Flood risk in unembanked areas

Part A Flooding characteristics: flood depth and extent

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Part A Flooding characteristics: flood depth and extent

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Contents

Summary

This flooding characteristics project in the Knowledge for Climate framework addressed the development of flood extent and flood depth maps for various return periods in present and future in the Rotterdam/Rijnmond region.

The following products were made:

Digital Elevation Model (DEM).

The DEM was constructed using detailed elevation data from four water boards and the municipality of Rotterdam. The horizontal resolution of these datasets was about 0.5m. The datasets were combined and resampled to a raster resolution of $5x5m^2$. The resulting dataset is particularly suitable for flood modelling using GIS, because the incorporated procedures emphasise in particular lower terrain elevation. Several project members manually checked the resulting map for correctness.

Flood extent and depth maps

In the project 'Knowledge for Climate-HSRR03b: Exploratory research water safety in the Rijnmond – Drechtsteden area' (in Dutch) by Stijnen and Slootjes (2010), water levels were calculated in a probabilistic way for various return periods. Based on the probabilistic water elevation data, flood extent and depth maps were generated using GIS for the unembanked areas in the Rotterdam/Rijnmond region. Algorithms are incorporated to ensure that no isolated flooded areas occur.
The water level data comprise various return periods (10 - 10000 years) for various climate scenarios: 2010 (present), 2050 (KNMI G+ climate scenario) and 2100 (Veerman climate scenario). A selected alternative adaptation strategy 'Closable but open Rijnmond' was used for the climate in 2050 and 2100.

Deliverables

The project has the following deliverables:
- Flood extent and depth maps in a Flood Map Atlas;
- Flooding animation in Google Earth;
- Flood depth and extent data as digital ESRI-grids;
- A sensitivity analysis for an alternative storm duration on the flooding extent/depth and a sensitivity analysis based on a smaller failure rate of the Maeslant storm surge barrier;
- An analysis of the flooding of various goods in the port of Rotterdam for each return period in the present situation.

The results of the research have been and will be used as input for various other projects in the Knowledge for Climate framework, among others damage assessment.

Results and conclusions

Resampling of flood extent and depth data from a cell resolution of $5x5m^2$ to a cell resolution $25x25m^2$ has a strong effect on the extent. From this study an increase of flood extent of approximately 20% was found as a result of applying an averaging resampling technique. Although it would have been nice to use $25x25m^2$ cells for damage assessment calculations from a computational point of view it was decided to use the most detailed data to avoid any bias. In general it may be stated that application of larger cell sizes result in overestimation of damage in assessments.

Flooding increases significantly as climate changes in 2050 and 2100 due to increasing sea water level and increased discharges on the river Rhine. At present flooding is normal at low return periods for natural floodplains. Port areas and industrial areas suffer from flooding only during higher return periods and flooding is rather shallow. This is the result of the higher terrain elevation in the man-made areas. From east to west the port areas in the Rotterdam area are newer and therefore raised above the original terrain elevation. These newer port areas suffer less from flooding. In the future also the port areas will flood more often. Roughly stated: the flooding properties for a 10 years event in 2050 are about equal to a 100 years event in 2010. The flooding properties of a 10 years event in 2100 are about equal to a 100 years event in 2050 or a 1000 years event in 2010. This is roughly an increase by a factor of 10 in return period for 2050 and once more in 2100.

A reduced failure rate of the Maeslant storm surge barrier shows in 2010, 2050 and 2100 significant effects on the flood extent and flood depth in the Rotterdam area; the effect is less in the Dordrecht area. This effect is related to influence of storm surges from the North Sea. Alternative storm durations of 29 hours instead of 35 hours has for Veerman (2100) scenario limited influence on the flood extent and depth, because water levels only reduce op to 6 centimetres. The reason for this limited effect is not clear.

The effects of the closable but open variant are small for flood extent and flood depth in the Port of Rotterdam area. Application of the closable but open variant does not show any significant reduction in inundated areas.

Flooding is simulated for the unembanked areas in this study. However, the adjacent areas protected by primary defenses may also suffer from flooding. Their protection levels (return period) vary from 2000 to 4000 and even 10.000 years (dike ring South Holland) in the observed study area. If these primary defenses fail, the flooding depth and flooding extent surpass the figures from unembanked areas. Failure of a primary dike ring reduces flooding in the adjacent unembanked areas. For this reason safety in areas within dike rings and unembanked areas should be considered integrally.

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Samenvatting

In dit waterveiligheid project in het kader van Kennis voor Klimaat zijn overstromingsdiepte en – omvang kaarten gegenereerd voor verschillende terugkeertijden in de huidige situatie en de toekomst als gevolg van veranderend klimaat. Het gebied waarop de studie zich heeft geconcentreerd is de regio Rotterdam/Rijnmond.

In grote lijnen zijn de volgende stappen doorlopen.

Constructie van een Digitaal Hoogte Model (DEM).

Het DEM is gemaakt voor het buitendijksgebied op basis van getailleerde hoogte datasets die afkomstig zijn van vier inliggende waterschappen en de gemeente Rotterdam. De toegeleverde datasets hadden een horizontale resolutie van ongeveer een 0.5x0.5m^2. Deze datasets zijn gecombineerd en geresampled naar een raster resolutie van 5x5m^2. Verschillende projectleden hebben, met kennis van het terrein, een check uitgevoerd op het DEM.

Bepaling van overstromingsomvang en diepte

In het kader van het project ‘Kennis voor Klimaat-HSRR03b: Eerste verkenning Waterveiligheid Rijnmond-Drechtsteden’ [Stijnen & Slootjes, 2010] zijn waterstanden op probabilistische wijze uitgerekend voor riviervakken van twee kilometer voor diverse herhalingstijden, klimaatscenario’s en maatregelen (afsluitbaar/open Rijnmond). In deze studie zijn genoemde waterstanden gebruikt om – in combinatie met het nieuwe DEM - in GIS overstromingsdiepte grids te genereren voor buitendijks gebied. De data omvat verschillende terugkeertijden (10 - 10000 jaar), verschillende zichtjaren 2010 (huidige situatie), 2050 (G+-scenario van het KNMI), 2100 (Veerman scenario) en één geselecteerde klimaat adaptie strategie (afsluitbaar/open Rijnmond) voor de zichtjaren 2050 and 2100.

Producten

De studie heeft de volgende producten opgeleverd:

- Een overstromingsdiepte kaarten atlas (Flood Map Atlas);
- Een overstromingssimulatie in Google Earth door het achter elkaars weergeven van de verschillende waterdieptekaarten en afgeleid hiervan een overstromingsfilm;
- Geografische waterdiepte bestanden in de vorm van digitale ESRI-grids;
- Een beschouwende gevoeligheidsanalyse voor het effect van een alternatieve stormduur (29 uur in plaats van 35 uur) en een afwijkende faalkans voor de Maeslantkering (1/1000 in plaats van 1/100) op het overstromingspatroon;
- Een analyse van diverse typen overstromende Rotterdamse havengebieden voor verschillende terugkeertijden in de huidige situatie.

Genoemde producten worden gebruikt in diverse andere projecten in het kader van Kennis voor Klimaat, onder meer voor een gedetailleerde schademodellering.

Resultaten en conclusies

Het resampelen van overstromingsdiepte van een resolutie van 5x5m^2 naar een resolutie van 25x25m^2 heeft een grote invloed op de diepte en omvang van de berekende overstroming. In deze studie werd een toename van het overstroomde oppervlak gevonden van 20% na resampelen met een gemiddelde filter. Hoewel het gebruik van de 25x25m^2 cellen gewenst leek voor het berekenen van schade vanuit het oogpunt van rekentijd is uiteindelijk toch gebruik gemaakt van de originele data met een resolutie van 5m*5m om overschatting van schade te voorkomen. In het algemeen kan worden gesteld dat grotere cellen een overschatting van de berekende schade laten zien.

Door klimaatverandering neemt het areaal overstroomt gedurende iedere herhalingstijd toe in het gebied in 2050 en 2100 als gevolg van zeespiegelstijging en verhoogde afvoeren op de rivier. Onder de huidige omstandigheden overstromen de natuurlijke uiterwaarden regelmatig, maar de buitendijkse haven en industriegebieden overstromen pas bij hogere herhalingstijden en relatief ondiep. Dit is het gevolg van de hogere terreinligging door ophoging. Van oost naar west neemt de terreinhoogte in de havens toe omdat de terreinen later zijn ontwikkeld. De berekende waterhoogten op de Nieuwe Waterweg vertonen verschillen ten opzichte van het gemiddelde tot 10 centimeter naar boven (Botlek) en naar beneden (centrum Rotterdam). Om deze redenen overstromen de havengebieden naar het

westen toe steeds minder. In de toekomst zullen ook de havengebieden steeds vaker overstromen. Daarbij geldt ruwweg dat de overstroming bij een herhalingstijd van 10 jaar in 2050 ongeveer een identiek patroon te zien geeft als de overstroming bij een herhalingstijd van 100 jaar in 2010. De overstroming bij een herhalingstijd van 10 jaar in 2100 geeft een ongeveer identiek patroon te zien als de overstroming bij een herhalingstijd van 100 jaar in 2100 of 1000 jaar in 2010. Dit is telkens een toename van de herhalingstijd met een factor 10 voor de overgang van 2010 naar 2050 en 2100 voor een zelfde overstromingsbeeld.

Een afnemende faalkans van de Maeslantkering van 1/100 tot 1/1000 heeft significant effect op het overstromingsbeeld in 2010, 2050 and 2100 bij de Nieuwe Waterweg; het effect is veel minder zichtbaar in de omgeving van Dordrecht. Het fenomeen is gekoppeld aan de invloed van storm op zee die landinwaarts afneemt. Het hanteren van een alternatieve stormduur van 29 uur in plaats van 35 uur voor het Veerman scenario geeft slechts betrekkelijk geringe reductie in de omvang van overstromingen, omdat de waterhoogte slechts beperkt afneemt met maximaal 6 centimeter. Voor het achterhalen van de oorzaak hiervan is nader onderzoek nodig.

Het effect van de afsluitbaar/open variant is beperkt in het Rotterdamse havengebied. Bij vergelijking van de percentueel overstroomde oppervlakken voor diverse typen goederen overslag/opslag zijn de verschillen niet zichtbaar.

