FRAMES pilot A58 and national highways in Zeeland

Final report

Rijkswaterstaat Zee en Delta

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SUMMARY

This report contains the final results of the FRAMES pilot A58/national highways in Zeeland. The pilot project studies how flooding risks can be cost-effectively minimised by application of the concept of multilayer safety (MLV). The project focusses not on preventing the mainland from flooding, but on minimizing the consequences as much as possible when flooding due to a dyke breach actually occurs.

This project first involved a network analysis of the A58 and the national highways within the province of Zeeland. Then province-wide vulnerability analyses were carried out for dyke breach flooding and pluvial flooding (by rain). For dyke breach flooding the maximum, worst-case dyke breach scenarios were adopted. The analysis shows that many national highways in Zeeland lie in a potential flood area.

Then the study focussed more closely on the A58 within dyke ring 31 (Reimerswaal) and various detail analyses were carried out. The vulnerability of the Vlaketunnel and the road bed of the A58 have been analysed further. For flooding (dyke breach), the analyses assumed both non-flood proof regional barriers and flood proof regional barriers. The Vlaketunnel seems to remain dry in the case of flood proof regional barriers. In the case of non-flood proof regional barriers dyke breach leads to flooding of the tunnel. The Vlaketunnel is not vulnerable to dyke breach flooding: even in extreme weather situations in the future the tunnel has adequate storage and drainage.

The analysis of the road bed of the A58 shows that 0 to 17 km from the 17.5 km within dyke ring 31 is prone to flooding, depending on how flood proof the regional barriers are. It is expected that the slopes do not become unstable. Further research into the stability of the road embankments is necessary because of the adopted starting points in the different preliminary studies and the indication of the limitation of applied models. Also considerable indirect damage occurs due to chain effects on the failure of the A58 (economic damage due to impeded traffic flow). The duration of the interruption of the A58 at a dyke breach ensures that the indirect damage is greater than the direct (material) damage. The results show that the connecting function of a network is determining for the potential indirect damage. The actual level of the indirect damage is dependent on the recovery time. The vulnerability analysis also shows that the impact and consequence of dyke breach is strongly dependent on how flood proof the regional barriers are. Non-flood proof barriers in general give a more extreme flooding profile in dyke ring 31. From the perspective of vital infrastructure the maintenance and upkeep of the regional barriers has added value.

Then measures have been identified for the A58 which limit the direct and/or indirect damage in the event of a dyke breach. Measures can be either individual (directed at a specific object) or collective (area focussed) and can focus on continued functioning (no more direct and indirect damage) or on quick recovery (reduction of recovery time and thus indirect damage). In total five different measures have been designed which have been reviewed on their cost effectiveness (effectiveness). A measure package is cost-effective if the sum of the benefits (avoided damage) is greater than the costs. The analysis shows that the cost/benefit ratio of all measures is unfavourable. A sensitivity analysis confirms these conclusions.

The results of the pilot show that including chain effects in the damage determination for failure of vital infrastructure is essential in the policy consideration for taking measures. However, with the current return times and safety standards of the primary flood defences, most of the measures do not seem to be cost-effective: linking them together is the only real option to make them cost-effective. Here it is observed that the current statistic for the failure probability of the primary flood defences is based on the climate of the past: return times can change in the future due to accelerated sea level rise. As a result measures that are not cost-effective now can become so in the longer term (autonomously). So the cost-benefit ratio of particular measures does become positive if the failure probability of the dyke routes of dyke ring 31 would be a factor of 3 higher.

1

INTRODUCTION

1.1 The FRAMES pilot project for Reimerswaal

This is the final report for the FRAMES pilot study for the A58 and the national highways network in the province of Zeeland that is carried out on the directions of Public Works and Water Management. The project has been made possible by a subsidy from the overarching FRAMES (Flood-Resilient Areas by Multi-layEr Safety) project of the European INTERREG Fund North Sea Region. Public Works and Water Management works within FRAMES together with eleven partners, including regional authorities, universities and area managers from the Netherlands, Belgium, Germany, the United Kingdom and Denmark. The theme vital and vulnerable functions also plays an important role in the Delta Program Spatial Adaptation (DPRA): one of the tasks that must be a component of climate resistant actions in policy in 2020. With the subject protection of vulnerable and vital functions there is in practice still relatively little experience, both in the province of Zeeland and in the Netherlands. This project provides this.

The project is focussed therefore on the vulnerability of the A58 in the municipality of Reimerswaal and the national highways in the province of Zeeland in relation to floods and flood damage. The research question is how flooding risks can be minimised cost-effectively by application of the concept of multilayer safety (MLV)[1]. The concept of multilayer safety originally distinguishes three coherent layers. FRAMES has added a fourth layer which focuses on the subsequent recovery (reconstruction):

- Layer 1 prevention: measures that prevent flooding.
- Layer 2 spatial measures: climate resistant arrangement that can limit consequential damage.
- Layer 3 crisis management: crisis consultancy, operational management, evacuations at high water.
- Layer 4 recovery: reconstruction.

The project focusses on the situation where dyke breach flooding or pluvial flooding actually occurs and the consequences are limited as much as possible: layer 2 up to and including 4.

[1] See the draft National Water Plan (2008) for an explanation.

Figure 1.1 Visualisation layer 1 up to and including 3 multilayer safety

The FRAMES pilot for the A58 is in view of the connecting position within the province of Zeeland and for the Netherlands a very relevant case for the analysis of the challenge and measures for the protection of vulnerable and vital infrastructure. The insights on the A58 can be scaled up to the national highways in the province and vice versa. Therefore province-wide analyses have been carried out and detail analyses have been carried out on the A58 within Reimerswaal. Then cost-effective measures are developed.

Figure 1.2 Map of national highways and A58

The research project involves co-ordination with the following studies which both focus on integral analysis of the infrastructure in Reimerswaal:
- RAAK project of the Zeeland University of Applied Sciences: the most important results are the fact sheets for all networks.
- FRAMES pilot Reimerswaal of the Province Zeeland, that is also carried out by Witteveen+Bos: the most important results are the developed packages of measures for individual and collective protection and damage limitation of the networks.

1.2 Reading directions

This report serves as final report of the FRAMES project A58/national highways. Chapter 2 describes the network analysis of the A58 and the other national highways. Then the province-wide analyses are described (chapter 3). Chapter 4 presents the detailed analyses. Chapter 5 contains an initial calculation of the (potential) direct and indirect damage in the event of flooding. Chapter 6 examines the possible mitigating measures for the A58. Chapter 7 explores the economic efficiency (effectiveness) of a number of packages of measures. Chapter 8 summarises the conclusions of the study and formulates (policy) recommendations.

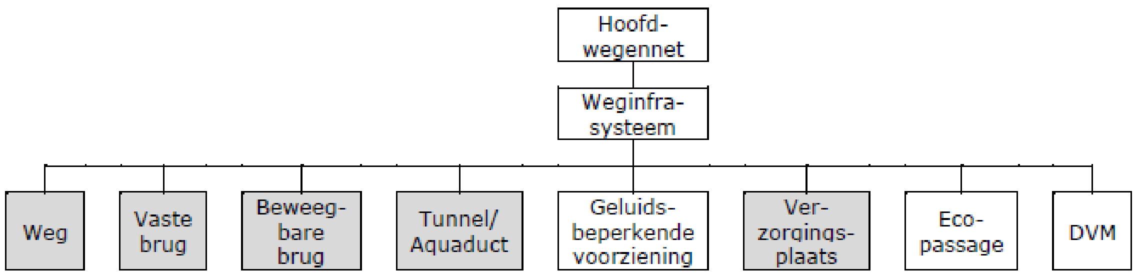
2

NETWORK ANALYSIS

2.1 Structuring of objects

The network analysis starts with a structuring of the A58 and the national highways within the province of Zeeland. For this the object tree is used as shown in figure 2.1. This object tree indicates from which main objects the road infrastructure system of a national highway has been built up. On the basis of the discussions during the workshop of 26 September 2018 a number of objects has been added: the objects 'culvert', 'underpass' and 'viaduct'.

Figure 2.1 Object tree of Public Works and Water Management (source: HWA directive Public Works and Water Management)



The above object tree has been detailed somewhat further for the national highways in Zeeland. The additional definitions are:

- Fixed bridge: there is only 1 fixed bridge within the province of Zeeland: the Kreekrak bridge over the Schelde-Rhine canal.
- Mechanical bridge: bridge in the national highway with a moveable part to the passage of ships. There are 3 types (retractable bridge, vertical lift bridge and swing bridge). There are 2 moveable bridges in Zeeland: Sluiskil bridge (Zeeuws Vlaanderen) and Grevelingen bridge (Bruinisse).
- Underpass: non-grade crossing of the national highway with cycling tunnels or tunnels for local roads (enclosed channel).
- Viaduct: non-grade crossing of the national highway with a secondary road.
- Tunnel/aqueduct: non-grade crossing of the national highway with a navigation channel. There are 3 tunnels in Zeeland: the Vlaketunnel, Dampoort aqueduct (at Middelburg) and the Sluiskil tunnel (currently still owned by the provincial government).
- Oosterschelde storm surge barrier: national highway runs on the storm surge barrier.

Figure 2.2 Viaduct

Figure 2.3 Underpass

Figure 2.4 Underpass

Figure 2.5 Viaduct

2.2 Analysis of national highways within Zeeland

The focus of this study is on the A58 within the municipality of Reimerswaal, but the other national highways within Zeeland are also considered. Figure 2.6 on the following page shows the national highways in the province of Zeeland consisting of:

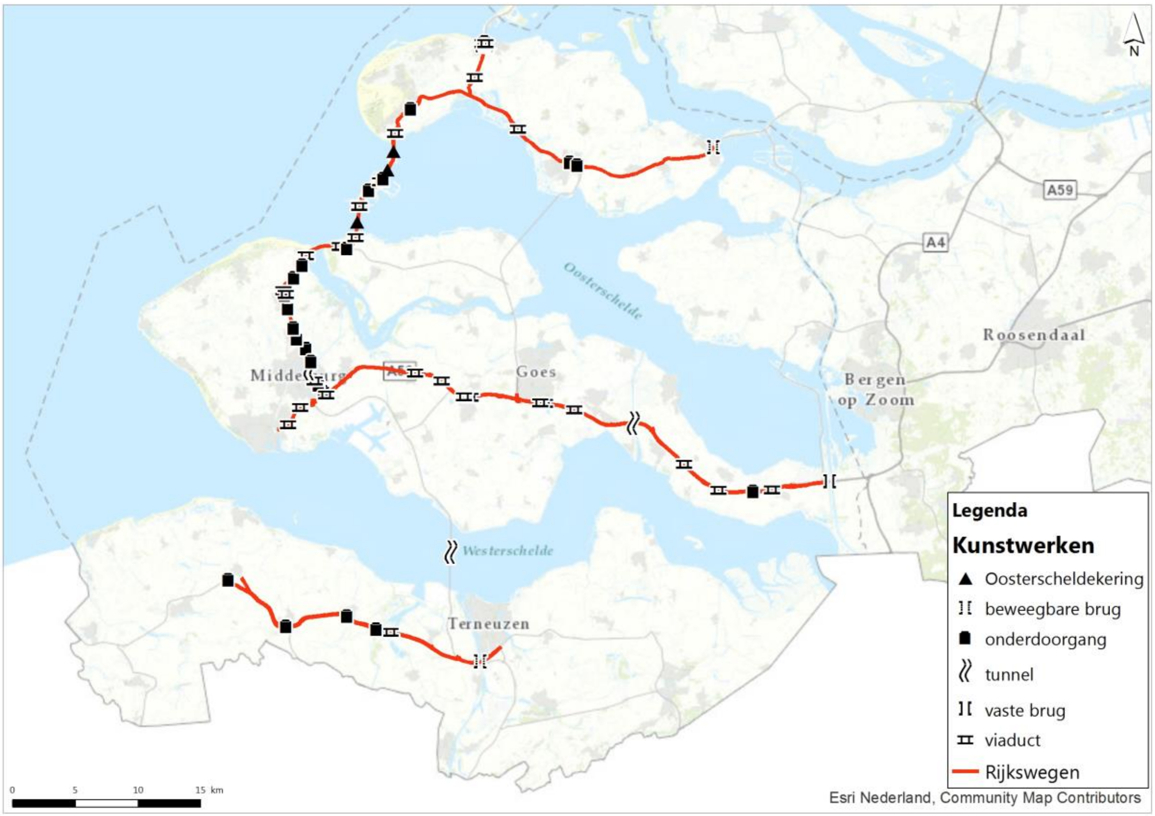
1 A58: from Markiezaat junction to Vlissingen.
2 N59/A59: from the Grevelingen dam to Serooskerke.
3 N57: from the Brouwersdam to Middelburg.
4 N61: from Terneuzen to Schoondijke.

For each of the national highways all the main objects have been charted. The vulnerability analysis (province-wide chapter 3 and detailed analysis chapter 4) has been carried out for different objects in this object tree.

Table 2.1 National highways and associated objects in Zeeland

Object	**A58**	**N59/A59**	**N57**	**N61**	**Total**
Length	**49.2 km**	**22.3 km**	**40.2 km**	**25.0 km**	
Fixed bridge	1				1
Mechanical bridge		1		1	2
Underpass (cycle tunnels or small roads)	1	2	16	4	23
Tunnel/aqueduct	1		1		3
Viaduct	14	1	14		23
Oosterschelde storm surge barrier			3	1	3
Total	**17**	**4**	**34**	**7**	**62**

Figure2.6 Overview of the national highways in the province of Zeeland



3

PROVINCE-WIDE ANALYSES

3.1 Scenarios and approach

Dyke breach scenarios
The starting point for the analysis of flooding (by a dyke breach) are the flood scenarios that have been determined in the program 'Veiligheid Nederland in Kaart' (VNK2). Here the maximum or worst-case flood scenarios with several breach locations are selected where a water level occurs with an overrun frequency of 1/4,000 years. For a further explanation for the production of the dyke breach scenarios, the reader is referred to the following framework.

Dyke breach scenarios
The program VNK2 analysed between 2006 and 2014 all primary water barriers and dyke rings in The Netherlands. The flood risks have been charted for each dyke ring. The flood risk consists of the failure probability of a dyke times the consequence of the flood.

Probability of flooding
Here the dyke ring has been divided up into different dyke sections (the piece of dyke within a dyke section has equivalent characteristics and thereby an equivalent probability per failure mechanism). For each dyke section a breach location has then been selected. In VNK2 an attempt was made to calculate the failure probability of a dyke section probabilistically. The failure probability differs thus from dyke section to dyke section.

Consequence of flooding
For each breach location the flooding due to dyke breach has been modelled for 3 different water levels; the water level with an overrun frequency of 1/4.000, 1/40,000 and 1/400,000 years. Also for each dyke ring a maximum or worst-case flooding scenario has been determined in which a combination of breaches takes place. For the 3 load conditions it is charted how much damage and how many victims a flood would cause. The probability rates of different flood scenarios are determined on the basis of the calculated failure probability rates per section and engineering structure.

The starting point for the above analysis is that the maximum water level coincides with the moment that a breach occurs. Another assumption is that the existing regional barriers do not fail. In the flood scenarios of VNK2 inner dykes are overtopped, but these do not lead to a breach in the regional barriers.

New standard
The old standards prescribe that a water barrier must be high and strong enough to hold back a particular water level (overrun probability). The new standard is based on both the probability of a flood (flood probability) and the consequences of this (amongst other things damage). The new standard assigns per dyke route a failure probability with which the dyke must comply.

Figure 3.1 shows the different dyke rings in the province of Zeeland, these are:
- Dyke ring 26 Schouwen-Duiveland.
- Dyke ring 27 Tholen and Sint-Philipsland.
- Dyke ring 28 Noord-Beveland.
- Dyke ring 29 Walcheren.
- Dyke ring 30 Zuid-Beveland West.
- Dyke ring 31 Zuid-Beveland East.
- Dyke ring 32 Zeeuws-Vlaanderen.

Figure 3.1 Dike rings in the province of Zeeland

Dike ring 31 - Reimerswaal

The FRAMES pilot project for Reimerswaal focuses on the vulnerability of vital infrastructure within dyke ring 31. Within dyke ring 31 different regional barriers are present, a trace of the phased land reclamation from the past (figure 3.1). During the term of the project it has been recorded that the VNK2 scenarios for dyke ring 31 Reimerswaal have been elaborated with the starting point that the regional barriers are not flood proof. This means that it has been assumed that during a breach of the primary flood defence all regional barriers also fail. This is not consistent with the agreed national systematics for VNK2. For those reasons new scenarios have been calculated by the province of Zeeland for Reimerswaal, but then with flood proof barriers as the starting point. In this project the analysis for the A58 within Reimerswaal has been carried out for both non-flood proof (calculation 1) and flood proof regional barriers (calculation 2).

Figure 3.2 Inner dykes within dyke ring 31. Purple: inner dyke with water management function, green: inner dyke withoutwater management function (source: VNK2 report 'Flood risk Dike ring 31 Zuid-Beveland', December 2011)

Pluvial flooding

In addition to dyke breach flood damage is also considered in this pilot project. For pluvial flood damage the PWO scenarios[1]of Scheldestromen Water Board are adopted. The PWO scenarios follow from the compliance of the water board with WB21 (water management 21st century) as accommodated in the NBW (National Administration Agreement Water). The scenario with a return time of T = 100 (2050) is used. The associated flooding, including already implemented measures, will comply with the WB21 challenges for the climate scenario in 2050.[2]

3.2 Vulnerability analysis

For dyke breach flooding and pluvial floodingthe vulnerability analysis has been carried out on a province-wide basis. This means that for each object in the national road network it has been analysed whether the object floods and what the water depth is. Here there are 2 issues:

- The water depth has been shown relative to the ground level. This means that at a viaduct the water depth has not been calculated on the basis of the level of the carriageway of the viaduct, but on the underpass under the viaduct.
- The cell size of the flood maps that have been carried out for flooding by a dyke breacht analysis is 100 m x 100 m. This means that a water level shows an average for a cell of 100 x 100 m and that no account has been taken of height differences in the ground level within that cell. Because the national highways are often an order of magnitude 2 to 4 narrower than the cell size, there is some uncertainty over the exact water depth on the national highway.

