A Statistical Approach for Spatial Analysis of Flood Prone Areas

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Abstract: A statistical concept is presented for the spatial analysis of flood hazards. It is especially useful in cases with many different hazardous processes such as failure of levees, obstruction by bridges and culverts. The method allows efficient and statistically correct generation of flood hazard maps that are relevant for the decision making in land use planning and protection measures.

Keywords: Hazard Assessment, Flood Plain Modelling, Land Use Planning, Protection Measures

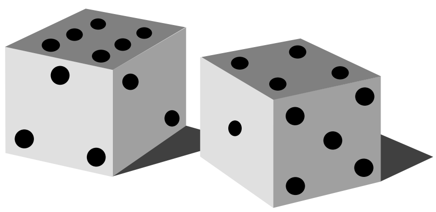
Introduction

Flood hazard assessment is based on information on the intensity and the frequency of flood events. The results of the hazard assessment such as hazard registers or hazard maps are used to depict the flood prone areas and deliver the information for land use planning or protection measures against flooding. Hazard maps play a key role in the new Swiss flood hazard policy (FOWM1997).

With the developments of new numerical methods the possibilities to predict the consequences of flood events have improved. Two-dimensional hydrodynamic models can be used for the prediction of flood intensities such as flow depths and flow velocities (Beffa 1998; Connell et al. 1998). With the reliability of these methods together with high quality terrain data it is possible to make flood predictions that are relevant, meaningful, and logically correct as required by Hamilton et al. (1994).

Experience shows that often there are a number of different processes involved that influence the hazardous impact of an event. Beside the initial process (e.g. a high discharge) there are consecutive processes to consider, e.g.

- failure of levees (from lateral bank erosion or piping failure)
- obstruction of sections by bridges or culverts
- reduction of channel capacity due to accumulation of sediments



Predicting the failure of a levee, defining position and extent of the breach, or finding out whether a bridge section will obstruct or not is somehow like playing dice. However, in many cases it is possible to assign a probability that a process is likely to occur in a given event, e.g. in 1 of 3 events, or that it is unlikely to occur, e.g. in 1 of 10 events. These statistical statements can be used as relative probabilities. In the sequel, different scenarios can be defined to describe the various processes that may occur during a flood.

Considering many different events increases the amount of work to be done. However, the procedure offers interesting aspects for the spatial analysis of the results. The present paper describes a statistical concept to be used to obtain the relevant products out of the amount of data coming out of the hydrodynamic modelling. Having the data in a condensed and illustrative format is essential for the decision making in land use planning and the design of protection measures.

Probability Analysis

The conception of the statistical analysis is based on the following elements:

Process	=	a physical action, e.g. failure of a levee, at a specific location
Event	=	the occurrence of one or more processes, e.g. high discharge in the main channel and failure of a levee
Scenario	=	the occurrence of an event for a given return period

An event is defined by its process(es) as can be seen in Figure 1. Since processes are the basic elements of the hazard analysis they should be defined first. Egli (1996) suggests the following procedure:

1) Identification of the primary process
2) Identification of consecutive processes
3) Assignment of relative probabilities to consecutive processes
4) Calculation of the total probability of the event

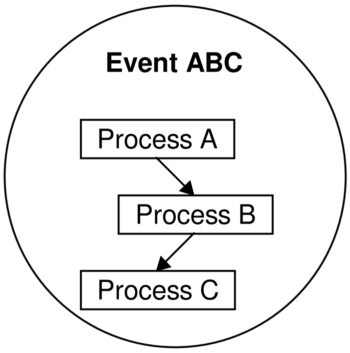


Figure 1 - Event and Processes

The probability of the occurrence of an event is given by the product of the probability of the primary process w_0 and the relative probabilities of the consecutive processes

$$w = w_0 w_1 w_2 ... w_n \tag{1}$$

where n = number of consecutive processes. For the relative probabilities one has to consider that the probability that a process does not occur is

$$w_{ni} = 1 - w_{ij} \tag{2}$$

where w_i is the relative probability of the process i. Accordingly, the sum of the probabilities from all events that share the same primary process is equal to the probability of the primary process. More details on probability analysis can be found in textbooks (e.g. Plate 1993).

