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## Abstract

A conceptual framework considering, in a statistical sense, the residual risk related to possible levee failures in flood hazard mapping is presented. The residual risk is separated into a “design hydraulic residual risk”, RRD, associated to levee failures caused by overtopping for low probability events with return period higher than the design value, and into the “structural residual risk”, RRS, in case of failure of the protection because of mechanisms other than overtopping, as piping, erosion, structural instability for medium and high probability events. Statistics of levee failure type and breach size on the Po, Piave, Tagliamento and Adige rivers, in Northern Italy, are estimated, as a function of river morphology and, for the Adige river, of flood intensity. A stochastic framework for probabilistic flood mapping is then discussed, taking into account in a Monte Carlo approach the effect of position, size, density of levees failures on the statistics of depth and velocity of inundated areas. An example is shown of the resulting water velocity uncertainty map which contributes to the residual hazard for the 100-year return period flooding map for a 23 km-reach in the middle-lower portion of the Po River. Implications for flood hazard mapping as requested, for instance, by the European Flood Directive 2007/60/EC are briefly discussed.

## Keywords

Floods • Flood hazard mapping • Geotechnical uncertainty • Residual risk • Levees

## 92.1 Introduction: Hazard and Risk Definitions

Flood hazard and flood risk mapping is a valuable non-structural measure implemented in several countries worldwide to mitigate the potential effects of floods on people,

buildings, infrastructure and the environment (Apel et al. 2004). In the past two decades, although the terminology on natural risks differs slightly within the scientific stream of disaster risk reduction (UNISDR 2009) and that of climate change adaptation, a consensus was reached on the definition of hydrogeological risk, especially after the work of Varnes and IAEG (1984) about the landslide hazard. In the physical sciences community the risk is generally defined as the combination of probability of occurrence of an event and its negative consequences, more precisely as the expected degree of loss caused by an event. According to the EC Flood Directive, flood risk results as “the combination of the probability of a flood event and of the potential adverse consequences” and the specific risk for a specific flood event, RS, can be defined as:

$$RS = f(I, H, V, Y, E) \quad (92.1)$$

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where:

- RS specific risk
- I intensity of the event (e.g. the flood volume, or the maximum water level)
- H hazard, or the probability that a potentially damaging phenomenon of a fixed intensity (I) will occur in a defined period of time and in a given area
- V vulnerability meaning the degree of loss to a given element or subject, as a consequence of a fixed event (I) and in function of the type (Y) of elements subject to risk. It is expressed on a scale from 0 (no damage) to 1 (total loss). It includes physical factors as susceptibility of a target to an external load and social and behavioral factors, as adaptive and coping capacity of a person or of a society (Giupponi et al. 2013)
- Y type of element potentially subject to disaster effects. Elements can be people, buildings, agricultural areas, vehicles, economic activities including public services and infrastructures or the cultural heritage
- E exposure, i.e. the quantity and, for tangible costs, the respective value of the elements (Y) subject to risk. It is, for instance, the value of a house exposed to flooding, or the number of people living in a flooded area

The general definition of risk as in (92.1) often finds its operational implementation as the product of a probability of occurrence of that event and the “value” of the damage, in absolute or relative terms, as the product of hazard, vulnerability and exposure. The specific risk function is complex, as factors are not independent (with the exception of I and Y), but in this simplified way it can be expressed, as:

$$RS = H(I) \times V(I, Y) \times E(Y) \quad (92.2)$$

In this paper, after showing statistics, partially unpublished so far, of levee’s failures in four Italian rivers, we share with the engineering geology community a methodology, recently presented in Mazzoleni et al. (2013), where the influence of residual structural hazard due levees’ failure because of piping or erosion on the flooding hazard mapping is assessed.

## 92.2 “Design” and “Structural” Residual Hazard and Risk

In floodplain areas protected by river embankments against floods with a design return period,  $T_d$ , in the standard practice flooding is generally assumed to occur because of levees crest overtopping. In principle the risk associated to the  $T_d$ -years event and to the more frequent events is zero and the residual risk is given as the sum of expected losses