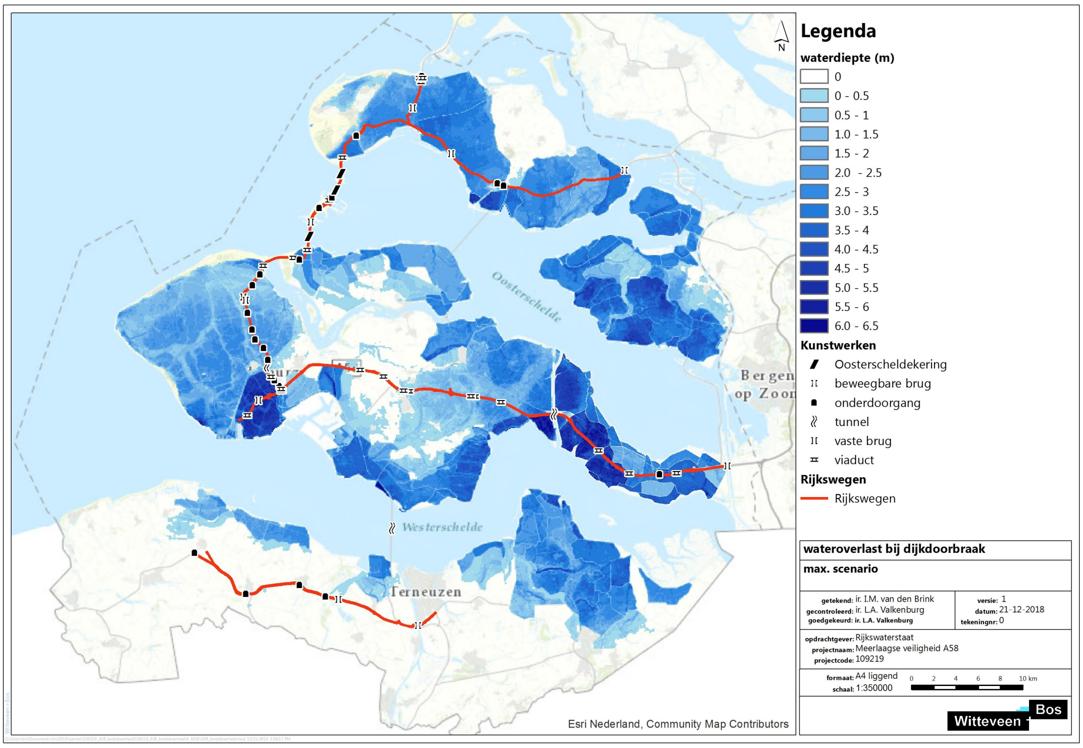
1 PWO stands for Planning for Water Challenge.

2 RWS observes that for the A58 itself the vulnerability to flooding both in the framework of the program Plan of Approach Replacement and Renovation of Pavements, and in the National Stress Test for the Main Road Network, will be determined (in 2019).

3.2.1 Dyke breach flooding

The dyke breach flooding analysis has been carried out for all the above-mentioned dyke rings. The result has been visualised in figure 3.3 and appendice I. In this map it is clear that the greatest water depths occur on the A58 within the municipality of Reimerswaal. This confirms the importance of the focus in the analyses on Reimerswaal. In the following tables it is indicated for each national highway which objects flood.

Figure 3.3 Province-wide analysis for flood protection (see appendice I for larger version)



A58

Most of the A58 in Zeeland is vulnerable to flooding. Of the total length of 49.2 km, 41.4 km is liable to flood in the event of a dyke breach. The results of the flooding analysis of the A58 with the VNK2 flood maps (non-flood proof regional barriers) have been included in table 3.1. The results of the new maps of the province of Zeeland (flood proof regional barriers) from December 2018 can be found in table 3.2 (see also appendice III). In both tables it has been shown for the A58 how many objects of each type are present within the province. It has then been indicated whether flooding occurs and what the water depth will be. Especially within the municipality of Reimerswaal objects will flood. The most important object is the Vlaketunnel. In the VKN2 scenarios more than 2 m water depth is expected. In the current report the starting point still is the analysis of VNK2 (non-flood proof regional barriers). These show that the Vlaketunnel floods without taking into account the the tunnel protection dykes (kanteldijken). Also in the maps of the province of Zeeland the Vlaketunnel seems to flood. In the detailed analyses of the A58 a further study is made of the consequences of the flooding on the objects and specifically on the Vlaketunnel. In that chapter it is determined whether the Vlaketunnel actually floods.

Table 3.1 Flooding pattern A58 (VNK2 scenario, non-flood proof regional barriers)

Object	Total	No flooding	Water depth < 0.50 m	Water depth 0.50 m-1.00 m	Water depth 1.00 m-2.00 m	Water depth > 2.00 m
Fixed bridge	1	1				
Mechanical bridge						
Underpass	1				1	
Tunnel/aqueduct	1					1
Viaduct	14	3	4	1	4	2

Table 3.2 Flooding pattern A58 (flood maps PZ, flood proof regional barriers)

Object	Total	No flooding	Water depth < 0.50 m	Water depth 0.50 m-1.00 m	Water depth 1.00 m-2.00 m	Water depth > 2.00 m
Fixed bridge	1	1				
Techanical bridge						
Underpass	1	1				
Tunnel/aqueduct	1					1
Viaduct	14	5	3		4	1

Role of flood proof regional barriers

When the difference of the flooding with and without flood proof regional barriers in Reimerswaal is considered (see also appendice III), it can be concluded that regional barriers have an important role in protecting the main road network in the event of a dyke breach. In general as a result of flood proof regional barriers, less objects flood or the flooding depth is smaller.

N59/A59

At the N59 at Schouwen-Duiveland all the objects of the national highway are likely to flood. Table 3.3 shows water depths at the different engineering structures. The road can flood almost over its entire length: of 22.3 km, 22.2 km is prone to flooding.

Table 3.3 Flooding pattern N59 (VNK2 scenario, flood proof regional barriers)

Object	Total	No flooding	Water depth < 0.50 m	Water depth 0.50 m-1.00 m	Water depth 1.00 m-2.00 m	Water depth > 2.00 m
Fixed bridge						
Mechanical bridge	1				1	
Underpass	2		1		1	
Tunnel/aqueduct						
Viaduct	1					1

N57

The N57 is also significantly prone to flooding. Of the total length of 40.2 km, 28.2 km will flood in the event of a dyke breach. Particularly in the western part of Schouwen-Duiveland and at Walcheren many objects will flood. At the objects on and around the Oosterschelde Storm Surge Barrier no flooding occurs. The results are summarised in table 3.4. An important object prone to flooding is the Dampoort aqueduct at Middelburg. This aqueduct is expected to be [1]1 to 2 m under water. The lessons learned from the analysis of the Vlaketunnel of the A58 are also relevant for this aqueduct.

Table 3.4 Flooding pattern N57 (VNK2 scenario, flood proof regional barriers)

Object	Total	No flooding	Water depth < 0.50 m	Water depth 0.50 m-1.00 m	Water depth 1.00 m-2.00 m	Water depth > 2.00 m
Fixed bridge						
Mechanical bridge						
Underpass	14	2 (at Oosterschelde storm surge barrier)	2	2	6	2
Tunnel/aqueduct	1				1	
Viaduct	14	5, of which 2 (at Oosterschelde storm surge barrier)	3	3	1	2
Oosterschelde storm surge barrier	3	3 (at Oosterschelde storm surge barrier)				

N61

At the N61 in Zeeuws-Vlaanderen no flooding of objects occurs in the event of a dyke breach. Therefore no table of this national highway has been included. Of the total length of 25.0 km, 0.8 km is liable to flood in the event of a dyke breach.

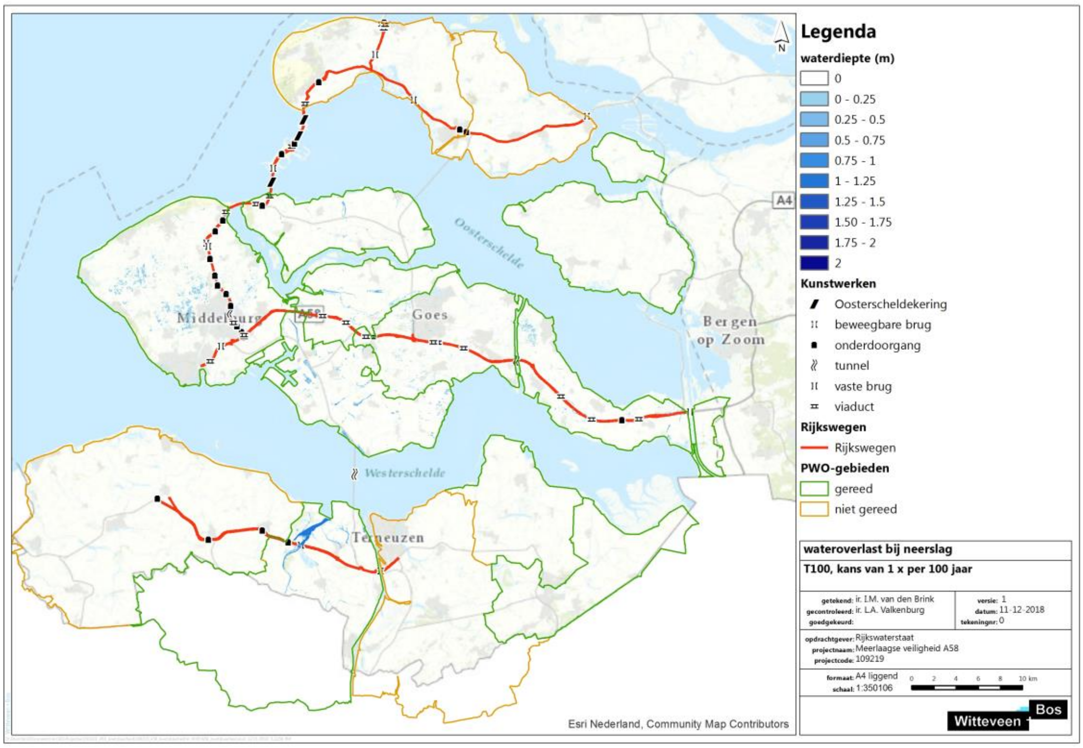
3.2.2 Pluvial flooding

Available data

The PWO-analyses are carried out by the Scheldestromen Water Board. In the PWO-analyses, pluvial flooding (inundation caused by rain) is analysed. At the moment of writing, a PWO flood map has become available for around half the province. In figure 3.4 and appendice II it has been indicated in green and orange for each PWO area whether the maps are available. For the N59, a part of the N57 and a part of the N61 no data are available. In table 3.5 it is therefore shown for each national highway for which objects results of the PWO scenario are available.

[1] Since the dyke breach scenarios of LIWO, with a resolution of 100 x 100 m, show only water depths and not water levels (water level relative to NAP) there is uncertainty about the real flood depths. This is because within a cell of 100 x 100 m, and certainly locally at an engineering structure, the ground level can vary considerably.

3.4 Province-wide analysis of flood damage (see appendice II for larger version)



Results

On the basis of the available PWO maps (figure 3.4) it has been assessed for each national highway whether objects are prone to flooding. A more detailed map can be found in Appendice II. Also it has been shown in the following table whether an object is likely to flood. An important marginal note here is that the PWO calculations take no account of the storage and pump-out capacity of tunnel installations. For those reasons the tunnels are totally flooded in the analysis. In the detailed analysis of the Vlaketunnel it is considered whether flood damage actually occurs.

Table 3.5 Flood damage pattern (on the basis of available PWO scenarios)

Object	A58 Total	A58 Available within PWO	N57 Total	N57 Available within PWO	N61 Total	N61 Available within PWO
Length	49.2 km	0.4 km flood damage (this relates to the Vlaketunnel)	40.2 km	0.3 km flood damage	25 km	0.65 km flood damage
Fixed bridge	2	2	4	2	1	1 (floods around 1 m)
Mechanical bridge					1	
Underpass	1	1	16	11	4	1
Tunnel/aqueduct	1	1 (floods around 5 m)	1	1 (floods around 5 m)	0	
Viaduct	13	13	10	5		

Link with national stress test Deltares

Deltares started in the fourth quarter of 2018 a national stress test for the national highways in the Netherlands. The results of this are expected to be available in the middle of 2019. For flood damage a 3Di analysis will possibly be carried out. If not, then use can be made of a semi-quantitative analysis of sensitivity of national highways to flood damage that is made in the framework of the Plan of Approach 'Replacement and Renovation of Pavements'. These results were not yet available at the time of writing this report. These results are expected to become available for the province of Zeeland in the summer of 2019. At that moment it is advisable to compare these with the results of the above PWO analysis and to assess whether this is of influence on the results and conclusions in this report.

4

DETAILED ANALYSES

4.1 Flooding by dyke breach

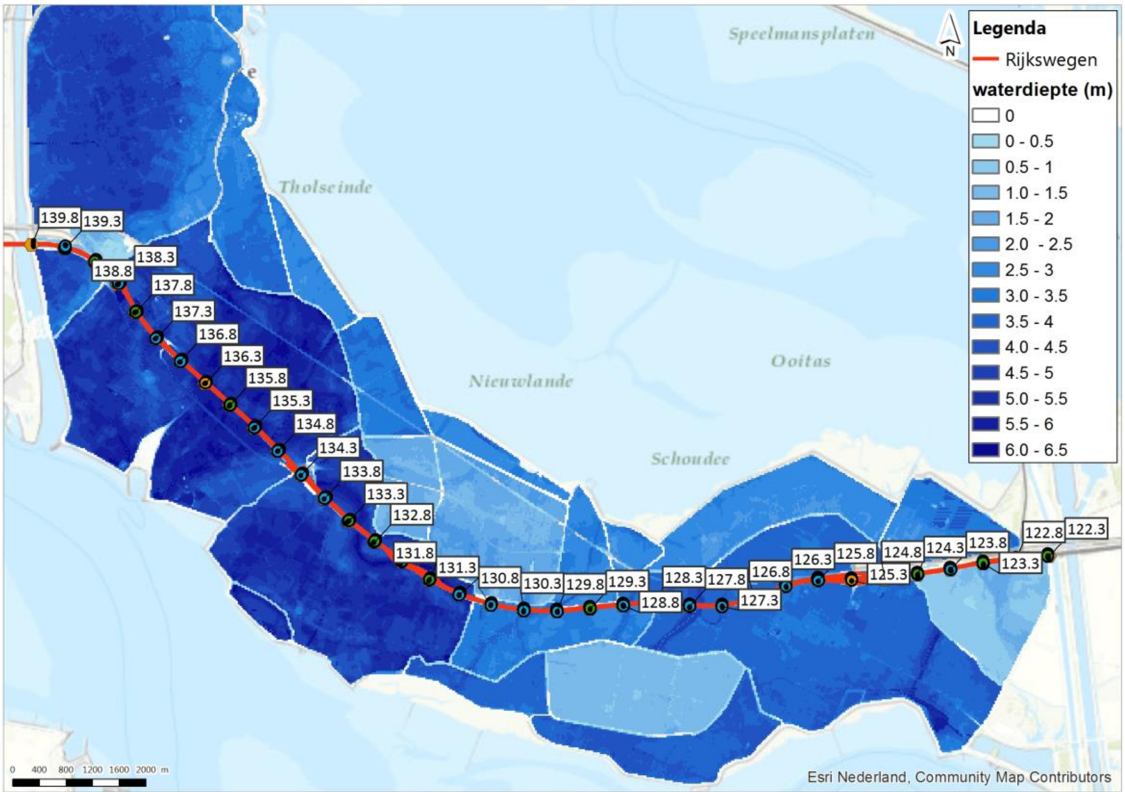
This paragraph presents a more in-depth look at the analysis of the flood protection of the A58 within Reimerswaal. First of all a detailed study is made of the flood pattern for the A58 in Reimerswaal. Next on the basis of this, the geotechnical stability and strain softening of the road bed of the A58 is considered. The effects of flooding on the Vlaketunnel are then studied.

4.1.1 Integral A58 route within Reimerswaal

Integral analysis of A58 route

The complete route of the A58 within dyke ring 31 within the municipality of Reimerswaal has been analysed on the basis of 36 detailed profiles. See figure 4.1 for the profiles shown on the map. This has been analysed for the worst case scenario where all breach locations on the Oosterschelde and Westerschelde occur will breach (starting from flood proof regional barriers). For the other dyke breach scenarios, see Appendice III.

Figure 4.1 Route A58



Analysis per profile

For each of the 36 profiles it has been analysed whether it relates to a road bed at ground level, a raised surface towards a bridge or a reduction in level towards an underpass or tunnel. A detailed cross-section has been made on the basis of the heights in AHN2 and the water depth has been determined on the basis of the VNK2 scenarios and the new flood maps of the Province of Zeeland from December 2018. In Appendice IV an example elaboration of the profile of hectometer pole 137.3 has been included.

VNK2 scenarios (non-flood proof flood defences)

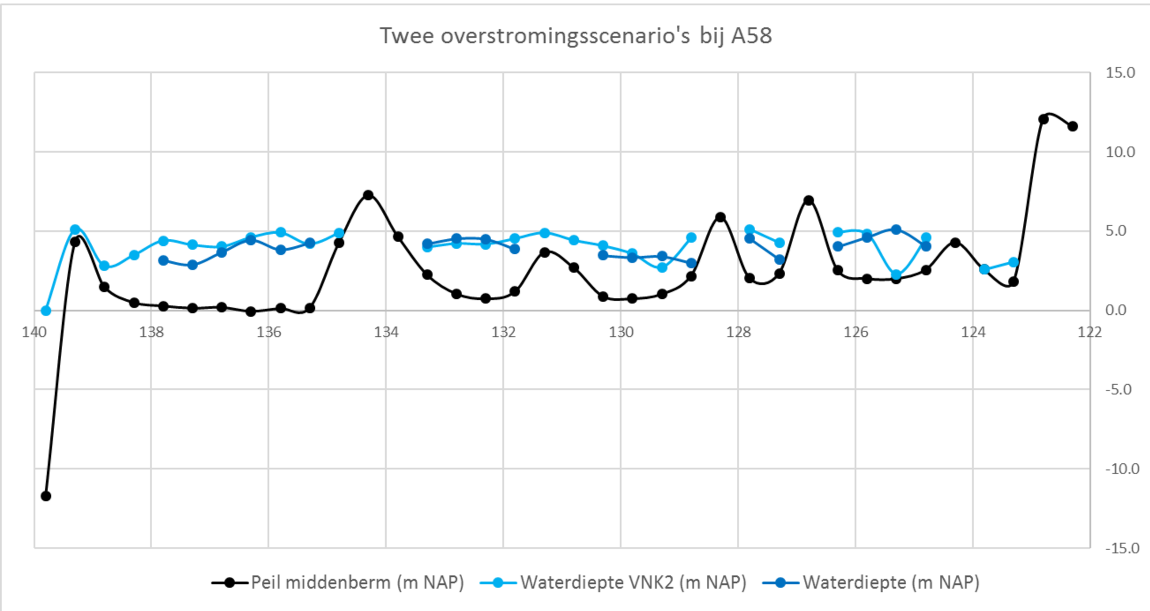
The summary of the analysis of the profiles with the VNK2 scenarios can be found in figure 4.2. The water level at a profile is determined on the basis of the water depth (comes from VNK2 scenario) and the ground level height (digital height model AHN). Because the VNK2 scenarios are available at a detail level of 100 x 100 m and water depths shows measured in m relative to ground level and not in water levels in m NAP) and the AHN at 50x50 cm (measured in m NAP), there is considerable uncertainty in the water levels for the profiles. The uncertainty is smaller with the flood maps of the province of Zeeland since here modelled water levels are also available.