In deze studie zijn buitendijkse gebieden onderzocht in het Rotterdam/Rijnmond gebied. Echter ook de nabijgelegen binnendijks gebieden kunnen overstromen. Deze gebieden kennen een beschermingsniveau van 2000, 4000 en 10.000 jaar in de huidige situatie. Als primaire keringen falen overtreffen de diepte en omvang van de overstromingen die van de buitendijkse gebieden in hoge mate. Het falen van een primaire dijkring heeft daarbij een nivellerende invloed op het waterpeil in nabijgelegen buitendijkse gebieden. Om deze reden moeten veiligheidsniveaus binnendijks en buitendijks in onderlinge relatie worden beschouwd.

Meer informatie kan worden opgevraagd bij Jan Huizinga van HKV<u>***Lijn in water***</u> in Lelystad of via e-mail: j.huizinga@hkv.nl

1. Introduction

1.1 Project background

Water safety in unembanked areas is of great public interest. The National Water Plan pays much attention to it and the Province of Zuid-Holland is currently developing a policy framework for building in these areas. There are only policy guidelines for water safety and building in the unembanked areas [Bergh, 2008]. Developments in the outer dike area are allowed under certain conditions, but at your own risk.
Because the floodplain areas are unembanked, the perception is that these areas are "unsafe". Traditionally, features in the outer dike area are 'protected' by increasing the elevation of the land to build. Closure of the Maeslant - and Hartel storm surge barriers during extreme storm events also protect against flooding. However, the Maeslant and Hartel barriers are primarily designed for safety behind the dikes.
Experiencing climate change (sea level rise, increased river discharge), it is important to regard the current and future situation related to water safety in the unembanked areas. It is not only important to know whether the probability of flooding increases, but also the effects on the current (development) functions and activities. It is also important to distinguish between existing and areas newly being developed, because the potential to take flood protection measures can differ substantially.

In the unembanked areas of the Rotterdam region (the area east of the Maeslant storm surge barrier in the New Waterway up to Dordrecht) within project Hotspot Region Rotterdam (HSRR02) the following sub-studies are conducted:

1. Flood depths in the unembanked areas: climate scenario calculations from HSRR09 are translated into flood maps. Maps are made based on possible climate adaptation strategies (e.g. Closable but open Rijnmond);
2. Flow velocity analysis for the quays in the port areas;
3. Vulnerability analysis of direct damage: based on the flood maps induced damage occurring in the outer dike area is determined (e.g. urban areas);
4. Vulnerability analysis of port infrastructure: analysis of the port infrastructure and the vulnerabilities, in particular those of the chemical industry.

This report focuses on part 1: developing flood depth maps. Unesco-IHE, Deltares and Royal Haskoning carry out the subprojects 2 through 4 respectively.

1.2 Objectives

Subproject 1, the development of flood maps, has the following objectives:

1. Generate a Digital Elevation Model (DEM);
2. Generate maps of flood extent and depth for the unembanked areas in the Rotterdam region for various return periods in various years (2010 (present), 2050, 2100 and one alternative adaptation strategy: Closable but open Rijnmond);
3. Determine sensitivities to variations in storm duration and the failure rate of the Measlant storm surge barrier;
4. Mutual sharing of knowledge with Unesco-IHE, Deltares and Royal Haskoning by conducting reviews and providing input into the mutual project components.

This subproject for the development of flood maps makes use of water level data calculated in the project: 'Knowledge for Climate-HSRR03b: Exploratory research water safety in the Rijnmond – Drechtsteden area' (in Dutch) [Stijnen & Slootjes, 2010]. The HSRR03b study is the original source of these water levels calculations. Methodology and results are discussed extensively in the report by Stijnen & Slootjes.

This project HSRR02 was carried out in a consortium with participation of the municipality of Rotterdam, the Port of Rotterdam, Royal Haskoning, HKV***CONSULTANTS***, Deltares and Unesco-IHE. The damage assessment by Veerbeek from Unesco-IHE and the damage methodology development for chemical plants by Lansen from Royal Haskoning were (partly) based on the reported flood characteristics from this research document.

2. Methodology and data

2.1 Methodology

For this study it was decided to construct flood maps using GIS, based on available probabilistically processed 1D water-level data. This probabilistic approach is based on running multiple 1D water-level simulations and post-processing in Hydra-B to get water level and appropriate statistics (e.g. return periods). See the report from Stijnen & Slootjes (2010) for more detailed information on data processing and assumptions.

Flood modelling using 2D models is at present not appropriate for this approach because these data were not available.

The water-level data came from the project Knowledge for Climate - HSRR03b [Stijnen & Slootjes, 2010] and the data had a spatial resolution of one water-level value for each consecutive 2 kilometres stretch (distance along the centre line of the river).

Using GIS a newly developed Digital Elevation Model (DEM) was subtracted from maps containing water-level data, resulting in an approximate flood extent and flood depth. The approximate flood extent maps were further processed to remove flooded 'islands' surrounded by elevated terrain or dikes. Checking the presence of flooded corridors between flooded areas and adjacent rivers did this.

2.2 Data collection

2.2.1 Terrain elevation

Municipalities and water boards have provided the elevation data. The data is summarized in Table 2.1.

Table 2.1 Source of the elevation data.

Terrain elevation data provider	Data type	Resolution source data	Artificial objects removed from dataset (filtering)
Municipality of Rotterdam	LiDAR	5m*5m	Yes
Water board Delfland	LiDAR	0.5m*0.5m	Yes
Water board Schieland & Krimpenerwaard	LiDAR	0.25m*0.25m	Yes
Water board Hollandse Delta	LiDAR	5m*5m	Yes
Water board Rivierenland	LiDAR	5m*5m	Yes

The areas for which the data have been delivered are shown in the Figures 2.1 and 2.2 below. Additionally the municipality of Rotterdam has provided elevation data on the elevation of the Rotterdam harbour area.

Figure 2.1 Elevation data providers (Gemeentewerken Rotterdam excluded).

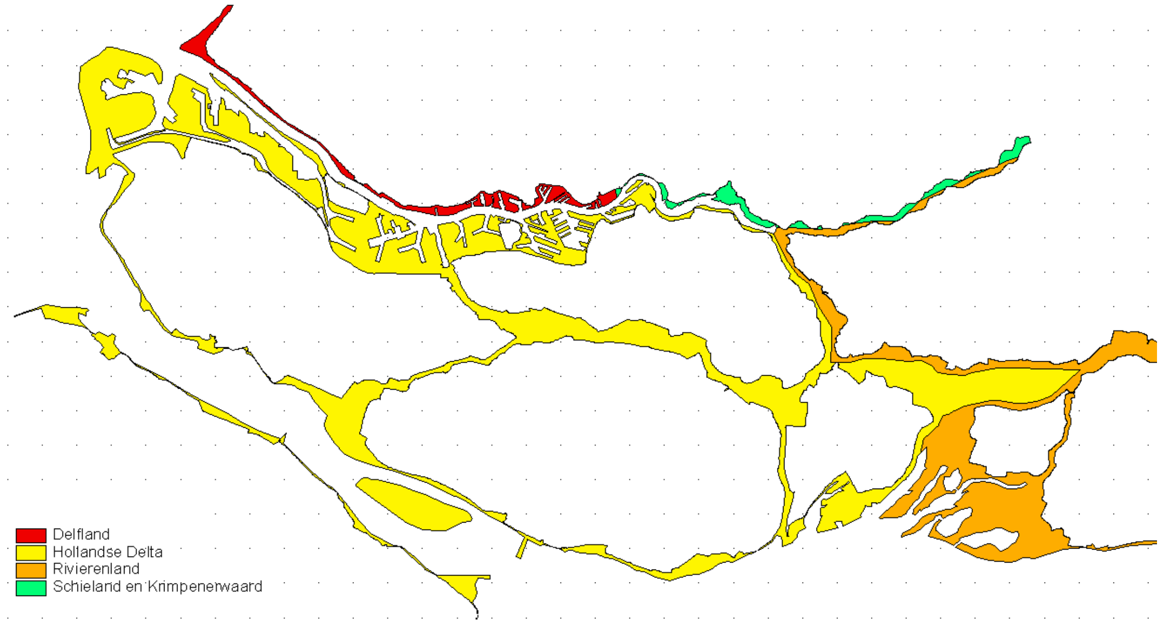

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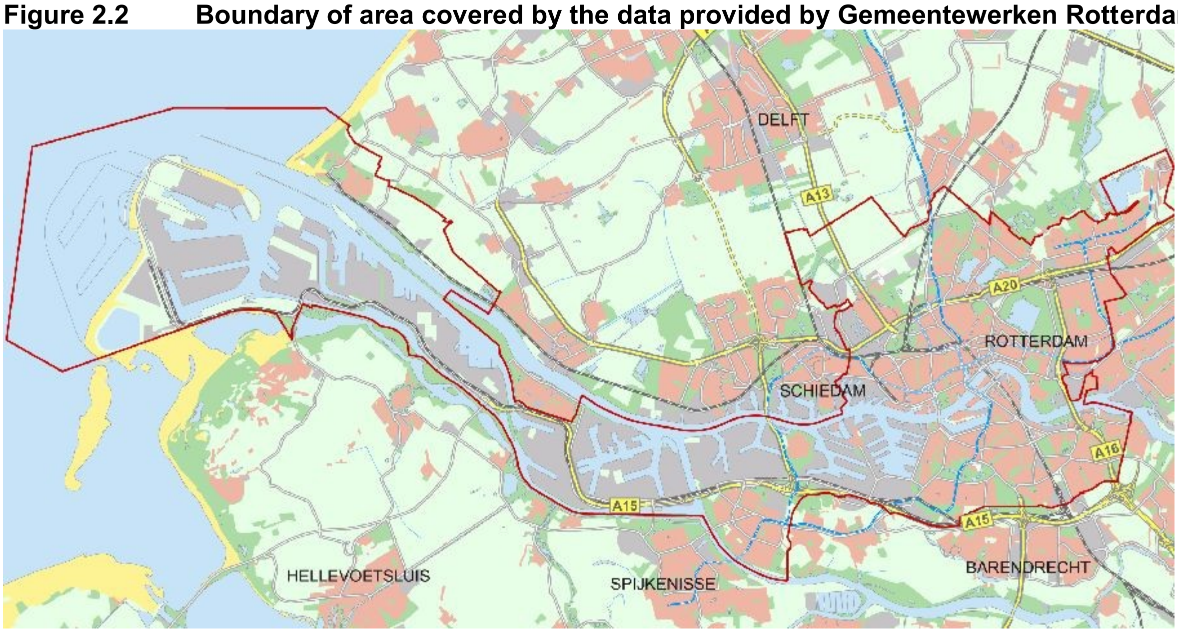
Figure 2.2 Boundary of area covered by the data provided by Gemeentewerken Rotterdam.



