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Development of a Flood Risk Model and applications in the management of hydrographical catchments

Resume

Flooding is a natural phenomenon and is highly unpredictable, therefore inundations are always possible. In Flanders, the organization responsible for the management of flooding of navigable waterways is the Waterways and Marine Affairs Administration (AWZ). They believe that a good approach in dealing with flooding takes into account the actual effects of the inundation by analyzing risk. Damage calculation is used as an essential element in risk calculations, where risk is defined as a mathematical combination of the potential damage and the frequency of flooding. The calculated risk maps are used as a basic input in (social) cost-benefit analysis because they allow an objective comparison of different alternatives in different hydrographical catchments. This paper describes the state of the art AWZ Flood Risk model and some applications where risk calculation is used to assess changes in time and as a tool for planning infrastructure in the future.

Keywords: flood damage, risk, GIS, Flanders, land use

Introduction

Until recently, it was quite generally thought that inundations could be avoided if dikes were high enough. To avoid flooding, the water has to be drained downstream as fast as possible. In water management, flood inundation maps were used as a base to define safety levels and a methodology based on the recurrence period of floods maps was constructed. The result of such approaches is that there is no clear distinction between areas where the flooding impact is devastating (e.g. flooding of urban fabric, infrastructure and industries) and areas where inundations with the same water level have little or even no economical effects. It was not possible to make accurate statistical comparisons of the level of security in the different hydrographical catchments by using these existing methods. Therefore it was necessary to develop techniques that would enable objective comparison of levels of security within hydrological catchments. These techniques should also enable efficient management of the 11 hydrological catchments within the Flanders region (Figure 1).

Nowadays, it is an accepted fact that flooding is a natural and unavoidable phenomenon and a total protection is socially and economically not justifiable and even technically not possible. Investments in water policy are still necessary but are no longer synonymous with hard infrastructure construction only, for example, dikes and wharfs, but there is a move towards installing soft infrastructure (for example, controlled overflow zones, river rehabilitation e.t.c). Permitting flooding within a controlled area or a higher water level in one place can circumvent or diminish flooding at another site where the effects would be more devastating. This is stated in the Governmental Note of ‘Public Works 2004-2009’ (Minister K. Peeters) that:
"... water cannot be controlled, at best it can be managed
... instead of preventing inundation, the starting point is to drive back the risks affecting safety"

**Figure 1:** Flanders region with indication of the eleven hydrographical catchments
Dender catchment (see applications) in grey

In addition to an upstream control of discharge and the delimitation of overflow zones, a uniform risk approach was developed in this on going research to compare the safety levels objectively in different hydrographical catchments. This methodology incorporated the Dutch damage functions (Vrisou van Eck *et al.*, 1999) adapted for the Flemish situation. This resulted in the development of a new methodology adapted for the management of navigable waterways within Flanders.

**Damage**

The risk methodology is based on the seriousness of the effects of flooding, mathematically combined with the opportunity of an inundation occurring. It is therefore imperative to define and calculate damage. There is no universally accepted definition of damage but for the purposes for this ongoing project it is defined as material losses due to a flood event. On the other hand the term risk is a mathematical combination of different potential damages and their recurrence period. Risk is the statistically expected annual cost expressed in monetary terms. Further definitions of risk are listed below.

In risk analysis, the replacement value of objects is used to characterize damage. This is more or less similar to the way insurance industries define damage and compensate it. An alternative is working with the value of the new object and not the replacement value. The last option is based on the assumption that the damaged property has to be totally renewed and the owner has to pay the full price.

Damage can be separated into different categories (De Maeyer *et al.*, 2003), for example:
- monetary valuable versus non monetary valuable damage;
- internal versus external damage;
- direct versus indirect damage.

