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Flood modeling for risk evaluation –a MIKE FLOOD sensitivity analysis

P. Vanderkimpen
Flanders Hydraulics Research, Antwerp, Belgium
Soresma, Antwerp, Belgium

P. Peeters
Flanders Hydraulics Research, Antwerp, Belgium

ABSTRACT
The flood risk for a section of the Belgian coastal plain was evaluated by means of dynamically linked 1D (breach) and 2D (floodplain) hydraulic models. First, a one-at-a-time factor screening was performed to evaluate the relative importance of various model processes and parameters. Subsequently, a systematic sensitivity analysis was added to establish the contribution of the most influential factors (breach growth and surface roughness) to hydraulic modeling uncertainty. Finally, the uncertainty associated with hydraulic modeling was compared to the uncertainty associated with coastal defense failure analysis. The former was found to be considerable, but nevertheless small compared to the latter.

Keywords: Flood risk, sensitivity analysis, MIKE FLOOD

1 INTRODUCTION

Flood risk analysis usually involves three distinct stages: (1) analysis of boundary conditions and flood defense failure probability, (2) hydraulic modeling of breach flow and flood propagation and (3) estimation of flood damage, casualties and risk. Each of these stages contributes to the overall flood risk uncertainty. The study reported in this paper aimed at quantifying the hydraulic modeling uncertainty and evaluating the relative importance of the uncertainty associated with the first and second stages of flood risk analysis.

2 REFERENCE MODEL

2.1 *Study area*

The study area (shown in Figure 1) covers the eastern part of the Belgian coastal plain, between Zeebrugge and the Dutch border. It is bordered by the sea to the north, canal embankments to the west and south and old sea dikes bordering a former tidal inlet (“Zwin”) to the east. It occupies an area of 75 km^2.

Figure 1. Study area (source: NGI).

2.2 Software

The model used in this study was constructed using the flood modeling package MIKE FLOOD (Danish Hydraulic Institute). This package offers the possibility to dynamically link 1D breach models (MIKE 11) to a 2D floodplain model (MIKE 21). For a full description of these models, reference is made to the software manuals (DHI, 2007).

2.3 *Boundary conditions*

Hydraulic boundary conditions (astronomical tide and storm surge) were obtained from an earlier analysis, carried out within the framework of the EU-funded Interreg IIIb project Comrisk (Anonymous (2005)). Three different return periods (4000 years, 10000 years and 40000 years) were considered. The studied storm surge lasts for 45 hours and is superimposed on three tidal cycles. Figure 2 shows the resulting storm water levels.

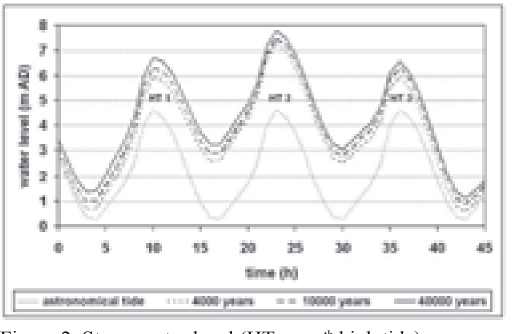

Figure 2. Storm water level (HT n = n[th] high tide).

2.4 *Breaches*

The number of breaches, breach locations and time of breaching were obtained from the coastal defense failure analysis performed as part of the Comrisk project. The location of the breaches is shown in Figure 3 and the time of breaching is summarized in Table 1.

Breach growth was described by means of time series for crest level and width. The initial depth equals 0 m for all breaches. The lowest crest level equals 6 m AD at Knokke (233-236), 5 m AD at Het Zoute (241-243) and 4 m AD at Zwin. Vertical growth takes place in less than 15 minutes for the breaches at Knokke and slightly more than 1 hour for those at Het Zoute and Zwin. Initial width equals 90 m at Knokke, 60 m at Het Zoute and 20 m at Zwin. Breaches at Knokke do not grow horizontally, whereas those at Het Zoute and Zwin were assigned a horizontal growth rate of 120 m/h. Maximum width equals 150 m at Het Zoute and 200 m at Zwin.