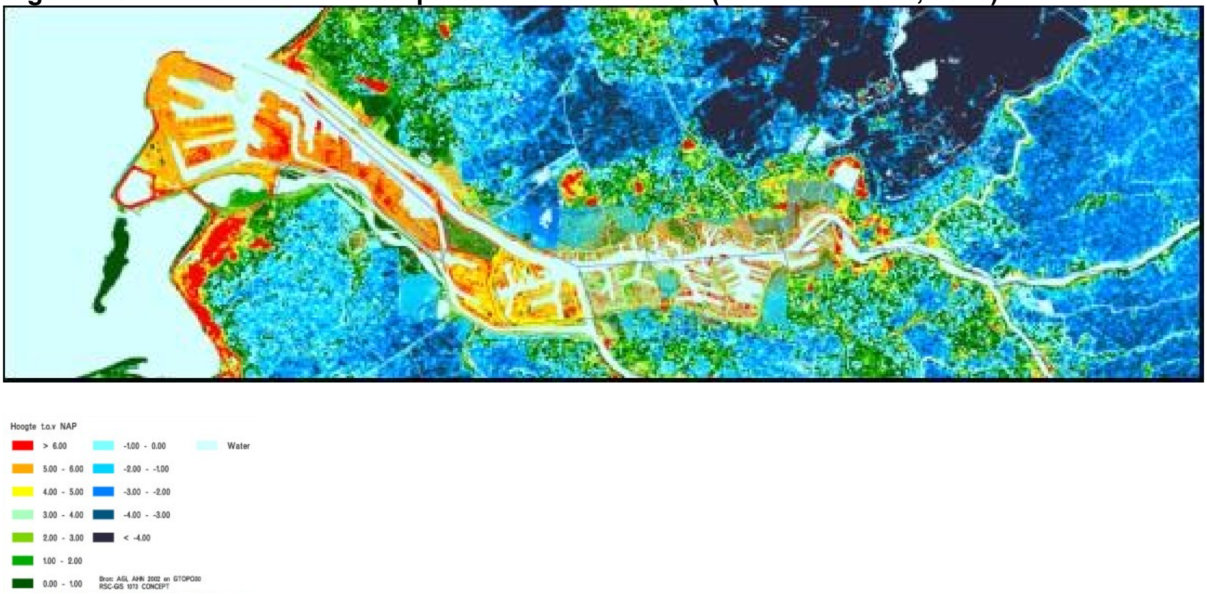
Terrain description

The terrain adjacent to the river in the Rotterdam region is elevated during the last century for port activities. Going from the Rotterdam city center (eldest port areas) the elevation increases westward in the direction of the North Sea (newest port areas). These new ports in Rotterdam are only flooded during extreme events due to the high terrain elevation.

Eastward from the centre of Rotterdam in the direction of Dordrecht the terrains along the river are also elevated for industry purposes, e.g. shipyards and ports, but the elevation is consistent with the older part of the port of Rotterdam in the city centre. The terrains are flooding during intermediate severe conditions.

The southern river branches in the Delta region are mainly original floodplains. As a consequence these terrains are flooded early and often. The Biesbosch area is a low-lying former tidal area that is flooded continuously. An elevation map of the northern part of the area (port of Rotterdam) is shown in figure 2.3. The blue colours (within the primary dike ring) have low elevations, the red coloured areas are most elevated.

Figure 2.3 Terrain elevation port of Rotterdam area (source: Lansen, 2010).



2.2.2 Water levels

Water-level data for various return periods, climate scenarios and variants are provided by HKV<u>CONSULTANTS</u> [Slootjes & Stijnen, 2010].
Only the areas up to the Maeslant storm surge barrier were considered. The port areas between the storm surge barrier and the North Sea are not taken into account.

Climate scenarios and storm duration

Climate change is expected to have major influences on the sea water level, Rhine/Meuse discharges and storm duration. This will have a large impact on the delta region. More severe and frequent flooding is expected for the unembanked areas. Also the normative water level (MHW) is expected to rise, making additional elevation of the primary dikes necessary.
For this study, considering the flooding of the unembanked areas in the Rhine/Meuse delta, two climate change scenarios were applied in addition to the current climate conditions. The first is the G+ scenario that is assumed to be representative for the year 2050. The Royal Netherlands Meteorological Institute [KNMI, 2006] developed the G+ scenario. A more extreme scenario is the Veerman scenario, assumed to be representative for the year 2100. This scenario was developed by a Dutch national commission (Veerman commission) and reported in 2008 [Delta commission, 2008].
In the table below a short description of the Climate scenarios is depicted.

Table 2.2 Short description of the climate scenarios.

Climate scenario	Normative Rhine discharge at Lobith [m^3/s]	Normative Meuse discharge at Borgharen [m^3/s]	Sea-level rise after 2006 [m]	Storm duration (hours)
Current situation (2010)	16.000	3800	0	29
KNMI '06 G+ (2050)	18.000	4600	0,60	35
Veerman (2100)	18.000	4600	1,30	35

In the maps produced a storm duration of 29 hours is assumed for the current situation and 35 hours for 2050 and 2100. In the sensitivity analysis an alternative storm duration of 29 hours (conform current approach) was considered for the case 2100.
The duration of 29 hours is the current value used in the calculations for the Hydraulische Randvoorwaarden [Rijkswaterstaat, 2007]. It is the mean storm duration in the present situation based on historical information according to the Dutch Meteorological Office (KNMI).

The various assumptions are based on the approach in the System Analysis Rhine/Meuse mouth [SRM, 2007] and Planologische Kern Beslissing Room for the River, long term [Rijkswaterstaat, 2005].

Failure of the Maeslant storm surge barrier

The Measlant storm surge barrier protects the hinterland against high water levels due to combined tidal effects and storm on the North Sea. If the storm surge barrier does not function, highly elevated water levels can be expected far inland.
For the calculations it was assumed that the failure rate of the Maeslant storm surge barrier is equal to 1/100 for each request to close [Duits & Thonus, 2007], [Akkeren, 2005], [Horvat, 2006]. This is the current estimation. Originally, the design failure rate was 1/1000 [Akkeren, 2005]. Calculations for the design failure rate were used to perform sensitivity analyses.

Measures

To counteract the effects of climatic change several measures were proposed by the Veerman commission [Deltacommissie, 2008]. Building additional barriers that can be closed or open depending on the weather conditions and discharge of the rivers may accomplish adaptation to the climatic change. One of the possible adaptation strategies is the Closable but open variant. This variant was applied in the flood depth and extent calculations. In the figure below the variant is shown.

Figure 2.4 Closable but open variant for adaptation to climate change.

In the following table the mapped combinations of return period, climate scenarios and measures are shown.

Table 2.3 Applied combinations of return period, climate scenarios and variants.

Return period [years]	Climate scenarios & variants				
	2010	2050 (G+ scenario)		2100 (V - scenario)	
	No measure	No measure	Lockable/Open	No measure	Lockable/Open
10	X	X	X	X	X
25	X				
50	X	X	X	X	X
100	X	X	X	X	X
250	X				
500	X				
750	X				
1000	X	X	X	X	X
1250	X				
2000	X	X	X	X	X
2500	X				
4000	X	X	X	X	X
5000	X				
7500	X				
10000	X	X	X	X	X
20000	X				
50000	X				

Eventually 45 datasets from combinations of return period, climate scenarios and variants have been processed.

Selection of the return periods 10, 50, 100, 1000, 2000, 4000 and 10.000 years was based on the following assumptions:

- Return periods comply to normative probabilities of the primary dike rings in the area;
- Reduction of the amount of processing: hydraulic variation between selected return periods is assumed to be optimal.

2.3 Data processing

ArcGIS and ArcInfo 9.2 of ESRI Inc. in combination with the Spatial Analyst/GRID extensions were used to process the data. Eventually most processing was written in AML to streamline and automate the processing.

2.3.1 Digital Elevation Model

The construction of the DEM in GIS comprised several steps. These steps are summarized below.

Consecutive steps for generating the DEM:

1. Resampling the various datasets to 5*5m^2 with the extent being a multiple of 5 meter. This ensures a correct alignment of cells when joining;
2. Joining the various resampled datasets into one large dataset. During joining an algorithm has been applied to ensure correct values in overlapping areas;
3. Insertion of erectable dike (kanteldijk) in the West Botlek area near the Hartelkanaal. This dike is erected in case of flood threat;
4. Removal of artefacts (bridges, harbour equipment, etc) by applying a land mask;

Conversion to an integer grid by converting terrain elevation values from meters + NAP to centimetres + NAP. This conversion resulted in a large data demand reduction.

The processing is described more detailed in Appendix 1.

An important warning for using the DEM is that is was generated with the use for flood modelling in mind. This is for the fact that during resampling from $0.5*0.5m^2$ to $5*5m^2$ always the minimum value from the 25 cells being processed is assigned to the corresponding $5*5m^2$ cell.

After the processing the product was reviewed by project members from Deltares (Nathalie Asselman) and the Port of Rotterdam (Rinske van der Meer).

