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Floods in changing streams

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Abstract Flood damage continues to rise in many parts of the world, even when measured in constant monetary units. The rise in flood damage is caused in some instances by the human settlement of flood plains, which augments the stock of property and exposed population within flood-prone areas. In other instances, flood damage increases in response to the cumulative effects of watershed impacts on the streamflow response to precipitation. In addition, the large uncertainty which surrounds the estimates of rare flood events, especially in ungauged streams, frequently leads to the under-estimation of flood risk. This article examines key factors that effect time-changing flood damage, and presents a case study that illustrates human-induced contributions to flood damage.

Key words channels; floods; hydraulics; rainfall; risk

INTRODUCTION

Everywhere throughout the world there are frequent and catastrophic losses of life and property caused by floods. Floods continue to inflict ever-increasing losses. Several factors explain this phenomenon. The first is the uncertain determination of flood magnitudes. The second is steady development in flood-prone zones, which exposes people and physical plant. Climate change has been hypothesized as a possible cause of more intense storms in various part of the world (Loáiciga *et al.*, 1996).

This work examines the elements of flood-risk assessment and the reasons behind the escalating losses from floods. Flood risk is defined herein as the probability of economic and life losses associated with high flow in rivers and concomitant high water levels in the surrounding flood plain. Flood-risk assessment, on the other hand, is the procedure by which flood risk is estimated. A case study of changing flood risk over time illustrates the principles presented in this work. Specifically, the impacts of the El Niño storms of March 1995 in the San Luis Obispo Creek's watershed (central California, USA) were chosen to illustrate the principles of changing flood-plain hydraulics examined in this article. Feasible alternatives for flood damage mitigation in the study area are identified

THE COMPONENTS OF FLOOD RISK ASSESSMENT

Figure 1 depicts the components of flood-risk assessment. The flood-frequency function (Fig. 1(a)) is combined with the flood level–flow rate function (Fig. 1(b)) to yield the flood level–frequency function (Fig. 1(c)). The latter function is then combined with the flood level–damage function (Fig. 1(d)) to produce the flood.

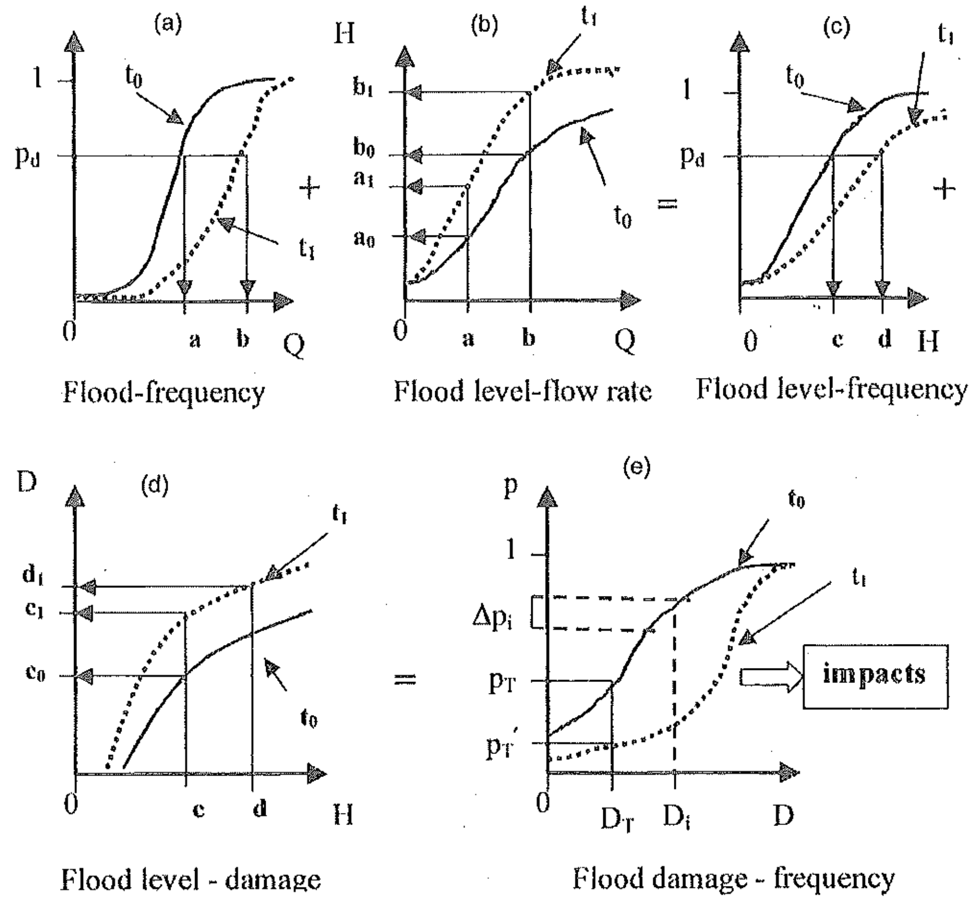

Fig. 1 Elements of flood-risk assessment (see text for discussion).