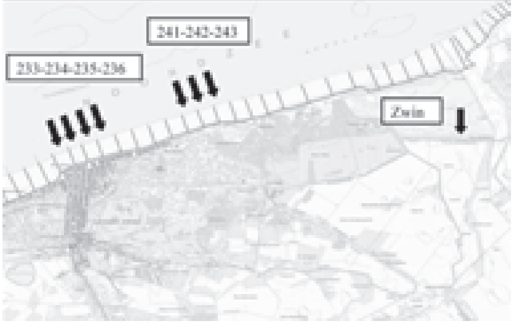

Figure 3. Breach locations (source: NGI).

Table 1. Time of breaching (HT n = n[th] high tide).

Breach	4000 y	10000 y	40000 y
233	HT 2 + 1 h	HT 2 + 1 h	HT 1 + 1 h
234	-	HT 2	HT 2
235	-	HT 2 + 1 h	HT 2 + 1 h
236	-	HT 2 + 1 h	HT 2 + 1 h
241	-	HT 2	HT 2
242	HT 2	HT 2	HT 1
243	HT 2	HT 2	HT 1
Zwin	-	-	HT 2

2.5 *Coastal plain*

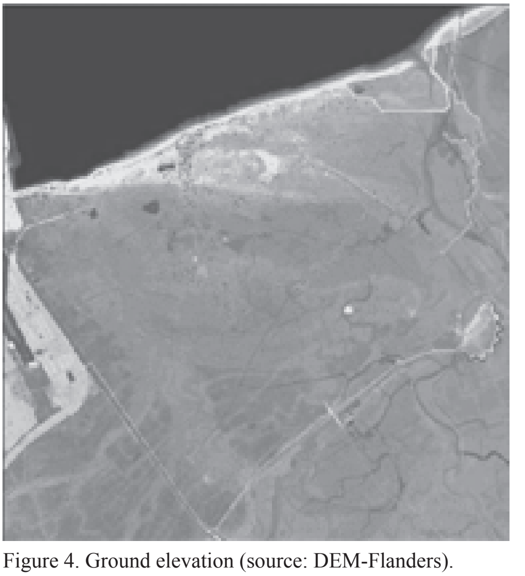

Figure 4. Ground elevation (source: DEM-Flanders).

The ground elevation in the coastal plain is shown in Figure 4. It ranges from sea level (black) to 15 m above sea level (white).

The land use is shown in Figure 5. The white areas correspond to the beach, dunes and tidal inlet. The black areas are urbanized and the grey areas are mainly rural.

Figure 5. Land use (source: Corine Land Cover).

2.6 *Flood damage and casualties*

Flood damage and casualties were computed by means of the procedures described in Vanneuville et al. (2006) and Verwaest et al. (2007). The calculations were limited to the Belgian part of the study area.

A distinction was made between "basic damage" and "additional damage". Basic damage refers to the damage caused by temporary inundation. It was estimated from the maximum water depth and a series of land-use dependent empirical damage functions. Additional damage refers to the damage caused by high flow velocities and mainly occurs in the vicinity of breaches. It was estimated by means of an empirical function, incorporating maximum water depth and maximum flow velocity.

$$D_b = \alpha_d D_{max} \quad (1)$$

$$D_a = \beta_d \beta_v (D_{max} - D_b) \quad (2)$$

where: D_b = basic damage (€/m²)
D_a = additional damage (€/m²)
D_{max} = maximum damage (€/m²)
α_d = depth damage factor (0-1)
β_d = depth damage factor (0-1)
β_v = velocity damage factor (0-1)

The number of casualties was estimated by means of an empirical function, based on maximum water depth and the maximum hourly rise.

$$C = \gamma_d \gamma_r I \quad (3)$$

where: C = number of casualties (#/m²)
γ_d = depth drowning factor (0-1)
γ_r = rise drowning factor (0-1)
I = number of inhabitants (#/m²)

The uncertainty associated with the use of these empirical functions may be considerable, but wasn't evaluated in the course of this study.