In the Flemish region, AWZ incorporates only the monetary valuable, internal, direct and indirect damage in analyzing risk. It means that non monetary valuable objects for example, goods with a high emotional value like photographs or collections, are taken out of the analysis and only the accepted price of the material itself is taken into account. Internal damage only occurs in situ the inundated areas. Finally, both direct and indirect costs are taken into account. Direct damage due to the effects of water involves
material property. Indirect damage occurs through production losses or cleaning up costs. Calculation of external damage, which is defined as damage outside the flooded region mainly due to customer supplier relations is difficult or even impossible to compute. This is because the reaction to flooding by customers or suppliers will be highly dependent on the individual entrepreneur, the duration of flooding, the affected stocks in every part of the industrial chain and other players on the same market.

This study covers inundations by rivers under the management of the AWZ, with the Flanders Hydraulic Research Division (FHR) responsible for the monitoring of waterlevels, discharges, inundations, hydrological research, environmental studies and hydraulics. Generally, detailed information of the hydraulic infrastructure in Flanders is not known, that is, internal composition, internal ground water level, resistance against uplift forces and so on. Only overflow is considered as a failure mechanism. Wave overtopping, piping, erosion of the outer slope and slip plane of inner and outer slope are conceptually taken into account. Flooding of sewer systems or the rising of the groundwater level above the ground is not taken into account.

When applying a methodology based on damage and risk calculations for the whole of Flanders, it is impossible to incorporate all the potential damage to individual objects within the flood plains. Objects are aggregated but it has to be kept in mind that the spatial resolution of basic data is different for different land use classes. The correctness and level of detail of the attribute data is also different or even not exactly known. This results in the generalization of potential damage assessment and conclusions are not valid at the level of the individual ‘object’.

For each homogeneous land use area, the maximum damage per surface is first calculated. These damage maps are combined with water level maps to compute the potential damage using depth-damage relationships (Figure 2). Maximum damage varies in relation to the type of object per land use and the their critical water levels for example, for cars it is 2 meters, agricultural land is 4 meters, industry 5 meters.

![Figure 2: Damage functions: potential damage (fraction of maximum damage) as a function of water depth](image-url)
In reality, artificial objects as houses and industrial buildings are a little bit higher than ground level. This level is taken into account because the damage-depth relationships are calibrated if water enters the building. Examples of the calculation method can be found in Vanneauville et al. (2003).

Risk

Several definitions for risk are possible (Coste 2001), for example:
1. Risk and law
   In an actual juridical context, a major risk is "unpredictable in its intervention and irresistible in its effects"
2. Risk and insurance
   Evaluation of a risk is the product of the strength and the probability of the intervention of an event to fear
3. Risk and culture – UNESCO
   "Risk is the intersection of an uncertainty and vulnerability"
   Risk = uncertainty x vulnerability

The last definition is adopted when defining a risk due to inundation of navigable waterways in Flanders.

Mathematically, risk is a combination of all potential damages and the probability of each event (formula 1).

\[ R = \sum_{i=1}^{n} \frac{1}{S_i} \]  

**Formula 1: risk as a combination of damages and probability**

where:  
- \( R \) = risk
- \( S_i \) = damage related to a flood with a return period of \( i \) years

Risk is an expression of the statistically expected annual damage in a limited zone. So calculation of damage and risk implies knowledge of potential exceptional water levels in waterways and their probabilities. Details of the propagation of water levels into the flood zone must be well known. The calculation of the statistical return periods is done by composite hydrographs for the upstream boundary condition and a discharge or water level relation of composite limnigraphs for the downstream boundary. Using this methodology, all return periods along the river and in the floodplains are the same for one simulation.

Using synthetic boundary conditions in the hydraulic river models makes it easier to compare different hydrographical catchments. Inundation maps indicating water levels are still essential, but are combined with damage maps derived from land use maps.