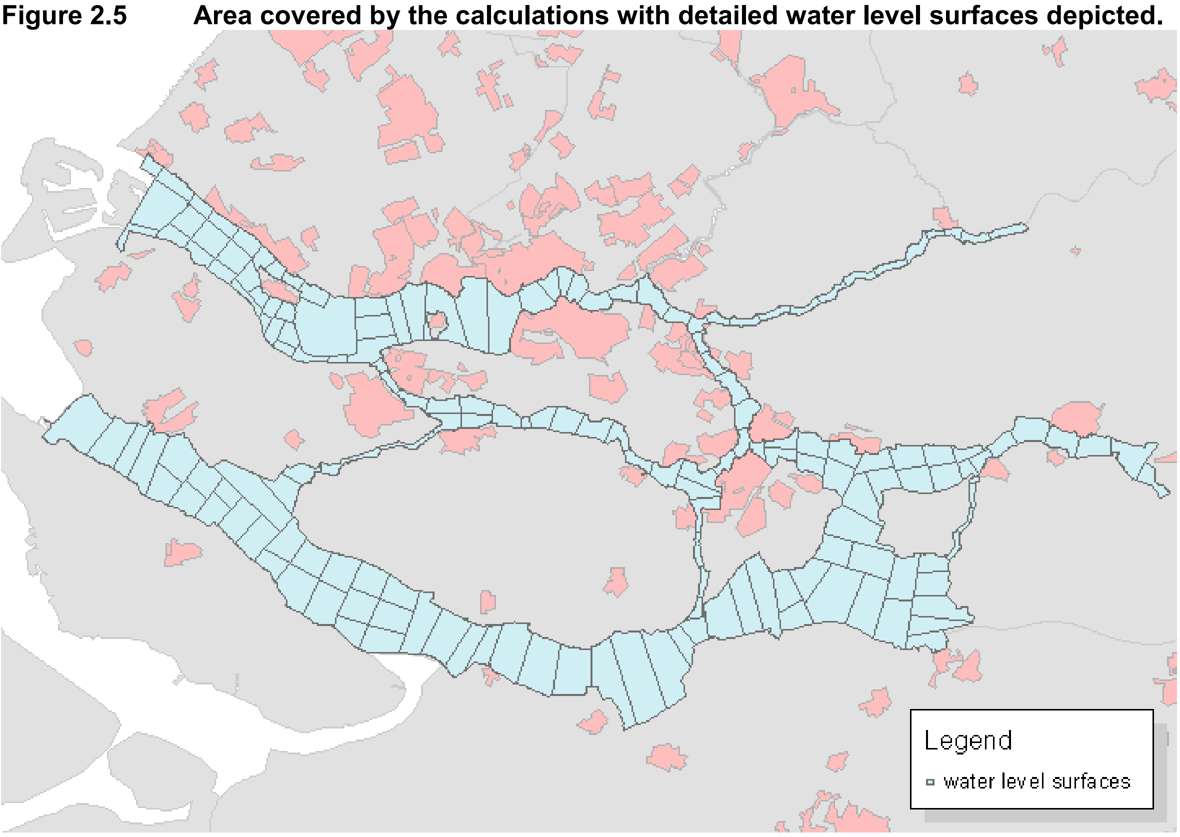
2.3.2 Water levels

As described water-level data were used for the following combination of return periods, climate scenario's and variants:

- Three periods: 2010, 2050 (G+ climate scenario), 2100 (Veerman climate scenario);
- Six return periods: 1, 10, 100, 1.000, 4.000, 10.000;
- Two variants: 'reference' (actual situation) and 'lockable/open';
- Failure rate of the Maeslant storm surge barrier equal to 1/100 for each request to close.

The area covered by the data is shown in figure below. Note that westward of the Maeslant storm surge barrier no data is generated, because only the area behind the storm surge barrier was studied. This means however that for the Maasvlakte and Europoort port areas no flooding calculations were made.

Figure 2.5 Area covered by the calculations with detailed water level surfaces depicted.



Consecutive steps for generating the water depth maps:

1. Assigning water-levels to polygons of assumed equal water-level;
2. Rasterizing the water-level polygon datasets in accordance with the extent and cell size of the DEM.

2.3.3 Flood depth and extent during flooding

The calculation of the flood depth and extent maps needed several steps to be performed in GIS.

Consecutive steps for generating the water depth maps:

1. Subtraction of DEM from water-level datasets. The result are ‘raw’ flood depth and extent datasets;
2. Checking the physical correctness of ‘raw’ water depth datasets: which flooded areas are physically connected to the river;
3. Removal of not physically connected water bodies.

In particular the check on physical correctness turned out to be time consuming. The processing procedure is described more detailed in appendix B.

To make damage calculations performed by IHE-Unesco less time-consuming, the flood depth maps were once more resampled to 25*25m^2. During this resampling the average of the flood depth of 5 cells of 5*5m^2 was calculated for each corresponding 25*25m^2 cell. A discussion on the resampling approach is given in the next chapter.

3. Results

Various products were made using selected water level datasets from the project 'Eerste verkenning Waterveiligheid Rijnmond-Drechtsteden' ('Explorations on water safety in the Rijnmond-Drechtsteden area) by Stijnen & Slootjes (2010). The results are presented in this chapter.

3.1 Effects of resampling on flood depth/extent

As described in paragraph 2.2.1 a DEM for the whole region was constructed, based on extremely detailed datasets from water boards in the region and the municipality of Rotterdam. This DEM in combination with the water level maps form the basis for the flood depth and extent maps. Eventually 45 datasets with flood depth and extend were generated. These datasets have a raster size of 5*5m^2.

Initially it was considered to be necessary to resample the datasets to reduce the load for damage calculations. For this reason 35 datasets were re-processed, because not all return periods from the current situation were incorporated in the damage assessment. During re-processing the average value of all (but at least one) cells from the 5x5m^2 grid was assigned to a 25x25m^2 cell. This method was selected to preserve flooded areas as much as possible. However, this resampling resulted in seriously increased flood extents. The effect of resampling on flood extent was investigated for the reference situation 2010. Results are given in the table below.

Table 3.1 Comparison of flooded area for datasets with 5x5m^2 and 25x25m^2 resolution.

	Return period [years]	10	50	100	1000	2000	4000	10000
Cell size for 2010 situation		**Flood extent [ha]**						
5x5m^2		8963	9639	9848	10418	10564	10808	11658
25x25m^2		11251	12081	12331	13089	13304	13640	14667
Percentual increase		20%	20%	20%	20%	21%	21%	21%

The table shows a bias of the area flooded by approximately 20%.

Not only the extent varies, also the average flooding depths change as a result of resampling. It was found that the resampling had profound effects in the port areas depending on flooding patterns. Especially very narrow flooding zones along the quays (ca 5m wide) showed large effects. Deviations between flood depth datasets for various return periods of up to of 1 meter plus were observed.
The effects of resampling on average flooding depth in the more natural floodplains were limited and independent of flooding pattern.

Based on these observations it was decided to perform the flood damage assessment using the 5x5m^2 dataset and not the 25x25m^2 dataset, in spite of the larger computational demands.

Interpretation
In this project the average value of all (but at least one) cell from the 5x5m^2 grid was assigned to a 25x25m^2 cell. This method was selected to preserve flooded areas as much as possible. This means that in theory it is possible that one single 5x5 m^2 cell is enlarged to one single 25x25 m^2 cell, resulting in an increase of the flooded area with a factor 25. The fact that 'only' 20% more flooded area is found after resampling can be attributed to the fact that flooded areas are on the average large and clustered.
The results lead to the recommendation to use flooding data that is as accurate as possible for damage assessments. Resampling (or use of coarser grids) will lead to overestimation of flood extent and flood depth in the study area.

3.2 Sensitivity analysis flooding

3.2.1 Introduction

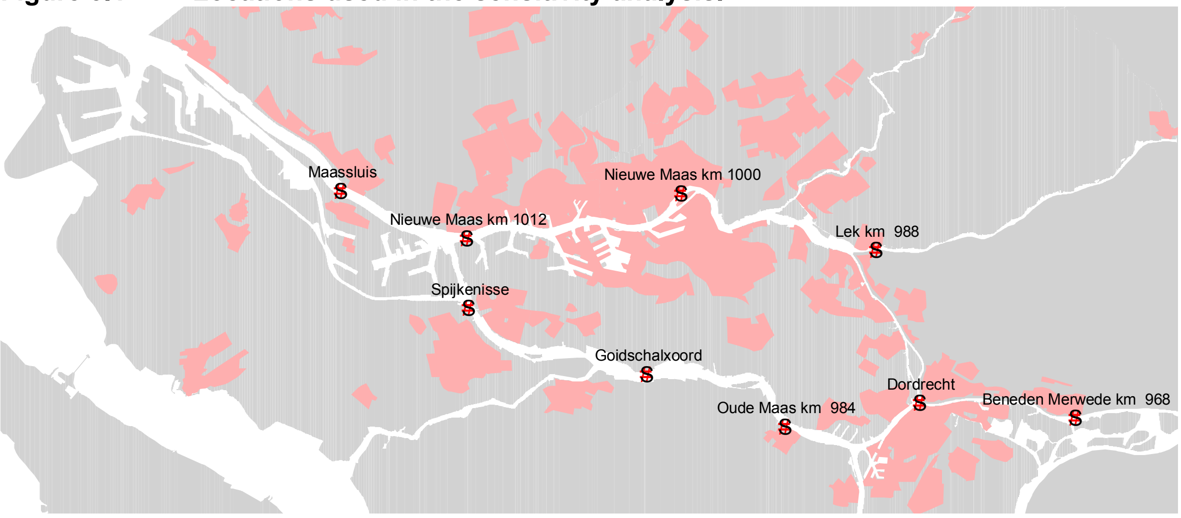
The first sensitivity analysis addresses the effects on flood extents of an alternative failure rate of the Maeslant storm surge barrier of 1/1000 instead of the current failure rate of 1/100.

The current failure rate of the Maeslant storm surge barrier is considered to be 1/100 [Duits & Thonus, 2007]. Failure is defined as failure to close on demand or collapse after closure. The failure rate of 1/100 means that in case the barrier closes once every 12 year (present situation), once in 1200 years a failure may be expected [Stijnen & Slootjes, 2010]. If the barrier has to close 30 times per year because of climatic change (as might be the case in the Veerman scenario), failure may be expected every 3 to 4 years [Stijnen & Slootjes, 2010]. The paragraph focuses on the effects on flood extent; more information on the calculated water levels is available in the report by Stijnen & Slootjes (2010).

The second sensitivity analysis addresses the effect of an alternative storm duration on flood extent. In the ordinary water level calculations for 2050 (G+) and 2100 (Veerman) a storm duration of 35 hours has been assumed (see Table 2.2). In this sensitivity analysis the effect of an alternative storm duration of only 29 hours is considered for the Veerman scenario without any measures. The paragraph focuses on the effects on flood extent; more information on the calculated water levels is available in the report by Stijnen & Slootjes (2010).

A map of the considered locations is shown in the Figure 3.1.

Figure 3.1 Locations used in the sensitivity analysis.



3.2.1 Alternative failure rate of the Maeslant storm surge barrier

As an alternative for the flood maps with a failure rate of 1/100 of the Maeslant storm surge barrier, flood maps with a failure rate of 1/1000 were made. Decreasing failure rate results in decreasing water levels in the probabilistic calculations for the various return periods and results in less flooding. Upgrading the Maeslant storm surge barrier can be seen as a possible measure/alternative for the future in addition to other variants and measures to diminish flooding as a result of climate change.
The table below shows water level reduction for specific probabilistic return period events between the current failure rate of 1/100 and 1/1000 (sensitivity analysis calculation) of the Maeslant storm surge barrier for the **situation (2010)** without any measures.

