River System Behaviour Effects on Flood Risk

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ABSTRACT: A risk-based safety approach is indispensable to support decision-making on flood protection strategies and measures. Hitherto the effects of river system behaviour on flood risk have usually been neglected. River system behaviour refers to the fact that the flood risk (or safety) of a particular area may depend on the safety of other adjoining areas. This paper presents a method for quantification of these effects. To this end state-of-the-art modelling techniques of the hydrodynamic loads on the flood defences and the geotechnical strength as well as a module for the estimation of flood damage have been integrated in a probabilistic framework. The method is illustrated by means of a case study, considering two dike failure mechanisms. Models of different degrees of complexity are applied to reduce the number of calculations for the computationally intensive hydrodynamic model.

1 INTRODUCTION

Detailed assessment of flood risks, both on regional as well as on national scale, has been a topic of extensive research in the Netherlands since the early nineties of the past century. A risk-based safety approach is indispensable to support decision-making on flood protection strategies and measures. Hitherto the effects of river system behaviour on flood risk have usually been neglected. River system behaviour refers to the fact that the flood risk (or safety) of a particular area may depend on the safety of other adjoining areas. It is possible that a measure to improve safety from flooding of a particular area might increase or decrease the safety of other areas, located within the same hydrological system.

For quantification of these effects, state-of-the-art modelling techniques of hydrodynamic loads, geotechnical resistance as well as a module for the estimation of flood damage have been integrated into a probabilistic framework (hereafter referred to as the computational framework).

The present study is a follow up of an earlier study carried out in the *Delft Cluster* research project in the Netherlands (*Van Mierlo et al 2003 and 2007*). This former study was a 'proof of concept' on a fictitious example case. In the current study the same basic concept, with a number of technical extensions, is applied to a real flood protected area in the Netherlands, situated between the rivers Rhine and Meuse.

2 RIVER SYSTEM BEHAVIOUR

A system considered in our study of river system behaviour is a geographically defined (river) flood prone area. It includes rivers or river branches within this area and (natural or man made) flood protection structures. The boundaries of the area must be chosen such that:

1. flood risk of the protected area depends solely on the discharge (load) characteristics of rivers or river branches and the strength characteristics of flood protections within the area,
2. at the boundaries of the area, discharge characteristics of the rivers or river branches are autonomous, i.e. are not influenced by potential flooding events within the area,
3. flood risk of external areas is not (significantly) influenced by potential flood events within the area and vice versa.

With river system behaviour within the area we mean the dependence of flood risk of parts of the protected area, due to failure of flood protection elsewhere within the area.

A distinction can be made between beneficial and adverse effects (or increase or decrease of safety) of system behaviour.

In case of a single river system, the failure of a local embankment might result in the fact that the flood hydrograph is attenuated and hence the hydraulic load on downstream located embankments is reduced, leading to an increase of the safety of the downstream areas. However, for more complex river networks (like the Rhine and Meuse river system in the Dutch delta) the failure of a local embankment may result in an increase of the hydraulic load on embankments elsewhere in the system.

An analysis of the effects of system behaviour on flood risk has to consider the following aspects (*Van Mierlo et al, 2003 and 2007*):

1 Hydraulic/hydrological aspects,
2 Geotechnical and structural aspects,
3 Flood risk aspects, and
4 Societal and institutional aspects.

This paper focuses on the first three aspects, constituting the computational framework. For a complete assessment also societal and institutional aspects must be considered, dealing with policy making, crisis management, risk perception and risk communication, as well as human interventions in the flood defence system.

3 COMPUTATIONAL FRAMEWORK

Before explaining the procedure for determining flood risk (see 3.5), first the components of the computational framework are discussed:

– Methods applied for establishing flood risk and failure probability,
– Considered dike failure mechanisms,
– Breach development in case of dike failure,
– Hydrodynamic modelling, including evaluation of failure mechanisms and upon failure controlling the breach development process,
– Determination of flood consequence (or damage modelling).

3.1 *Definition and methods for establishing Flood Risk and Failure Probability*

The definition of flood risk in this study is the combination of the occurrence probability of potential flood scenario's and the associated consequences. In other words, the general problem in determining the risk R can be expressed as the expected damage:

$$R = E[D] = \int D(\underline{x}) f(\underline{x}) d\underline{x} \tag{1}$$

where: $E[\cdot]$ = expectation operator
D = damage
$\underline{x}$ = vector of random variables
$f(\underline{x})$ = probability density of $\underline{x}$

The random variables in $\underline{x}$ are parameters relevant for the strength of and loads on the flood defences as well as parameters to estimate the damage as a function of flood characteristics. Note that the damage can be multi-dimensional. In the following, the capitalized monetary damage and human casualties will be treated apart, both according to the same principles.