2.7 *Flood risk*

The annual flood risk was estimated from the damage and casualties associated with return periods of 4000, 10000 and 40000 years, following the procedure described in Vanneuville et al. (2002).

3 FACTOR SCREENING

3.1 *Approach*

The model described in the previous section was used as a reference. The impact of several factors (processes, parameters, options,…) was examined by altering one factor at a time and comparing the results generated by the new model to those of the reference model. In the following paragraphs, each scenario will be identified by means of an abbreviated code.

3.2 *1D Breach model*

The following modifications were evaluated:

Time of breaching: for each breach, the time of breaching was set half an hour earlier ("TBe") and half an hour later ("TBl").

Horizontal growth rate: the horizontal growth rate was reduced from a value of 120 m/h (Comrisk) to a more realistic value of 30 m/h (from literature review) ("HG").

Vertical growth rate: the vertical growth rate was doubled ("VG").

Growth by erosion: the time series describing breach growth were replaced by an erosion model. This model is based on the Engelund-Hansen sediment transport equation and was calibrated to the empirical Verheij-vanderKnaap breach growth model. Two versions were evaluated: without ("GE1") and with ("GE2") horizontal growth at Knokke.

Breach flow equations: the standard equations (Borda losses) were replaced by an alternate set (NWS DAMBRK) ("BFE").

3.3 *2D Floodplain model*

Roughness: the surface roughness (Strikler's k) was modified from 32 (default value) to 40 ("SRl") and 20 ("SRh"). In addition, surface roughness was varied as a function of land use ("SRv"). The land use classes and corresponding roughness coefficients are shown in Table 2.

Table 2. Surface roughness as a function of land use.

Land use	Roughness coefficient (Strickler)
Urban	10
Industry and infrastructure	15
Recreation	20
Agriculture	25
Forest	10
Nature	25
Beach and dunes	30
Aquatic nature	30
Water	35

Eddy viscosity: eddy viscosity was changed from its initial value of 1 m^2/s to 0.1 m^2/s ("EVl") and 10 m^2/s ("EVh").

Coriolis force: the Coriolis force (active by default) was deactivated ("NC").

Flooding and drying: the threshold depths for flooding of dry land and drying of flooded land were increased from 0.01 m and 0.005 m to 0.02 and 0.01 m ("FD").

Elevation model: the impact of the elevation model (grid size and representation of flood diverting landscape elements) was studied by means of a different model version. The results will be reported elsewhere (Vanderkimpen et al. (2008)).

3.4 *Coupled models*

Simulation period: the simulation period, originally limited to the duration of the storm, was extended by 12 hours ("SP").

Time step: the model time step was increased from 2 s to 4 s ("TS").

Momentum transfer: in the reference situation, only volumes are exchanged between models. In this scenario, exchange of momentum was activated as well ("MT").

Output interval: the output interval was reduced from 30 minutes to 10 minutes, to evaluate its impact on post processing ("OI").

3.5 *Boundary conditions*

Wind friction: wind friction was calculated from the wind speed shown in Figure 6 and a reduced wind friction coefficient (0.0008). The reduction accounts for sheltering by non inundated landscape elements ("WF").

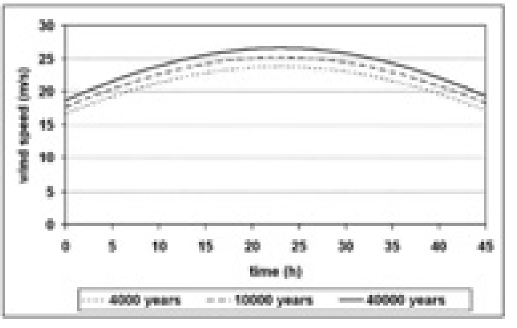

Figure 6. Wind speed.