Table 3.2 Water-level reduction for a reduced failure rate of Maeslant barrier in 2010.

	Return period [years]	10	100	1000	2000	4000	10000
Location		**Water-level reduction [m]**					
Maassluis	*Nieuwe Waterweg km 1019*	0.00	0.00	0.02	0.04	0.07	0.17
Vlaardingen	*Nieuwe Maas km 1012*	0.00	0.00	0.02	0.04	0.07	0.17
Rotterdam	*Nieuwe Maas km 1000*	0.00	0.00	0.02	0.04	0.07	0.17
Krimpen a/d Lek	*Lek km 988*	0.00	0.00	0.02	0.02	0.04	0.07
Dordrecht	*Beneden Merwede km 976*	0.00	0.00	0.01	0.01	0.02	0.03
Spijkenisse	*Oude Maas km 1002*	0.00	0.00	0.02	0.04	0.06	0.16
Goidschalxoord	*Oude Maas km 994*	0.00	0.00	0.02	0.02	0.04	0.09
Puttershoek	*Oude Maas km 984*	0.00	0.00	0.01	0.02	0.02	0.05
Dordrecht	*Beneden Merwede km 976*	0.00	0.00	0.01	0.01	0.02	0.03
Sliedrecht	*Beneden Merwede km 968*	0.00	0.00	0.00	0.01	0.01	0.01

From Table 3.2 it can be concluded that a lower failure rate of 1/1000 of the Maeslant storm surge barrier instead of the present failure rate of 1/100 results for the situation in 2010 in lower water-levels of locations near the storm surge barrier. The 'Nieuwe Maas' (locations Maassluis & Vlaardingen & Rotterdam) shows a decrease in water level of up tot about 20 cm for return periods from 2000 up to 10.000 years. This is in agreement with the findings in the report "Achterlandstudie Maeslantkering" [Bijl, 2006]. For these locations the effect of the decrease in flood levels on the flood patterns is that the flood pattern of 1/4.000 becomes representative for 1/10.000 events and the 1/2000 flooding pattern becomes representative for 1/4000 events. The flooding pattern for return periods greater than 2000 years remain virtually unchanged. As the table shows, all other locations have no significant water-level reduction, so reduction in flooding extent and depth is minimal.

The 'Oude Maas' (location Spijkenisse) shows a decrease in water level of approximately 0.1 to 0.2 m as well. The effect on the flooding is that the pattern of 1/4000 event becomes representative for 1/10.000 event for this particular location; the rest of the area remains almost unchanged. The 1/2000 flooding pattern becomes representative for the flood pattern for these locations in the case of 1/4000. The flood pattern for return periods smaller than 4000 years remains unchanged.

Water level reduction for specific probabilistic return period events between the current failure rate of 1/100 and 1/1000 (sensitivity analysis calculations) of the Maeslant storm surge barrier for the **Veerman climate scenario (2100)** without any measures are shown in the table below.

Table 3.3 Water-level reduction for a reduced failure rate of Maeslant barrier in 2100.

	Return period [years]	10	100	1000	2000	4000	10000
Location		**Water-level reduction [m]**					
Maassluis	*Nieuwe Waterweg km 1019*	0.03	0.24	0.47	0.50	0.52	0.53
Vlaardingen	*Nieuwe Maas km 1012*	0.03	0.23	0.44	0.46	0.48	0.50
Rotterdam	*Nieuwe Maas km 1000*	0.04	0.23	0.45	0.47	0.48	0.49
Krimpen a/d Lek	*Lek km 988*	0.02	0.08	0.18	0.19	0.21	0.22
Dordrecht	*Beneden Merwede km 976*	0.02	0.05	0.05	0.06	0.06	0.07
Spijkenisse	*Oude Maas km 1002*	0.03	0.22	0.36	0.38	0.40	0.43
Goidschalxoord	*Oude Maas km 994*	0.02	0.12	0.13	0.13	0.14	0.16
Puttershoek	*Oude Maas km 984*	0.02	0.06	0.06	0.07	0.07	0.08
Dordrecht	*Beneden Merwede km 976*	0.02	0.05	0.05	0.06	0.06	0.07
Sliedrecht	*Beneden Merwede km 968*	0.01	0.02	0.02	0.02	0.02	0.02

From Table 3.3 it can be concluded that a lower failure rate for the Veerman scenario of 1/1000 instead of the present failure rate of 1/100 year results for the Maeslant barrier in lower water levels near the barrier. The 'Nieuwe Maas' (locations Maassluis & Vlaardingen & Rotterdam) shows a decrease in water levels up to 0.5m. The effect on the flooding pattern is that the 1/1000 flood pattern may be set representative for 1/10.000 events for these particular locations and that the 1/100 flooding pattern may be set representative for the 1/1000 event. As the table shows, other locations have no reduction water level so flood extent and depth remain identical.
The 'Oude Maas' (location Spijkenisse only) also shows a decrease in water level; up to approximately 0.4m. The effect on the flooding is identical to the situation in the 'Nieuwe Maas'. Other locations show minor decrease in water level, so flood extent and depth remain the same.

Additional analysis shows that in 2010 as a rule of thumb for return periods between 100 and 10.000 years about 20 centimetre water level reduction results in 50% less flood extent in the Rotterdam area. In 2100 the water levels are higher, so shallow flooding occurs in large parts of the Rotterdam area. In this case as a rule of thumb a level reduction of about 40 centimetres reduces the flood extent with 50%.

Interpretation
The strong influence of the failure rate of the Maeslant storm surge barrier on water levels eastward of it originates from the strong influence of storm surges on the North Sea in this area. Further from the barrier in upstream direction the discharge of the river Rhine gains importance on influencing water levels, while the influence of the North Sea gradually levels out. This pattern is clear in both Table 3.2 and Table 3.3.

3.2.2 Effect of alternative storm duration at the North Sea

A comparison is made between the calculation of the Veerman scenario (2100) without any measures, a storm duration of 35 hours, a discharge at Lobith of 18.000 m3/s and a failure rate of the Maeslant storm surge barrier of 1/100 year versus alternative model runs with a storm duration of 29 hours and for the rest identical parameters. Results are shown in Table 3.4.

Table 3.4 Water-level reduction for reduced storm duration on the North Sea in 2100.

	Return period [years]	**1000**	**2000**	**4000**	**10000**
Location		**Water-level reduction [m]**			
Maassluis	*Nieuwe Waterweg km 1019*	0.03	0.02	0.01	-0.01
Vlaardingen	*Nieuwe Maas km 1012*	0.03	0.02	0.02	0.00
Rotterdam	*Nieuwe Maas km 1000*	0.02	0.01	0.01	0.00
Krimpen a/d Lek	*Lek km 988*	0.02	0.02	0.01	-0.02
Dordrecht	*Beneden Merwede km 976*	0.06	0.04	0.02	0.00
Spijkenisse	*Oude Maas km 1002*	0.04	0.03	0.02	0.00
Goidschalxoord	*Oude Maas km 994*	0.05	0.03	0.00	-0.02
Puttershoek	*Oude Maas km 984*	0.05	0.04	0.02	0.02
Dordrecht	*Beneden Merwede km 976*	0.06	0.04	0.02	0.00
Sliedrecht	*Beneden Merwede km 968*	0.02	0.01	-0.01	-0.02

Note that negative water-level reduction implies a water-level increase!

From Table 3.4 it can be concluded that a shorter storm duration of 29 hours instead of 35 hours does not show any significant flood extent reduction on any location for the return periods shown, because the water levels change only to a very limited extent.

Interpretation
The effect of storm duration is probably related to areas where sea influence dominates, areas where riverine influence dominates and the intermediate area where both phenomena have influence. More detailed research is necessary to reveal the origin of the observations.

3.3 Flooding animation

All flood maps calculated for the current situation (2010) were converted to a geo-referenced image sequence to be played in Google Earth. This so-called KMZ can be opened in Google Earth from version 4.1 and later and shows the increase of flood depth and extent with increasing return period. Some examples from this ‘film’ are shown from Figure 3.2 to Figure 3.7.

The results from Google were converted to a stand-alone Windows AVI film that can be played on any modern version of Windows Mediaplayer or Apple Quicktime. The film visualizes the increase and the decrease of flooding. The decrease of flooding is the reverse of the flooding increase for visualisation purposes only. This may not represent a correct physical process because of possible occurrence of backwater behind dikes or elevated terrains.

Figure 3.2 Current climate: example 10 year flood (Image source: Google)

Figure 3.3 Current climate: example 100 year flood (Imagesource: Google)

Figure 3.4 Current climate: example 1000 year flood (Image source: Google)

Figure 3.5 Current climate: example 2000 year flood (Image source: Google)

Figure 3.6 Current climate: example 4000 year flood (Image source: Google)

Figure 3.7 Current climate: example 10.000 year flood (Image source: Google)

The following observations can be made from the images depicting the present situation.

The floodplains in the southern part of the images (Hollands Diep and Oude Maas) are mainly natural floodplains, except for the Dordrecht area. They experience flooding during all repeat times. Increasing return periods do not significantly change flooding patterns. However, flood depths do increase.

The northern part of the images shows more differentiation. This is the area where the ports are located in Rotterdam and Dordrecht. The oldest port areas in the centre of Rotterdam are flooded only partly for return periods up to 100 years. For return periods of more than 1000 years flooding is significant here. The newest ports in the western part show only minor flooding up to a return period of up to 4000 years. Only during a 10.000 years flood significant port areas in the western Botlek is flooded.

The observed locations were elevated during the construction of the ports, showing increasing terrain elevation in westward direction (newer ports). From the water level calculations for many observed return periods it may be concluded that upstream of the Maeslant storm surge barrier the water level decreases (Botlek) and then increases again (centre of Rotterdam), both by approximately 10 centimetres. Upstream from the centre of Rotterdam the water levels decline to lower values again.