Usually the primary process is a high discharge whose value depends on the return period. In this case the same event should be considered for different return periods to account for the complete continuum of the flood risk, e.g. from the smallest flood when a failure can occur to the Probable Maximum Flood. In practice only a limited number of return periods is considered, e.g. the 10, 30, 100, and 300 year discharges.

Example

Given a river channel that is separated by levees from a flood plain. From geotechnical analysis it is assigned that the levee is likely to fail at two positions A and B, where A is upstream from B (see Figure 2).

The probability of a breakout at A or B is assumed to be 1 of 5 for a 30 year flood and 1 of 2 for a 100 year flood. The outflow from the breach is estimated as 100 m^3/s and 200 m^3/s for the 30 and 100 year flood, respectively.

Considering the processes A and B there are four different events that are possible to occur for a given return period as can be seen in the event tree in Figure 3

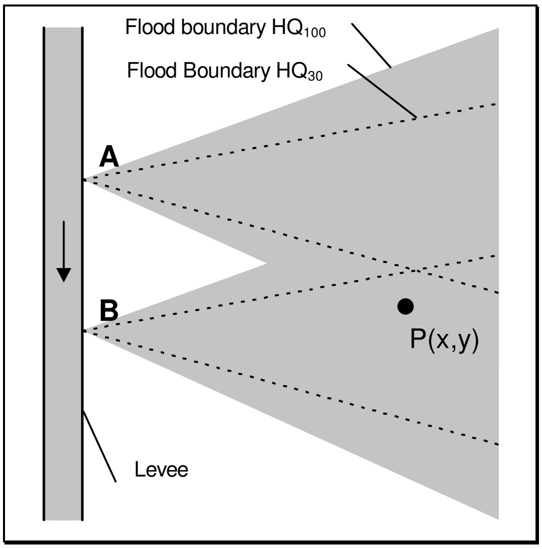


Figure 2 - Situation with River Channel, Flood Plain, and Breach Positions A and B

It is accepted that if the levee fails at A it will not breach at B in the same event. However it can breach first at B and afterwards at A.[1] In other words, the breaching at A is stochastically independent of B, but B is influenced by A. The event tree with the assigned probabilities is given in Figure 4.

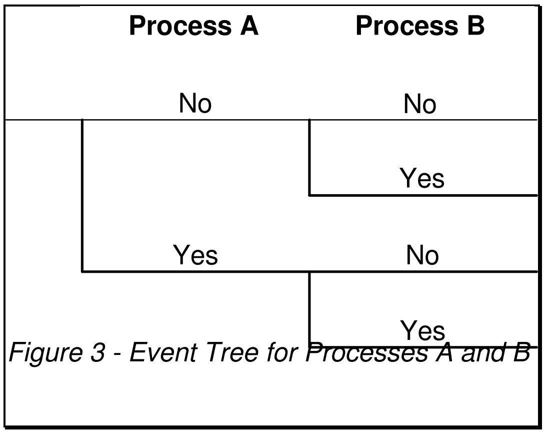


Figure 3 - Event Tree for Processes A and B

Difficulties with applying the event tree arise if processes depend from each other (A from B and B from A) and for events where the succession of the different processes is important. Fortunately the domain of influence in the upstream direction is limited and the processes upstream are not influenced by the processes further downstream. Therefore, the listing of the processes in the event tree should consider the direction of the flow.

Applying equation (1) the event tree analysis delivers the probability for each scenario. It can be seen that the return period of a scenario is different from the return period of the primary process, e.g. the scenario „*breakout at A during a 30 year flood*“ has a return period of 150 years.

[1] For simplicity the scenario of a levee failure at both A and B is not considered. Instead it is assumed that the breaching occurs either at A or B. Regarding the flood intensities this is a conservative assumption.