Polygons, lines and point objects

Most of the land use maps of the basic model are based on interpretations of satellite images: Corine Land Cover (based on Landsat), Small Scale Land Use Map of Flanders and Brussels (based on Spot), and a classification based on IKONOS imagery. Regional zoning plans, digital topographic vector maps and statistical data on community or sub-community level are added. The land use maps derived are more detailed for classes where the expected potential damage is high for example, urban fabric and industrial zones, and is less detailed for classes where the expected economic damage is low for example, semi-
natural areas, water bodies, and forests.

The risk model is constructed for the public authority, therefore both private and public goods must be included. Risk is further refined by integrating line elements (e.g. roads and railways) and point elements (e.g. drinking water installations, historical buildings, telecommunications infrastructure, subway entries, e.t.c) into the spatial information. These line and point elements are selected for their significant difference from the environment in potential damage and damage functions. All this information is combined as shown in figure 3.

**Figure 3: Combination of point, line and polygon elements in land use maps**

**Victims**

Potential economic damage for a specific flood is dependent on the maximum water level. Victims are defined here as „mortal victims, directly related to the inundation“. Both the maximum water level and rising velocity are taken into account in computing the risk for victims. The results for victims’ risk are taken out of the material risk based on economic damage. Controlling the height of extreme water levels or on recurrence periods through interventions can have different effects on economic damage and victims. For example, raising the level of a dike can decrease the material damage or risk but increases the risk for victims if the dike fails. Studies are being undertaken, for example, in the United States to try to make victims monetary valuable. In Flanders, this approach will probably not be adopted because policy makers have chosen to keep it out of the economic risk analysis.

A lot of factors influence the number of victims due to inundation in Flanders and they are grouped as ‘inundation characteristics’ and ‘inundated zone characteristics’. For example, meteorological conditions and water quality are inundation characteristics and construction materials and evacuation possibilities are characteristics of the inundated zone. Time is a key factor influencing almost all the other characteristics. Different formulas to define the relationship between victims and inundation characteristics can be found in De Maeyer et al. (2004). Figure 4 is an illustration of the formulas for victims chosen in the Flemish case.
Unlike buildings, infrastructure, crops and other stationary objects, people can move and their location is constantly changing. This presents a problem in the victim model in the way people are spread over the flooded zone. Though statistical data of habitants is available, it does not pinpoint exactly where individuals are located at any particular day or time. The underlying assumption made in the Flemish case is that people are ascribed to their houses, though this is more probably accurate at night time versus day time. This can be justified by the fact that warning times are longer and organizing evacuations during floods at night are more difficult. The number of victims calculated is considered as a kind of an upper boundary condition. Combination of several inundations to define a victims risk is done exactly in the same way as for damage (Formula 1).

Applications

There are several possible applications for the damage and risk calculation model. Taking into account only the actual land use, hydraulic and meteorological conditions, it is possible to define the expected annual costs for all private and public goods, due to inundations. It becomes more interesting when comparisons are made through simulations.

When working in an operational environment, it is not the past that is of main interest but the future. Planned alternatives can be compared with a recorded flood event for example, the land use patterns in the past are known, but extrapolations or assumptions have to be made in predicting future patterns. The scale of human intervention can differ a lot, from local adaptations to master plans for a whole river catchment. In both cases, risk methodology is a useable tool if the uncertainty in the basic data and interactions during the calculation are well described.
**Application 1: Denderbellebroek**

The Denderbellebroek (DBB) is situated downstream on the Dender catchment, just before the Dender flows into the Scheldt. The Denderbellebroek marsh (Figure 5) is used as a storage area for the Dender when its water level is too high and it is not possible to drain the water into the Scheldt because of its tidal regime. When the water level in the Scheldt is low enough and the Dender can drain into Scheldt, the water is pumped out of DBB into the Dender.