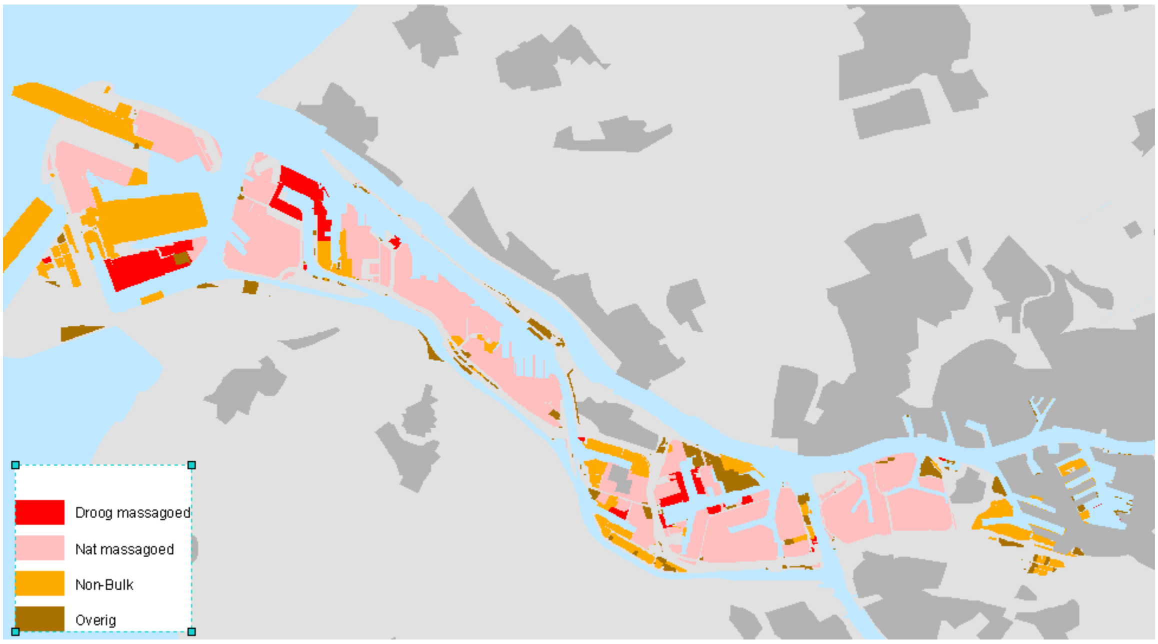
Interpretation

The flooding patterns in the port areas are related to terrain elevation, as the water levels for many return periods do not differ with more than 10 cm from the average in the port area between the Maeslant storm surge barrier and the town of Krimpen aan den IJssel. Any further upstream, water levels do decline, as influence of riverine discharge increases and influence of the sea decreases.

3.4 Flooding ratio per type of goods in the port of Rotterdam

The Port of Rotterdam is interested in the amount of flooded area for various types of goods. For this reason flood maps were combined with maps depicting goods type distribution in the ports. For each type of goods the ratio of flooded against total area was calculated. For this study one variant (lockable/open) was studied in addition to the present situation.

Figure 3.8 Distribution of goods categories in the port of Rotterdam (source: Port of Rotterdam).



The results are shown in the figures below.

Figure 3.9 Distribution 2010 flooded-non flooded per cargo type - no measures.

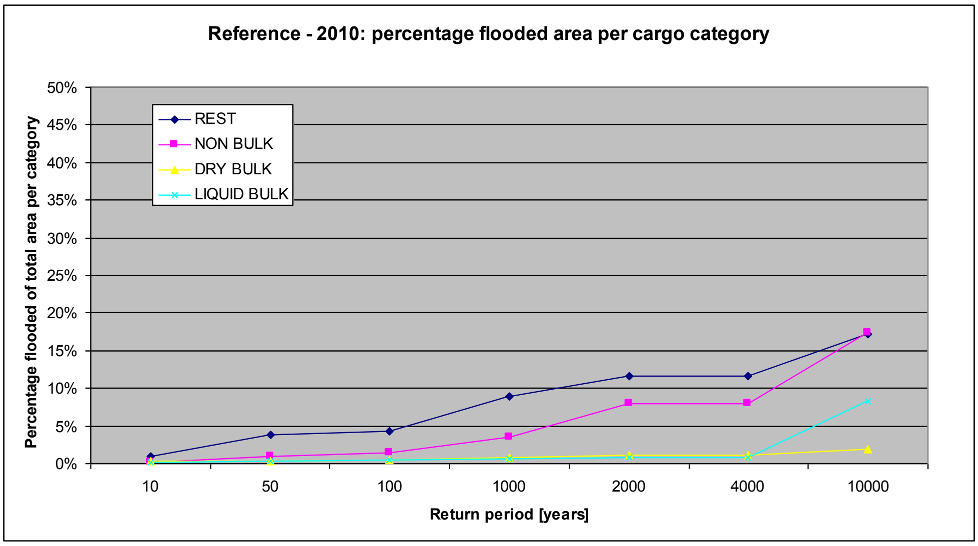


Figure 3.10 Distribution 2050 flooded-non flooded per cargo type – no measures.

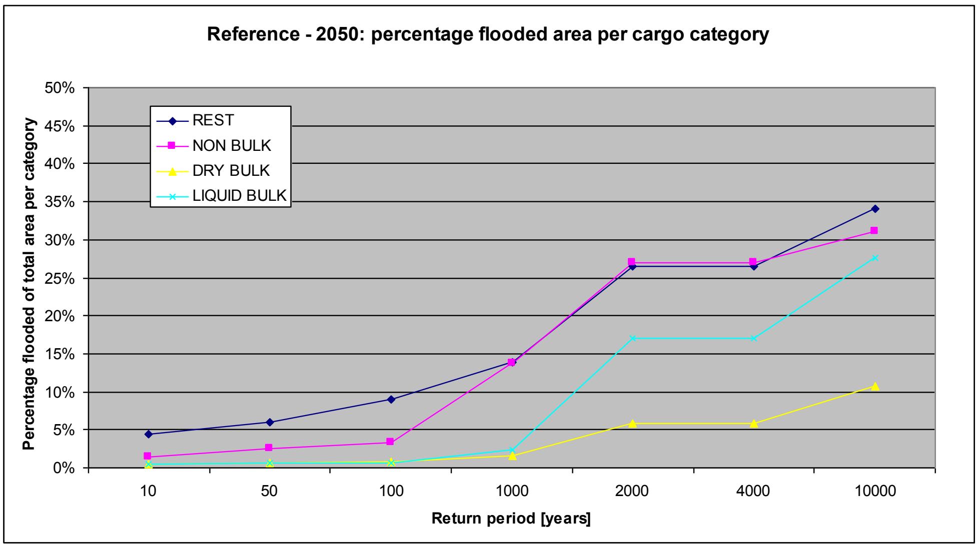


Figure 3.11 Distribution 2100 flooded-non flooded per cargo type – no measures.

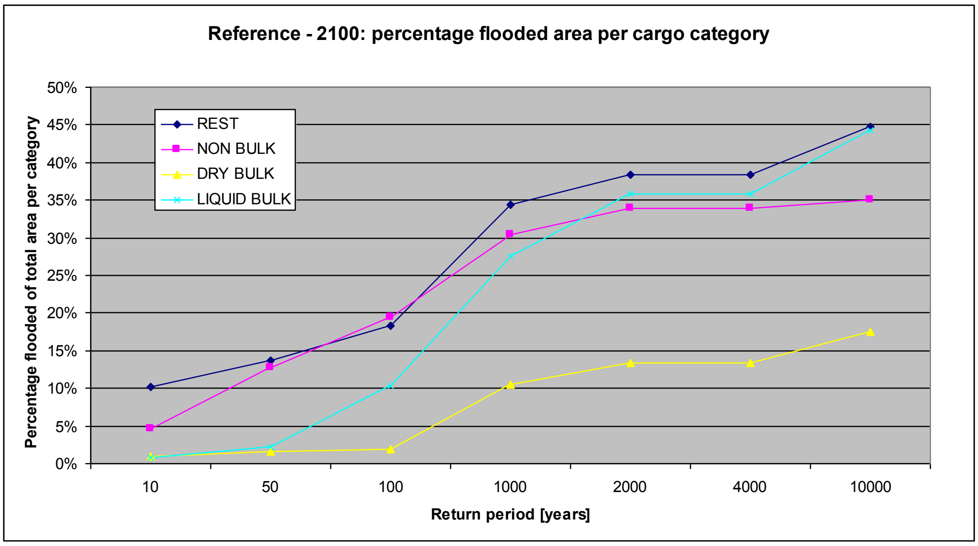


Figure 3.12 Distribution 2050 flooded-non flooded per cargo type – lockable/open.

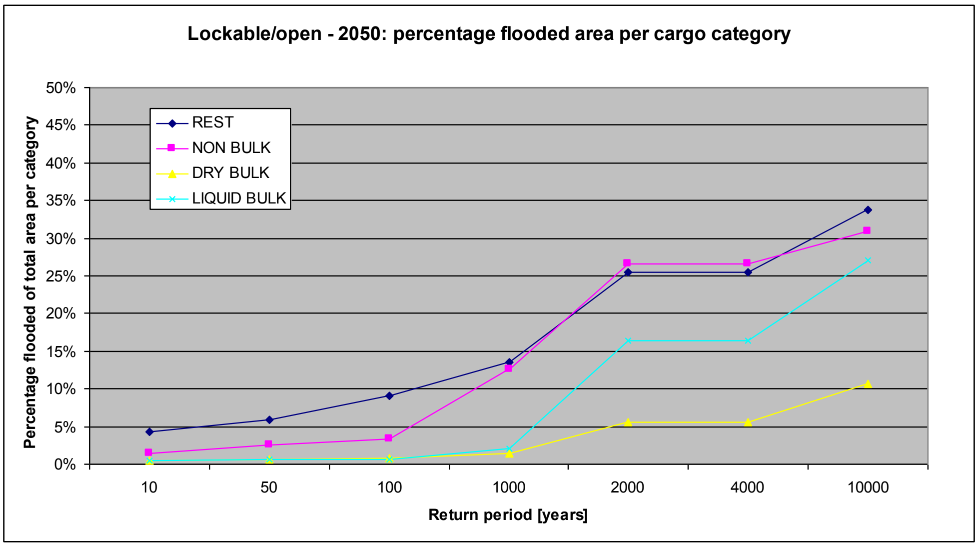
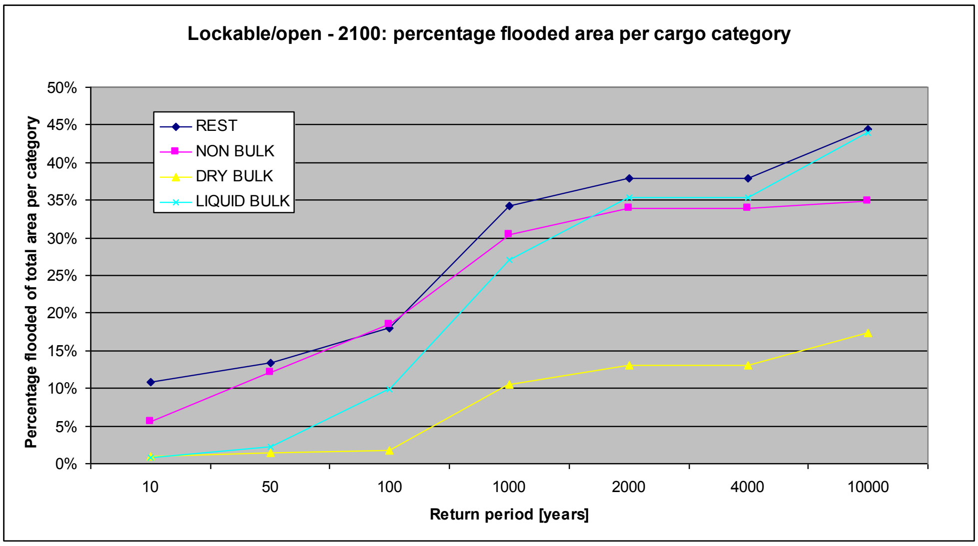


Figure 3.13 Distribution 2100 flooded-non flooded per cargo type – lockable/open.