Wave overtopping: the overtopping discharges computed during the Comrisk project and shown in Table 3 were added as additional inflows ("WO").

Table 3. Overtopping discharge.

Section	Width (m)	Q (l/s/m) 4000 y	Q (l/s/m) 10000 y	Q (l/s/m) 40000 y
220	30	23	52	196
233	75	186	269	682
234	113	61	109	352
235	150	1	51	305
236	138	1	73	438
240	48	0	10	58
241	0	0	64	385
242	20	139	235	713
243	0	184	271	707
246	0	0	4	23
Zwin	2000	0	1	4

3.6 *Breach growth*

The maximum breach width computed by the erosion based breach growth models (scenario GE1 and GE2) is summarized in Table 4.

For the breaches at Het Zoute (241-243) the breach width increases as the return period increases.

For the breaches at Knokke (233-236) this is not the case because breaches do not grow (GE1) nor interact with each other (GE2). During a storm with a return period of 40000 years, breach 233 grows very quickly, thereby hampering the growth of neighboring breaches. The growth of the breaches at Knokke (GE2) hardly influences the growth of the breaches at Het Zoute and Zwin.

3.7 *Inundations*

Inundations were characterized by means of the total volume of water, the maximum flooded area and an index incorporating all variables influencing damage and casualties:

$$HI = \sqrt[4]{A\,d\,v\,r} \tag{4}$$

where: HI = hydraulic index
A = flooded area (m^2)
d = maximum water depth (m)
v = maximum flow velocity (m/s)
r = maximum rise (m/h)

The results are summarized in Table 5. For each variable, the relative deviation from the reference situation is shown.

Table 4. Breach width computed by erosion based breach growth models (GE1 and GE2).

Breach	Ref (m) 4000 y	GE1(m) 4000 y	GE2 (m) 4000 y	Ref (m) 10000 y	GE1 (m) 10000 y	GE2 (m) 10000 y	Ref (m) 40000 y	GE1 (m) 40000 y	GE2 (m) 40000 y
233	90	90	99	90	90	97	90	90	200
234	-	-	-	90	90	114	90	90	109
235	-	-	-	90	90	96	90	90	95
236	-	-	-	90	90	96	90	90	95
241	-	-	-	150	72	72	150	73	72
242	150	83	83	150	89	89	150	131	131
243	150	80	80	150	86	86	150	116	115
Zwin	-	-	-	-	-	-	200	166	166

Table 5. Variation of inundation volume (V), inundation area (A) and hydraulic index (HI).

Scenario	V (%) 4000 y	A (%) 4000 y	HI (%) 4000 y	V (%) 10000 y	A (%) 10000 y	HI (%) 10000 y	V (%) 40000 y	A (%) 40000 y	HI (%) 40000 y
TBe	51	42	16	42	28	16	12	3	8
TBl	-41	-29	-24	-34	-30	-18	-11	-3	-7
HG	-15	-10	-9	-11	-9	-5	-13	-4	-9
VG	33	24	13	25	17	10	6	1	4
GE1	5	3	0	0	0	-1	-26	-11	-15
GE2	5	3	1	2	1	0	-23	-8	-12
BFE	5	3	2	5	4	3	10	2	5
SRl	7	5	5	8	6	5	5	1	4
SRh	-18	-11	-12	-19	-18	-9	-14	-6	-9
SRv	-49	-40	-28	-47	-40	-23	-28	-15	-16
EVf	1	1	1	1	1	1	1	0	1
EVl	1	2	1	2	2	1	1	0	1
EVh	-17	-11	-10	-18	-18	-7	-11	-3	-7
NC	0	0	0	0	0	0	0	0	0
FD	-1	-1	1	0	-1	1	0	0	0
SP	2	5	-1	1	8	-1	0	2	0
TS	1	1	0	1	0	0	0	0	0
MT	0	0	0	0	0	0	0	0	0
OI	0	0	5	0	0	5	0	0	3
WF	4	9	2	5	7	2	4	0	3
WO	2	1	1	2	2	1	2	0	1

The time of breaching very strongly influences the hydraulic results. Vertical growth rate, horizontal growth rate and growth model (time series or erosion) all exert a significant influence. The choice of breach flow equations, however, turns out to be of minor importance.