The analysis clearly shows that the A58 within Reimerswaal will largely flood: 7 of the 36 profiles do not seem to flood. Of the total length of 17.5 km within Reimerswaal 14.0 km is prone to flooding or 17.0 km for the combined Oosterschelde or combined Westerschelde and Oosterschelde scenario respectively. The average water depth above the central reservation is 2.0 m.

Flood maps for the province of Zeeland (flood proof regional barriers)

On the basis of the new maps that are made for dyke ring 31, it can be indicated with more certainty whether there is a likelihood of flooding. The results have been included in figure 4.1. The analysis of the new maps suggests that a smalelr part of the A58 within Reimerswaal is under water than in the earlier analysis: 16 of the 36 profiles will not flood. Of the total length of 17.5 km within Reimerswaal only with a combined Westerschelde and Oosterschelde scenario does flooding occur over a length of 10 km. With the combined Oosterschelde scenario there is no flooding. The average water depth above the central reservation is 1.5 m.

Figure 4.2 Cross section of A58 and the flood maps. Light-blue non-flood proof regional barrier (VNK), dark-blue flood proof regional barrier (province of Zeeland)



4.1.2 Geotechnical stability of road bed

This paragraph considers the stability of the road bed of the A58. In this the profiles from 4.1.1 are adopted as input.

Deltares preliminary study

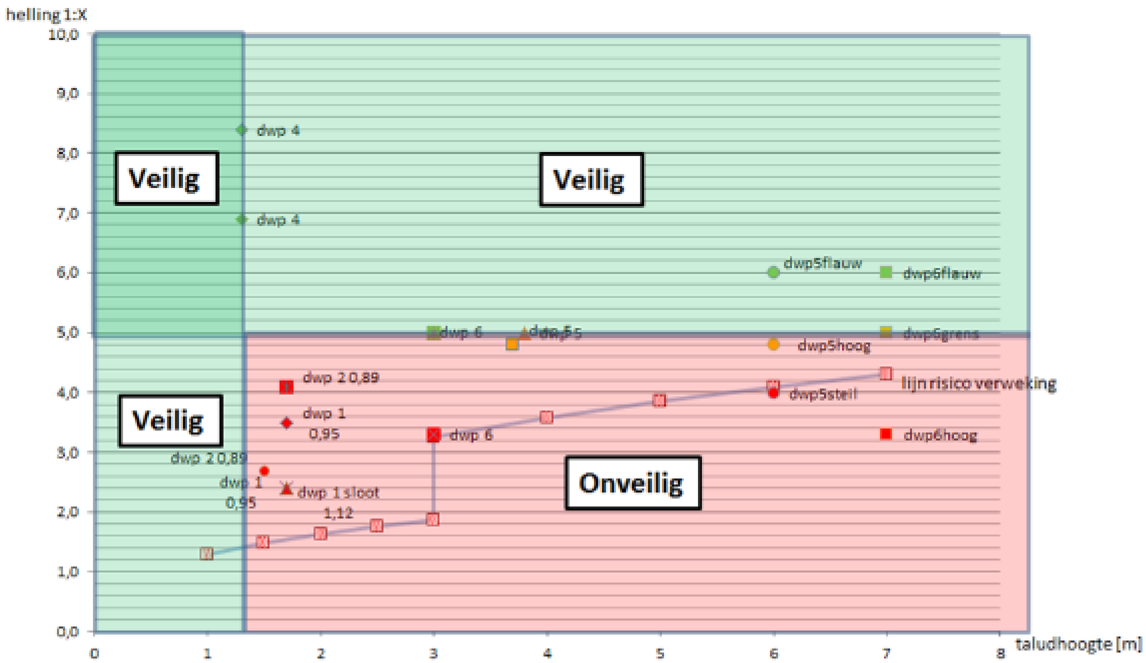
The Deltares study 'Vulnerability of road beds during and after flooding' (2014) has investigated the stability of road beds of national highways. On the basis of cases geometrical assessment criteria have been drawn up and then applied to the transverse section of all national highways. General conclusions are drawn on the basis of the cases linked to the combination of embankment gradient and road height.

The analysis has been carried out as follows:

- D-GeoStability has been used as calculation tool.
- The water height on the road has not been considered (not relevant for the calculation), the groundwater level has been accepted up to road level.
- Soil structure has been taken over from the DINO service (peat or clay, the sub-grade has been assumed to be sand).
- The considered failure mechanisms for the stability are:
  - Strain softening of the road bed: normative in the acute phase if the road is permanently flooded and the embankments subside.
  - Instability due to shear (macrostability according to the Bishop method): normative in the recovery phase if the water level drops and the embankments become unstable as a result. Here an allowance has been made for:
    - Traffic load (the road is in use): 20kN/m^2.
    - The time required to pump out the flood water has been set at 1 day.

The results of the analysis can be seen in figure 4.3.

Figure 4.3Results of Deltares study (taken over from Deltares report, 2014)



In figure 4.3 the embankment height has been plotted relative to the slope. For strain softening the grey line is normative. If the characteristics of a road bed are plotted under the line, there is - according to the Deltares research - an unsafe situation. A road bed with a slope of 1:5 and an embankment height of 5 m is, for example, safe as regards strain softening. Above the line there is a safe situation. For shear stability this has been indicated with the red plane and the green planes. A road bed with a slope of 1:3 and an embankment height of 5 m is, for example, unsafe as regards shear stability.

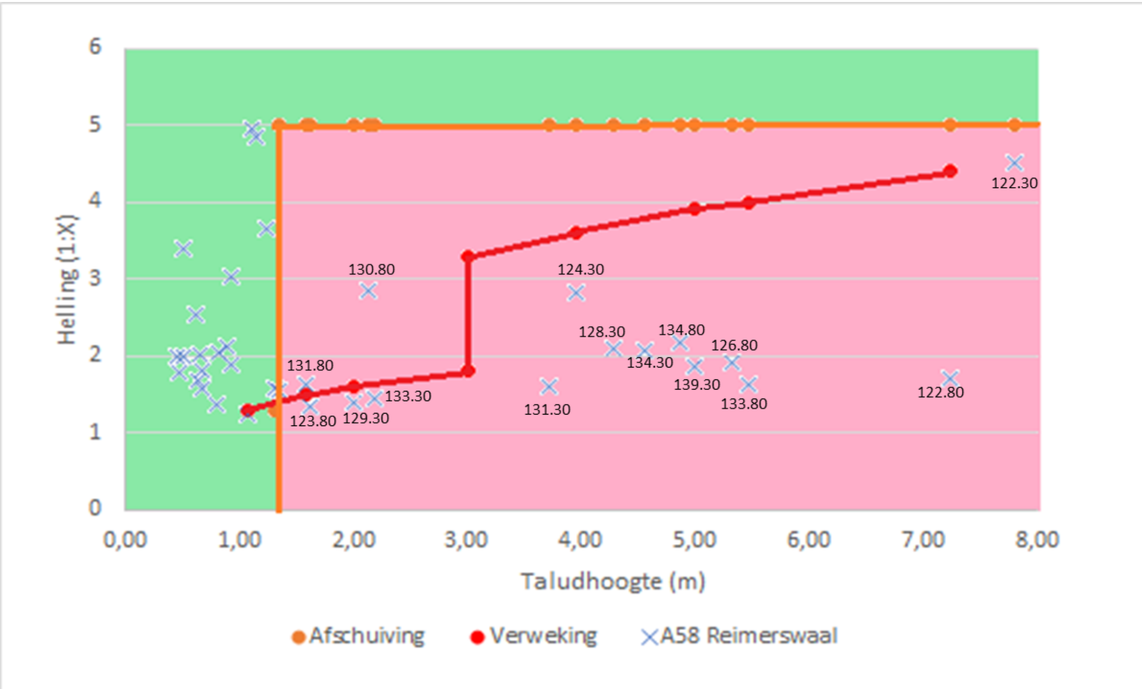
Analysis of A58 starting from failure criteria Deltares (2014)

Making use of the geometrical failure criteria of Deltares the transverse sections of the A58 have been analysed. Here the following points have been considered for each transverse section:

1. Height of road bed on the basis of the AHN2.
2. Maximum slope of embankments in the road profile: the average of the AHN height over 2 m. The roadside ditches, with a depth of around 1.2 m are filtered out here, because these do not lie directly on the road.
3. Flooding depth at the road on the basis of the VNK2 flood maps.

The results can be seen in figure 4.4. In this figure the two lines of the Deltares study can be seen: shear stability in orange and strain softening in red. The profiles are plotted with blue crosses. With this it can be assessed whether a profile is possibly unsafe, with as an important marginal note the fact that the starting points of the analysis of Deltares are too conservative (see the following paragraph). Also it is observed that not all profiles are (completely) under water. Thus the profiles around hectometer poles 122 km (Kreekrakbrug) and 139 km (Vlaketunnel) do not flood or only do so to a limited extent.

Figure 4.4 Comparison of physical characteristics of A58 with Deltares results (safe in green, not safe in red)



Thesis research Zeeland University of Applied Sciences

Another study into the assessment of the stability and erosion resistance of the national highway A58 in Reimerswaal has been carried out in the framework of a thesis research project of the Zeeland University of Applied Sciences University (Steur, 2018). The approach is comparable to Deltares with other starting points: the pump-out time is 10, 20 or 30 days and the traffic load is variable. The considered failure mechanisms are macroinstability and erosion of the embankments due to wave formation. Strain softening is not considered. The conclusion here is that the national highway A58 has adequate stability during a flood and that the verges are erosion-resistant.

Assessment of preliminary studies for the A58 Reimerswaal

The present question for this FRAMES study is whether for the A58 in Reimerswaal damage can be also expected if the road floods. The Deltares study (2014) for the whole main road network of the Netherlands analyses embankment height and slope to determine whether the road bed will be damaged. The outcomes of this approach are not entirely clear. It seems as if the effective flooding depth of a road is not included and only geometrical parameters are investigated. In Zeeuws-Vlaanderen, for example, many parts of the national highway are classified as unsafe, while no flooding is expected here. To determine this, first the starting points of the preliminary studies are assessed to consider the usability of the results:

- Soil structure on the basis of DINO service: more information is unavailable, so this is the best available information;
- Flooding depth implicitly included via the groundwater level: in general a real assumption, because for most profiles the water is higher than the road and complete saturation of the road bed with groundwater is normative for the stability.

On the failure mechanism ‘strain softening’ the following matters are observed:

- Strain softening is assumed to occur when the water has risen to the top of the carriageway (or the 'acute phase').
- For the assessment of strain softening use is made of CUR recommendation 113. This recommendation has been drawn up for the assessment of bank stability of sand excavation pits, where it is stated that in the Netherlands observations have also been made in Zeeland in particular at the tidal channels. In both cases it is thus a matter of direct contact between water and sand in a dynamic system. With a road embankment slope there will be in general terms a surface cover. In the Deltares document it is distinguished that this has a favourable effect, but this is not further quantified.
- In accordance with CUR recommendation 113 there must be 3 elements for the occurrence of strain softening: an introductory mechanism (difficult to quantify), adequately loosely packed sand over a minimum layer thickness of probably 2 to 5 m and an unfavourable slope geometry.
- In the Deltares analysis an assumption is made on the packing density of the road bed, as being 'loosely packed' and so sensitive to strain softening. This assumption is very debatable. For national highways standard RAW provisions are applicable[1]. It is not likely that the sand under the pavement and just outside it is loosely packed. If the soil under the national highways and embankment slopes is closely packed, processing is not a relevant failure criterion.

In summary, the probability that strain softening occurs on embankment slopes with vegetation along motorways is estimated as very small.

On the failure mechanism of macroinstability the following matters are observed:

- Macroinstability is assumed to be likely to occur when the water drops again (or the 'recovery phase');
- Deltares studied that accepting any damage (up to 6 m) has a large impact on the compliance/non-compliance of the stability of the road, relative to the assumption that no damage is accepted. This means that the calculated instability will usually involve small sliding surfaces (with limited damage to the road as a whole). With small sliding surfaces the modelling starting points are even more sensitive;
- The assumption for the drop of the groundwater level in 1 day at shearing is too conservative. The vulnerability analysis of the FRAMES pilot study in Reimerswaal indicates that the pump-out time amounts to a minimum of 2 - 7 weeks. It is expected that with a longer pump-out time shearing occurs less quickly than calculated. This is confirmed by the study of the HZ. It is also unclear how the reaction of the water level in the slope has been modelled. Presumably this has been done also fairly conservatively, since sand has good permeability and this will follow the outside water level fairly well;

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[1] Amongst other things:

- 22.02.07.05 The degree of compaction (test 3) of sand that has been incorporated as fill or elevation at a depth of more than 1.0 m below the surface of the carriageway, and that is situated above the free water level present in road subgrade at the time just before the introduction of fill or elevation, must amount to at least 93 %. The average degree of compaction must amount to at least 98 %.
- 22.02.07.06 The degree of compaction (test 3) of sand that has been incorporated in the sand bed at a depth of less than 1.0 m below the surface of the carriageway, must amount to at least 95 %. The average degree of compaction must amount to at least 100 %.

- Traffic load of 20 kN/m^2 at shearing: the traffic load is realistic in quantitative terms. To prevent shearing, however, the choice can be made to use the road only if the water level has dropped adequately.

In summary, here the probability of the failure of road embankment slopes due to macroinstability is estimated as relatively small. The study of Zeeland University seems to confirm this. Only very steep slopes that come under water can possibly shear.

In view of the above observations it is assumed that the road embankment slopes in Reimerswaal do not fail or only fail in a limited way. In the damage determination (chapter 5) the starting point is minimum damage. In the case of the measures (chapter 6) a measure is estimated for the further reduction of the probability of failure (by the weakening of the slopes) but this measure is not considered further in the determination of the cost effectiveness.

4.1.3 Vlaketunnel and flooding by dyke breach

At the Vlaketunnel protection dykes (kanteldijken) have been provided on both sides of the tunnel to prevent flooding of the polder from the tunnel. The tunnel protection dykes also work, however, the other way round: they protect the tunnel against flooding from the polder. The minimum height of the tunnel protection dyke is NAP +3.80 (see figure 4.5).

Figure 4.5 Height of tunnel protection dyke

In the flood maps the light blue colour shows that the tunnel protection dyke is flooded (see figure 4.6). It is however important to realise that the resolution of the VNK2 scenarios is 100 x 100 m, so that the question is whether the tunnel protection dykes have been included adequately in the height model and thus in the dyke breach scenarios.

Figure 4.6 Flood map combined Westerschelde and Oosterschelde scenario, starting from flood proof barriers (simulations of province of Zeeland, light-blue and dark-blue is water. According to this simulation the Vlaketunnel is flooded)

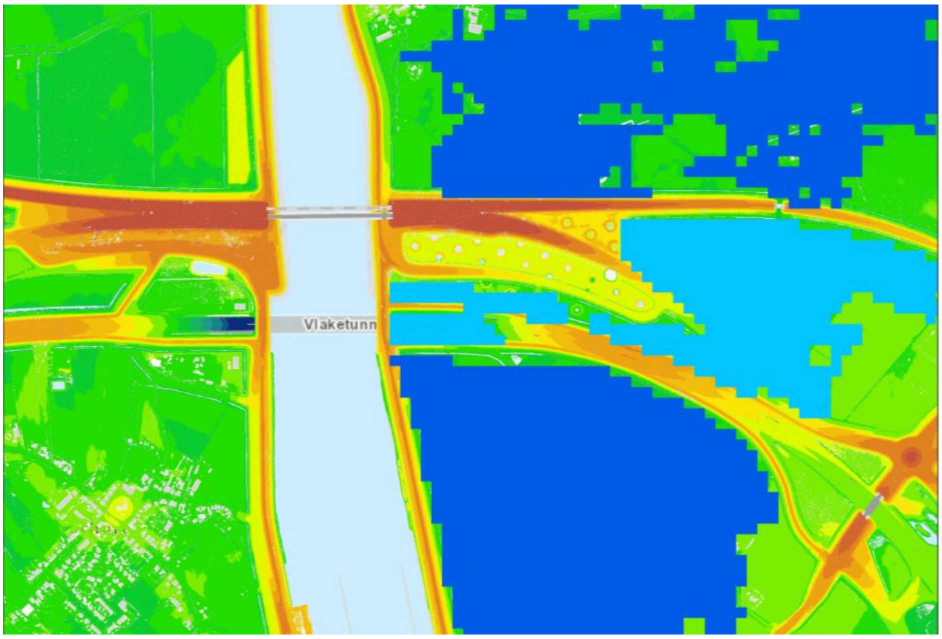


Table 4.1 shows the maximum water level at the tunnel protection dyke for different dyke breach scenarios. This shows that the Vlaketunnel does not flood with flood proof regional barriers. In the case of non-flood proof regional barriers the tunnel protection dyke is not high enough and the Vlaketunnel floods in both the combined Oosterschelde scenario and in the combined Westerschelde and Oosterschelde scenario. The Vlaketunnel sustains damage.

Table 4.1 Water levels at Vlaketunnel protection dyke

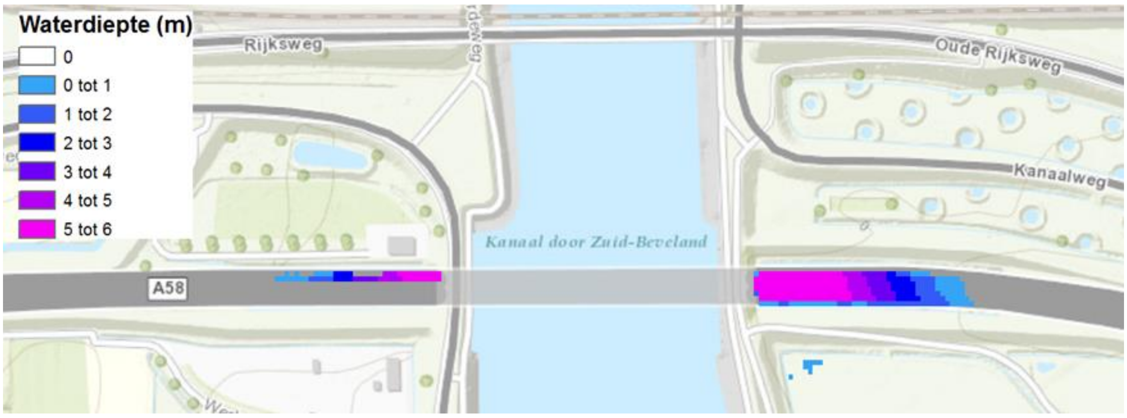
Water level (m NAP)	non-flood proof regional barriers	flood proof regional barriers
Oosterschelde	3.90 m NAP	0
Westerschelde and Oosterschelde	5.00 m NAP	3.62 m NAP

The large resolution of the dyke breach scenarios presumably explains why the flood maps indicate that the Vlaketunnel floods, while the tunnel protection dyke in reality is found to be high enough for the scenarios with flood proof regional barriers.