The figures show that in the present situation less than 20% of the respective areas is flooded even during a flood with a return period of 10.000 years. The categories ‘rest’ and non-bulk’ have about the same flooding ratio. The category ‘liquid bulk’ has a flooding ratio of about 10% and ‘dry-bulk’ has a flooding ratio of about 2%.

In 2050 the flooded area is expected to increase. Between 25% and 35% of the area used for the good categories ‘rest’, ‘non–bulk’ and ‘liquid-bulk’ will be flooded during a 10.000 years flood. The figure shows that also in the 2050 situation ‘dry-bulk’ is experiencing the least flooding in a 10.000 years flood of about 10%.

In 2100 the flooded area is expected to increase over 2050. Between 35% and 45% of the area used for the good categories ‘rest’, ‘non–bulk’ and ‘liquid-bulk’ will be flooded during a 10.000 years flood. The figure shows that also in the 2100 situation ‘dry-bulk’ is experiencing the least flooding: about 17%.

The closable but open variants show minor reduction of the flooding ratios in 2050 and 2100 of only 1 or 2%.

Interpretation

From the figures it can be concluded that the categories ‘rest’ and ‘non-bulk’ experience most percentual flooding for any return period. The reason is that these cargo categories are mainly located in the eastern part of the port, which experiences severe flooding due to lower terrain elevation. Large areas ‘non-bulk’ on the Maasvlakte in the western part of the port are not considered in the flooding simulations, because they are located on the sea side of the Maeslant storm surge barrier for which no water elevation data is computated.

The category ‘dry – bulk’ suffers relatively the least from flooding, because these port areas are located in the western part of the port, on terrains being more elevated.

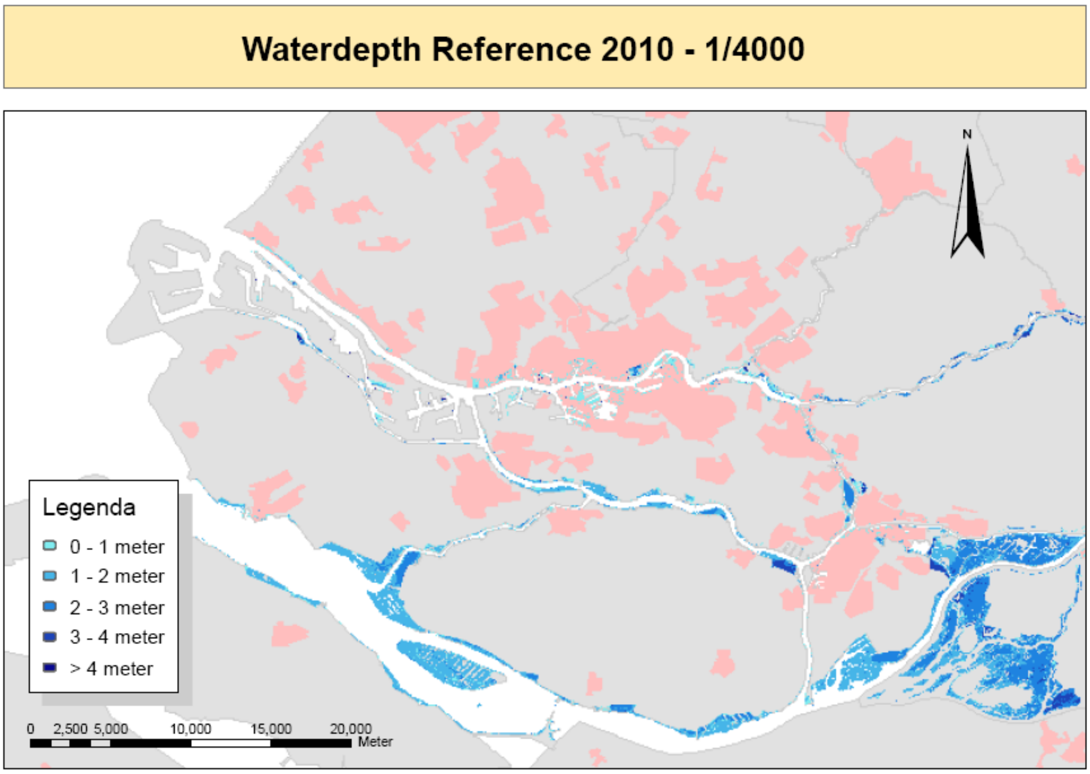
The category ‘liquid-bulk’ is evenly distributed over all port areas in the Rotterdam area. It experiences intermediate percentual flooding. The percentual flooding of the category ‘liquid bulk’ increases stronger in 2050 and 2100 until it equals the categories ‘rest’ and ‘non-bulk’. This is related to flooding of the western Botlek.

In 2050 and 2100 there is no significant difference between situation with – and the situation without the closable but open measures.

3.5 Flood maps and Flood Map Atlas

All flood maps are collected in appendix 3. Each map represents one unique combination of a measure (reference (no measures) versus closable but open measure), a climate scenario (current climate, KNMI G+ scenario or Veerman scenario) and specific return periods (all: 10, 50, 100, 1000, 2000, 4000, 10.000 years).

Figure 3.14 Example from the Floodmap Atlas: flooding during 1/4000 situation in 2010.



Based on the flood simulations some key figures can be graphically presented.

First the flooded area is considered and then the area averaged flooding depth.

3.6 Flood extent

Concise results from the flood maps regarding flood extent are given below.

Figure 3.15 Flooded area for various return periods, years and measures – lineair scaling.

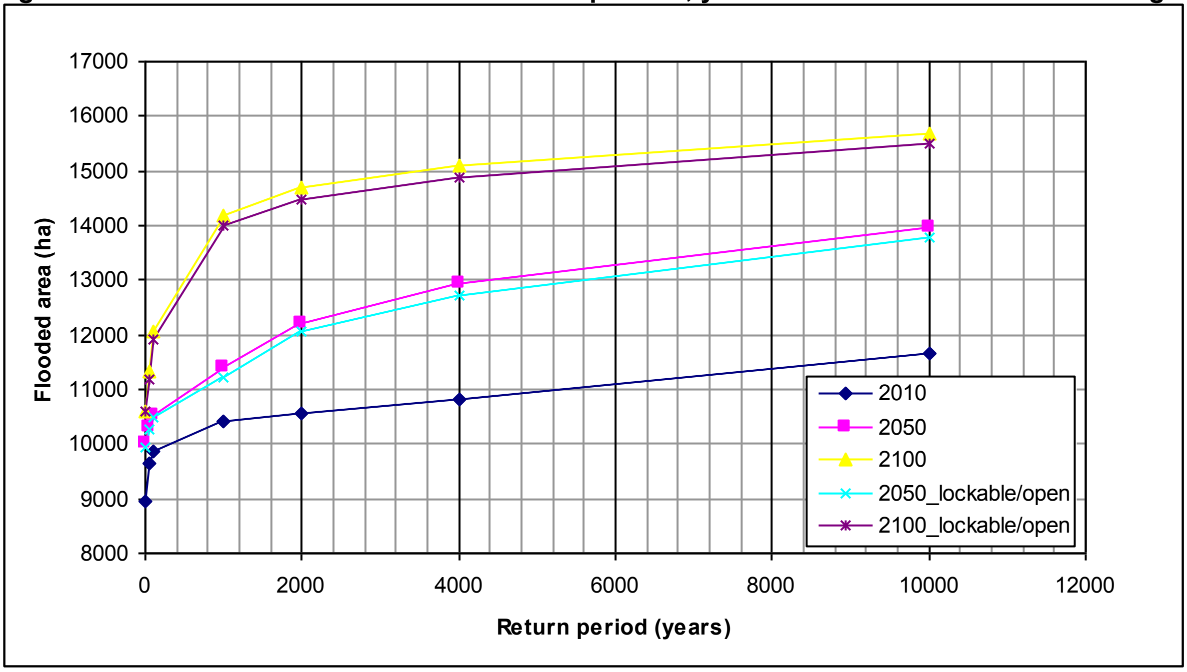
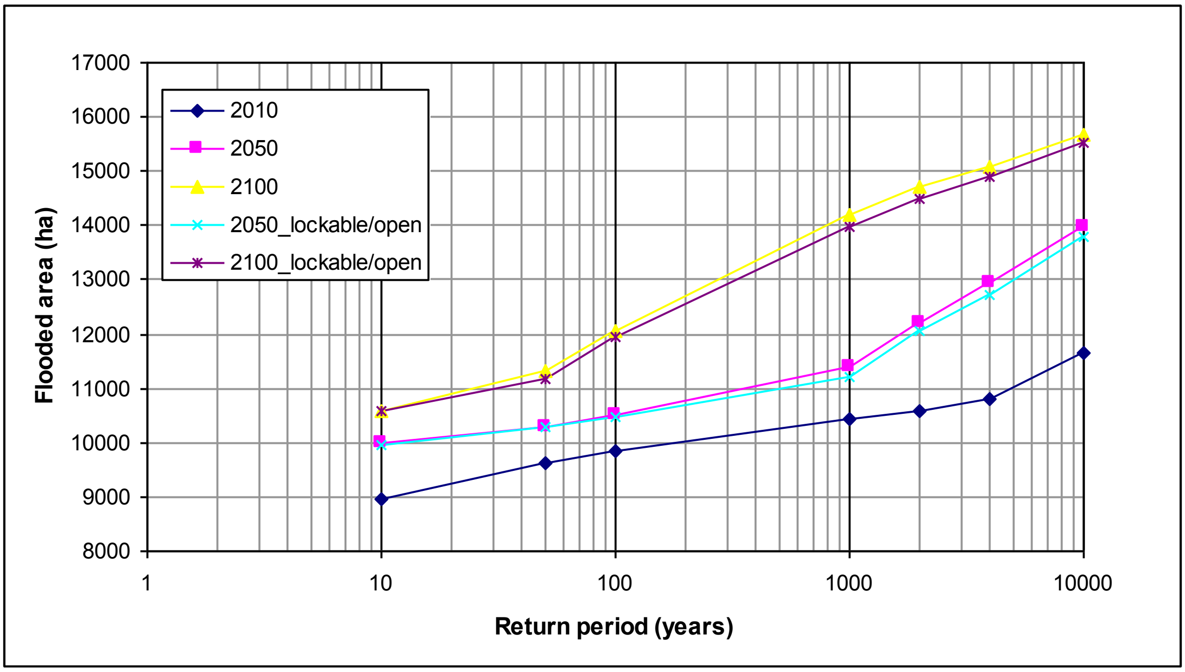