Changes in surface roughness and eddy viscosity have a comparable impact. The spread on surface roughness values (20 – 40) is much lower than the spread on eddy viscosity values (0.1 – 10). Therefore, the relative impact of surface roughness is higher than the relative impact of eddy viscosity. The use of a variable surface roughness causes a significant decrease in flooding. The dominant land use (agriculture) has a higher roughness (25) than the default value (32) and a number of areas near the coast (urban and infrastructure) have a significantly higher roughness (10).

The impact of the Coriolis force turns out to be negligible. The flood and dry parameters do not have a strong impact either.

The simulation duration has a limited influence on hydraulic results. This conclusion is influenced by the assumption that breach bottom levels are not eroded to a level below astronomical high tide. Therefore, an increase of the simulation duration will allow redistribution of flood water, but no additional inflow.

The use of a larger time step has a very limited influence. The same holds for activating momentum transfer.

The output interval mainly affects the maximum vertical rise, which is obtained through post processing of model output.

The impact of a given factor often depends on the return period. Some of the trends are caused by the specific configuration (topography and land use) of the study area. Therefore, results from this case study may not apply to other regions.

3.8 *Flood damage and casualties*

For a limited number of scenarios, flood damage and casualties were computed. The relative results are shown in Table 6.

Table 6. Variation of basic damage (BD), additional damage (AD) and casualties (C).

Scenario	BD (%) 4000 y	AD (%) 4000 y	C (%) 4000 y	BD (%) 10000 y	AD (%) 10000 y	C (%) 10000 y	BD (%) 40000 y	AD (%) 40000 y	C (%) 40000 y
TBe	55	45	139	26	23	34	11	30	15
TBl	-63	-62	-80	-29	-32	-45	-12	-17	-16
HG	-15	-23	-18	-2	-5	-2	-4	-10	-2
VG	29	28	56	15	1	20	5	8	5
GE2	8	-4	14	4	4	9	0	9	21
SRv	-26	-64	-20	0	-47	9	-4	-54	13
OI	0	0	1	1	0	23	1	0	8
WF	2	1	1	0	2	-1	-2	0	-3
WO	15	2	28	6	1	6	7	9	21

The results for damage and casualties often show other trends than the hydraulic results, even when compared to the most relevant hydraulic variable. These differences are caused by the spatial variation of land use (damage) and population density (casualties). Therefore, the importance of a given hydraulic factor for flood risk analysis should not be judged solely on the basis of hydraulic results.

3.9 *Flood risk*

The flood risk (total damage and casualties) has been summarized in Table 7. Once again, relative deviations have been used.

Table 7. Variation of damage risk and casualty risk.

Scenario	damage (%)	casualties (%)
TBe	47	92
TBl	-55	-59
HG	-14	-11
VG	25	38
GE2	6	15
SRv	-25	-7
OI	1	7
WF	-5	-7
WO	3	1

Time of breaching and breach growth strongly influence damage and casualty risk. The most influential parameter in the floodplain model is the surface roughness.

4 SENSITIVITY ANALYSIS

4.1 *Approach*

The uncertainty associated with the hydraulic model was roughly estimated by means of a systematic sensitivity analysis. This analysis was based on a strongly simplified procedure, analogous to the one applied in the European IMPACT project (Morris, 2005):

1. determine the most probable values for the parameters in the 1D breach model and the 2D flood model.
2. select a combination of parameter values for the 1D breach model resulting in minimal and maximal breach growth.
3. select a combination of parameter values for the 2D flood model resulting in minimal and maximal flood propagation.
4. run a number of simulations with the coupled 1D and 2D models:

- an initial simulation using the most probable parameter values for the breach and flood models.
- at least two additional simulations using the corresponding minimal and maximal breach and flood models.
- the remaining six combinations of minimal, most probable and maximal breach and flood models.