damage–frequency function (Fig. 1(e)). These functions (shown in Fig. 1(a)–(e)) are examined and discussed next.

The flood-frequency function

Let us start the flood-risk analysis with an overview of the flood-frequency function, depicted in Fig. 1(a). The set of points $\{Q(p), p\}$, where p is a sequence of non-exceedance probabilities, e.g. $p = 0.90, 0.96, 0.98, 0.9867, 0.99, \ldots$ (with associated return intervals $= 1/(1-p) = 10, 25, 50, 75, 100, \ldots$, in years), and $Q(p)$ is the flood quantile associated with each probability p, define a flood-frequency function. Damaging floods typically have return intervals of 10 or more years. In the United States, important facilities, such as interstate bridges, are designed to pass the 100-year event (other vital facilities may require even greater design return intervals). Less essential facilities are designed typically for the 25- or 50-year events. The flood-frequency function is a centrepiece of flood-risk assessment because it is from it that design floods are determined. Much has been written about the difficulties that arise in determining the flood-frequency function from measured streamflow at a stream gauge (see Loáiciga, 1989). The primary obstacle stems from instrumental streamflow records which are often too short to properly characterize rare events, say 50-year or rarer floods, at most sites where the information is needed. Frequently, and this is the case of primary interest in this work, the hydrologist is confronted with ungauged basins, where no instrumental records exist at all.

In ungauged basins, regression equations are developed based on data from gauged basins, where all basins (i.e. gauged and ungauged) share a type of climatic similarity (this statistical approach is sometimes called regionalization, or regional analysis). Drainage area (A, in km^2), mean annual precipitation (P, in cm), and an elevation index (H, in thousands of metres) are common independent variables used to predict a flood quantile of specified probability, such as the 100-year flood (= Q_{100}, the 99% quantile). For example, in the central-coast region of California, where the case study of this work is located, the following regional equation was fitted to estimate 100-year flows (in m^3 s^{-1}) in ungauged basins (Waananen & Crippen, 1977):

$$Q_{100} = 0.0746 A^{0.88} P^{0.84} H^{-0.33} \tag{1}$$

The elevation index H in equation (1) varies between 0.0305 and 1.22. H is calculated by first determining the distance (L) along the main stream from the gauging site where Q is needed, to the basin divide. The elevations (in thousands of metres) of the points along the main stream that are located distances of $0.10L$ and $0.85L$ from the gauging site are averaged, and that average is H (Waananen & Crippen, 1977). In any ungauged drainage basin (of fixed drainage area, mean annual precipitation, and topography) several regional equations can be used to derive an estimate of the flood-frequency function for the said basin, provided that a sufficient number of quantiles (e.g. Q_2, Q_{10}, Q_{25}, Q_{50}, Q_{75}, Q_{100}) are regionalized. The US Geological Survey has developed regionalized equations for many regions of the United States, which, used in ensemble, provide an estimate of the flood-frequency function within an important range of return intervals.

Flood quantiles change over time in impacted basins

The uncertainty of flood-quantile estimates, such as those obtained from equation (1) or from fitted flood-frequency functions, can be very large (Loáiciga, 1989; Loáiciga & Marino, 1991). But even under the assumption that a flood-frequency function is accurately estimated at a time t_0, it may change rapidly over time, say within a decade or two from its estimation. The situation is illustrated in Fig. 1(a), in which the true flood-frequency curve at time t_0 shifts to a different position a few years later, at time t_1. Such changes in the flood-frequency function are frequently triggered by modifications to the land and the water resources within a basin: deforestation, urbanization, and inter-basin water imports tend to increase a flood quantile $Q(p_d)$ from an initial level a to a posterior level b, as shown in Fig. 1(a). The latter effect, which we name quantile inflation, as it tends to increase over time as a function of population and/or basin utilization, increases the flood risk due to the larger flood peaks which are generated within the basin as time goes by.