Primary Process	**Process A**	**Process B**	**Return Period / Probability**
Discharge HQ_{30}	No	No	**T=47**
w_0=0.0333	w_1=0.8	w_2=0.8	**w=0.0213**
		Yes	**T=188**
		w_2=0.2	**w=0.0053**
	Yes	No	**T=150**
	w_1=0.2	w_2=1.0	**w=0.0066**
Discharge HQ_{100}	No	No	**T=400**
w_0=0.01	w_1=0.5	w_2=0.5	**w=0.0025**
		Yes	**T=400**
		w_2=0.5	**w=0.0025**
	Yes	No	**T=200**
	w_1=0.5	w_2=1.0	**w=0.0050**

Figure 4 - Event Tree for Two Levee Failures: T = Return Period in Years, w = Probability per Year

For every scenario a numerical model estimates the flood intensities (e.g. the maximum flow depths and velocities). From the practical point of view two-dimensional models are more efficient to apply than one-dimensional models as they allow a direct estimate of the flood intensities on flood plains. Nonetheless the model output becomes difficult to survey and time consuming to analyse if a large number of scenarios is considered. To simplify the results these scenarios need to be combined into one map.

Spatial Analysis

For the spatial analysis of the scenario data the probability of each scenario has to be considered. For stochastically independent events the total probability is given by

$$W = \sum_{i=1}^{m} w_i \qquad (3)$$

where m = number of relevant events. The exact meaning of „relevant" is defined in the following. For this reason the concept *of scenario cards* is introduced. A scenario card can be defined as *„a set of information to describe the hazard variables for each scenario at a given location"*. A scenario card contains the ID of the event, the total probability of the scenario w, and the flow variables, e.g. maximum flow depth h and velocity v.

The scenario cards for point P in Figure 2 are shown in Figure 5. The flow depths are non-zero except for the first card from the left. This card is non-relevant for the further analysis.

A	A	B	B
w = 0.0066 h = 0.0 m v = 0.0 m/s	w = 0.0050 h = 0.6 m v = 0.8 m/s	w = 0.0053 h = 0.9 m v = 0.8 m/s	w = 0.0025 h = 1.2 m v = 1.5 m/s

Figure 5 - Scenario Cards with Event ID, Probability w, Flow Depth h, and Flow Velocity v for Point P in Figure 2

How to Estimate the Probability of Getting Flooded

For planning measures it is important to know how often an area gets flooded. The probability of flooding can be estimated by the following procedure:

1) For every event select the card with the highest probability value (and $h \neq 0$)
2) The sum of the probabilities of the selected cards is the probability of flooding at this location

The procedure holds for statistically independent events. Step 1 determines the relevant scenario for each event ID. In step 2 the total probability is calculated applying equation (3). Regarding our example, cards number 2 and 3 in Figure 5 contain the highest probability value for event A and B, respectively. Thus, the probability of flooding is estimated as w = 0.0050 + 0.0053 = 0.0103 that corresponds to a return period of 97 years.

The procedure can be applied to each point in the modelled area to obtain a probability map of getting flooded as illustrated in Figure 6. It can be seen that areas close to the levee affected by a breach at A or B have a lower probability of getting flooded than areas with a larger distance from the levee that are affected by breaches at both A and B.

The resulting map depends on the number of return periods being considered. A number of four return periods has been found a minimum to obtain an accurate representation of the probability values.