In the presented computational approach, Monte Carlo simulation is applied to generate a finite set of realizations of the random variables, from which the risk can be estimated as:

$$R = E[D] = \frac{1}{N}\sum_{i=1}^{N} D(\underline{x}_i) \tag{2}$$

where: $\underline{x}_i$ = i^{th} realization of $\underline{x}$

The definitions in (1) and (2) may relate to any time interval and region in space, e.g. the annual expected damage of a certain geographical region.

The reliability of the flood defence system is determined in a similar manner and is expressed in terms of the probability of failure:

$$P_f = \int_{Z<0} f(\underline{x}) d\underline{x} \tag{3}$$

Where $Z<0$ refers to the region in the random variable space where the performance function is negative. A performance function, associated with some failure mechanism, divides the space of random variables, involved in the failure mechanism description, into an unsafe subspace (where Z<0, implying failure) and a safe subspace (where Z>0, implying non-failure). The boundary between the regions is called the limit state (hyper) surface, where Z=0. The performance function is based on limit state analysis of the failure mechanism, yielding a limit state function (LSF) that expresses the limit state as a function of the random variables.

Formula (3) can be evaluated by means of structural reliability methods like the First Order Reliability Method (FORM) or Monte Carlo Sampling (MCS), amongst others. MCS is more time consuming than FORM for relatively low numbers of random variables as in this problem. When a system involves two or more different failure mechanisms, consequently as many LSF and performance functions have to be defined. With MCS several (nonlinear) LSF can be evaluated simultaneously, whereas FORM treats only one LSF at a time by means of linearization. For obtaining the system reliability, FORM results can be combined using system reliability techniques, e.g. (Rackwitz & Hohenbichler, 1983). The computational framework comprises modules with both options, using FORM or MCS.

For the presented case study, MCS was the method of choice, therefore the failure probability is estimated by:

$$P_f = \frac{1}{N}\sum_{i=1}^{N} I_{Z<0}\left(\underline{x}_i\right) \tag{4}$$

where $I_{Z<0}(x)$ is an indicator function being 1, if x is in the subspace Z<0 and 0 elsewhere.

3.2 *Failure mechanisms (geotechnical modelling)*

The modular structure of the developed computational framework allows the implementation of virtually any structural model to represent the resistance of the flood defences.

For the area treated in the presented case study we are dealing mainly with river dikes. Previous risk analyses have shown that the dominant (most probable) failure mechanisms in the area are ‘heave and piping’ and ‘overflow and erosion of the inner slope’ (*see VNK 2005*). For sake of simplicity, analytical and semi-empirical expressions are used as descriptions for the failure mechanisms. Other mechanisms are neglected for the time being and their contribution to the failure probability is speculated to be small. More detailed analyses in the future will also have to consider other structures, like locks, that form part of the flood defence system.

Each mechanism is formulated as a performance function Z:

$$Z = R(\underline{x}) - S(\underline{x}) \tag{5}$$

with:
$R(\underline{x})$ resistance part of the mechanism
$S(\underline{x})$ load part of the mechanism

Both *R* and *S* are functions of the considered random variables $\underline{x}$. It implies that if *Z<0*, this is considered as failure and vice versa.

The described mechanisms are initiating mechanisms in a sense that they initiate failure of the dike. Once an initiating mechanism occurs, we assume that breach development occurs (see 3.2.4).

3.2.1 *Heave and piping*

This mechanism is a classical phenomenon in the Netherlands, where often a relatively thin and light clay and peat top layer with low permeability is situated above sandy layers near dikes (see Figure 1).

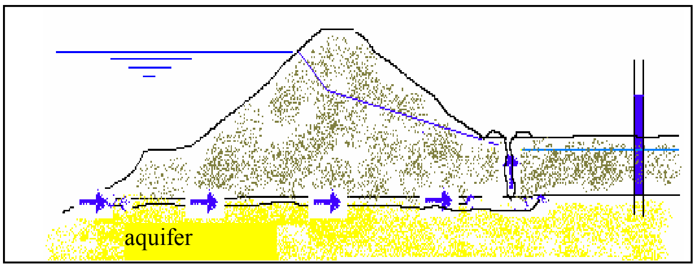

Figure 1: Heave and piping (illustration)

If these sandy underground layers are in hydraulic contact with the river, high pressures are built up during high water events. This can cause heave and breach up of the top layer on the land side. Subsequently, a backward erosion process is initiated. Water starts flowing in the sand layers from the river side towards the land side of the dike triggered by the hydraulic gradients, finally damaging the integrity of the dike body by undermining it.

For heave, a simple equilibrium approach is adopted (effective vertical stress at the bottom of the top layer smaller than zero) and for piping the approach by Sellmeijer (see *TAW 1999*) is used as a mechanism description, in which a critical head difference is determined based on geometrical and soil properties. For details, reference is made to (*Vrouwenvelder 2003*).