Changes in the flood level–flow rate function

Figure 1(b) shows a prototypical flood level–flow rate function. The graphical representation of the mathematical relationship between flood (water) level (or stage) and flow rate in a stream (and its overbanks) is called the rating curve. Changes in a basin, such as flood-plain filling, bridge and culvert construction, accelerated erosion, channel obstruction by exotic plant species, and, in general, increases in flood-plain (hydraulic) roughness by human encroachment in the flood plain, cause the flood level to rise even when the flow rate remains constant. This situation is illustrated in Fig. 1(b), where the flow rates a and b are associated with water levels a_0 and b_0, respectively, according to the initial rating curve at time t_0, while their water levels rise to a_1 and b_1, respectively, at a later time t_1.

Figures 1(a) and 1(b) show also that a rise in flood level for a given flood quantile can happen even when the rating curve remains unmodified. Consider the situation where the flood quantile $Q(p_d)$ increases from a to b, already discussed in the context of Fig. 1(a). That quantile change is carried over to the rating curve in Fig. 1(b), where the water level increases from a_0 to b_0. The critical case of change impacts arises, however, when both the quantile $Q(p_d)$ and the rating curve change in the time interval $t_1 - t_0$. In this instance, the flood level rises from the initial a_0 to b_1.

Flood levels and flood damage rise over time

Figure 1(c) illustrates the rise in flood level from an elevation c (at time t_0) to d (at time t_1) corresponding to the flood quantile Q(pd). The rise in flood level (or stage) can be due to: (a) increase in the flood quantile; (b) increase in the flood level while the flow rate remains constant; or (c) to a combination of flood quantile and flood-level rises.

The flood-damage function, represented in Fig. 1(d), changes over time. It is seen in Fig. 1(d) that the effect of flood-plain development is to increase total damage. That increase need not be caused by higher flood levels; the accumulation of property value in the flood plain over time suffices to shift the flood level–damage curve upwards, as shown in Fig. 1(d), where the damage increases from c_0 to c_1 (at times t_0 and t_1, respectively) for the same flood level c. For a given return interval $1/(1 - p_d)$, the most likely scenario is that increases in flood damage are due to a larger flood quantile $Q(p_d)$ and to an upward shift of the flood level–damage curve. In Fig. 1(d) this is illustrated by a change in flood damage from c_0 to d_1.

Cumulative impacts raise the flood risk

The final component of risk assessment, the flood damage–frequency function, is illustrated in Fig. 1(e). Notice that the function is shifted rightwards from its initial position at time t_0 to a different position at a subsequent time t_1. That shift is caused by any one, or combinations of, the following: (a) changes in the flood-frequency function; (b) changes in the rating curve; (c) changes in the flood level–damage function. The flood damage–frequency curve is an important function, for it summarizes all the hydraulic, economic, and probabilistic information needed to make quantitative statements about flood risk. Let us define the flood risk as the probability that the flood damage (D) in any year exceeds a certain tolerable level, say D_T. At time t_0 the risk, R_0, is expressed mathematically by the following:

$$R_0 = P(D \geq D_T) = 1 - P(D < D_T) = 1 - p_T \tag{2}$$

It is evident from Fig. 1(e) that the risk at a later time t_1, R_1, has increased relative to the risk at time t_0 and is given by:

$$R_1 = 1 - p'_T > R_0 \tag{3}$$

In the classical analysis of flood damage, the expected annual flood damage is commonly calculated. The expected annual flood damage at time t_0 is given by the following expression:

$$\overline{D_0} = \int_{p=0}^{p=1} D\,\mathrm{d}p \tag{4}$$

The integral of equation (4) is approximated numerically or graphically from the flood damage *vs* frequency curve as follows:

$$\overline{D_0} \cong \sum_i D_i \cdot \Delta p_i \tag{5}$$

in which the probability increment Δp_i and the corresponding average damage D_i are shown in Fig. 1(e). The expected annual flood damage for time t_i is calculated similarly, and Fig. 1(e) implies that it is clearly larger than that for time t_0.