4.2 *1D Breach model*

The number of breaches, the location of the breaches and the time of breaching all greatly influence flood model results. The identification of these variables is, however, part of the failure analysis and will not be considered a source of uncertainty for the hydraulic modeling itself.

A major source of uncertainty in the breach model is the horizontal growth rate. This rate is strongly affected by the assumption whether deeply founded high rise buildings built along the coastal defense might collapse or not.

Breach growth was described by means of MIKE 11's erosion based growth model. In this model, the horizontal growth rate is linked to the vertical growth rate by means of a Side Erosion Index (SEI), expressing the ratio of horizontal to vertical growth. Three cases were distinguished: no growth (SEI = 0), average growth (SEI = 2) and fast growth (SEI = 15). The average value was obtained by calibrating MIKE 11's erosion based growth model to an empirical breach growth equation developed by Verheij-vanderKnaap. It results in a horizontal growth rate of a few meters per hour. The value for fast growth was estimated from literature values for observed breach growth rates. It corresponds to a horizontal growth rate of a few dozen meters per hour.

4.3 *2D Floodplain model*

A major source of uncertainty in the floodplain model is the surface roughness. The larger the roughness, the larger the uncertainty, as evidenced by a larger spread of literature values. This uncertainty was taken into account by applying a constant, absolute margin of uncertainty to the values for Strickler's roughness coefficient, listed in Table 2. This automatically results in a higher relative margin of uncertainty for the roughest surfaces, which are characterized by the smallest roughness coefficient. Once again, three cases were distinguished: low roughness (values increased by 5), average roughness (values unchanged) and high roughness (values reduced by 5).

4.4 *Coupled models*

The three scenarios for breach growth and the three scenarios for surface roughness combine into nine scenarios for the coupled breach and floodplain models. Each scenario will be identified by means of a two character code. The first character refers to a low (L), medium (M) or high (H) breach growth rate and the second to a low (L), medium (M) or high (H) flood propagation rate (corresponding to a high, medium or low surface roughness).

The scenario "MM" is used as a reference. The scenarios "LL" and "HH" represent the best case (minimal flooding) and worst case (maximal flooding) combinations. The scenarios LM and HM provide an insight into the impact of breach growth, whereas the scenarios ML and MH are used to estimate the impact of flood propagation.

Table 9. Computed breach width for the best case (LL), reference (MM) and worst case (HH) scenario.

Breach	LL (m) 4000 y	MM (m) 4000 y	HH (m) 4000 y	LL (m) 10000 y	MM (m) 10000 y	HH (m) 10000 y	LL (m) 40000 y	MM (m) 40000 y	HH (m) 40000 y
233	60	62	73	60	61	68	60	64	89
234	-	-	-	60	68	110	60	69	115
235	-	-	-	60	62	77	60	62	74
236	-	-	-	60	66	100	60	63	80
241	-	-	-	60	66	99	60	66	102
242	60	67	106	60	68	115	60	74	133
243	60	68	114	60	71	136	60	87	188
Zwin	-	-	-	-	-	-	96	161	398