3.2.2 *Overflow and erosion of the inner slope*

In the considered regions wave overtopping is considered negligible, because there is usually insufficient fetch for significant wave generation. On the other hand, very high river discharges can lead to overflow of the dike. The river level exceeds the dike crest level (see Figure 2).

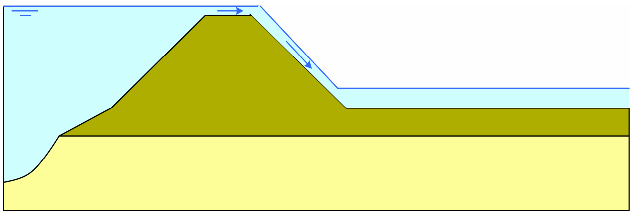
Figure 2: Overflow

The overflow discharge is considered critical, when it causes erosion of the cover layer at the inner slope of the dike (usually grass and/or clay). The formulation of these mechanisms is based on empirical formulae for determining a critical overflow duration with a certain critical discharge over a slope covered with a grass layer. For details, reference is made to (*Vrouwenvelder 2003).*

3.2.3 *Time dependence of failure mechanisms*

The time dependence is not explicitly treated with the formulations of the initiating mechanisms. Including time dependence might have an impact on the initiation of failure and is expected to have even more impact when system effects are considered. This is due to quicker changes of the river head caused by sideways outflow through dike breaches. Therefore, these effects should be considered in the future.

3.2.4 *Breach development*

The previously described mechanism descriptions are used to detect the initiation of failure, i.e. the loss of integrity of the dike. Once this occurs, a timedependent breach growth formulation is applied (e.g breach development a function of the flow passing through the dike breach) and the geometrical model is adapted accordingly (dike crest level decreases locally and the breach grows in width). This influences the further hydrodynamic development as well. For the present case, the breach growth formula by Verheij and Van der Knaap (2002) has been applied.

3.3 *Hydrodynamic modelling*

Flood risk analysis naturally considers hydraulic respectively hydrodynamic aspects as the main load components on the flood defences, like river heads or wave conditions. For the presented analysis it was necessary, in addition to predicting extreme loads throughout the considered system, to model the effects of local failures on the further development of the flood pattern. For this is the main driving mechanism in river system behaviour. Therefore, in each SOBEK computational time-step (±30 s), except for flood propagation also the failure mechanisms (see 3.2) assigned to each defence structure (e.g. dike section) are evaluated. Furthermore, in case of dike failure, the hydrodynamic model initiates dike breach. Thereafter the hydrodynamic model computes breach growth as function of the actual flow through the dike-breach (see 3.2.4). Evaluation of failure mechanisms as well as breach development are effected through the Real-time control (RTC) module in SOBEK. The 2D model of the considered area comprises both, the rivers and the protected area including the dikes. Hence, also the interaction between the development of river levels, breach development and inundation patterns is accounted for.

The flood pattern (e.g. maximum water depth, maximum flow velocities and the speed at which water levels rise) are the main input for determining the damage per scenario (see 3.4). These flood patterns, as already mentioned above, were computed using SOBEK (Dhondia, J.F. and G.S. Stelling, 2004), a one- (1D) and two (2D) dimensional hydrodynamic software package, developed at Deltares (until 2007 WL|Delft Hydraulics).

3.4 *Consequence / Damage modelling*

The damage per scenario is determined using the '*HIS Damage and Victims Module'* (HIS-SSM, see *Huizinga 2004*). This module is a GIS-based tool that requires the characteristics of the flood pattern (see 3.3) and the type of ground use as main input.

Per type of land use there are damage functions defined to relate the expected economical damage and the expected number of victims (*Jonkman 2007*) to the water depth in inundated areas and optionally also to the expected flow velocities. This is illustrated in Figure 3.

3.5 *Procedure for Determining Flood Risk*

The calculation procedure comprises five steps:

STEP I: Determination of hydraulic loads without considering effects of river system behaviour.

Initially, hydrodynamic calculations are carried out for the chosen geographical model, assuming absence of river system behaviour effects. That is, the hydraulic loads on the dikes are computed assuming that the entire flood wave passes through the system without any dike failure. These computations are carried out for a range of boundary conditions in terms of peak discharge at the upstream boundary of the system.