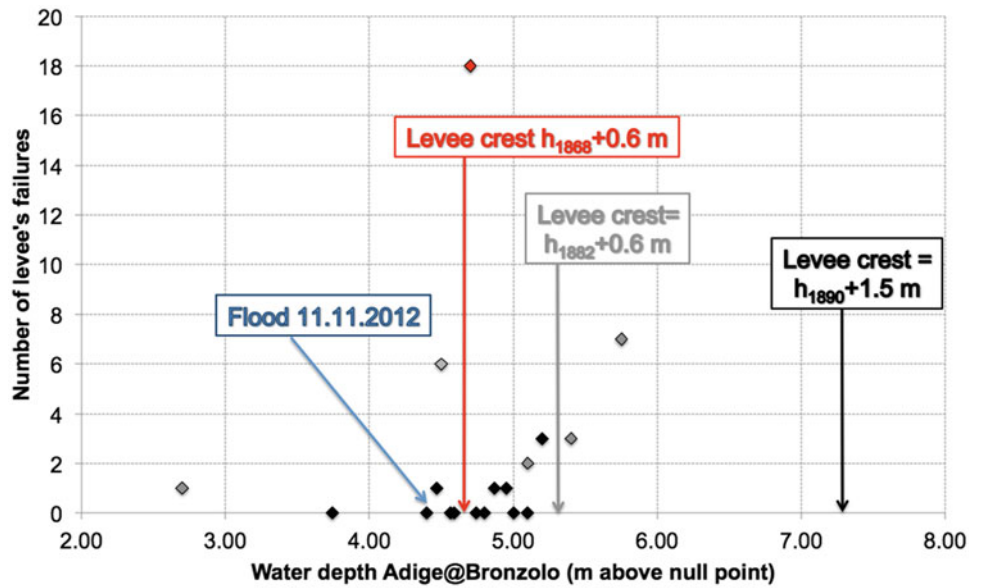
resulting from events with return period higher than the design return period  $T_d$ . But the assumption that river embankments protect against all events with return period smaller than the design one is not conservative and can induce a wrong perception of safety in land protected by levees. In fact, levees failures can occur not only as a consequence of levees’ overtopping but also because of collapse induced by several other mechanisms, as piping or erosion, triggered when the water level in the river is less than the  $T_d$ -years design level. Structural protections leave a residual risk RR, defined as “the risk that remains in unmanaged form, even when effective disaster risk reduction measures are in place, and for which emergency response and recovery capacities must be maintained” (UNISDR 2009). The residual risk is not only the risk associated to levee failures caused by overtopping for low probability events with return period higher than  $T_d$  (we will call this “design hydraulic residual risk”, DRR and the respective hazard is DRH), but also in case of failure of the protection because of mechanisms other than overtopping, as piping, erosion, structural instability. We will call this “structural residual risk”, SRR, and the respective “structural residual hazard”, SRH, depends on several factors and sources of uncertainties (Apel et al. 2004), as:

- the hydrological uncertainties related to the flood magnitude;
- the climatological ones related to the non-stationarity of climate and landuse;
- the geotechnical uncertainties due to breach location and levees fragility (Vorogushyn et al. 2010);
- the hydraulic uncertainties related to the cross section, roughness, presence of topographic obstacles influencing the flood propagation in floodplain areas (Di Baldassarre et al. 2009).

## 92.3 Results Discussion and Conclusion

In this study we focus on the geotechnical uncertainties and to their impact on flood hazard mapping as a consequence of levees failures because of piping or erosion. Statistics of levees failure on four major Italian rivers in Northern Italy over the last two centuries, reported in Ranzi et al. (2013) and partially derived after data collected and processed by Turitto et al. (2010), show that, on average, levees breaches occur in the four rivers with a frequency of 0.8 levees’ failure century<sup>-1</sup> km<sup>-1</sup>, in a range between 0.5 and 1.1 for levees designed with a return period of about 100 years. Figure 92.1, obtained by processing data by Werth (2003) for the Adige river, one of the four investigated, shows a weak dependence on the water level by the frequency of levees breaches in the river between Merano and S.Michele

**Fig. 92.1** Statistics of levees' failures on the Adige river between Merano and S. Michele a/Adige as a function of the maximum water depth at Bronzolo gauge