![Location map of Denderbellebroek](image)

**Figure 5: Location map of Denderbellebroek, see figure 1 for Dender catchment area in Flanders**

If there are extremely high water levels on the Dender for several days, pumps are not able to empty the DBB anymore and there is threat of flooding as several brooks flow into the DBB area. Finally, when the water in the Dender cannot flow into the Scheldt during high tide and not in the full DBB, the whole surrounding area is under threat of flooding. At first, installation of pumps with a higher discharge capacity was considered. Simulations of the hydraulic Dender model proved that discharge sluices would be much more efficient and are expected to be less costly than pumps. Several hydraulic calculations showed that discharge sluices of 12 meter width are sufficient to empty the DBB in time during low tides into the Scheldt.

A risk calculation was executed. The actual situation was compared with the planned alternative of using 2 discharge sluices, each of 6 meters (Figures 6 to 8). Comparison of the inundation maps of the actual situation and the planned alternative showed a decrease in water depth and a smaller extent of flooding. Although, it intuitively implies an improved scenario, it is impossible to quantify that improvement. Performing the risk calculations demonstrated that there is a 30% risk decrease in the study area. The risk within the upstream sections of the Dender remained stable. Although the values on the risk map (and the risk difference map) cannot be interpreted as exact values, they provide a good estimate of the decrease in risk.

Although there is flooding to the north of the controlled inundation zone, the water levels decreased significantly. Statistically, the floods in this area were lowered. This resulted in a reduced water level on a small area, in this case a residential area although the same effect can occurs when the land use is industry or infrastructure. This therefore has a significant influence on the total risk.
As stated before, it is not only an economic evaluation that has to be made by the water management but the social aspects also have to be considered. When the cost of intervention can be justified in comparison to the benefits, it does not necessarily mean that the benefits will be significant. The social aspects considered include the number and nature of people affected. The effects include damage due to flooding, loss of natural and historical values, nuisance during construction or maybe even permanent discomfort. Human mortalities are also taken into account as negative effects.
Some simulations are now being undertaken to study the effects and probabilities of dysfunctional sluices during high water periods. Initial results show an increase in the inundation area and water levels and so therefore an increase in risk. However, the situation seems to be improved with pump installations only and no discharge sluices and better than other studied alternatives where there are more pump installations.

The difference in risk between the two situations for example the actual state and a planned alternative, are the benefits realised after performing an economic cost-benefit analysis. The benefit of reduced annual damage has to be compared with all costs to evaluate the alternative situation. These costs include not only the construction cost but also the cost of execution within a pre-defined time period (e.g. 50 or 100 years) for which the intervention is planned to be effective. The economic optimum (see figure 9) will be reached when the sum of all costs including residual damage and the cost of policy actions is minimal (Vannewville et al. 2003).

![Figure 8: Difference in risk between the actual situation and the planned alternative (green to blue values: decrease of risk after construction of discharge sluices) (background: topographic map 1: 10,000 © NGI Belgium)](image1.png)

![Figure 9: Economic optimum in the cost benefit analysis.](image2.png)
Application 2: Evolution of risk in different hydrographical catchments

This project was carried out for MIRA, the Nature and Environment Report of the Flemish Land Agency (MIRA 2004). The aim was to search for indicators of change in the environment within a medium long period. The risk of flooding, as defined earlier in this text, is used as an indicator for “Disruption of water management” (MIRA 2004). For different catchments in the Flanders (Dender, Demer and Meuse), risk calculations were made for the situations in 1995, 2000 and 2004.

As expected, the economic damage and risk was highest within the urban fabric and industrial areas. Other areas with a lot of infrastructure also had high risk. Due to the extensive agricultural land, that is, arable land, meadows, and low-lying areas mostly used for agriculture in the past, the total risk to agriculture is significant within the catchments (Figure 10).

![Figure 10: Contribution to the total risk in the Dender catchment for different land use classes.](image)

In the Dender catchment, the contribution of urban fabric to the total risk seemed to have increased between 1995 and 2004. This can also be attributed to a general increase in the urban fabric surface area. Standardization in the classification systems applied in the observed time period could have also influenced these results through ambiguous class definitions. The land use maps used for 1995 do not have exactly the same class definitions for urban fabric as in 2000 and 2004, therefore further study will be necessary.