4.2 Pluvial flooding to Vlaketunnel

It has also been studied whether the Vlaketunnel is vulnerable to pluvial flooding. The key question is whether the tunnel remains dry in the future climate in cases of extreme rainfall. Here the concept of ‘extreme rainfall’ has been adopted with different return times, including the design return time of 1x per 250 years.

Figure 4.7 Overview of PWO calculated flooding at Vlaketunnel

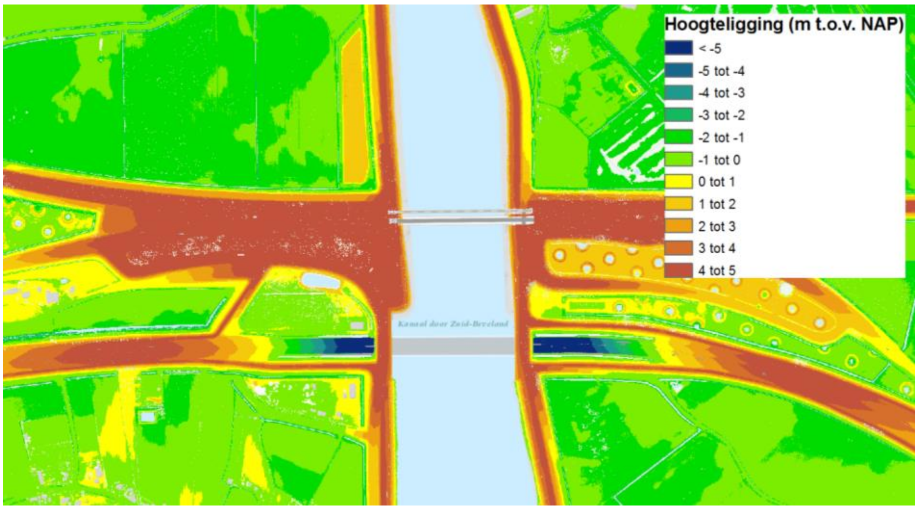


4.2.1 System analysis of tunnel

Height situation

Figure 4.8 shows the height situation around the tunnel. At the access ramps there is a tunnel protection dyke. A tunnel protection dyke is a flood barrier that prevents the tunnel flooding in the event of a dyke breach at the adjoining polder. The tunnel protection dyke has a height of at least NAP +3, 8 m.

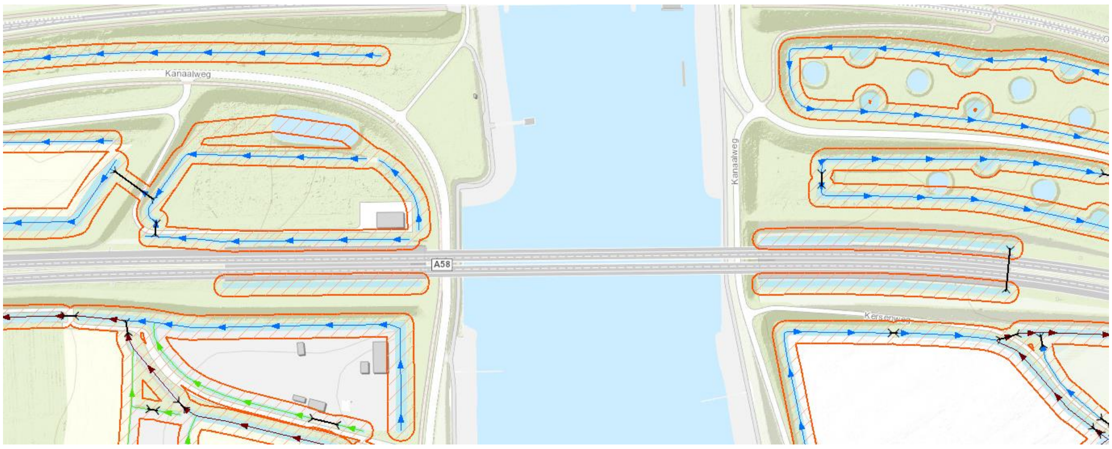
Figure 4.1Height situation



Surface water system

Figure 4.9 shows the surface water system. This shows that the water channels to the north of the western access ramp are connected to the surface water system. These water channels are managed by the water board. The summer and the winter reference waterlevel lies at NAP -2 m. The water channels to the south of the western access ramp and at the eastern access ramp are under the management of Public Works and Water Management. It is not known which water levels are maintained in these water channels. On the basis of the height measurements a water level of NAP -1.2 m is estimated. Information from the water authority can be used to check whether this estimate is correct. The water levels at the eastern access ramp are maintained by means of a pump. It is not known how the water level is maintained to the south of the western access ramp. Possibly the water infiltrates to the surrounding level area.

Figure 4.9 Surface water system

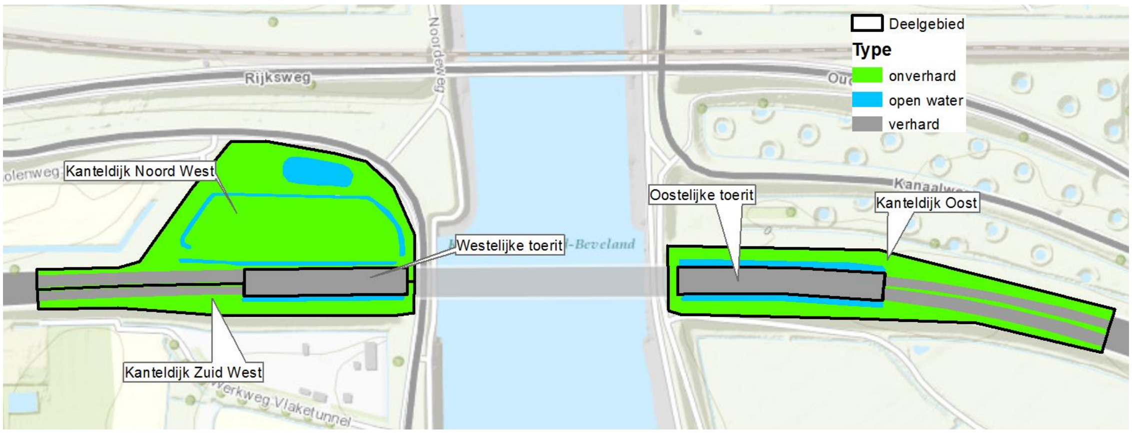


Water system

The drainage system of the Vlaketunnel consists of 5 subareas:
- Eastern tunnel protection dyke;
- Eastern access ramp;
- North-western tunnel protection dyke;
- South-western tunnel protection dyke;
- Western access ramp.

Figure 4.10 shows the 5 subareas.

Figure 4.10 Layout of Vlaketunnel drainage system



Surfaces

Table 4.2 gives the type of surface for the different subareas.

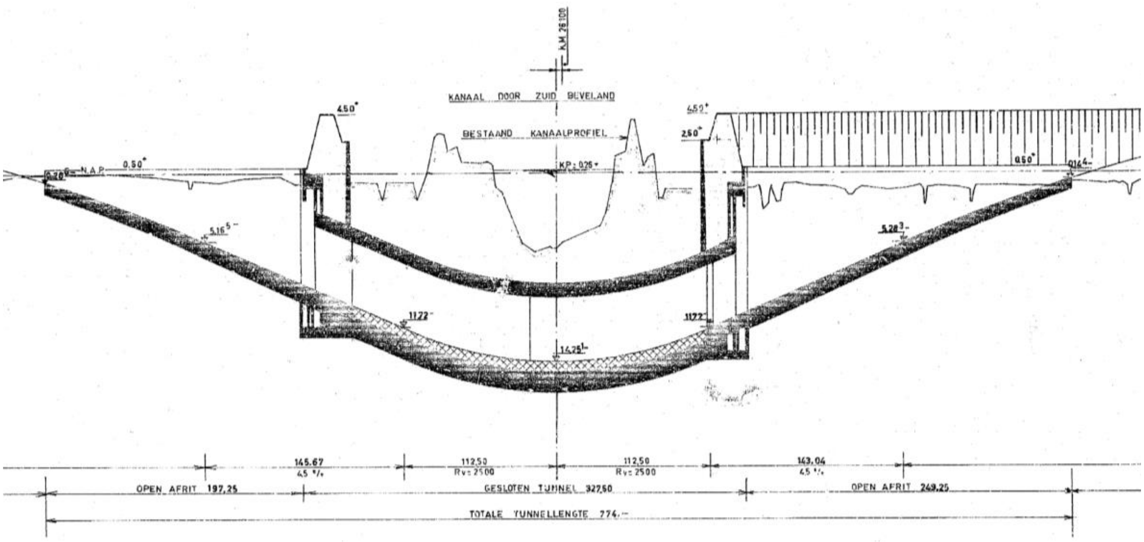
Table 4.2 Size of surfaces per subarea

	Western access ramp (m^2)	Eastern access ramp (m^2)	Eastern tunnel protection dyke (m^2)	North-Western tunnel protection dyke (m^2)	South-West tunnel protection dyke (m^2)
Paved	6,217.2	7,912.8	7,223	3,643	2,758
Unpaved	0	0	19,162	35,319	8,423
Open water	0	0	4,347	5,299	1,405

Longitudinal profile

Figure 4.11 shows the longitudinal profile of the road. Including the open part the tunnel is 774 m long. At the deepest point the road lies at NAP -14.25 m.

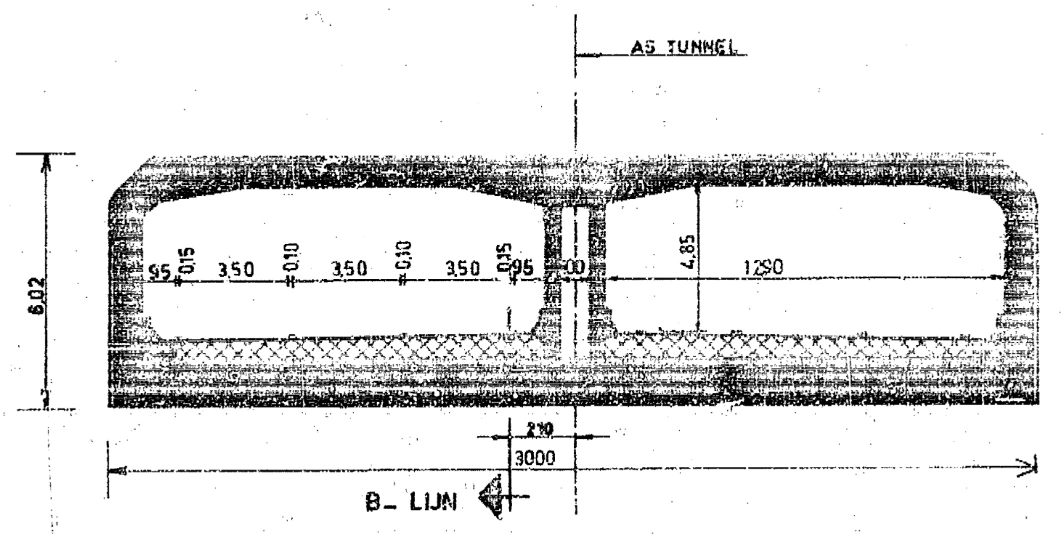
Figure 4.11 Longitudinal profile



Transverse profile

Figure 4.12 shows the transverse profile of the tunnel for the closed part.

Figure 4.12 Cross section



Storm water underground storage areas and pumps

The Vlaketunnel has 4 storm water underground storage areas with pumps:

- East underground storage area with a discharge to the canal through Zuid-Beveland.
- West underground storage area with a discharge to the canal through Zuid-Beveland.
- Middle underground storage area with a discharge to the east and the west underground storage area.
- Sloping underground storage area, this storage takes care of the discharge from the East Flood Defence subarea.

Table 4.3 shows the characteristics of the underground storage areas and the pump installations.

Table 4.3 Characteristics of underground water storage areas and pump installations

	Dimensions	East underground water storage area	West underground water storage area	Middle underground water storage area	Sloping underground water storage area
Pump capacity	m^3/h	237.6	302.4	324	188
Of pumps	#	3	3	2	2
Capacity of underground water storage areas	m^3	972	972	42	7

HWA-pipes

In the tunnel duct a HWA removes the storm water to the underground water storage areas. These pipes have a diameter of 300 mm.

4.2.2 Flood damage analysis

Normative showers and approach

Table 4.4 shows the rainfall events from the standardised stress test (DPRA, 2018). For each subarea of the water system the review has been carried out. The results have been described in the following paragraphs.

Table 4.4 Storm performance stress test

Repetition time (year)	Duration	Precipitation quantity (mm)
100	1 hour	70
250	1 hour	90
1,000	2 hours	160

The applied method to carry out the review varies per subarea. For the tunnel construction (Eastern and Western access ramp) information is available on the position and diameter of the pipes, the pump capacity and the size of the underground water storage area. This information has been converted into a hydrodynamic model. In the review InfoWorks was used.

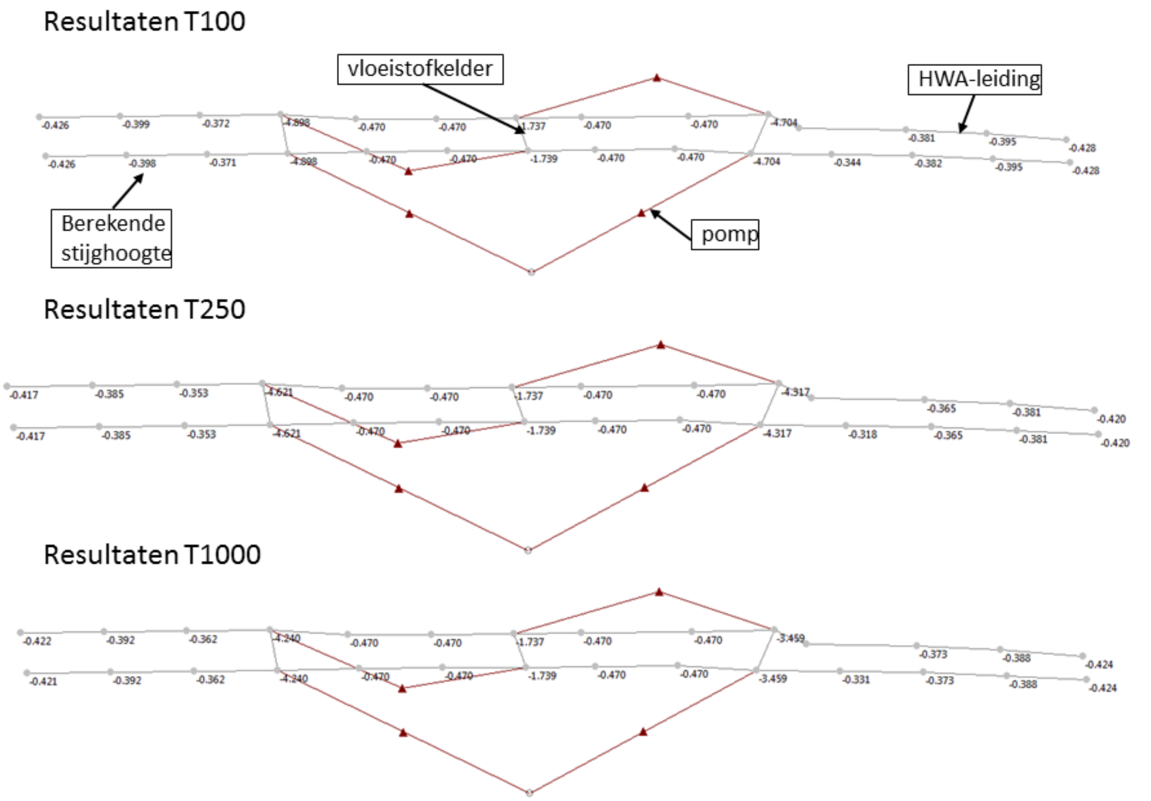
For the other subareas the information is limited. There is no information available on soil structure, and dimensions of water channels and the maintained water level. As a result the analysis cannot go beyond a review on the basis of a simplified water balance.

Eastern and western access ramp

Figure 4.13 shows the review results for the Vlaketunnel. The figure schematically shows a top view of the discharge lines, underground water storage areas and the pumps of the HWA-system At the discharge lines the calculated rise heights have been shown for the different rainfall events. The rise heights give the height relative to the carriageway (so a negative value means no water on the road). The figure shows that the drainage system can handle the 3 rainfall events without 'water-on-road' being calculated. The rise heights remain more than 30 cm under the carriageway.

The figure also shows that the rise heights for the T250-rainfall events are higher than the rise heights for the T1000-rainfall event. This is caused by the rainfall intensity. At the T250-rainfall events the rainfall intensity is 90 mm/h and at the T1000-rainfall event this amounts to 80 mm/h.

Figure 4.13 Maximum rise heights in m relative to carriageway



Eastern tunnel protection dyke

For the review of the subarea Eastern tunnel protection dyke a water balance has been drawn up. Table 4.5 shows the results. For the unpaved surface a run-off coefficient of 0.3 has been adopted in accordance with the 'Manual highway engineering, Design rainwater drainage' of Public Works and Water Management. For paved surface and for open water the run-off coefficient is 1. The water balance provides a maximum level rise of 0.55 m. In view of the height difference between the water level (NAP -1.2) and the height of the carriageway (NAP -0.45 m) flooding does not occur. This means the water does not flow on the access ramp.

Table 4.5 Water balance for Eastern Flood Defence Dike

Description	Unit	T100	T250	T1000
Rainfall quantity	mm	70	90	160
Duration	hour	1	1	2
Discharge unpaved	m3	402	517	920
Discharge paved	m3	304	391	696
Discharge open water	m3	506	650	1,156
Discharge pumps	m3	188	188	376
Open water storage	m3	1,024	1,371	2,395
Level increase open water	m	0.24	0.32	0.55

South-western tunnel protection dyke

The results with the water balance for the subarea South-West tunnel protection dyke have been shown in table 4.6. The water balance provides a maximum level rise of 0.25 m. In view of the height difference between the water level (NAP -1.2) and the height of the carriageway (NAP -0.45 m) flooding does not occur. This means the water does not flow on the access ramp.

Table 4.6 Water balance for South-West Flood Defence Dike

Description	Unit	T100	T250	T1000
Rainfall quantity	mm	70	90	160
Duration	hour	1	1	2
Discharge unpaved	m3	177	227	404
Discharge paved	m3	98	126	225
Discharge open water	m3	193	248	441
discharge pumps	m3	0	0	0
Open water storage	m3	468	602	1,070
Level increase open water	m	0.11	0.14	0.25

North-west tunnel protection dyke

The results with the water balance for the subarea North-West tunnel protection dyke has been shown in table 4.7. The water balance provides a maximum level rise of 0.72 m. In view of the height difference between the water level (NAP -2.8 m) and the height of the carriageway (NAP -0.45 m) flooding does not occur. This means the water does not flow on the access ramp.