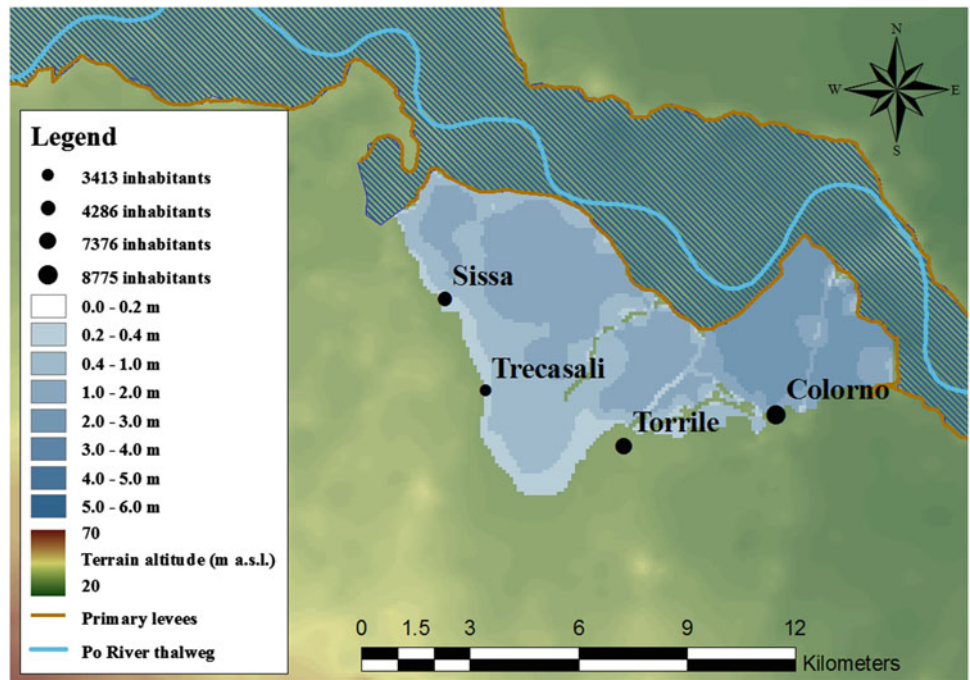
a/Adige, thus showing how a mixed deterministic and probabilistic approach needs to be implemented to draw flood hazard maps.

The methodology developed in Mazzoleni et al. (2013) to generate, from statistics of levees breaches, maps of structural residual flood hazard is summarised here.

- (1) A T-years return period flood hydrograph is routed with a hydraulic model along a river reach (in the case study a 23-km reach of the Po river).

- (2) The possible locations of the levee breaches were chosen as those most prone to failure on the basis of the hydraulic gradient  $J = \Delta h/L_s$ , where  $\Delta h$  is the maximum value of water head between the inward and outward face of the riverbank cross section and  $L_s$  is the critical path across the critical.
- (3) Then, the “geotechnical uncertainty” related to the breach size was taken into account through a Monte Carlo assessment of different levee failure scenarios (Aureli and Mignosa 2004), by selecting for each of the

**Fig. 92.2** The standard deviation of the water depth (m) map computed for the 100-year return period design flood after the 96 ensemble levee failure scenarios on the 23-km reach of the Po river (dashed) between the Taro and Parma rivers



8 selected locations 3 breach widths derived from the observed data and 4 breach depths based on the actual levees depths at each of the 8 sections. As a result 96 (8 sites  $\times$  3 widths  $\times$  4 depths) breach outflow hydrographs scenarios were available.

- (4) The 96 outflow hydrographs, obtained in a simplified manner were propagated in the flooded area by means of the 2D model LISFLOOD-FP in order to study the unsteady flood propagation in the floodprone areas. In this way 96 maps of maximum water depth and 96 maps of maximum flow velocity were generated.
- (5) The maps obtained during the previous step were used to derive weighted-mean and standard deviation maps of water depth and flow velocity in the flood prone area.

An example of the resulting standard deviation of water depth is shown in Fig. 92.2 obtained for a river reach of the Po river and which completes the information provided in maps shown in Mazzoleni et al. (2013). The implication of such a map in view of the implementation of the European Flood Directive 2007/60/EC is that areas which have, in principle, no design flooding hazard and risk because they are protected against flooding because of levees overtopping, now are shown to be exposed to the risk of flooding because of the structural residual risk of levees failure. In this way the systematic underestimation of flood risk can be corrected. Assuming, for sake of simplicity, that the joint probability density function  $p(h, x)$  of the flooding water depth  $h$  in the flooding area resulting from a water level  $x$  in the river is the product of the marginal density functions of water depth  $p_h(h)$  and the river water level  $p_x(x)$  the total hazard of  $h$ -exceedance is

$$H(h) = \int_h^\infty p_h(h) \left[ \int_0^L p_x(x) dx + \int_L^\infty p_x(x) dx \right] dh$$

$$= SRH + DRH \quad (92.3)$$

thus showing to urban and land planners the relative weight

of the structural residual hazard SRH and the design residual hazard DRH for levees protecting against floods with water level in the river less than  $L$ .

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