at that location (USACE 2010).

Finally, a steady flow analysis with a subcritical flow regime were simulated for the aforementioned peak discharge values for high, medium and low probability flood events which corresponds to return periods of 10, 100 and 500 years. The main output from the HEC-RAS simulation results were the generation of water surface elevations for each scenarios which were found equal to +0.37m, +0.58m and +0.72m above the roadway surface elevation whereas figure 4 demonstrates for the culvert location the water surface profile for high probability flood event.



Cross Section - Warning Geometry is newer than output.

River: Loforrema

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Fig. 4. Water surface elevation for high probability flood event

Thus, under every scenario the culvert is overflowed by considerable height water and it is insufficient of routing even high probability flood events which repeatedly have been manifested in the area. Finally, a bridge with a roadway surface elevation +0.72 from the current road deck it would capable to neutralize any flood risk in the area.

5 Concluding Remarks

The proper dimensions of hydraulic structures can prevent the water from overflowing the structure and it will cancel the associate risks to the human life and property as well as the flood damage to the surrounding areas. This study investigated a culvert's suitability for the flood wave routing of discharges with different probabilities within the framework of the E.U. Flood Directive. Once all the necessary inputs, channel shape and slope, field survey cross-sections, culvert structural specifications and flow data, were inserted to HEC-RAS, the water surface elevations for all scenarios were interpolated.

The analysis of the hydraulic model outputs indicated the replacement of the existing culvert from a bridge, so it would be capable to receive the flood events of low probability (500year return period). Flow capacity with culverts is typically less than of a bridge and the losses are greater while the replacement of a culvert from a bridge is a more expensive solution (Methods et al., 2003). Finally, such types of studies are important to detect a decline in flood prevention ability before a potentially catastrophic flooding occurrence (Shih et al., 2014) and to properly dimension a culvert or a bridge with identical procedures.

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