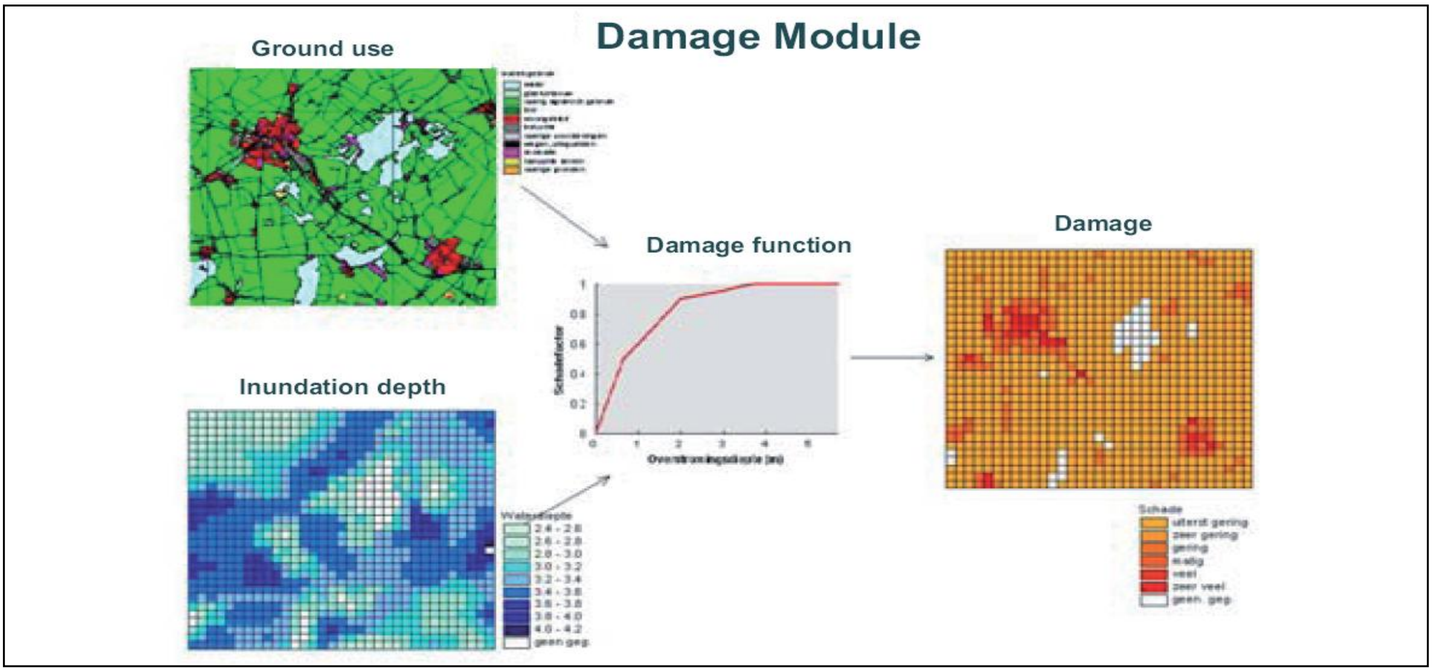

Figure 3: Flood damage determination with HIS-SSM (VNK 2005)

STEP II: A representative set of realisations, conditional upon failure.

At prefixed potential breach locations reliability analyses per section are carried out using Crude MCS. The realizations comprise properties of the dikes regarding the considered failure mechanisms as well as peak discharges at the upstream boundary of the geographical model. The load on the analyzed dike sections are interpolated between the values computed in step I. Loads and resistances are compared using performance function as described in section 3.2.

The results of this step are the probability that at least one dike (section) fails, a representative set of realizations, conditional upon failure (at least one dike section fails) and the complementary set of realizations, in which no failure occurs.

STEP III: Hydrodynamic calculations, allowing for effects of river system behaviour.

The hydrodynamic consequences (i.e. determining the flooding pattern) including the effects of dike failures and overflow are determined for the representative set of realizations obtained in step II. This is done by means of SOBEK calculations as described in section 3.3.

STEP IV: The corresponding damages.

No damage is assumed for the set of Monte Carlo realizations from step II, in which no dike failure occurred.
For the flooding patterns determined in step III, the expected direct economic damage as well as the expected number of human casualties is determined with the HIS-SSM module as described in section 3.4. The damage and casualty estimates are best estimates, thus, no uncertainty is considered in their determination.

STEP V: Determination of Flood Risk
Using equations (2) and (4) in section 0 and the flood damage established in step IV, flood risk and failure probabilities for the entire area as well as per prefixed potential breach location can be determined accounting for effects of river system behaviour. Note that the flood risk equals the failure probability of the dike ring times the average damage of the subset of realisations treated in steps III and IV.