Table 4.7 Water balance for North-West tunnel protection dyke

Description	Unit	T100	T250	T1000
Rainfall quantity	mm	70	90	160
Duration	hour	1	1	2
Discharge unpaved	m3	741	954	1,695
Discharge paved	m3	371	477	848
Discharge open water	m3	255	328	583
Discharge pumps	m3	0	0	0
Open water storage	m3	1,368	1,758	3,126
Level increase open water	m	0.31	0.40	0.72

4.2.3 Conclusion

To check whether there is water on the motorway in the case of extreme rainfall on the motorway the drainage system has been assessed with the standardised stress tests. The review shows that none of the rainfall events (T100, T250 and T1000) result in water on the carriageway.

4.3 Flood damage: quick scan of design standards

The design standards for motorways and engineering structures in the field of water drainage have been considered in this paragraph. Here a study has been made of directives from different years to be able to make the comparison. First of all the design criteria for the carriageway are given. Then the criteria for the drainage system. Afterwards the design criteria are compared with recent climate insights.

4.3.1 Summary of design standards

Design standards for drainage system with Manual for Highway Construction Design Rain Water Drainage

In the Manual for Highway Construction Design Rain Water Drainage 1988 two criteria are stated that apply when designing a drainage system. Since in the Manual for 2012 there are no new/other criteria a reference is made to 1988. It is assumed that the following criteria apply also now:

1. Rainfall intensity (l/s/ha): The rainfall intensity is used for the determination of the discharge capacity of the drainage system. It is recommended to use the following rainfall intensities:
   - 100 l/s/ha where there is adequate catchment next to the pavement and there is no danger of water on the hard shoulder or run-off onto verges and slopes.
   - 167 l/s/ha where there is inadequate catchment next to the pavement, for the sewers of central reservation and if there is a danger of run-off onto verges and slopes.
   - 200 l/s/ha where there is no space next to the pavement for extra catchment. Typical examples are tunnels.
2. rainfall quantity (mm/unit time) with a particular return time: The rainfall quantity used for determining the storage capacity of the drainage system and flowrate of the discharge itself. This calculation is necessary if natural drainage is lacking or when third parties restrict the discharge into a nearby water channel. It is recommended to assume the following quantities:
   - T = 10 years for situations where, after the storage in the drainage system has been filled, there is adequate space next to the pavement for extra catchment.
   - T = 50 years for situations where, after the storage in the drainage system has been filled, there is only a limited space next to the pavement. Typical junctions and interchanges can be considered here.
   - T = 250 years for situations where, after the storage in the drainage system has been filled, there is no space next to the pavement. Typical examples are tunnels.

For the rainfall quantity use is made of a rainfall duration line or rain curve. Figure 4.14 on the following page shows the rainfall duration line of 1988, 2007 and 2050. It is well known that the T250 shower in 1988 for short rainfall durations was less extreme than in 2007. For the T10 and T50 there is a situation where the showers in 1988 and 2007 were around the same. For 1988 the rain curve of Braak is used. For 2012 and 2050 the rainfall duration line of Buishand and Wijngaard is used. An increase of 30 % has been adopted for 2050 in the context of climate change.

Design standards for carriageway drainage with Design Directive for Motorways (2007)

To prevent flooding on the carriageway each pavement is designed with a minimum cant gradient of 2.5 %. With a cant gradient transition from a straight line to a curve with an equal or larger cant gradient no problem with the water drainage can be expected. In the case of a fluctuating cant gradient transition, however, a cross section will always occur where the cross slope is 0 % (cant gradient zero point). Around the cant gradient zero point a drainage problem can occur. Particularly the occurrence of larger water layer thicknesses (2.5 mm or more) must be prevented on account of the reduction of the view that occurs (particularly caused by splashing and spray water) and on account of the smaller friction between the tyre and the wet carriageway. Amongst other things the rainfall duration and rain intensity are determining for the occurring water layer thickness and the length of the puddles on the road.

The following starting points underpin the drainage requirements for the design and dimensioning of the cant gradient transition:

- Rain intensity 36 mm/h.
- Rainfall duration 5 minutes.
- Water layer thickness maximum 2 - 3 mm.
- Puddle length maximum around 10 m in one of the ruts.

To know whether the cant gradient variation actually delivers adequate drainage, information is necessary on, for example, excessive rain intensity or a strongly dominant wind direction. If these sorts of circumstances occur, it must be determined in dialogue with specialists whether the spatial alignment of countervailing provisions is necessary.

Directive on rainwater drainage for bridges and viaducts (2017)

This new directive examines the design of rainwater drainage for bridges and viaducts. The design of roads and tunnels is not discussed in this report. This directive takes into account the then prevailing views on extreme rainfall. Here return times of 1x per 10 years and 1x per 50 years are adopted with periods of time up to 120 minutes for the climate of 2085. For the dimensioning of large bridges a dynamic calculation should be carried out. With small bridges a dynamic calculation is unnecessary.

An essential component in the design of the rainwater drainage is the edge marking criterion[1]. At the dimensioning of the rainwater drainage system for road parts with a maximum speed greater than or equal to 100 km/h the following reference period should be adopted for the edge marking criterion:

1. For bridges and viaducts, where it is physically impossible that larger water heights than 30 cm occur on the carriageway, a reference period of 10 years should be adopted.
2. For bridges and viaducts, where it is possible that water heights of 30 cm or more can occur on the carriageway, a reference period of 50 years should be adopted.

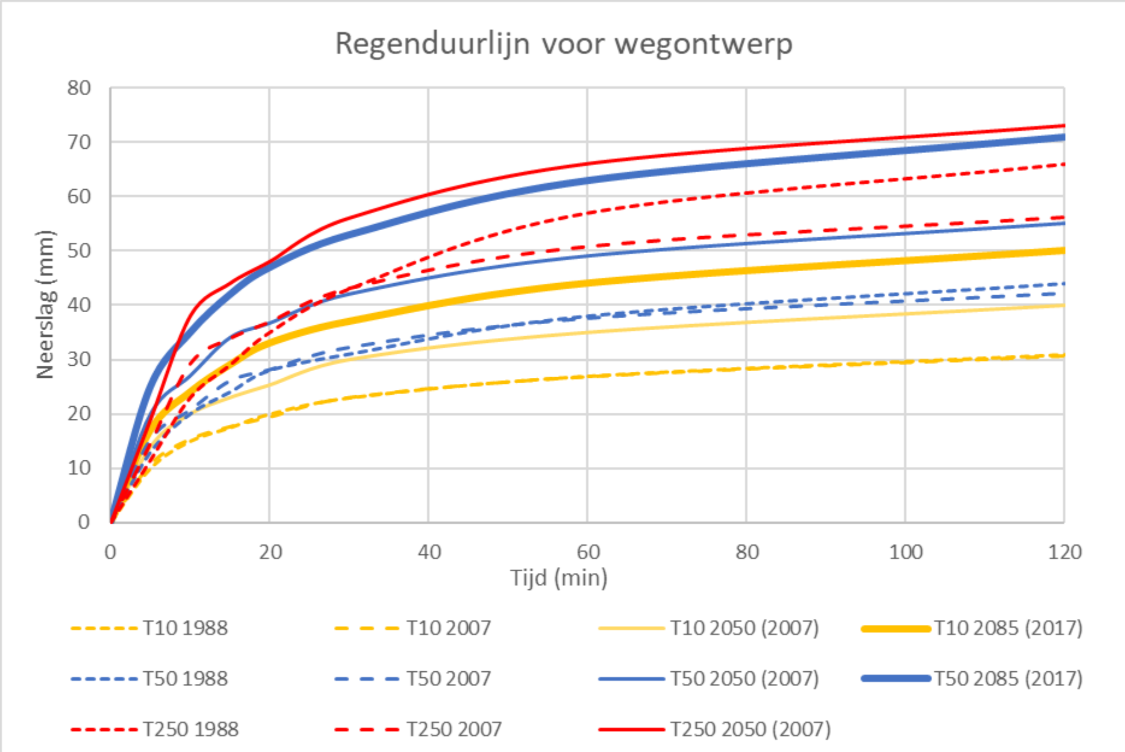
As a rule a reference period of 10 years is adopted for bridges and viaducts. For bridges with high closed wall girders a reference period of 50 years should be adopted.

Comparison development design rainfall in design standards

In the following figure the changing insights into the design rainfall have been visualised.

[1] Meaning of edge marking criterion: the pavement serves as storage of superfluous storm water in the form of 'puddles' with a maximum size.

Figure 4.14 Changing insights into rainfall duration line



4.3.2 Comparison with recent climate insights

The design directives are based on the climate of the past. The 2007 directive already uses a climate surcharge of 30 %. This is sensible because climate change ensures that extreme rainfall occurs more frequently than 30 years ago. In other words, an extreme rainfall event with the same return time gives more rainfall than 30 years ago. The first question is to what extent the 30 % surcharge on extreme rainfall is in line with the observed extreme rainfall.

New insights

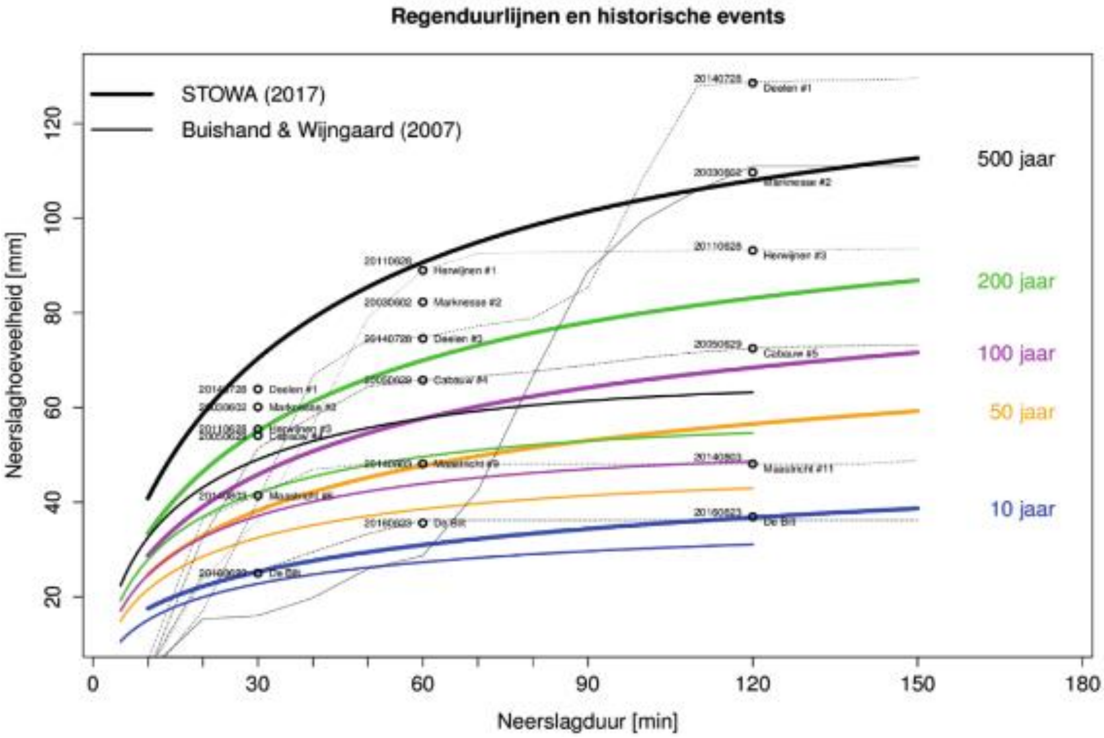
In 2017, STOWA has carried out a statistical study into recent extreme rainfall in the Netherlands with HKV and the KNMI. The considered period is 2002 to 2016. The conclusions have been summarised in figure 4.15. In short, the observations of the last 15 years show that the extreme rainfall is more frequent than expected 10 years ago and that this is becoming more extreme. The rainfall of 1 x 500 years is approximately 26-71 % larger than previously calculated. With a return time of 1x 100 years this is 17-41 % and at 1x 10 years approximately 15 %. The consequence is that the rainfall duration line of 1x 200 years now agrees with the rainfall duration line of 1x 50 years. Regional differences in extremes will be studied in an addition to the report by STOWA.

In 2018 an intensive process has also been completed for standardisation of test rainfall events for the climate stress tests. These rainfall events are also used for the test of the Vlaketunnel. The following table shows this. These rainfall events are approximately 20 % more extreme than the rainfall duration line STOWA indicates.

Table 4.8 Showers stress test

Repetition time (year)	Duration	Precipitation quantity (mm)
100	1 hour	70
250	1 hour	90
1,000	2 hours	160

Figure 4.15 Insights in STOWA research study



Meaning for design directive

The design rainfall events from the design directive have been visualised in figure 4.15. These are compared with the recent insights of STOWA and the standardisation of the climate stress tests. Insights at the comparison

- STOWA research study:
    - The T10 and T50 with 30 % climate surcharge are comparable with the STOWA results. The essential difference is that the rainfall duration lines relate to recent observations (2002-2016): thus the current climate. The extreme rainfall, which had been expected for 2050 in the 2007 design directive, is now found be to falling already on the basis of the current rainfall data and analysis of STOWA. The 2017 design directive assumes more extreme rainfall for 2085 than the research study of STOWA and better reflects recent insights;
    - higher return times are already more extreme than expected for 2050. The rainfall duration line of T200 in the STOWA research study assumes 70 mm in 60 minutes, the design directive from 2007 with 30 % climate surcharge gives 66 mm in 60 minutes at T250. So this design rainfall event for 2050 is already outdated. The design directive from 2017 and associated extreme rainfall for 2085 fits in with the latest insights of STOWA;
- The rainfall event in the standardised climate stress test at T = 250 years gives a considerably higher rainfall sum than the rainfall duration line with 30 % climate surcharge from the design directive of 2007. The standard assumes 90 mm in 60 minutes, the rainfall duration line assumes 66 mm in 60 minutes.

4.3.3 Conclusion

The extreme rainfall that has been included in recent and less recent design directives is outdated. This also applies for recent design directives in which a climate surcharge has been included. This means that objects that are designed and built on the basis of these directives, comply more with the requirements that were specified for the object at the time of building. It is important to study whether this insight is more widely known within Public Works and Water Management and to inventory which initiatives are running to determine the consequences of this. Witteveen+Bos works, for example, for Public Works and Water Management on the revision of the design directives for the design of rainwater drainage for tunnels. Existing tunnels, such as the Vlaketunnel, can be assessed on the more extreme rainfall. At the Vlaketunnel the installations are also found to comply with requirements of the future climate. The drainage and pump installations of the tunnel also comply with the requirement of no flooding at a return time of 1x 250 years even with a changing climate.

5

DAMAGE DETERMINATION

5.1 Estimate of damage

The first estimate of the direct damage to the A58 is based on the results of the vulnerability phase described in this report. The damage determination has been divided up into direct and indirect damage. The flood protection analysis has shown that many objects flood and thus possibly suffer damage due to flooding. On the basis of the analysis of pluvial flooding (by rainfall) no problems have been identified. On the basis of the analysis of the design directives a generic risk has been identified because the extreme rainfall events due to climate change have already become heavier than expected in the past.

5.1.1 First determination of damage mechanisms at flooding (dyke breach)

At flooding of the different objects of the national highways different damage mechanisms can occur. These are described in table 5.1. Also a first indication of the damage has been included here.

Table 5.1 Damage categories per object type

Object	Damage categories	Damage costs (first indication)
Road	- Very serious: complete erosion or instability of road bed - Serious: instability, strain softening or erosion of part of road bed and construction - Limited: surface damage caused by pollution and deposition of sediment	- 100 % of the investment costs - 10 % of the investment costs - 1 % of the investment costs
Exits and access ramps	- Very serious: complete erosion or instability of road bed - Serious: instability, strain softening or erosion of part of road bed and construction - Limited: surface damage caused by pollution and deposition of sediment	- 100 % of the investment costs - 10 % of the investment costs - 1 % of the investment costs
Filling station	- Very serious: complete replacement of the filling station - Limited: surface damage caused by pollution and deposition of sediment	- 100 % of the investment costs - 10 % of the investment costs
Fixed bridge	- Very serious: failure of the construction - Serious: instability or damage to construction - Limited: surface damage caused by pollution and deposition of sediment	- 100 % of the investment costs - 20 % of the investment costs - 5 % of the investment costs
Underpass	- Very serious: failure of the construction - Serious: instability or damage to construction - Limited: surface damage caused by pollution and deposition of sediment	- 100 % of the investment costs - 20 % of the investment costs - 5 % of the investment costs
Tunnel/aqueduct	- Very serious: failure of the construction	- 100 % of the investment costs

Object	Damage categories	Damage costs (first indication)
	- Serious: damage to construction and installations - Limited: surface damage caused by pollution and deposition of sediment	- 20 % of the investment costs - 1 % of the investment costs
Viaduct	- Very serious: failure of the construction - Serious: instability or damage to construction - Limited: surface damage caused by pollution and deposition of sediment	- 100 % of the investment costs - 20 % of the investment costs - 5 % of the investment costs

5.1.2 Unit prices for direct damage

The unit prices for the determination of direct damage are based on the report of Public Works and Water Management from October 2018 and on expert judgement from other projects. The most important unit prices are:

- motorway per km: EUR 12,000,000.00 per direction of travel (Wegwijzer klimaatadaptatie voor het hoofdwegennet, Rijkswaterstaat, 2018, page 70);
- slip-road and exit (including engineering structures): EUR 10,000,000.00 (expert judgement assumption);
- filling station: EUR 2,000,000.00 (expert judgement assumption);
- underpass (cycle tunnel): EUR 1,000,000.00 (expert judgement other project);
- Vlaketunnel: EUR 100,000,000.00: original building costs (from 1972-1975) of Fl. 38,000,000.00 indexed by 4 % price increase over 45 years;
- viaduct: EUR 4,000,000.00 (expert judgement other project).

5.1.3 Direct damage to A58 within Reimerswaal

On the basis of the vulnerability analysis the direct damage per dyke breach scenario has been estimated. The estimated claims for damage are indicative and intended as an order-of-magnitude estimate. Tables 5.2 and 5.3 show the direct damage on the basis of the flood maps with non-flood proof regional barriers (VNK2 scenarios). Table 5.4 shows the direct damage on the basis of the flood maps with flood proof regional barriers (Province of Zeeland).