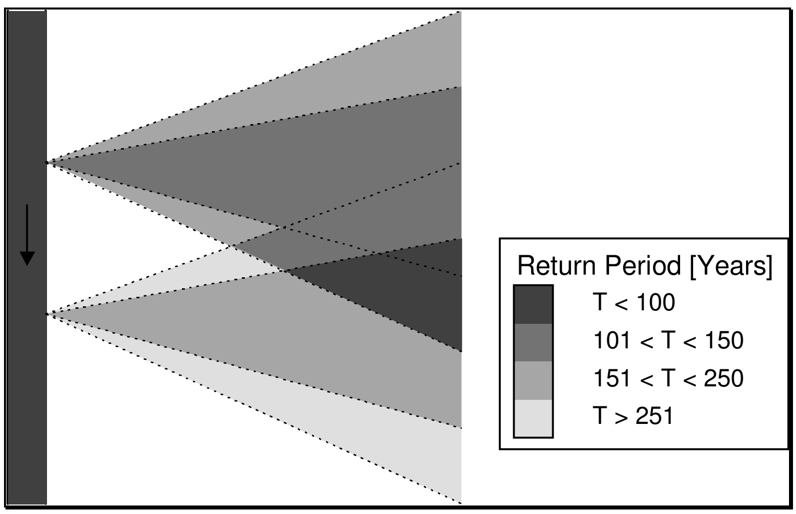


Figure 6 - Probability Map for Flooding

How to Estimate the Flow Depth for a Given Probability

For the design of local protection measures it is important to know the maximum flow depth for a certain return period. It can be estimated by the following procedure:

1) Sort the scenario cards so that the card with the lowest flow depth is on top of the stack
2) Determine the probability of flooding for the cards in the stack as given in the previous section
3) If the probability of flooding is higher than the given probability put the card on top of the stack aside and go back to step 2.
4) The wanted flow depth is taken from the last card on the stack (conservative estimate) or from the card that has been placed aside (non-conservative estimate).

Applying the procedure to the example given above the cards are sorted as shown in Figure 7.

The probability of flooding for these cards has been estimated to 0.0103 (or T = 97 years) in the previous section. For a given return period of 100 years the card on top of the stack is put aside according to step 3. For the remaining card stack the probability of flooding is estimated as w = 0.0053 (or T = 188 years) which is a lower probability than the given value (0.01). According to step 4 the flow depth is estimated in the range of 0.6 to 0.9m.

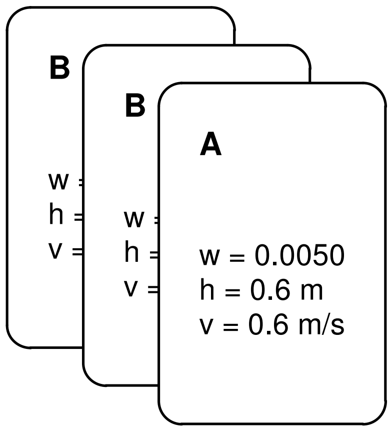


Figure 7 - Card Stack after Sorting

The procedure avoids interpolation between the intensity values of different scenarios as this could produce incorrect or non-physical results. Accordingly, the differences between the intensity values of succeeding scenario card on the stack should be limited. This is done by increasing the number of return periods being considered.

Applying the procedure to the modelled domain a map of the flow depths for a given probability is obtained as illustrated in Figure 8.

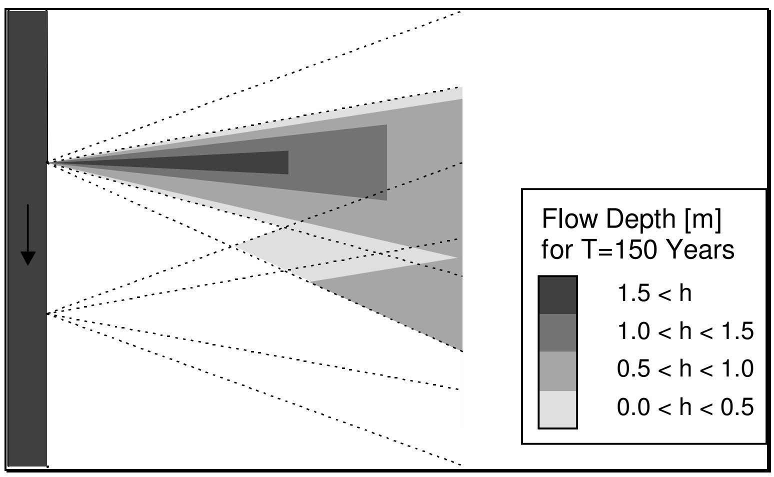


Figure 8 - Map Showing Flow Depth for Return Period of 150 Years

How to Estimate Hazard Values

The Swiss flood hazard policy relies on the assumption that the hazardous impact of a scenario is proportional to the product of flood intensity and probability (Egli 1996), i.e.