4 CASE STUDYCASE DESCRIPTION

The described computational framework has been applied to the upper (river dominated) part of the Rhine and Meuse river basin, in the eastern part of the Netherlands. The model area or studied region included eighteen Dutch dike ring areas as well as two German polders located along the Niederrhein.
In this case study potential dike breach locations were only considered in one dike ring, called "Dijkring 41: Land van Maas en Waal" (see Fig. 4). At all other locations dike-sections cannot fail, but may be overtopped as soon as river levels exceed dike levels. More precisely 5 dike sections along

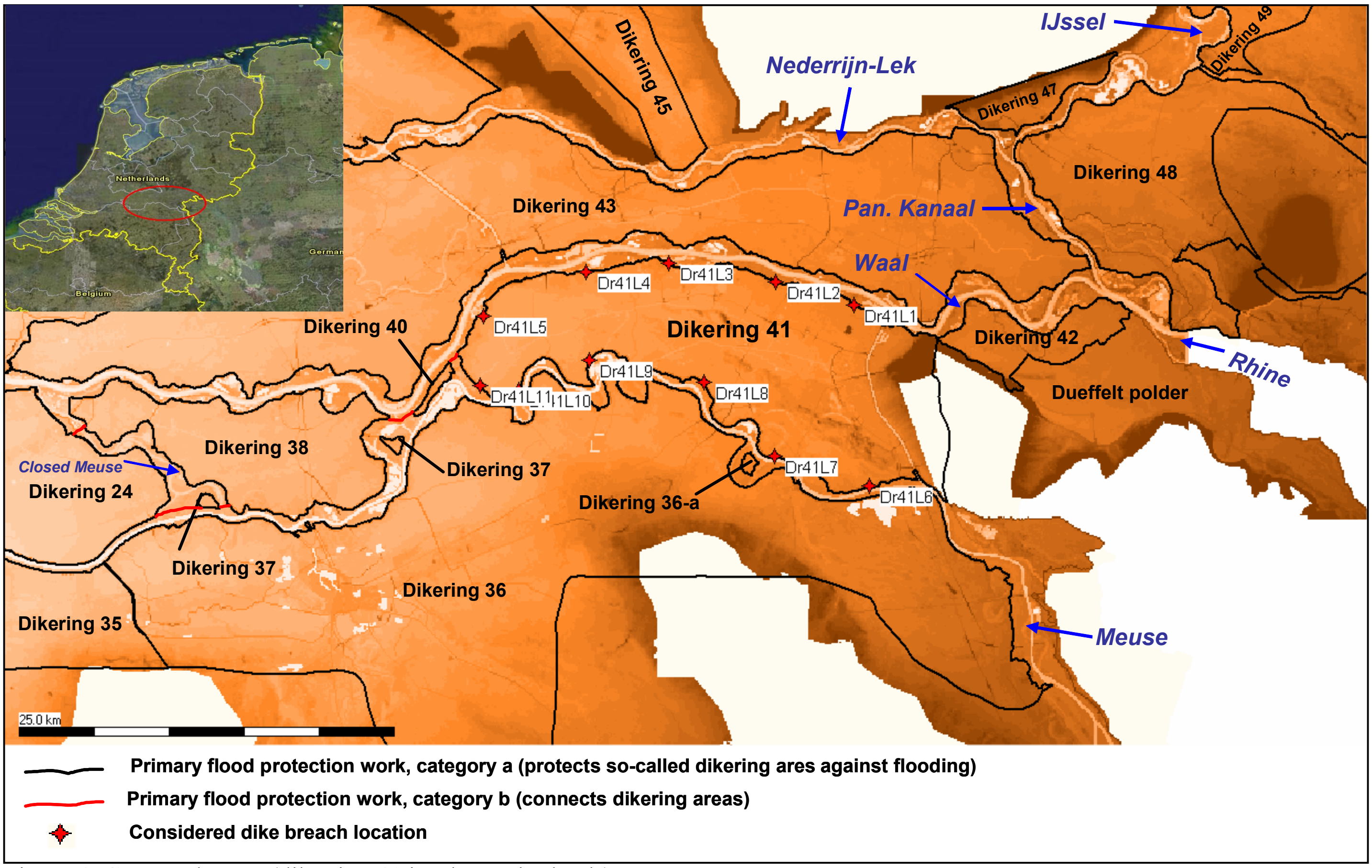

Figure 4: Case study area (dike ring 41 in The Netherlands)

river Waal (Dr41L1 - Dr41L5) and 6 dike sections along river Meuse (Dr41L6 - Dr41L11) were considered. These dike sections were selected based on the flooding characteristics of the concerned area. These eleven potential dike breach locations are used for a characterization of the flood risk. Additional research will be needed to see, if these locations are sufficient to characterise the flood risk of this area.

The analysis used $N = 7\ 10^6$ Monte Carlo realizations of the input parameters (Crude Monte Carlo).

4.1.1 *Initial and boundary conditions*

Upstream at river Rhine (e.g. at Lobith) and upstream at river Meuse (e.g. at Vierlingsbeek) flood hydrographs ($Q=f(t)$) with a certain return period were imposed. Downstream at the Meuse as well as on the river Rhine branches (deterministic) stage-discharge relationships were used.