Table 5.2 Overview of indicative damage on the basis of provisional sums with Combined Western and Oosterschelde scenario, non- flood proof regional barriers

Object	Quantity or number	Length or number flooded	Assumption for damage due to flooding per unit (EUR)	Damage (EUR)
Road	17.5	- 17 km with flooding without stability problems - 0 km with stability problems	- 240,000.00 per km (1 % investment) - 12,400.00 per km (10 % investment)	4,100,000.00
Exits and access ramps	3	3	100,000.00 (1 % of investment)	300,000.00
Filling station	2	2	2,000,000.00 (100 % of investment)	4,000,000.00
Fixed bridge	1	0		0.00
Underpass	1	1	50,000.00 (10 % of investment	100,000.00
Tunnel/aqueduc t	1	- Flood scenario: damage to installations and construction	- 20,000,000.00 (20 % of investment)	20,000,000.00
Viaduct	7	7	200,000.00 (5 % of investment)	1,400,000.00
Total				**29,900,000.00**

Table 5.3 Overview of indicative damage on the basis of provisional sums with Combined Oosterschelde scenario, non-flood proof regional barriers (amounts rounded off)

Object	Quantity or number	Length or number under water	Assumption for damage due to flooding per unit (EUR)	Damage (EUR)
Road	17.5	- 12.6 km with flooding without stability problems - 0 km with stability problems	- 240,000.00 per km (1 % investment) - 12,400.00 per km (10 % investment)	3,400,000.00
Exits and access ramps	3	2	100,000.00 (1 % of investment)	200,000.00
Filling station	2	1	2,000,000.00 (100 % of investment)	2,000,000.00
Fixed bridge	1	0		0.00
Underpass	1	1	50,000.00 (10 % of investment	100,000.00
Tunnel/aqueduct	1	- Flood scenario: damage to installations and construction	- 20,000,000.00 (20 % of investment)	20,000,000.00
Viaduct	7	5	200,000.00 (5 % of investment)	1,000,000.00
Total				**26,700,000.00**

Table 5.4 Overview of indicative damage on the basis of provisional sums (Combined Western and Oosterschelde scenario, flood proof regional barriers)

Object	Quantity or number	Length or number under water	Assumption for damage due to flooding per unit (EUR)	Damage (EUR)
Road	17.5	- 10 km with flooding without stability problems - 0 km with stability problems	- 240,000.00 per km (1 % investment) - 2,400,000.00 per km (10 % investment)	2,400,000.00
Exits and access ramps	3	3	100,000.00 (1 % of investment)	300,000.00
Filling station	2	2	2,000,000.00 (100 % of investment)	4,000,000.00
Fixed bridge	1	0		0.00
Underpass	0	0		0.00
Tunnel/aqueduct	1	0		0.00
Viaduct	7	7	200,000.00 (5 % of investment)	1,400,000.00
Total				**8,100,000.00**

In the case of the Oosterschelde scenario and flood proof regional barriers, no damage occurs to the A58.

5.1.4 The indirect damage due to chain effects

The indirect damage has been extensively studied in the FRAMES pilot focussing on Reimerswaal. The conclusions are set out below. The analysis has determined the costs for cancelled journeys, diversions and congestion for various journey starting points and destinations.

Table 5.5 Costs per day for the 3 categories of commuter traffic.

	Journey starting point or destination Reimerswaal, costs in EUR	Through Reimerswaal, costs in EUR	Not through Reimerswaal, costs in EUR	Freight traffic, costs in EUR	Total in EUR
Cancelled journeys	2,629,000.00				2,629,000.00
Diversions		min: 122,000.00 max: 375,000.00			min: 122,000.00 max: 375,000.00
Congestion		min: 416,000.00 max: 1,275,000.00	min: 148,000.00 max: 456,000.00	246,000.00	min: 810,000.00 max: 1,977,000.00
Total	2,629,000.00	min: 538,000.00 max: 1.650.00,00	min: 148,000.00 max: 456,000.00	246,000.00	**min: 3,561,000.00** **max: 4,981,000.00**

However, here it is necessary to take into account behavioural changes. In the case of traffic congestion people will decide to travel outside peak times or to choose another route. Also after some time the residents of Reimerswaal will go back to their work or elsewhere to work, so that the absenteeism costs decrease. In the determination of the cost effectiveness a reduction factor will therefore be applied.

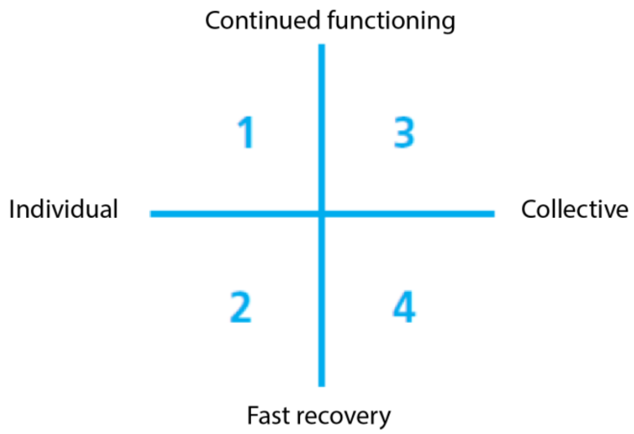
6

DEVELOPMENT OF MEASURES

6.1 Action perspectives

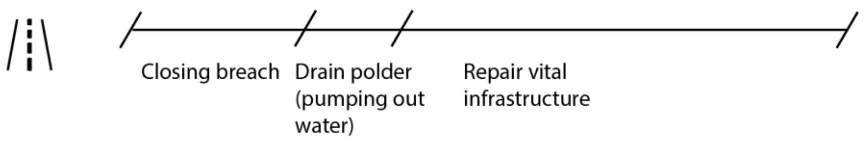
The measures in layer 2 and 3 and in the additional layer 4 of multilayer safety have been developed on the basis of action perspectives. This pilot project focusses on the determination of action perspectives and measures for the A58 (individual). The measures at area level (collective) that limit the flood risk are a component of the FRAMES pilot project for Reimerswaal. The flood protection measures have been elaborated in a sketch design and indicative cost estimate. In the following figure the four action perspectives have been indicated.

Figure 6.1 Four action perspectives



In the FRAMES pilot project for Reimerswaal a division has been made in the three phases of recovery. See also figure 6.2. This study is mainly about the third stage of recovery: the repair of the A58 itself.

Figure 6.2 Basic calculation of recovery time with main measures (partly parallel implementation possible)



6.2 Measures

Inventory and clustering

During the workshop of 15 January 2019 measures were identified within the four quadrants. The report from this workshop is available separately. For the measures for flood protection of the A58 within Reimerswaal the following clustering is adopted:

1 Continued functioning of the A58 via:
    - Collective compartmentalisation of Dijkring 31.
    - Raising the height of the A58.
2 Fast repair of the A58:
    - Making the objects flood-resistant.

The measures for flood damage have not been clustered, because no specific vulnerability has been recorded at the A58 in Reimerswaal. The analysis of historical design directives indicated that objects from the past are possibly inadequately prepared for rainfall that is or is becoming more extreme due to climate change. The measures have therefore been introduced to limit this risk.

Elaboration of promising flood protection measures

Promising measures focus on reduction of the direct damage to the networks and the reduction of indirect damage. The designs give a first insight into the costs and the spatial feasibility of measures.

6.2.1 Promising flood protection measures

Continued functioning through compartmentalisation

The compartmentalisation measure has been studied as part of the FRAMES pilot project for Reimerswaal. In this report a variant of this measure is elaborated. By strengthening only the regional barriers to the north of the A58 the national highway is protected against dyke breaches from the Oosterschelde. For the design of these regional barriers (land dykes) it has been assessed what the water depth is and how high the flood defences must be. This has resulted in a sketch design that consists of two main components:

1 strengthening and raising the height of the regional barriers that are not sufficiently high;
2 strengthening regional barriers that are adequately high.

This design has been shown in figure 6.3.

Figure 6.3 Continued functioning through compartmentalisation

The cost indication for the sketch design can be found in the following table.

Table 6.1 Cost indication of compartmentalisation - north A58 (amounts rounded off)

Measure	Quantity	Costs (in EUR) per unit	Costs in EUR
Raising the height of regional barriers (m3)	91,390	15.00	1,400,000.00
Acquisition of land (m^2)	22,280	10.00	200,000.00
Maintenance of flood defences with adequate height (m)	8,300	100.00	800,000.00
Surcharge for spatial adaptation	100 %		2,400,000.00
Surcharge for contractor costs	25 %		600,000.00
Unforeseen	100 %		2,400,000.00
Total			**7,800,000.00**

Continued functioning by raising the road

A second option for the continued functioning of the A58 is the integral raising of the A58 to above the expected flood level. This means that the motorway is raised over the whole length to a height of NAP 4.8 m. In the elaboration of this measure an allowance has been made for a transverse profile of 50 meters wide and a gradient of 1:3 for the raised part. The current road has an average height of NAP 2.8 m. This means that a net increase in height of 2.0 m is necessary. The costs for this sketch design have been summarised in table 6.2.

Table 6.2 Cost indication for integral increase in height (amounts rounded off)

Measure	**Quantity**	**Costs (in EUR) per unit**	**Costs in EUR**
Removal and provision of paved surface (m^2)	437,500	120.00	52,500,000.00
Acquisition of land (m^2)	270,000	10.00	2,700,000.00
Provision of raised section in sand	2,366,667	15.00	35,500,000.00
Surcharge for spatial adaptation	50 %		45,400,000.00
Surcharge for contractor costs	25 %		22,700,000.00
Unforeseen	100 %		90,700,000.00
Total			**249,500,000.00**

Fast recovery through flood resilience of A58

The last measure is based on the concept of fast recovery. This means that flooding of the national highway in the municipality of Reimerswaal is accepted, but the road is so adapted that the damage and the recovery time is minimal. For the occurrence of flooding the slopes of the motorway have been reduced to minimise the probability of erosion, instability and strain softening. The road only needs to be cleaned after the water has been pumped away. In addition the tunnel protection dyke at the Vlaketunnel is raised to 4.8 m to prevent flooding (in case of non-flood proof regional barriers). This means that the road must be raised over an adequate length to have a good horizontal alignment for the traffic. The tunnel is immediately available without the necessity for any repair. The costs for the measure have been included in the following table.

Table 6.2 Cost indication for speedy recovery - raising the tunnel protection dyke (amounts rounded off)

Measure	**Quantity**	**Costs (in EUR) per unit**	**Costs in EUR**
Acquisition of land for tunnel protection dyke (m^2)	15,000	10.00	200,000.00
Removal and provision of paved surface for tunnel protection dyke (m^2)	12,500	120.00	1,500,000.00
Raise tunnel protection dyke at Vlaketunnel (m^3)	67,000	15.00	1,000,000.00
Surcharge for spatial adaptation	50 %		1,400,000.00
Surcharge for contractor costs	25 %		700,000.00
Unforeseen	50 %		1,400,000.00
Total			**6.200.000,00,00**

Reduction of slopes

Strengthening the slopes has been stated as a possible measure for achieving flood resilience. The costs have been determined in the following table. In the vulnerability analysis it has been assessed to what extent damage to slopes can occur. From this analysis it has been found that there is a very small probability of failure. This measure has not been included therefore in the package of measures and the determination of the cost effectiveness.

Table 6.3 Cost indication for reduction of slopes (amounts rounded off)

Measure	Quantity	Costs (in EUR) per unit	Costs in EUR
Acquisition of land (m^2)	444575.9569	10.00	400,000.00
Provision of raised section in sand for slopes (1:3)	134391.9657	15.00	2,000,000.00
Surcharge for spatial adaptation	50 %		1,200,000.00
Surcharge for contractor costs	25 %		600,000.00
Unforeseen	50 %		1,200,000.00
Total			**5,400,000.00**

6.2.2 Pluvial flooding

The measures to prevent flood damage have been thematically clustered:
- Intensification of maintenance: management of verges, ditches and pits.
- Design road profile again: thickness, cant gradient or type of asphalt and design of verges.
- Traffic management: reduce speed and communication about this at the time of flooding.
- Improve regional water system: increase A-water channels/ culverts / pump capacity for the discharge.

No measures have been designed and estimated at sketch design level. This is because within Reimerswaal no specific risks have been identified.

7

COST EFFECTIVENESS OF MEASURES

This chapter determines the cost effectiveness of the following packages of measures[1]:
1 Compartmentalisation - total.
2 Compartmentalisation - north.
3 Protection of pumping stations.
4 Raising the A58.
5 Increasing the height of the tunnel protection dyke at Vlaketunnel.

A package of measures is cost-effective if the sum of the benefits (avoided damage) is greater than the costs[2]. This can be expressed with a cost-benefit ratio. A measure is cost-effective if:

$$\frac{\text{Benefits}}{\text{Costs}} > 1$$

The benefits of the packages of measures consist of a drop in the annual expectation value (JVW) of the (direct and indirect) damage that occurs at the dyke breach scenarios relative to the situation without extra measures. Here it has been assumed that the packages of measures are effective: due to implementation of the measures the damage can be prevented 100 %.

Costs and benefits seldom occur at the same time. Taking into account a positive time preference, to make the benefit and costs mutually comparable, all amounts refer back to the valuation time (2019). Here in accordance with the Cabinet standpoint [3]a discount rate of 4.5 % is adopted. Furthermore the starting point has been perpetual annual benefits (avoided damage) and annual costs. The calculation of the annual costs is based on the method of equivalent annual costs, where the total life cycle costs have been converted to an average per year. In this a percentage of the investment costs has been taken for management and maintenance.

7.1 Summary of direct and indirect damage

In table 7.1 and 7.2 there is a summary of the direct and indirect damage to the A58.

1 The measures 'compartmentalisation - total', 'protection of pumping stations' have been developed in the FRAMES pilot project of the province of Zeeland. For additional information on these measures the reader is referred to the final report of the Reimerswaal pilot project. For the completeness of this project the measures are included in the analysis of the cost effectiveness.

2 In previous reports there has been reference to cost effectiveness. Cost effectiveness is the measure of the effectiveness of expenditure. In other words, it is examined which measure has the lowest costs to achieve a particular objective. In this pilot project there is no previously defined (safety) objective for vital infrastructure. Therefore the focus is on cost effectiveness and the benefits are weighed against the costs.

3 Ministry of Finance, 2015.

Table 7.1 1Direct damage to A58 (amounts have been rounded off)

Network	Non-flood proof regional barriers (VNK2)		Flood proof regional barriers (PZ)	
	Maximum Oosterschelde scenario	Maximum Oosterschelde and Westerschelde scenario	Maximum Oosterschelde scenario	Maximum Oosterschelde and Westerschelde scenario
A58	EUR 26,300,000.00	EUR 29,200,000.00	-	EUR 8,100,000.00

Table 7.2 Indirect damage to electricity network and A58

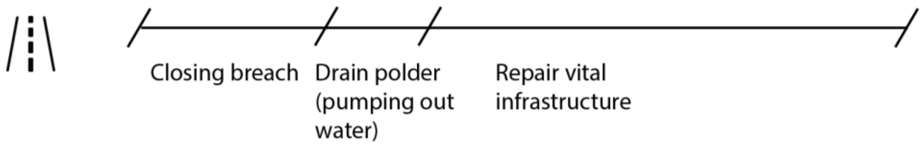
A58	Damage per day
Cancelled journeys, diversions, congestion	EUR 4,271,000.00

The damage amount in table 7.2 still does not take into account behavioural changes during and after a flood. In the case of traffic congestion people will decide to travel outside peak times or to choose another diversion route. Also after some time the residents of Reimerswaal will go back to their work or elsewhere to work, so that the absenteeism costs decrease. In the determination of the total indirect damage to the A58 it is assumed therefore that the damage decreases after 2 - 3 weeks to 60 % of the estimated amount.

7.2 Recovery times and cost effectiveness of measures

The total recovery time at a dyke breach consists of 3 components (see figure 7.1) Below the different starting points are discussed for the recovery time and effectiveness of the measures.

Figure 7.1 7Basic calculation of recovery time with main measures (partly parallel implementation possible)



Starting points in baseline scenario

- Recovery time for closure of breach locations: 3 months.
- Recovery time for pumping out area[1]: only emergency pumps of Water Board are available. Recovery time is 7 weeks.
- With non-flood proof regional barriers the A58 fails in both the combined Oosterschelde and the combined Westerschelde- and Oosterschelde scenario.
- In the case of flood proof regional barriers, the A58 only fails in the combined Westerschelde- and Oosterschelde scenario. With the combined Oosterschelde scenario the A58 is protected against damage and interruption.
- With non-flood proof regional barriers the Vlaketunnel protection dyke does not comply and this sustains damage.
- With flood proof regional barriers, the tunnel protection dyke complies and the Vlaketunnel is protected.
- Recovery time of A58 if Vlaketunnel floods: 4 months.

[1] This has been determined in the FRAMES pilot project for Reimerswaal (see final report FRAMES pilot project for Reimerswaal).

- Recovery time of A58 if Vlaketunnel does not flood: 2 weeks (no major physical damage occurs to the rest of the network).

Starting points for packages of measures

Starting points:

- At compartmentalisation - in total no more damage to the networks occurs.
- At compartmentalisation - in the north no more damage to the A58 occurs with the combined Oosterschelde scenario. With the combined Westerschelde- and Oosterschelde scenario damage still occurs.
- For the protection of pumping stations the starting point is the pump capacity of all emergency pumps of the Water Board and all existing pumping stations. The recovery time for pumping out of the area is reduced by 5 weeks.
- If the A58 is raised the A58 no longer sustains any damage.
- If the tunnel protection dyke is raised no damage occurs any more to the Vlaketunnel [1]and the recovery time decreases from 4 months to 2 weeks (but indirect damage can still occur since the A58 can still be interrupted by flooding).

Cost effectiveness of measures with flood proof and non-flood proof regional barriers

The cost effectiveness of the measures is determined, starting from non-flood proof or flood proof regional barriers. In table 7.3 the recovery time and the resulting indirect damage has been shown for each scenario starting from non-flood proof regional barriers. In table 7.4 the cost effectiveness of each measure is determined (non-flood proof regional barriers). In table 7.5 the recovery time and the resulting indirect damage per scenario has been shown starting from flood proof regional barriers. Table 7.6 then determines the cost effectiveness of each measure (flood proof regional barriers).

[1] For the Vlaketunnel to function properly this requires, besides the fact that no damage to the tunnel itself may occur, electricity for various services (traffic queue signalling, lighting, rainwater pumping, fire brigade etc.). The assumption is that the Vlaketunnel is or can be connected back from the west side of the Vlaketunnel (from dyke ring 30) after 2 weeks.