$$H = I * w \qquad (4)$$

with H = hazard value, I = flood intensity, and w = probability per year. The details of the hazard analysis, including the definition of intensity values from given flow parameters, are given in FWOM (1997). For computation purposes the intensity can be defined as a function of flow depth and flow velocity as

$$I = \begin{cases} 0 & \text{for } h = 0 \\ 0.3 + 1.35\,h & \text{for } h > 0 \text{ and } v < 1\,m/s \\ 0.3 + 1.35\,h\,v & \text{for } v > 1\,m/s \end{cases} \qquad (5)$$

with h and v in standard units (Beffa 2000). Note that the definition Eq. (5) gives non-dimensional intensity values which is questionable but politically accepted. Using (4) and (5) the flood prone areas are classified in three hazard levels as given in Table 1.

Hazard Value	Hazard Level	Directions
H < 0.01	low	measures required for sensitive objects
0.01 < H < 0.1	medium	construction allowed under restrictions
H > 0.1 or I > 3	high	no buildings allowed that host people or animals

Table 1 - Hazard Values, Hazard Levels, and Corresponding Directions for Measures

The hazard values from different scenarios are estimated in an analogous way as for the probability of flooding:

1) For each event select the card with the highest hazard value
2) The sum of the hazard values of the selected cards gives the total hazard value at this location

For the hazard analysis the event cards are completed with the values for the intensity and the hazard as shown in Figure 9. Applying the procedure the total hazard value is estimated as H = 0.0055 + 0.0080 = 0.0135 that corresponds to a medium hazard level (see Table 1). Therefore, measures have to be taken if objects are built in this area.

A

w = 0.0050
h = 0.6 m
v = 0.8 m/s
I = 1.1
H = 0.0055

B

w = 0.0053
h = 0.9 m
v = 0.8 m/s
I = 1.5
H = 0.0080

B

w = 0.0025
h = 1.2 m
v = 1.5 m/s
I = 2.7
H = 0.0068

Figure 9 - Scenario Cards with Intensity I, and Hazard Value H

If the procedure is applied to the modelled area a hazard map is obtained showing the decrease of the hazard levels with the distance from the levee (Figure 10).

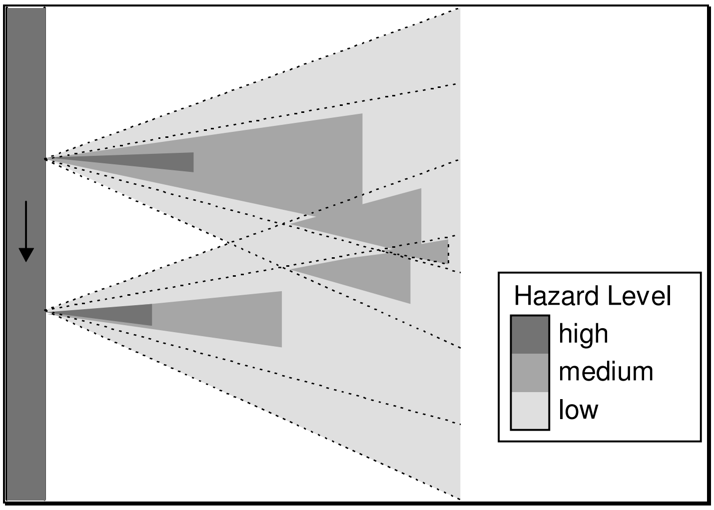


Figure 10 - Hazard Map Showing the Hazard Levels on the Flood Plain

Conclusions

The presented methods consider the many different scenarios with the various processes that occur on a flood plain and enables for a statistically correct treatment of the probabilities. The results and their applications are

- probability of flooding for planning measures
- depth of flow for the design of protection measures
- hazard levels for planning measures and risk analysis

The implementation of the procedures in a computer program is straightforward. Used in combination with a two-dimensional flow model the methods enable us to produce the relevant maps in an efficient and modelling based way. Further, the impact of protection measures on the flood plain can easily be modelled.

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