Contribution to total risk of the industrial zone occurred between 1995 and 2000, while there were decreases observed in agriculture and other land uses. In this study, generalized data was used, therefore the role of local improvements designed to combat flooding, for example, new small controlled overflow zones or more efficient use of local expropriates and groins are not always clearly identifiable. The absolute value of risk increased for all land use classes, due to inflation or more general due to the evolution of prices, but the relative contribution to the total values evolves in a different way.

Future monitoring and evaluation is therefore imperative because the economic value of areas will evolve differently over time. For specific situations, for example, application 1-Denderbellebroek, local objects can be brought into the model in a more detailed way. When comparing different catchments, this is less useful and calculation times will be significantly increased. One of the first considerations made in developing this methodology for risk calculations was to ensure that the data used for the whole of Flanders had the same positional and attribute accuracy. Projects like MIRA further ensure that all time series data be based on the same algorithms and definitions.
Conclusions

The risk methodology developed and implemented in this project is an essential component of economic cost-benefit analyses. This technique is useful for evaluating flooding effects on property and victims within the floodplain. Comparisons of damage and risk on a specific site over time are made available and can be extended every time when more composite hydrographs and hydraulic models are available. Changes in the hydraulic infrastructure and also differences in land use over time can be investigated. Risk calculations also enable objective comparisons of different catchments or different regions in general. Because all results must be interpreted in a relative way, the method is more useful for comparisons rather than for computing the exact risk as a monetary value per surface area per time.

Ultimately, a risk calculation is also one of the main inputs in a social cost-benefit analysis. With the information from risk calculations, policy makers and water managers will be able to weigh the economic damage against less quantifiable factors, for example, natural and historical values.

When risk calculations are being undertaken for all navigable waterways in Flanders, there will be need to define a Flemish Safety Level, that is, a single standard of protection against flooding (HIC-WLH 2003). This means that, based on risk calculations, policy makers of the Flemish Government and administration work on an edict that guarantees the same protection against flooding for each citizen in Flanders. The same protection can be defined as the same risk for every individual.

The methodology and calculations schemes are ready to use in an operational environment. Further improvements are advisable, for example the transition from individual risk to community or societal risk. An event is less acceptable when a lot of people are negatively influenced by it at once. Even if the probability of occurring is very low, if it negatively affects a lot of people then it is also less desirable. A well known example is found in traffic studies where more people die in car accidents then in plane crashes. Nevertheless most attention goes to airplane accidents. Flooding is also an event concerning many people at once, so the social acceptance, willingness to pay to avoid situations and the social cost-benefit optimum can be reached more directly when societal risk is brought into the methodology.

Everywhere in Western Europe, flood safety levels are being defined by taking into account the effects of inundation. All regions or countries use methodology and calculation schemes based on the available data and based on their specific needs. Due to local situations, the accent of models is different everywhere in Europe. The Flemish method can deal effectively with damage due to salt water and its flexibility allows the addition of new sub models. Some additional elements like old windmills, drinking water areas, telecommunication infrastructure and so on are taken into account. This new Flemish model is detailed where necessary and calculates many scenarios fast when answers are required immediately. On the other hand, the German method is more detailed for indirect damage and in Great Britain much more detailed damage classes for urban fabric are taken into account.

Some comparisons for example in Proses (2004) have been made to compare the results of the Flemish and Dutch risk calculation studies. There are research plans to compare more methodologies by calculating risk for small areas using techniques developed in Great Britain, Germany, The Netherlands, Belgium and Denmark. It will also be advisable to calculate risk in several areas in different countries using same methodology. The results of all these studies will not necessarily lead to the adoption of a single method for the whole of Western Europe, but must make it possible to compare results from different countries in a more detailed way. Unfortunately, rivers and flooding areas does not stop at national boundaries and actions to avoid damage and decrease risk on an international scale will be more efficient if objective comparisons of the methodologies are possible.
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