Table 7.3 Recovery times (in weeks) and indirect damage with non-flood proof regional barriers

Scenario	Baseline		Compartmentalisation - total		Compartmentalisation - north		Protection of pumping stations		Raising the A58		Increasing the height of the Vlaketunnel tunnel protection dyke (kanteldijk).	
	OS	OSWS	OS	OSWS	OS	OSWS	OS	OSWS	OS	OSWS	OS	OSWS
Recovery time at breach locations (weeks)	12	12	12	12	12	12	12	12	12	12	12	12
Recovery time for pumping stations (weeks)	7	7					2	2	7	7	7	7
Recovery time for electricity (weeks)	52	52					52	52	52	52	52	52
Recovery time for A58 (weeks)	16	16					16	16	0	0	2	2
Total recovery time for electricity (weeks)*	4	4	0	0	0	4	4	4	4	4	4	4
Total recovery time A58 (weeks)	35	35	0	0	0	12	30	30	0	0	21	21
Total indirect damage to electricity (EUR)	83,700,000.00	83,700,000.00	-	-	-	83,700,000.00	83,700,000.00	83,700,000.00	83,700,000.00	83,700,000.00	83,700,000.00	83,700,000.00
Total indirect damage to A58 (EUR)	**627,800,000.00**	**627,800,000.0**	-	-	-	**215,300,000.00**	**538,100,000.00**	**538,100,000.00**	-	-	**376,700,000.00**	**376,700,000.00**

* The starting point for indirect damage to electricity is that there is no damage outside dyke ring 31 after 4 weeks.

Table 7.4 Cost effectiveness of measures with non-flood proof regional barriers (discount rate 4.5 %)

Scenario	Baseline		Compartmentalisation - total		Compartmentalisation - north		Protection of pumping stations		Raising the A58		Increasing the height of the Vlaketunnel protection dyke (kanteldijk).	
	OS	OSWS	OS	OSWS	OS	OSWS	OS	OSWS	OS	OSWS	OS	OSWS
Total direct damage (EUR)	33,000,000.00	35,900,000.00	-	-			33,000,000.00	35,900,000.00	6,700,000.00	6,700,000.00	13,000,000.00	15,900,000.00
Total indirect damage (EUR)	711,500,000.00	711,500,000.00	-	-	-	299,000,000.00	621,800,000.00	621,800,000.00	83,700,000.00	83,700,000.00	460,400,000.00	460,400,000.00
Annual risk (EUR)		250,000.00		-		600,000.00		220,000.00		30,000.00		160,000.00
CW_benefit (EUR)				5,600,000.00		4,200,000.00		700,000.00		4,900,000.00		2,000,000.00
Investment cost of measure (EUR)				37,200,000.00		7,800,000.00		1,200,000.00		249,500,000.00		6,200,000.00
Annual maintenance (%)				3.00 %		3.00 %		5.00 %		/		/
Life cycle of measure (year)				50		50		30		/		/
CW_measure (EUR)				43,100,000.00		9,000,000.00		1,700,000.00		249,500,000.00		6,200,000.00
Cost/benefit ratio				0.13		0.47		0.41		0.02		0.32

Table 7.5 Recovery times (in weeks) and indirect damage with flood proof regional barriers

<table>
<tr><th>Recovery times</th><th colspan="2">Baseline</th><th colspan="2">Compartmentalisation - total</th><th>Compartmentalisation - North**</th><th colspan="2">Protection of pumping stations</th><th colspan="2">Raising the A58</th><th>Increasing the height of the tunnel protection dyke (kanteldijk)**</th></tr>
<tr><td>Scenario</td><td>OS</td><td>OSWS</td><td>OS</td><td>OSWS</td><td rowspan="9">N/A</td><td>OS</td><td>OSWS</td><td>OS</td><td>OSWS</td><td rowspan="9">N/A</td></tr>
<tr><td>Recovery time at breach locations (weeks)</td><td>12</td><td>12</td><td>12</td><td>12</td><td>12</td><td>12</td><td>12</td><td>12</td></tr>
<tr><td>Recovery time for pumping stations (weeks)</td><td>7</td><td>7</td><td></td><td></td><td>2</td><td>2</td><td>7</td><td>7</td></tr>
<tr><td>Recovery time for electricity (weeks)</td><td>52</td><td>52</td><td></td><td></td><td>52</td><td>52</td><td>52</td><td>52</td></tr>
<tr><td>Recovery time for A58 (weeks)</td><td>2</td><td>2</td><td></td><td></td><td>2</td><td>2</td><td>0</td><td>0</td></tr>
<tr><td>Total recovery time electricity (weeks) *</td><td>4</td><td>4</td><td>0</td><td>0</td><td>4</td><td>4</td><td>4</td><td>4</td></tr>
<tr><td>Total recovery time A58 (weeks)</td><td>0</td><td>21</td><td>0</td><td>0</td><td>0</td><td>16</td><td>0</td><td>0</td></tr>
<tr><td>Total indirect damage to electricity (EUR)</td><td>-</td><td>83,700,000.00</td><td>-</td><td>-</td><td>-</td><td>83,700,000.00</td><td>-</td><td>83,700,000.00</td></tr>
<tr><td>Total indirect damage to A58 (EUR)</td><td>-</td><td>376.700.00,00</td><td>-</td><td>-</td><td>-</td><td>287,000,000.00</td><td>-</td><td>-</td></tr>
</table>

* The starting point for indirect damage to electricity is that there is no damage outside dyke ring 31 after 4 weeks.

** In the case of flood proof regional barriers the package of measures compartmentalisation - north or increasing the height of tunnel protection dykes (kanteldijken) provides no benefit, since these offer no additional protection to the electricity network or the A58

Table 7.6 Cost effectiveness of measures in the case of flood proof regional barriers

Scenario	Baseline		Compartmentalisation - total		Compartmentalisation - North*	Protection of pumping stations		Raising the A58		Increasing the height of the tunnel protection dyke (kanteldijk)*
	OS	OSWS	OS	OSWS		OS	OSWS	OS	OSWS	
Total direct damage (EUR)	6,200,000.00	14,800,000.00	-	-	N/A	6,200,000.00	14,800,000.00	6,200,000.00	6,200,000.00	N/A
Total indirect damage (EUR)	-	460,400,000.00	-	-		-	370,700,000.00	-	83,700,000.00	
Annual risk (EUR)	100,000.00		-			80,000.00		20,000.00		
CW_benefit (EUR)			2,200,000.00			400,000.00		1,800,000.00		
Investment cost of measure (EUR)			37,200,000.00			1,200,000.00		249,500,000.00		
Annual maintenance (%)			3.00 %			5.00 %		/		
Life cycle of measure (year)			50			30		/		
CW_measure (EUR)			43,100,000.00			1,700,000.00		249,500,000.00		
Cost/benefit ratio			0.05			0.24		0.01		

* In the case of flood proof regional barriers the package of measures compartmentalisation - North or increasing the height of tunnel protection dykes provides no benefit, since these offer no additional protection to the electricity network or the A58

7.3 Results of cost effectiveness

Table 7.7 shows the cost-benefit ratios of the different measures. No measure is found to be cost effective: the cost-benefit ratios are always smaller than 1 and the costs do not weigh up against the benefits.

Table 7.7 Cost-benefit ratios of packages of measures

Cost/benefit ratios	Non-flood proof regional barriers (VNK2 scenarios)	Flood proof regional barriers (scenarios of province of Zeeland)
Compartmentalisation - total	0.13	0.05
Compartmentalisation - North	0.47	N/A
Protection of pumping stations	0.41	0.24
Raising the A58	0.02	0.01
Increasing the height of the tunnel protection dyke (kanteldijk).	0.32	N/A

Sensitivity analysis

The above results are strongly dependent on the employed starting points. An important uncertain factor is, for example, the duration of the indirect damage for businesses outside Reimerswaal. In the analysis above a duration of 4 weeks has been adopted. To check the robustness of the conclusions a sensitivity analysis has been carried out. The following starting points have been studied:

- Duration of indirect damage to electricity outside dyke ring 31: 4 weeks, 8 weeks, 12 weeks.
- Duration of recovery time for pumping out area: 10 weeks, 15 weeks, 20 week.
- Investment cost of measures: 1x or 2x as expensive.

Table 7.8 shows the minimum and maximum cost-benefit ratios obtained in the sensitivity analysis. The cost-benefit ratios of all measures are also not favourable among other starting points.

Table 7.8 Cost-benefit ratios of packages of measures in sensitivity analysis

Cost-benefit ratios	Non-flood proof regional barriers (VNK2 scenarios)	Flood proof regional barriers (scenarios for province of Zeeland)
Compartmentalisation - total	0.07 - 0.19	0.06 - 0.10
Compartmentalisation - North	0.26 - 0.69	N/A
Protection of pumping stations	0.21 - 0.41	0.12 - 0.24
Raising the A58	0.01 - 0.03	0.01 - 0.01
Increasing the height of the tunnel protection dyke (kanteldijk).	0.16 - 0.32	N/A

8

CONCLUSIONS

8.1 Vulnerability analysis

8.1.1 Province-wide analyses

In general the flooding by dyke breach analysis shows that many national highways in Zeeland are in an area prone to flooding. This applies especially for Reimerswaal, Schouwen-Duiveland and to a less extent for Walcheren and Zuid-Beveland. The detailed analysis of Reimerswaal gives insight into the vulnerabilities of the national highways to flooding and delivers insights that can be scaled up to other parts of the national highways in Zeeland.

In the province-wide analysis of pluvial flooding no major problems have been identified. A marginal note is that for all parts of Zeeland flood maps were available at the Scheldestromen Water Board. A vulnerable point is the N61 at Terneuzen in Zeeuws-Vlaanderen where the road can flood over a length of a few hundred meters.

8.1.2 Detailed analyses in Reimerswaal

For the Vlaketunnel the following insights have been obtained:
- Flooding by dyke breach: tunnel seems to remain dry in the case of flood proof regional barriers. It has been recorded that the tunnel protection dyke has not been raised with the primary water barrier (in other words, the current primary water barrier is higher than the Vlaketunnel protection dyke). The assumption of non-flood proof regional barriers leads in the flooding map to flooding of the tunnel;
- Pluvial flooding: even in extreme rainfall events in the future the tunnel has adequate storage and drainage.
- In general terms the resolution of the VNK2 dyke breach scenarios is found to be too coarse for the analysis of specific objects.

The analysis of the road bed of the A58 shows:
- Depending on the flood map 0 to 17 km of the 17.5 km within Reimerswaal floods.
- It is expected that the slopes do not become unstable, there is a very limited probability that instability of steep and high slopes can occur.
- Further research into the stability of the road embankments is necessary: a sensitivity analysis of employed starting points (considered failure mechanism, pump-out time, taking into account flooding or no flooding, traffic load) and indicating the limitation of applied models has been indicated.

The damage is strongly dependent on the flood resistance of individual objects. For the Vlaketunnel it is important to prevent flooding. The road bed itself is less vulnerable. The duration of the interruption of the A58 ensures that the indirect damage is higher than the direct damage.

Flood damage has been identified as a general risk: this is because objects from the past have been built on the climate of the past. This is not the case with the Vlaketunnel, but for other critical objects such as the aqueduct at Middelburg it is not known yet.

8.2 Measures

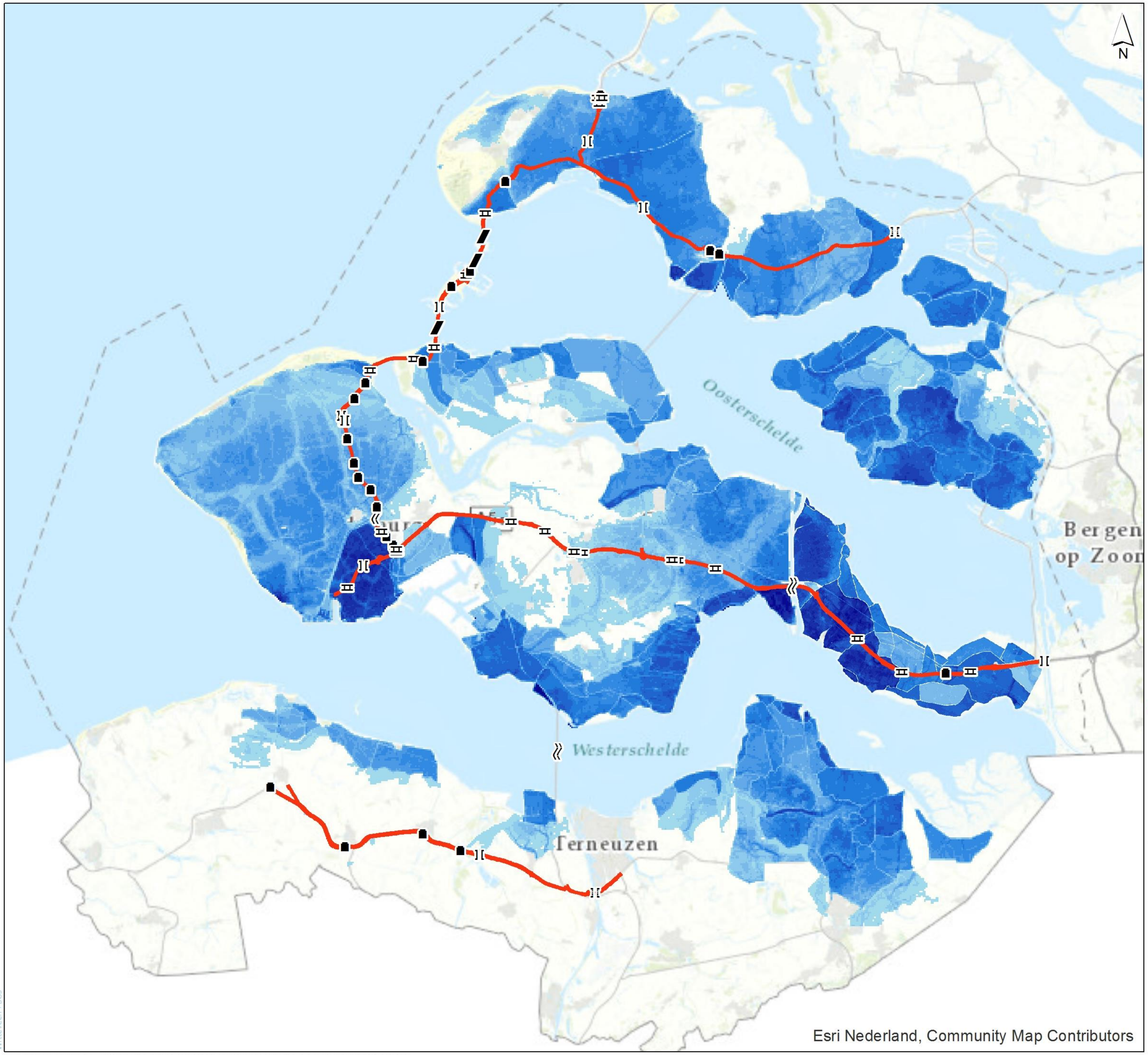
For the A58 different measures have been developed for continued functioning or fast recovery:
- Adapting large-scale infrastructure always requires major investments.
- Taking measures purely for layer 2 - protection of the infrastructure - is very expensive: the cost indication for the measures varies between EUR 6,000,000 and EUR 250,000,000.
- Linking into planned investments can significantly reduce the costs.
- Including climate adaptation as a standard component in MIRT explorations and plan studies is essential to assess the existing infrastructure on its climate resilience and for the affordability of measures.

8.3 Cost effectiveness

The following insights on cost effectiveness have been gained:
- Indirect damage can be higher than direct damage and must be therefore included in damage determination.
- With the current return times and safety standards of the primary flood defences most measures do not seem to be cost effective: linking to other measures is the only real option.
- An important marginal note is the fact that statistics are also based on the climate of the past: return times can change in the future, particularly through accelerated sea level increase. As a result measures that are not cost-effective at this moment, can become cost-effective in the longer term (autonomously).
- In the current situation increasing the height of the tunnel protection dyke is cost-effective if the failure probability of the dyke routes is a factor of 3 higher (failure probability Oosterschelde dyke 1:1000, failure probability Westerschelde dyke 1:3333).

Appendices

APPENDICE: MAP FOR FLOOD PROTECTION ANALYSIS



Legenda

waterdiepte (m)

- 0
- 0 - 0.5
- 0.5 - 1
- 1.0 - 1.5
- 1.5 - 2
- 2.0 - 2.5
- 2.5 - 3
- 3.0 - 3.5
- 3.5 - 4
- 4.0 - 4.5
- 4.5 - 5
- 5.0 - 5.5
- 5.5 - 6
- 6.0 - 6.5

Kunstwerken

- Oosterscheldekering
- beweegbare brug
- onderdoorgang
- tunnel
- vaste brug
- viaduct

Rijkswegen

- Rijkswegen

wateroverlast bij dijkdoorbraak

max. scenario

getekend:	ir. I.M. van den Brink	versie:	1
gecontroleerd:	ir. L.A. Valkenburg	datum:	21-12-2018
goedgekeurd:	ir. L.A. Valkenburg	tekeningnr:	0

opdrachtgever: Rijkswaterstaat
projectnaam: Meerlaagse veiligheid A58
projectcode: 109219