4.1.2 *Dike characteristics*

Dike sections in the model can fail as a result of loads exerted on its river side as well as on its dike ring side, i.e. the dike is considered symmetric in terms of failure mechanisms for sake of simplicity.

As already mentioned, for all the other dike rings in the system it is assumed that its surrounding dikes cannot fail. However, these dikes can overflow as soon as river levels exceed dike levels.

Data on the probability density functions for the dike (resistance) parameters in the model region were available from the FLORIS project (VNK 2005).

4.2 *Results*

For STEP I a number of hydrodynamic model runs was carried out for a range of flood waves ($Q=f(t)$).

The evaluation of the $7\ 10^6$ Monte Carlo realizations in STEP II in the simplified model, neglecting system effects and using the water levels determined in STEP I, lead to 65 scenarios, in which at least one dike section failed in the system. This leads to an estimate of the failure probability for the dike ring of $P_f = 9.3\ 10^{-6}$ *[1/year]*, i.e. the probability per year of a flood event in the area as a consequence of a dike failure (*Remark: The absolute value of the failure probability is not considered to be representative for this dike ring, since in the calculations made no length effects were accounted for and only ten infinitesimally small locations were chosen. It is only of indicative nature.*). The variation coefficient of the failure probability estimate is about:

$$COV(P_f) = 1/sqrt(65) = 12\ \%$$

That is sufficiently precise for the present purpose. By the way, this failure probability is not influenced by effects of river system behaviour. The calculation time for STEP 2 on a standard issue 2 GHz Windows PC was about 12 hours.

In STEP III 56 hydro-dynamic computations were made for the representative set determined in the previous step. Computational efforts on a standard issue 2 GHz Linux PC varied from 140 to 580 hours (6 to 24 days) per model run. The required computational time is roughly a linear function of the maximum discharges imposed at the upstream boundaries.

The influence of system effects on the results becomes obvious when looking at the number of failures per potential breach location including and disregarding system effects, as illustrated in Table 1.

Table 1: Failure per potential breach location

Location	failures without system effects (STEP II)	failures with system effects (STEP IV / V)
Dr41L1	34	26
Dr41L2	32	16
Dr41L3	27	12
Dr41L4	19	3
Dr41L5	28	9
Dr41L6	13	11
Dr41L7	1	0
Dr41L8	11	2
Dr41L9	1	0
Dr41L10	3	0
Dr41L11	1	1

The table implies that in STEP II without system behaviour there have been runs with several dike failures per run at different locations. In step IV, accounting for system behaviour, the number of failure decreased in most of the cases per location. In this case there has been a positive effect of river system behaviour on the number of expected dike failures.

The damage determined in STEP IV is a function of, amongst others, the maximum water depth in flooded areas. such an outcome is illustrated in Figure 5.

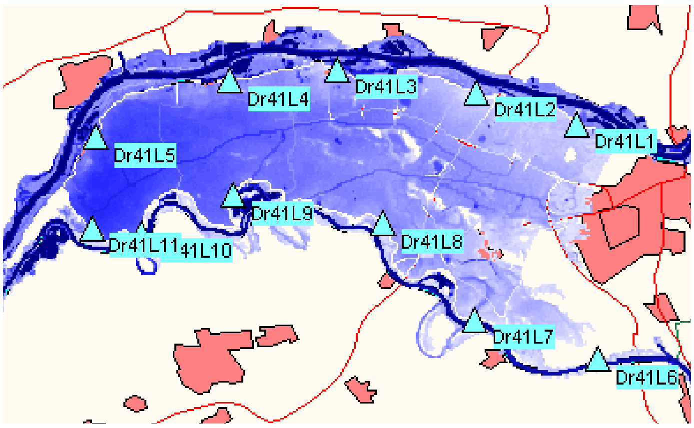

Figure 5: Maximum water depths after a scenario run

Finally, in STEP V the risk is determined in the dimensions of direct economical damage and human casualties. In this case the risk in terms of expected damage would be R = $E[D] = 5.5\ 10^4$ € per year for dike ring 41 (see eq. 2).