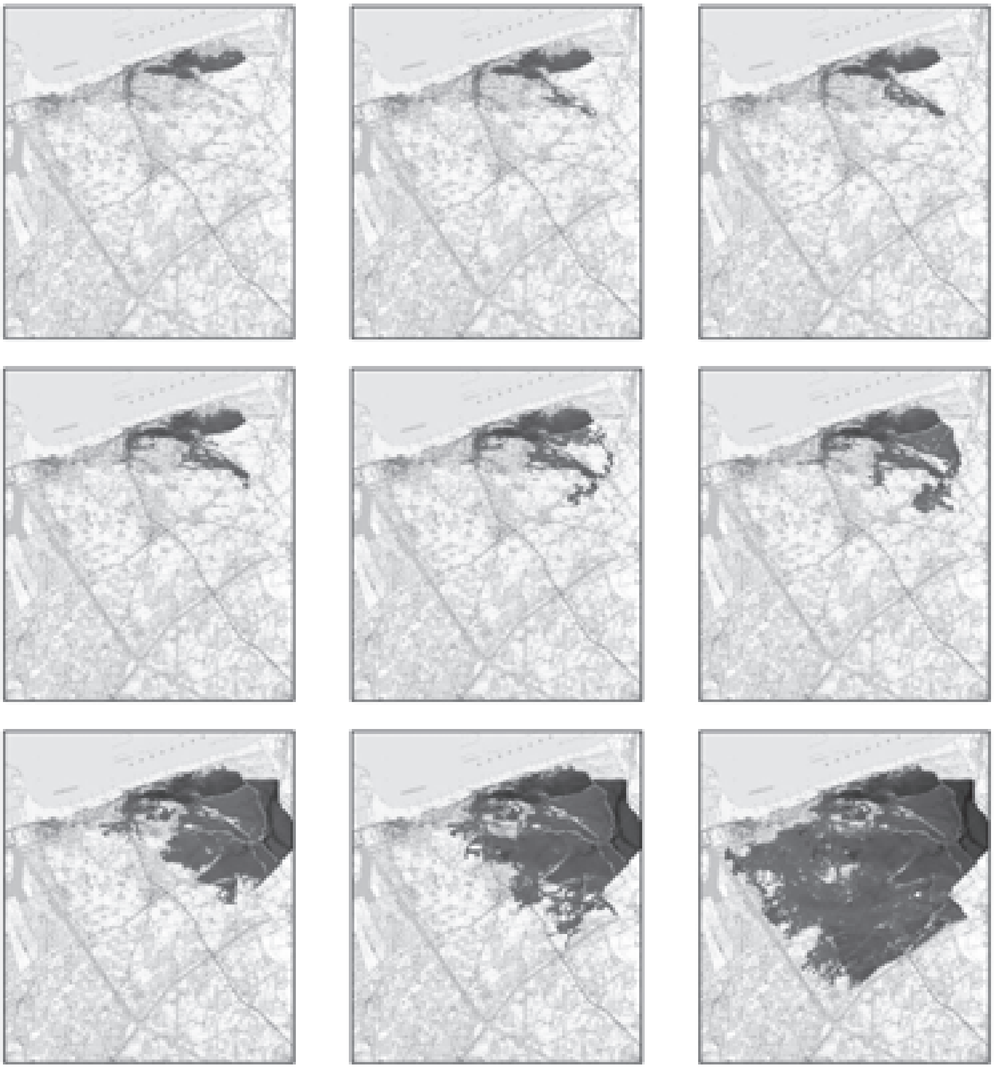

Figure 7. Flooding as a function of return period (rows) and scenario (columns).
(top row = 4000 years, middle row = 10000 years and bottom row = 40000 years).
(left column = best case (LL), middle column = reference (MM) and right column = worst case (HH))

Table 10. Variation of inundation volume (V), inundation area (A) and hydraulic index (HI).

Scenario	V (%) 4000 y	A (%) 4000 y	HI (%) 4000 y	V (%) 10000 y	A (%) 10000 y	HI (%) 10000 y	V (%) 40000 y	A (%) 40000 y	HI (%) 40000 y
LL	-28	-22	-11	-25	-26	-11	-29	-24	-16
HH	34	19	15	29	39	8	81	88	26
ML	-26	-20	-10	-24	-25	-11	-14	-13	-6
MH	22	13	10	18	27	4	12	19	2
LM	-2	-1	-1	-2	-3	-1	-17	-15	-9
HM	9	7	3	8	11	2	60	66	20
LH	18	11	8	15	23	2	-8	-5	-5
HL	-20	-17	-8	-19	-22	-8	36	36	15

Table 11. Variation of basic damage (BD), additional damage (AD) and casualties (C).

