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Modelling floods and damage assessment using GIS

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Abstract River flooding can have a severe impact on society. To reduce the potential damage in the future, structural measures, such as increasing the storage capacity inside or outside the river bed or improving dikes, are essential. To support decision making when choosing and evaluating adequate measures, Delft Hydraulics developed a flood hazard assessment model. The important river related aspects of flooding and managing floods (safety, agriculture, industry, etc.) all have a spatial component. Therefore the GIS package ARC/INFO turned out to be a valuable tool in developing the model. For a series of discharges, the model calculates the flooding depth in the flood plains and the damage assessment. The model was successfully applied to calculate the impacts of potential strategies for the river Meuse in the south of The Netherlands after the flooding of December 1993.

INTRODUCTION

River flooding has a severe impact on society. The many recent floods in The Netherlands started a discussion on responsibility for the consequences of flooding. The civilian population in the river valley should be acquainted with and prepared for flood risk. On the other hand, the public authorities do have a responsibility to take effective measures that reduce the risk of floods. The discussion led to an increasing demand for flood hazard assessment models that will help to analyse the consequences of flooding and the effects of (combinations of) measures. The model presented here focuses on the socio-economic impacts of flooding, not on the ecological impacts.

FLOODING RISK

The model was developed from the viewpoint of risk, where risk is defined as the expected damage $E(x)$ multiplied by the probability of occurrence $P(x)$ of an event x:

$$R(x) = E(x)P(x) \tag{1}$$

(e.g. a discharge with a recurrence interval of 1/1250 per year)

Given the event x, there are two possibilities (Table 1): the risk is accepted and no measures are taken or the risk is too high, indicating that the probability of occurrence

Table 1 Flooding risk.

Probability	Damage	Accept	Measures
Low	Low	Yes	-
Low	High	No	Short term
High	Low	No	Long term
High	High	No	Short and long term

or the expected damage is unacceptable. In the case of unacceptable damage, a disaster plan should exist for taking short term measures in case of flooding. In the case of an unacceptable probability of occurrence, structural measures have to be planned, that improve the flood retaining mechanisms. The flood hazard assessment model described here supports decision making for the long term.

THE FLOOD HAZARD ASSESSMENT MODEL

General concept and data

Damage depends mainly on three factors:

- **Land use** There is a number of land use types such as agriculture, industry, habitation, etc.; the real estate properties of each land use type are also important, for example the prices of houses, the size of the factory, the average number of persons per house in a region, the number of floors in a building, etc.
- **Flooding depth** Water levels in a river depend on the slope of the river and the discharge. For a given discharge, the water levels are calculated by a hydraulic model. Given the water levels in the river, the elevation of the land and the presence of dikes and other high grounds are factors determining the flood extent.
- **Spatial distribution** The spatial distribution of both land use and flooding depth is important for determining damage. The spatial distribution of the land use types and the land level are supposed to be available as GIS maps.

Damage functions have to be defined that depend on these three factors. These functions may differ with location and land use type. All functions should be non-decreasing for increasing discharges; the larger the discharge, the deeper the flooding depth.

Within the Flood Hazard Assessment Model, a flood model calculates the flood extent whereas a damage assessment model calculates the expected yearly damage. The user decides on the discharges and strategies (combinations of measures) for which the damage assessment is to be calculated. The results of the calculation are presented to the user as tables, maps and text reports.

The concept of the Flood Hazard Assessment Model is depicted in Fig. 1.

The flood model

Part of the methodology is a one-dimensional hydraulic model of the river. For a given discharge curve at the upstream boundary of the model, the hydraulic model calculates