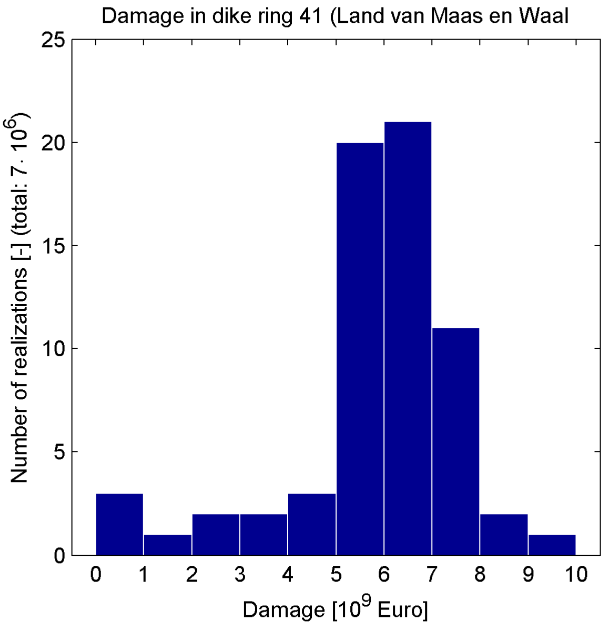

Figure 6: Histogram capitalised economic damage

As illustrated in Figure 8, the mean value of the damage, considering only the runs that lead to damage, was *5.9 10^9 € per year* with a variation coefficient of 0.29. That suggests that there is something like a typical damage value in case of an inundation of this dike ring, regardless of the way it is realised. This aspect requires further investigation.

The risk in terms of human casualties would be an expected value of *6.8 10^{-3} per year* (see eq. 2 with number of casualties for *D*). The histogram in Figure 6 shows that the representative scenarios do not yield a symmetric distribution (mean = 730) of casualties and a relatively high variation coefficient of about 0.50.

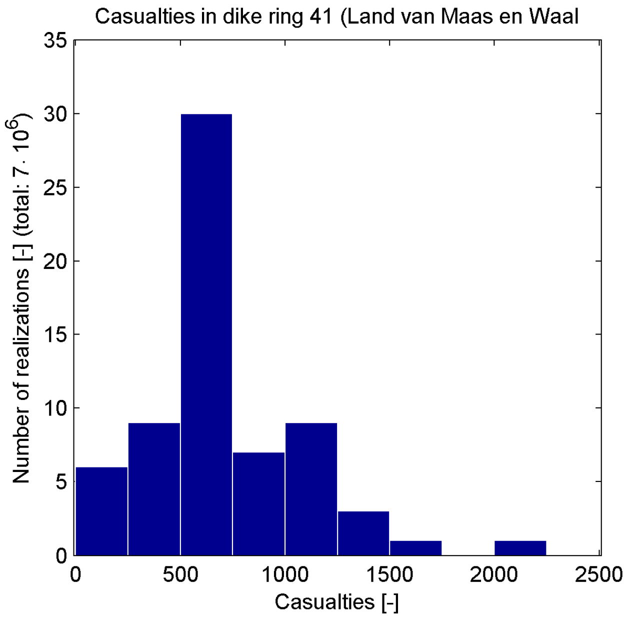

Figure 7: Histogram casualties

The numerical results so far only gave an indication of the importance of accounting for effects of river system behaviour (see table 1 and comments). This is mainly due to the fact that only one dike ring was considered in this test case. However, a closer look at the scenarios themselves reveals these effects clearly.

For instance in one scenario (no. 3, see Figure 7) the left Waal dike at location Dr41L1 fails as result the selected strength parameters and the hydraulic loads, exerted by a flood wave on river Rhine with peak discharge of 18.900 m^3/s. As a result of this dike failure, water flows through dike-ring 41 towards locations Dr41L10 and Dr41L11. Successively, the right Meuse dikes at locations Dr41L10 and Dr41L11 fails as result of loads, exerted on their dike-ring side. Consequently, a large volume of Rhine water flows towards river Meuse, that had to convey an upstream flood wave with a peak discharge of 4.300 m^3/s. The inflow of river Rhine water results in the overtopping of dikes along dike-rings 36, 38 and 39 (see Figure 7). In other words although the dikes along dike ring 36, 38 and 39 could not fail in this model setup, flooding of these three dike rings occurred as result of river system behaviour.

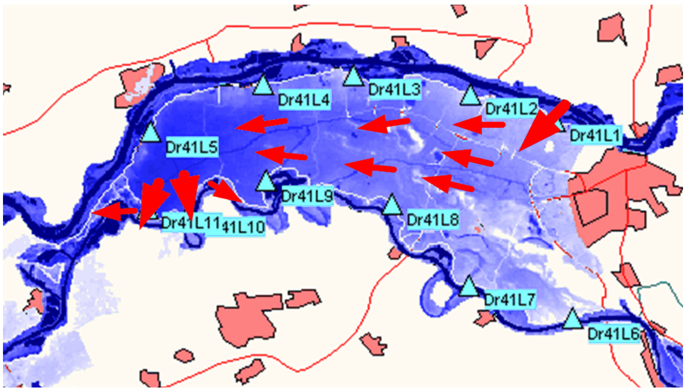

Figure 8: Flood pattern scenario 3

In another scenario (no. 23), a flood wave on river Rhine was imposed, having an extremely large peak discharge of 21.100 m^3/s. It is to be doubted, if such peak discharge from a physical point of view can occur on river Rhine. The overflow along dike ring 42, located upstream of dike ring 41, resulted in a decrease of water levels along downstream located Rhine tributaries Nevertheless, dikes along river Rhine tributaries were overtopped, resulting in flooding of three other neighbouring dike rings. The peak discharge on river Meuse was also large with 4,700 m^3/s, which resulted in failure at location Dr41L6. Consequently, dike ring 41 was flooded, resulting in a decrease of water levels downstream on river Meuse, leading to a reduction of loads on other dike rings. This is an example of beneficial effects of river system behaviour.