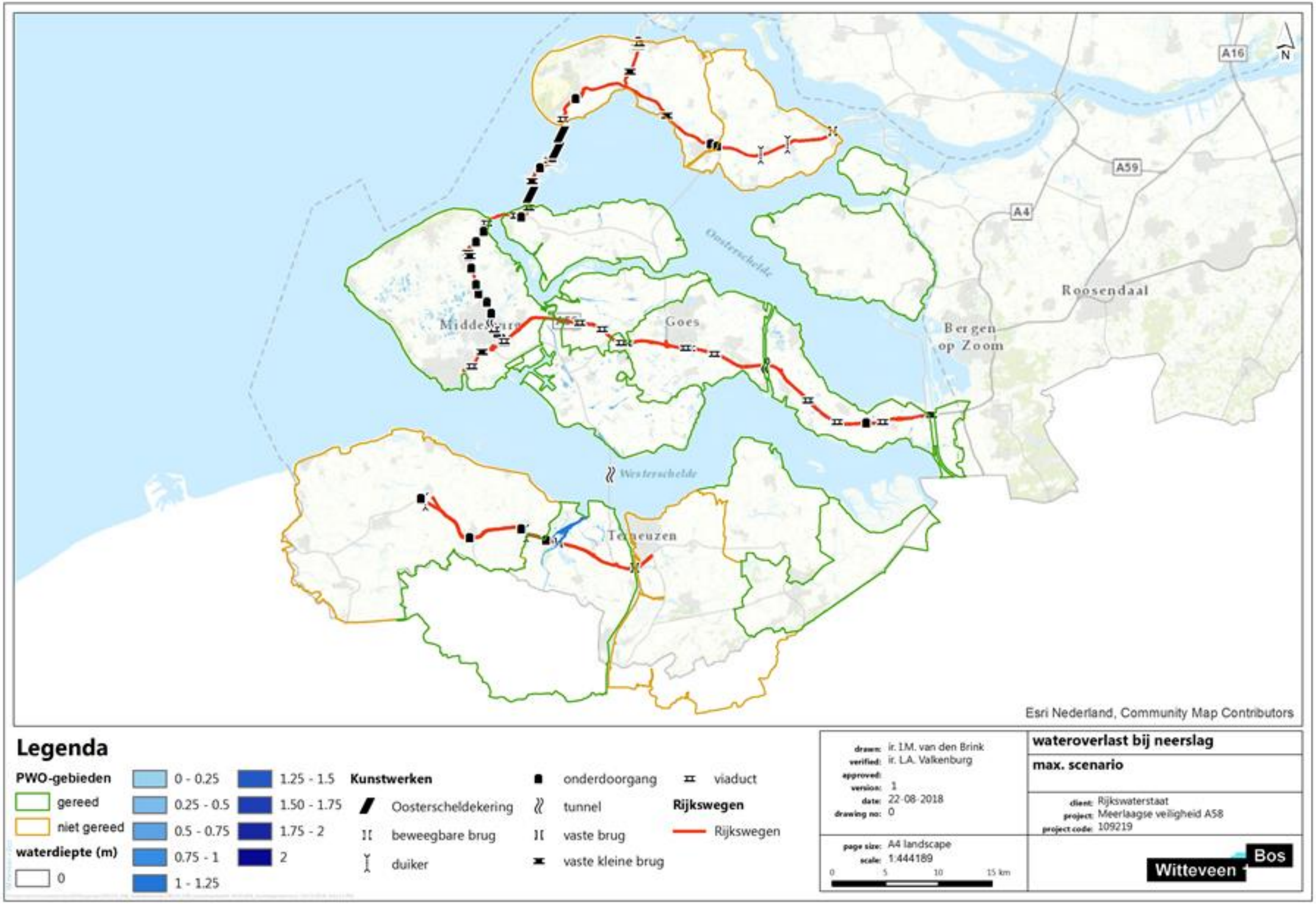
formaat: A4 liggend
schaal: 1:350000

0 2 4 6 8 10 km

Witteveen + Bos

II

APPENDICE: MAP FOR FLOOD DAMAGE ANALYSIS


A16
N
A59
A4
Oosterschelde
Roosendaal
Goes
Bergen op Zoom
Middelburg
Westerschelde
Terneuzen
Esri Nederland, Community Map Contributors
Legenda
PWO-gebieden
gereed
niet gereed
waterdiepte (m)
0
0 - 0.25
0.25 - 0.5
0.5 - 0.75
0.75 - 1
1 - 1.25
1.25 - 1.5
1.50 - 1.75
1.75 - 2
2
Kunstwerken
Oosterscheldekering
beweegbare brug
duiker
onderdoorgang
tunnel
vaste brug
vaste kleine brug
viaduct
Rijkswegen
Rijkswegen
drawn: ir. I.M. van den Brink
verified: ir. L.A. Valkenburg
approved:
version: 1
date: 22-08-2018
drawing no: 0
page size: A4 landscape
scale: 1:444189
0 5 10 15 km
wateroverlast bij neerslag
max. scenario
client: Rijkswaterstaat
project: Meerlaagse veiligheid A58
project code: 109219
Witteveen + Bos

III

APPENDICE: DYKE BREACH SCENARIOS A58

Legenda

Dijkring
- 31
- ★ Breslocaties

waterdiepte (m)
- 0
- 0 - 0.5
- 0.5 - 1
- 1.0 - 1.5
- 1.5 - 2
- 2.0 - 2.5
- 2.5 - 3
- 3.0 - 3.5
- 3.5 - 4
- 4.0 - 4.5
- 4.5 - 5
- 5.0 - 5.5
- 5.5 - 6
- 6.0 - 6.5

Infrastructuur
- niet doorwaadbaar
- doorwaadbaar

][Kunstwerken

Uitgangspunt: niet standvaste regionale keringen

drawn: ir. I.M. van den Brink
verified: ir. W.R. Debucquoy
approved:
version: 1
date: 24-07-2018
drawing no: 0

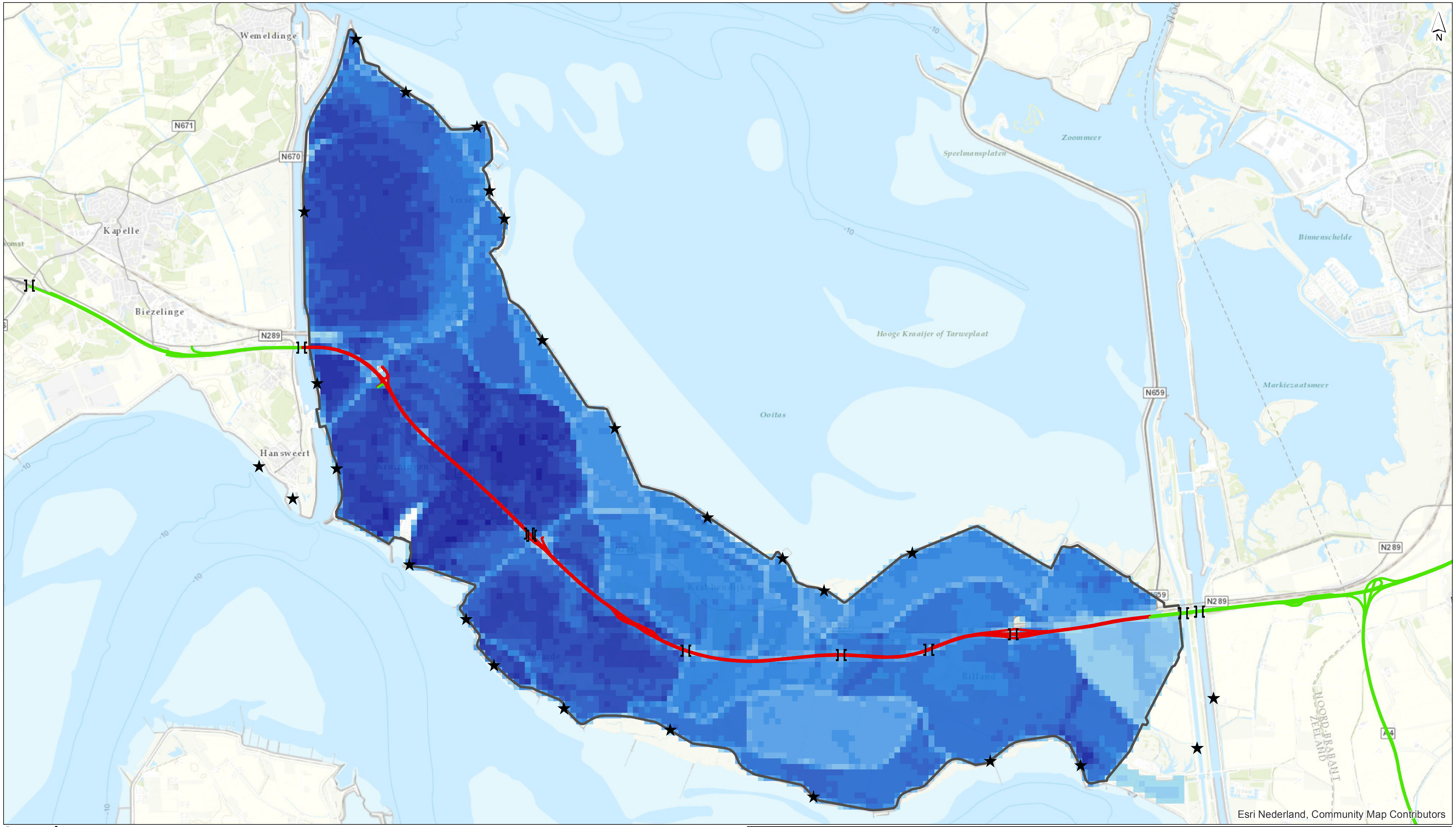
page size: A3 landscape
scale: 1:64360
0 500 1000 1500 2000 2500 m

Vitale Infrastructuur Reimerswaal

Dijkdoorbraak - max scenario Oosterschelde Netwerk A58

client: Provincie Zeeland
project: Kwetsbaarheidsanalyse Vitale Infrastructuur RW
project code: 105918

Witteveen + Bos



Legenda

Dijkring

31

★ Breslocaties

waterdiepte (m)

0

0 - 0.5

0.5 - 1

1.0 - 1.5

1.5 - 2

2.0 - 2.5

2.5 - 3

3.0 - 3.5

3.5 - 4

4.0 - 4.5

4.5 - 5

5.0 - 5.5

5.5 - 6

6.0 - 6.5

Infrastructuur

Niet doorwaadbaar

Doorwaadbaar

][Kunstwerken

Uitgangspunt: niet standvaste regionale keringen

drawn: ir. I.M. van den Brink
verified: ir. W.R. Debucquoy
approved:
version: 1
date: 24-07-2018
drawing no: 0

page size: A3 landscape
scale: 1:64360

0 500 1000 1500 2000 2500 m

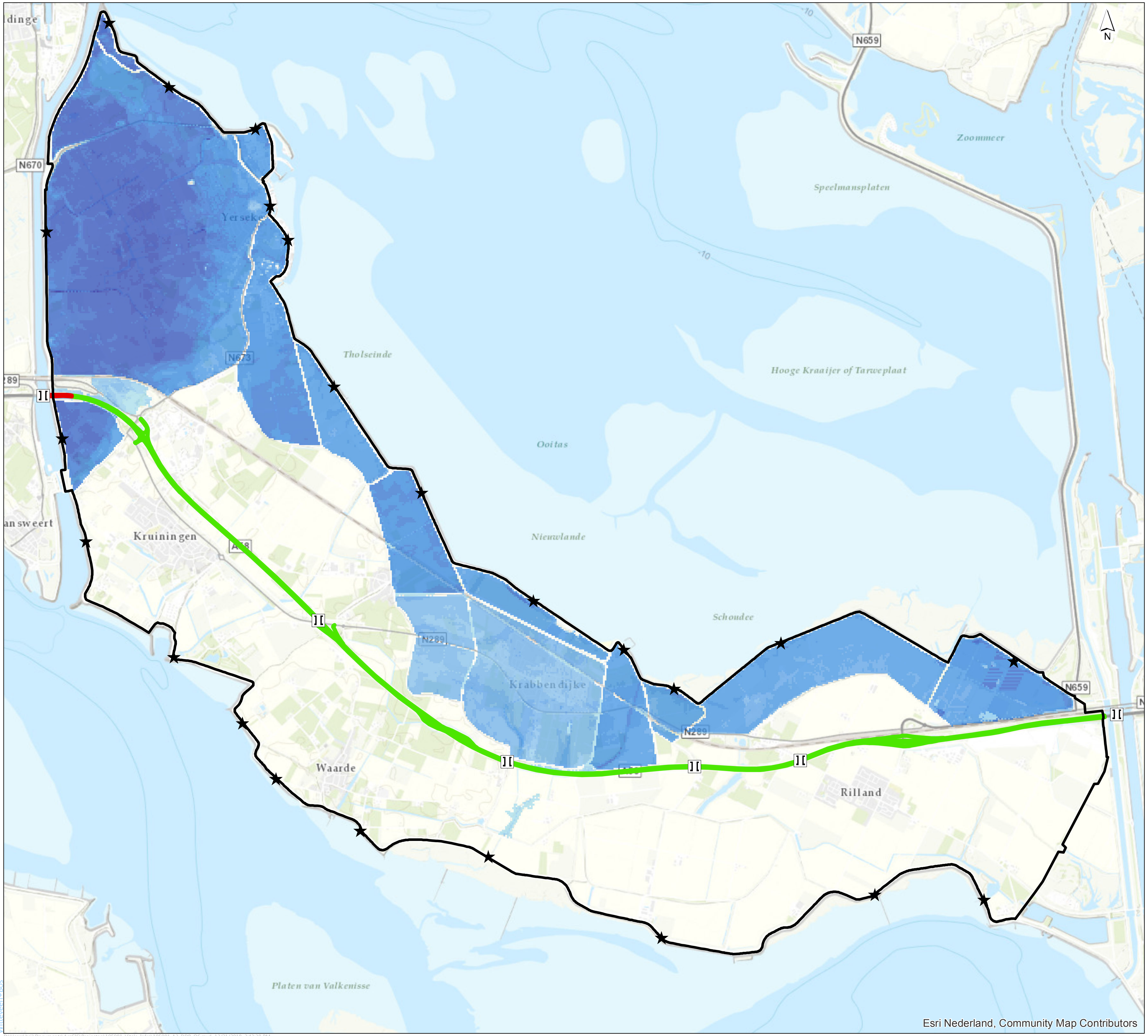
Vitale Infrastructuur Reimerswaal

Dijkdoorbraak - max scenario Oosterschelde en Westerschelde

Netwerk A58

client: Provincie Zeeland
project: Kwetsbaarheidsanalyse Vitale Infrastructuur RW
project code: 105918

Witteveen + Bos



Legenda

- Dijkring 31
- ★ breslocaties

Waterdiepte (m)

- 0
- 0 - 0.5
- 0.5 - 1
- 1.0 - 1.5
- 1.5 - 2
- 2.0 - 2.5
- 2.5 - 3
- 3.0 - 3.5
- 3.5 - 4
- 4.0 - 4.5
- 4.5 - 5
- 5.0 - 5.5
- 5.5 - 6
- 6.0 - 6.5

Infrastructuur

- niet doorwaadbaar
- doorwaadbaar
- Kunstwerken

Uitgangspunt: standvaste regionale keringen

Vitale Infrastructuur Reimerswaal

Dijkdoorbraak - max. scenario Oosterschelde Netwerk A58

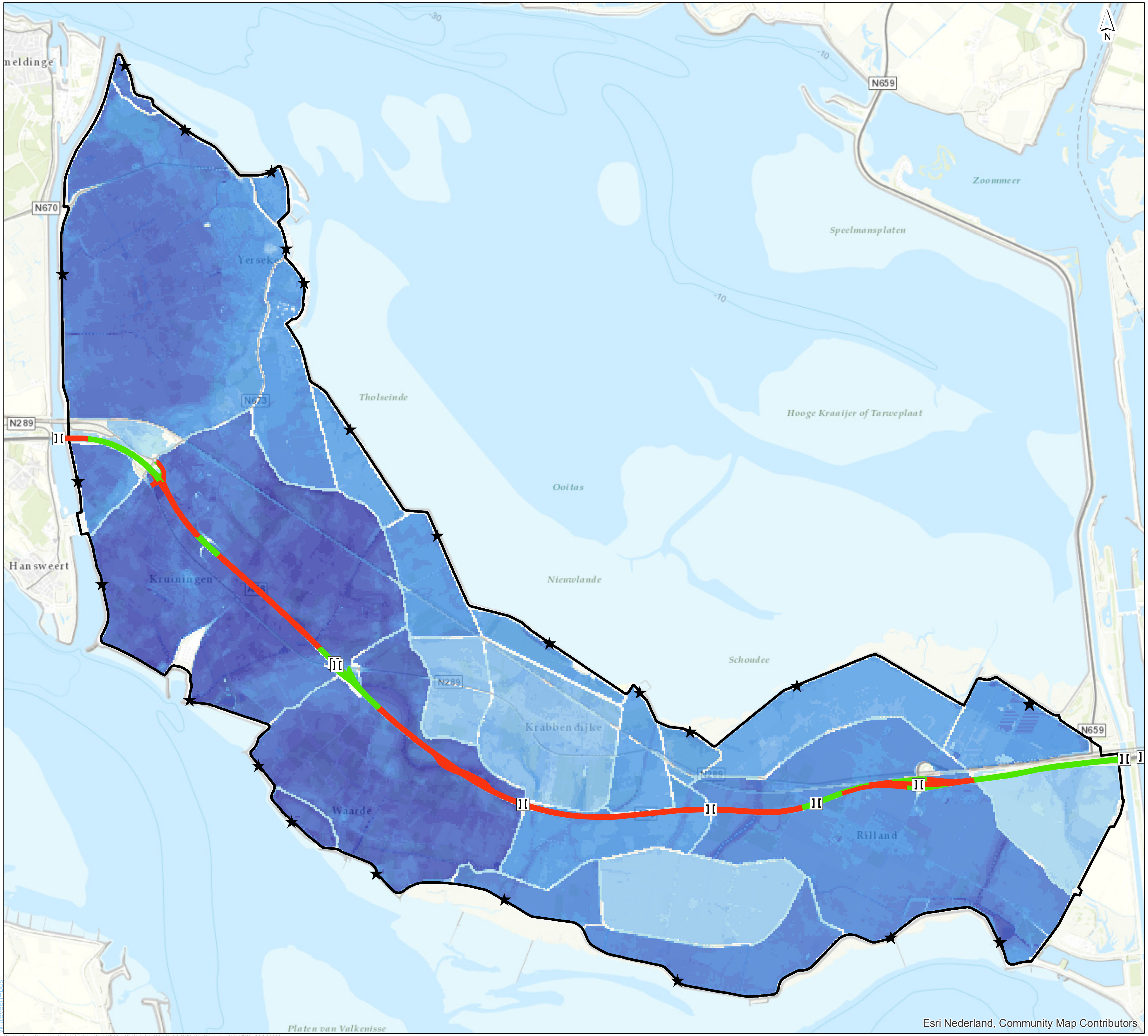
getekend: ir. I.M. van den Brink	**versie:** 1
gecontroleerd: ir. W.R. Debucquoy	**datum:** 21-12-2018
goedgekeurd: ir. L.A. Valkenburg	**tekeningnr:** 0

opdrachtgever: Provincie Zeeland
projectnaam: Kwetsbaarheidsanalyse Vitale Infrastructuur Reimerswaal
projectcode: 105918

formaat: A3 liggend
schaal: 1:55000

0 500 1000 1500 2000 2500 m

Witteveen + Bos



Legenda

- Dijkring 31
- ★ Breslocaties

waterdiepte (m)

- 0
- 0 - 0.5
- 0.5 - 1
- 1.0 - 1.5
- 1.5 - 2
- 2.0 - 2.5
- 2.5 - 3
- 3.0 - 3.5
- 3.5 - 4
- 4.0 - 4.5
- 4.5 - 5
- 5.0 - 5.5
- 5.5 - 6
- 6.0 - 6.5

Infrastructuur

- **niet doorwaadbaar**
- **doorwaadbaar**
-][Kunstwerken

Uitgangspunt: standvaste regionale keringen

Vitale Infrastructuur Reimerswaal

Dijkdoorbraak - max. scenario OS en WS
Netwerk A58

getekend: ir. I.M. van den Brink	versie: 1
gecontroleerd: ir. W.R. Debucquoy	datum: 21-12-2018
goedgekeurd: ir. L.A. Valkenburg	tekeningnr: 0

opdrachtgever: Provincie Zeeland
projectnaam: Kwetsbaarheidsanalyse Vitale Infrastructuur Reimerswaal
projectcode: 105918

formaat: A3 liggend
schaal: 1:55000

0 500 1000 1500 2000 2500 m

Witteveen + Bos

IV

APPENDICE: EXAMPLE ELABORATION PROFILE 137.3