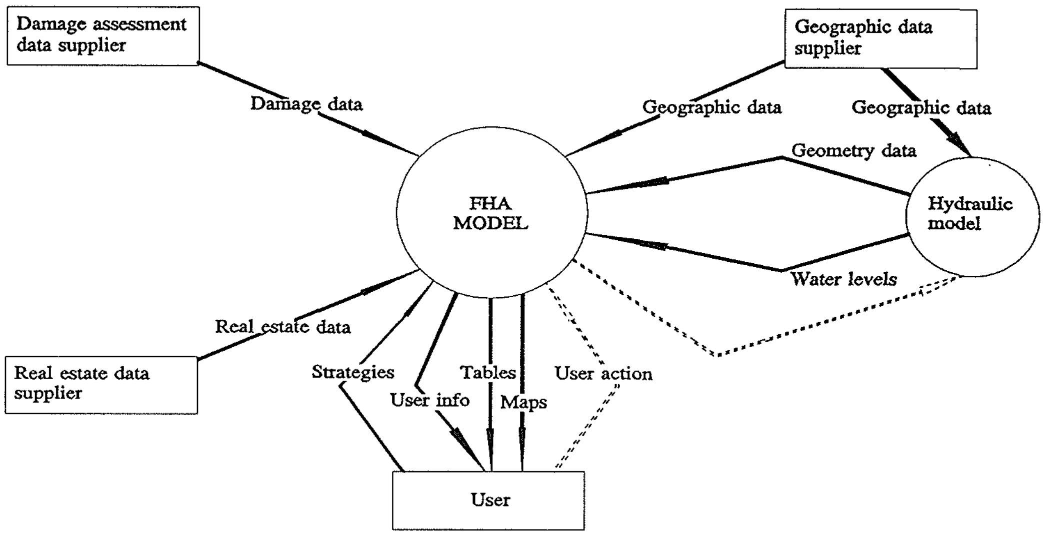

Fig. 1 Conceptual scheme of the Flood Hazard Assessment Model.

the water levels at discrete points in the river for each defined time step. The flood model uses the maximum water level during the simulation time in each water level point as input.

Within the GIS, the flood plain is divided into influence areas, one per water level point. The flood plain is further divided into elevation polygons, based on a subdivision of the flood plain in elevation levels, generated from a digital terrain model, classified in e.g. 10 cm classes. Dikes and other terrain jumps are added to complete the elevation model. The elevation data and the topology were supplied by GIS as a second input source to the flood model.

With the input supplied by the hydraulic model and the GIS, the flood model calculates the flooding. The model starts at the water level points in the river. From there, it searches for neighbouring polygons that are below the water level in the river and are not protected by a dike. As a result, the model calculates the water depth for each polygon in the flood plain and each discharge.

Instead of the one-dimensional hydraulic model, a two-dimensional hydraulic model would be a realistic alternative to calculate flooding depths that serve as input to the damage assessment model.

The time aspect of filling and emptying the flood plains is not taken into account, since the flood model only uses the maxima of a discharge curve. Therefore, the result of the flooding calculations will be an overview of all areas that will finally be flooded due to the high water.

Since the flood hazard assessment model is designed to support decision making on the long term, the flood model suffices. However, if short term decision making had to be supported as well, then the time aspect, especially of filling, would be important; it makes a great difference if the time to evacuate people is limited to only one hour or a full day (24 h).

The damage assessment model

A differentiation into four damage categories is applied, namely public authorities, private persons, industry and agriculture.

These categories have been derived from the types of land use. Since the damage depends on land use, flooding depth (land elevation) and spatial distribution (e.g. based on zip code), maps with these themes have to be overlain within the GIS to obtain so-called damage units (Fig. 2).

The damage assessment model first checks whether the unit is flooded or not. If flooded, a land use type and location dependent damage function is applied to calculate the damage. The flooding depth must exceed a certain threshold level to cause damage. Given an event x the damage in a unit with land use type L at location S, is calculated by the following function:

$$f_{L,S}(x) = \begin{cases} 0 & \text{if } \mathrm{d}(x) < c_{L,S} \\ g(L,S,x)\mathrm{d}(x) & \text{if } \mathrm{d}(x) \geq c_{L,S} \end{cases} \tag{2}$$

where: $g(L, S, x)$ = calibration factor for land use type L at location S; $d(x)$ = the flooding depth related to the event x; and $c_{L,S}$ = threshold for the flooding depth.

REDUCING DAMAGE

The scope for applying measures

Applying measures aims to reduce damage and to protect people from getting flooded to a level at which the risk of flooding is socially accepted. For example, dikes should be high and strong enough to retain water levels occurring due to a discharge with a recurrence interval of 1/1250 per year. However, the profits have to counterbalance the costs of dike improvement.

Three types of measure are distinguished:

- river engineering measures (e.g. deepening the summer bed or widening the winter bed);
- dike improvement and building new dikes; and
- prohibition of building in the flood plains: in the last ten years many new activities have been started in flood plains (in The Netherlands) which have caused a lot of flood damage.

The river engineering measures lower the water levels at high discharges. Dike improvement measures are applied to be allow dikes to retain the water in extreme situations.