5 CONCLUSIONS

In the past, the effects of river system behaviour were not taken into account in flood risk analyses. The presented computational framework enables us to assess these effects.

Although only one dike ring was considered in the analysed case study, still the importance of considering effects of river system behaviour was demonstrated. Hence, the study is to be contemplated as proof of concept. The effects of river system behaviour would be more pronounced in case dike failures along all dike ring areas were considered. Unfortunately, this was not feasible before finishing this paper. This is, however, a goal for 2008.

5.1.1 *Computational framework*

- The computational framework is a modular framework that allows for implementation of all kinds of modules concerning probabilistic calculation techniques, structural models of flood defences, hydrodynamic modelling or damage assessment.
- The framework is suitable for including the effects of river system behaviour into flood risk analysis.
- The manner in which flood risk is determined, combining information about the land use with the potential flood characteristics calculated in a hydrodynamic model, is far more realistic than earlier approaches as for example in the FLORIS project.
- In the Netherlands currently there is a discussion about the efficiency of segmenting dike rings into smaller units by building dikes within these flood protected areas in order to palliate consequences in case of flooding. The presented tool is suitable for evaluating the efficiency of such plans in terms of risk.

5.1.2 *Case Study*

- The case study showed that system effects can be significant and is considered a proof of concept.
- The effects of river system behaviour are expected to be more pronounced, when larger regions are considered, e.g. several dike rings. This is supported by the effects found in the analysis.
- In the case study, in some scenarios the land side of a dike failed as a consequence of loads exerted on it from the inundated hinterland. As, mentioned earlier, the dikes were considered symmetric in terms of resistance parameters. The effect of this simplification has to be investigated in future studies.
- Even though a Crude Monte Carlo simulation is carried out, as in the case study, it was feasible to carry out the computations with reasonable time effort. This is because the computationally intensive hydrodynamic model has only to be run for scenarios that include at least one failure within the system. The efficiency could still be increased by applying Importance Sampling.
- An assumption for this case study was that the eleven chosen potential breach locations would give a representative image of the risk for the model region. This assumption has to be verified by additional calculations with more of such locations.

5.1.3 *Outlook*

The research project, within which this study has been carried out will finalize at the end of 2008. The goal until then is to apply the presented method to a larger model area with several dike rings. Furthermore, the effects of assumptions made in the proof of concept are to be investigated (symmetry of dikes, number of potential breach locations, etc.).

Furthermore, calculations without considering system effects, but with the same method for the flood pattern will be carried out in order to assess the (order of magnitude of) the error made disregarding system effects.

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REFERENCES

Dhondia, J.F. and Stelling, G.S., *Sobek 1D-2D integrated hydraulic model for flood simulation – its capabilities and features explained*, in sixth International Conference on Hydroinformatics, Singapore, Liong Phoon&Babovic (eds), World Scientific Publishing Compagny, ISBN 981-238-787-0.

Hohenbichler M., Rackwitz R., *First-order concepts in system reliability*, Structural Safety, 1983, pp. 177-188.

Huizinga, H.J. et al., 2004, *HIS-Schade en Slachtoffermodule*, version 2.1, manual. DWW-2005-004. RWS Dienst Wegen Waterbouwkunde.

Jonkman, S.N., 2007, *Loss of life estimation in flood risk assessment,* dissertation, Delft University of Technology, The Netherlands.

TAW, 1999, report "Zandmeevoerende wellen".

Van Mierlo, M.C.L.M. et al, 2003, *Effects of River System Behaviour on Flood Risk*, Delft Cluster-publication: DC1-211-1, Delft, The Netherlands.

Van Mierlo, M.C.L.M. et al, 2007, *Assessment of floods risk accounting for River System Behaviour*, Intl J. River Basin Management Vol 5, No 2 (2007), pp 93-104.

Verheij, H.J. and Van der Knaap, F.C.M., 2002, *Modification Breach Growth Model in HIS-OM*, WL|Delft Hydraulics, Q3299 (in Dutch).

VNK, 2005, *Flood Risk and Safety in the Netherlands* (Floris Study – Full Report), Dutch Ministry of Transport, Public Works and Water Management, , ISBN 90-369-5604-9.

Vrouwenvelder, A.C.W.M. et al, 2003, *Theoriehandleiding PC-Ring*, versie 3.0. TNO Bouw.