Scenario	BD (%) 4000 y	AD (%) 4000 y	C (%) 4000 y	BD (%) 10000 y	AD (%) 10000 y	C (%) 10000 y	BD (%) 40000 y	AD (%) 40000 y	C (%) 40000 y
LL	-32	-32	-54	-29	-39	-50	-37	-45	-54
HH	46	38	82	34	79	71	62	75	313
ML	-30	-31	-52	-28	-39	-49	-19	-31	-26
MH	30	34	58	21	48	38	9	29	21
LM	-2	-1	-4	-2	-4	-4	-15	-14	-32
HM	11	6	17	7	10	12	38	46	232
LH	25	29	49	17	40	29	-3	18	-15
HL	-25	-26	-46	-23	-38	-42	22	2	174

4.5 *Breach growth*

The maximum breach widths obtained with the reference (MM), best case (LL) and worst case (HH) scenario are summarized in Table 9.

In the reference situation breach growth is very limited, except for the breach in the Zwin dike. This is caused by the short duration of breach flow (due to high breach crest level) and backwater effects (due to high surface roughness in urbanized areas).

4.6 *Inundations*

Inundations were characterized by means of the parameters described in section 3.7. The results are shown in Figure 7 and Table 10.

The uncertainty associated with breach growth and surface roughness turns out to be considerable. For return periods of 4000 and 10000 years the uncertainty associated with surface roughness dominates, whereas for a return period of 40000 years the influence of breach growth is the largest. This shift can be explained by the strong impact of the breach in the Zwin dike, which only occurs with a return period of 40000 years.

4.7 *Flood damage*

The results for flood damage and casualties are listed in Table 11.

The uncertainty surrounding damage and casualties shows the same trends as the uncertainty surrounding hydraulic results: for return periods of 4000 and 10000 years the uncertainty associated with surface roughness dominates and for a return period of 40000 years the influence of breach growth is the largest.

4.8 *Flood risk*

The relative variation of flood risk (total damage and casualties) has been summarized in Table 12.

Table 12. Variation of damage and casualty risk.

Scenario	damage (%)	casualties (%)
LL	-33	-54
HH	48	144
ML	-28	-45
MH	26	45
LM	-4	-12
HM	16	76
LH	20	30
HL	-16	15

The table shows that both types of risk are subject to a considerable amount of uncertainty. In general, the uncertainty surrounding damage is smaller than the uncertainty surrounding casualties. In the case of damage, the impact of surface roughness is most important, whereas for casualties the impact of breach growth can be significant as well.

4.9 *Failure analysis*

The analyses presented in the previous sections were based on the breaches (number, location and time of breaching) identified in the course of an earlier failure analysis (Comrisk project).

In support of the development of an Integrated Coastal Master Plan, a new analysis of the failure behavior of the coastal defenses along the Belgian coast is currently under way. This analysis is based on new data and a methodology different from the one used in the Comrisk project. Preliminary results indicate that most likely no breaches will occur along the eastern part of the coast, not even during a storm with a return period larger than 40000 years, reducing risk to almost nothing. The new failure analysis indicates that the uncertainty associated with failure behavior is likely to outweigh the uncertainty associated with hydraulic modeling. In this case, uncertainty analysis should be focused entirely on failure analysis rather than flood modeling.

5 CONCLUSION

The results from a flood risk analysis can be very sensitive to a number of hydraulic model parameters or processes. For a given factor, the impact may depend on the return period and the impact on hydraulic results may differ from the impact on damage and casualties. For the study area, the most influential factors are breach growth and surface roughness. These observations may not apply to other regions.

The uncertainty associated with hydraulic flood modeling can be significant and can be roughly estimated by means of two additional simulations. The relative importance of the major sources of uncertainty (breach growth and surface roughness) depends on the return period and the risk type (damage or casualties).

The contribution of hydraulic model uncertainty to overall flood risk uncertainty can be considerable, but is nevertheless small compared to the uncertainty associated with flood defense failure probability. Within the framework of overall flood risk evaluation, available resources should preferentially be directed towards an improved quantification of the flood defense failure probability.

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