Analysis of the flood hazard assessment calculations

The flood hazard assessment model serves as a tool to analyse the consequences of potential strategies. The calculated value of the strategies is expressed in the following units:

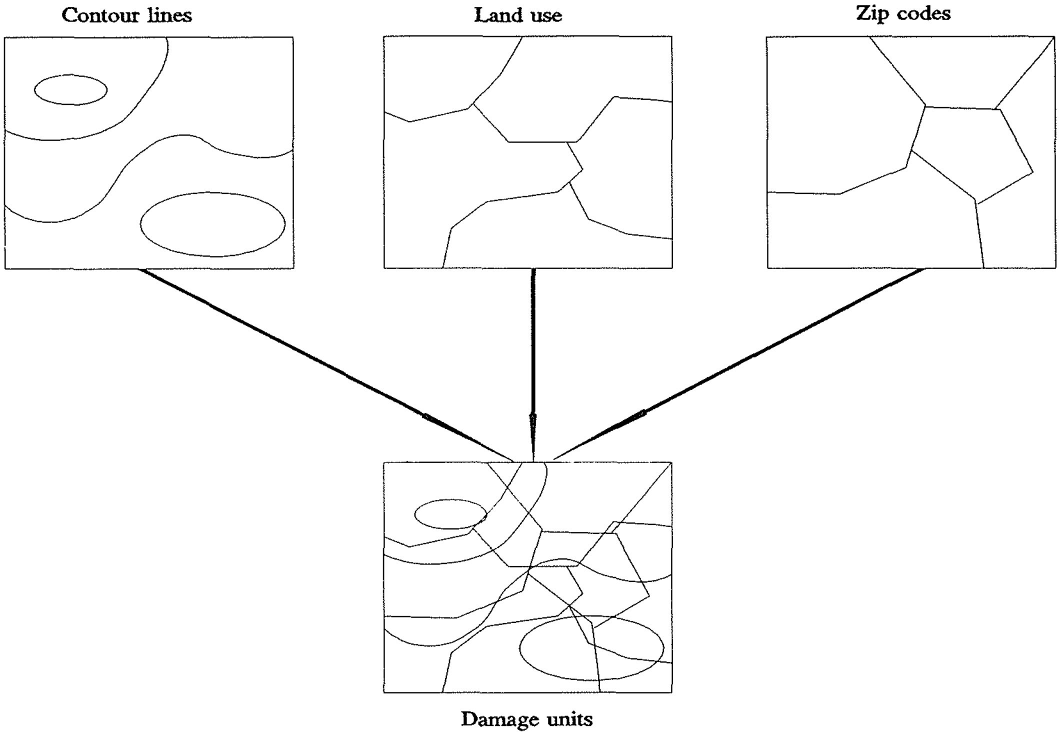

Fig. 2 Damage units.

- present value of the reduction in material damage and the remaining material damage (Mf, millions of Dutch Guilders):
- regional spread of these values (GIS maps):
- spread per municipality of damage suffered by public authorities, private persons, industry and agriculture (GIS maps).

The present value of the flood damage related to a strategy i is calculated according to:

$$PV = \sum_{t=1}^{T} \frac{B_i(1+rs)^t}{(1+R)^t} \tag{3}$$

where: PV = present value (Mf, millions of Dutch Guilders); B_i = flood damage for strategy i (Mf); T= time horizon; R = real discount level (no inflation) (-); rs = real increase in value (-); and t= year.

The evaluation of the strategies is based on the expected reduction of water overload. Since the expected damage per year is related to the variation in river discharges, the flood hazard assessment is integrated over the probability of occurrence, with R = 0.05 and rs = 0.01. The contribution to the present value of a discharge i is given by:

$$PV = \sum_{i=1}^{n} \left(P_i - P_{i+1}\right)\frac{(S_i + S_{i+1})}{2}25 \tag{4}$$

Table 2 Total damage caused by the River Meuse in December 1993 (Mf is million Dutch Guilders).

Damage category	Total estimated (Mf)
Private sector	**96.51**
- houses	80.76
- cars	1.00
- caravans	13.50
- gardens	1.25
Agricultural industry	**19.38**
Industry	**73.96**
- factories, building companies, trade, service	71.25
- extraction of raw materials	2.71
Institutions	**2.58**
Public sector and public utilities	**61.25**
- schools, buildings and terrains	6.55
- river infrastructure	21.93
- land infrastructure	15.43
- public utilities	7.30
- cleaning, service	10.04
Total	**253.69**

Table 3 Damage for a set of discharges, without and with measures (Mf is million Dutch Guilders).