AN EXAMPLE OF TIME VARYING, HUMAN-INDUCED FLOOD DAMAGE

The San Luis Obispo Creek basin, California, has a mean annual precipitation of 55.9 cm year^{-1} and a mild Mediterranean climate with warm, dry, summers (June–September) and wet, cool, winters (December–March). The drainage area is 183.9 km^2, and its elevation index (see equation (1)) is 0.0914. The creek flooded on 10 March 1995, causing widespread damage in its lower reach

The predominant land use in the lower San Luis Obispo Creek is agricultural, mainly apple orchards. There are also a few resort facilities and exclusive housing tracts on the flood plain. Flood damage affected all land uses in the lower San Luis Obispo Creek in the March of 1995, a strong El Niño year. This study focuses on the change in flood levels caused by flood-plain changes that took place between 1969 and 1995. Those changes were: (a) orchard planting and filling of agricultural land; (b) building of the Ontario bridge; (c) invasion of stream channel and overbanks by exotic plant species; (d) filling of the flood plain to create a recreational vehicle (RV) park. Table 1 shows the change in flood-plain hydraulic roughness (i.e. Manning's n) associated with the four flood-plain changes cited above. Those changes were determined by the author based on an analysis of hydraulic characteristics in the lower San Luis Obispo Creek from the late 1960s to 1995 (Loáiciga, 1999).

Table 1 Flood factors and the associated change in flood-plain hydraulic roughness.

Flood factor	Increment in hydraulic roughness	Hydraulic roughness
Base condition (1969)	–	0.030
1. Orchard farm	0.035	0.065
2. Ontario bridge	0.030	0.095
3. Vegetation	0.015	0.110
4. RV park	0.008	0.118
Final roughness (1995)	0.118	

The 24-h storm of 9 and 10 March 1995, had a depth of 12.48 cm and a return period of about ten years. The historical 24-h maximum is 15.5 cm (recorded in March of 1969, which was another El Niño season (Loáiciga, 1999). The measured rainfall depths during 9 and 10 March 1995, do not support the argument that unusual rainfall was the primary cause of high flood levels on those dates. In other words, in March 1969, the study area had wet antecedent moisture conditions (as it did in March 1995), experienced more intense storms than in March 1995, and yet did not cause damage in the lower San Luis Obispo Creek. The clue to this paradox are hydraulic changes in the flood plain that occurred between 1969 and 1995, and which were summarized in terms of the flood-plain hydraulic roughness in Table 1.

RESULTS OF FLOOD-PLAIN EFFECTS ON WATER LEVELS

Regionalized equations for the 10-, 25-, 50-, and 100-year floods in the San Luis Obispo Creek were obtained from Waananen & Crippen (1977). Their values, in $m^3 s^{-1}$, are 240, 329, 408, and 475, respectively. The river hydraulics model HEC-2 (US Army Corps of Engineers, 1990) was implemented to simulate water levels in the lower San Luis Obispo Creek. The pre-development (1969) water levels were calculated for the four flow values quoted above and a flood-plain roughness equal to 0.03. The post-development (1995) water levels were calculated for the same four flow values and roughness equal to 0.118. Simulation results are presented for a reference stream cross-section located at latitude N35°11′11″ and longitude W120°42′50″, which in HEC-2 is called section 36+38. This location is where most of the flood damage occurred on 10 March 1995. Table 2 shows the pre-development and post-development water levels at the reference cross-section 36+38. It is seen there that for the selected return periods and their associated flow rates, the water levels increased sharply (over 2 m in all cases shown in Table 2) as conditions changed from pre-development to post-development conditions. The data in Table 2 demonstrate that the flow rate *vs* flood level function and the frequency *vs* flood level function were modified in the lower San Luis Obispo Creek. Those data imply that the frequency *vs* flood damage function was modified also, and that the flood risk was larger in 1995 than in 1960. The latter implication follows from the fact that for the same return period, the flood level, and hence, the flood damage, was larger in 1995 than in 1969.

Table 2 Simulated pre-development (1969) and post-development (1995) water level at cross-section 36+38.

Return period (years)	Flow rate ($m^3 s^{-1}$)	Pre-development water level (m)	Post-development water level (m)
10	240	6.18	8.23
25	329	6.68	8.78
50	408	7.08	9.23
100	475	7.41	9.61

CONCLUSIONS

This paper has presented a theory for the ex-post facto analysis of flood-plain changes and their impacts on the hydraulic response and flood risk in a watershed. A case study demonstrated that over a 25-year period, the lower San Luis Obispo Creek, California, experienced rises in flood level on the order of 2 m and higher for return periods of 10, 25, 50, and 100 years.

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