Discharge of Meuse at Borgharen ($m^3 s^{-1}$)	Return time (year)	Damage with present situation (Mf)	Damage reduction by dike improvement (Mf)	Resulting damage (Mf)
3860	1500	716	0	758
3545	570	489	0	590
3310	270	273	0	281
3305	270	273	220	53
3120 (December 1993)	160	203	161	42
2990	110	174	138	36
2750	56	116	90	26
2500	27	76	58	18
2120	9	21	14	7
2000	7	0	0	0

where: PV = present value; P_i = probability of occurrence of discharge i; S_i = calculated damage for discharge i; and 25 = a factor for capitalizing.

CASE STUDY

The Flood Hazard Assessment model was applied to calculate the impact of several strategies for the river Meuse in the south of The Netherlands. During the flooding of December 1993 large areas along the river Meuse were flooded, causing enormous damage to industries, agriculture, private persons, infrastructure, etc. (Table 2).

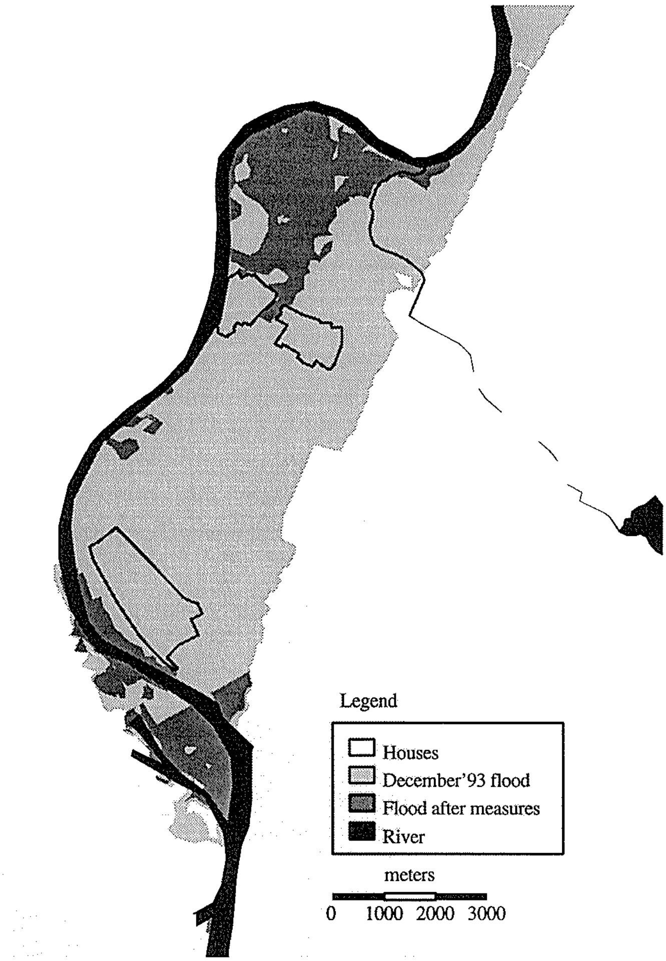

Fig. 3 GIS maps of flooded area without and with measures.

For eight discharges, calculations were made with the flood hazard assessment model (Table 3). The model was applied to the actual situation as well as to a range of strategies.

The main set of river engineering measures that were recommended comprised a combination of river engineering and dike improvement measures. The proposed river engineering measures were aimed at widening the summer bed in the southern part of the river and lowering the summer bed in the middle and northern parts. The dike improvement measures consisted of building new dikes around high-risk locations along the entire river and improvement of existing dikes (Fig. 3).

The flood model was validated by means of aerial photographs of the December 1993 flood, with a discharge of 3120 $m^3 s^{-1}$ and flood maps for a 1600 $m^3 s^{-1}$ discharge, during which the river starts flooding. For the calibration of the damage assessment model for the river Meuse, damage data (organized by zip code) of the December 1993 flood were used.

REFERENCE

Delft Hydraulics (1994) *Onderzoek Watersnood Maas, Schademodellering* (Investigation flooding of the Meuse River, damage modelling), Part 9. Delft Hydraulics, Delft, The Netherlands.