Figure 3.16 Flooded area for various return periods, years and measures – log scaling.



The total area considered amounts to 47300 hectares. This represents all unembanked areas in the study area.

Observations 2010

Most of the flooded areas during the 10 years flood in the present situation are natural terrains – the so-called floodplains. The figures show that in the present situation the flooded area increases from around 9000 ha for water levels with a return period of 10 years to around 11500 ha for water-levels with a return period of 10.000 years. This is an increase of about 30%.

Initially there is a strong exponential increase between return periods of 10 years and 1000 years. From 1000 years and on the increase of flooded area gradually levels out.

During a 10.000 years flood in the present situation 24% of the total area considered is flooded.

Observations 2050
For the 2050 situation the figures show the flooded area increases from around 10000 ha for water-levels with a return period of 10 years to around 14000 ha for water-levels with a return period of 10.000 years. This is an increase of about 40%.

Initially there is a strong exponential increase between return periods of 10 years and 4000 years. From then the flooded area increases gradually.

In 2050 during a 10.000 years flood 30% of the total area considered is flooded.

The flood extent for a return period of 10 years in 2050 is identical to the flood extent with return period 200 years of in 2010. This is about a factor 10.

Observations 2100
For the 2100 situation the figures show the flooded area increases from around 10500 ha for water-levels with a return period of 10 years to around 15500 ha for water-levels with a return period of 10.000 years. This is an increase of about 48%.

Initially there is a strong exponential increase between return periods of 10 years and 2000 years. From then the flooded area increases gradually.

In 2100 during a 10.000 years flood 33% of the total area considered is flooded.

The flood extent in 2100 with a return period of 10 years is identical to a return period of 100 years in 2050 or 2000 years in 2010. This is about a factor 10 again.

Observations closable but open variants
The closable but open variants show only slightly smaller flooded areas in 2050 and 2100. Until return periods of 100 years the difference increases. From return periods of 1000 years the difference remains constant at about 200 ha for both 2050 and 2100. This implies a flood extent reduction up to 2%.

Interpretation
Flooding during a 10 years event in the present situation relates to natural floodplains. Events with a repeat time of 10 years in 2050 or 2100 show increased flood extents of 1000 and 1600 ha over the present situation. These areas can be addressed as flooding of ports or industrial areas due to higher water levels.

The various years and variants all show a trend break at a flooding amount of around 11.000 ha. Any further increased return period results in a stronger flood extent increase. This is related to flooding of large port areas in Rotterdam (Botlek-west). There is roughly a repeating factor 10 in return period decrease between the return periods of the scenarios for 2010, 2050 and 2100.

3.7 Area averaged flooding depth

Concise results from the flood maps regarding flood depth are given below.

Figure 3.17 Area averaged flooding depth (cm) for various return periods, years and measures – lineair scaling.

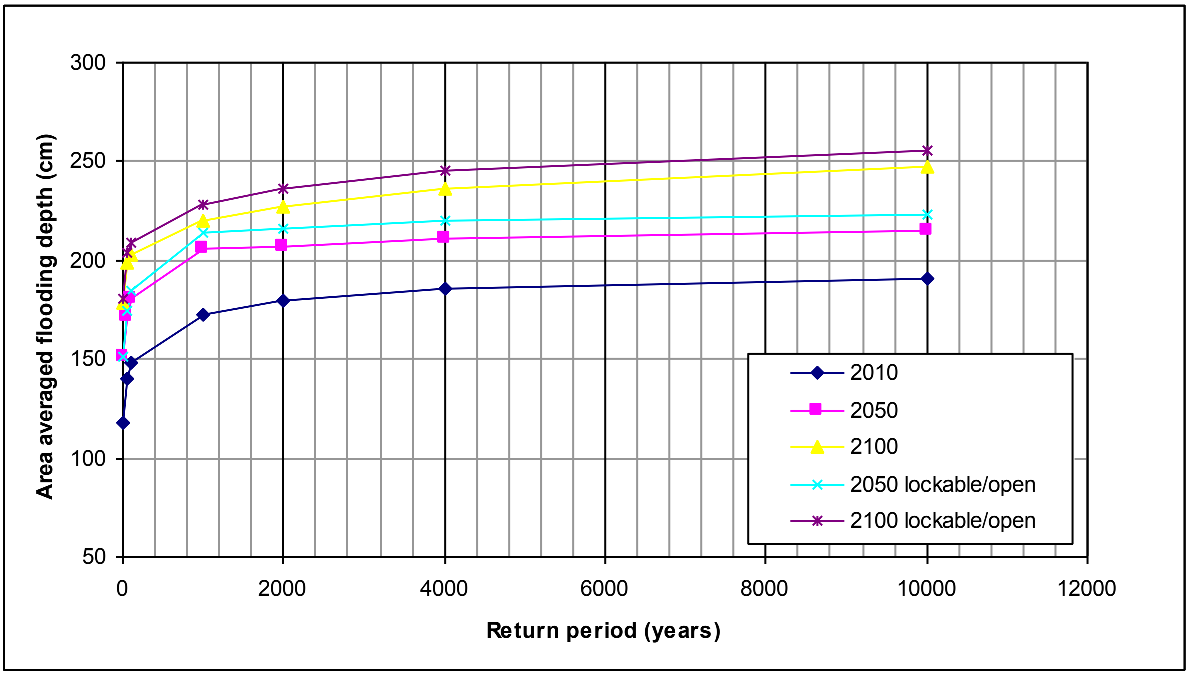
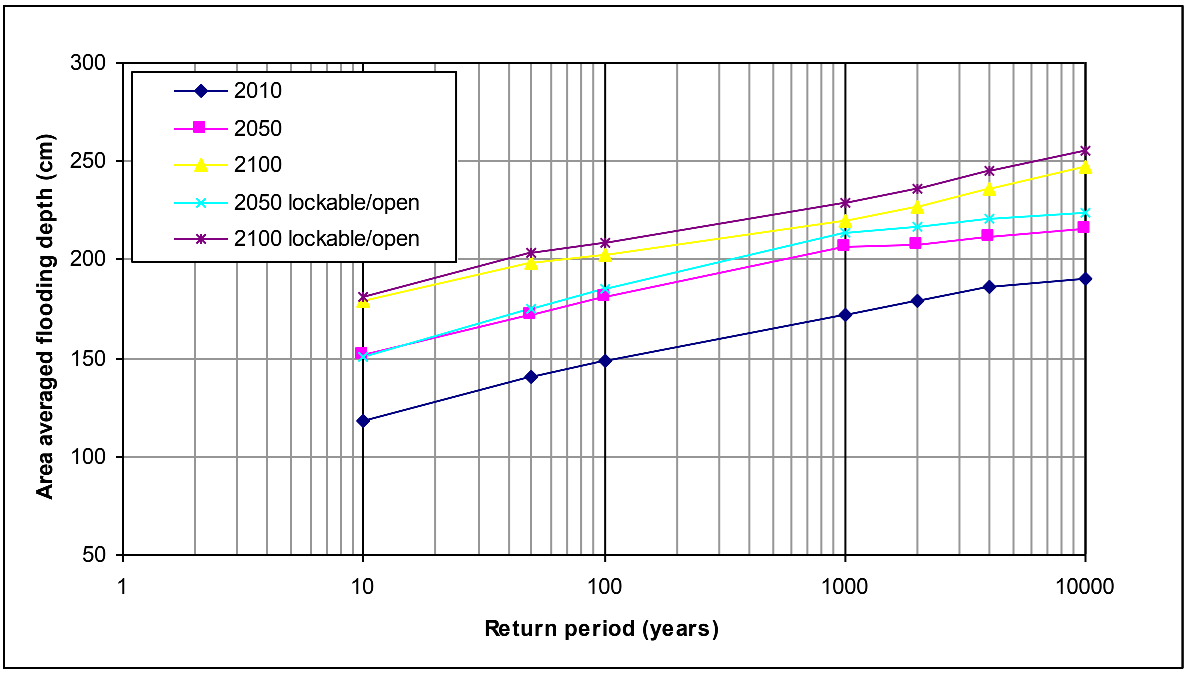


Figure 3.18 Area averaged flooding depth (cm) for various return periods, years and measures – logarithmic scaling.



Observations 2010
Most of the flooded areas during the 10 years flood in the present situation are natural terrains – the so-called floodplains. The figures show that in the present situation the area averaged flood depth increases from around 120 cm for water levels with a return period of 10 years to around 190 cm for water levels with a return period of 10.000 years. This is an increase of about 58%.

Initially there is a strong exponential increase between return periods of 10 years and 1000 years. From 1000 years and on the increase of flood depth gradually levels out.

Observations 2050
For the 2050 situation the figures show the area averaged flood depth increases from around 150 cm for water-levels with a return period of 10 years to around 225 cm for water-levels with a return period of 10.000 years. This is an increase of 50%.

Initially there is a strong exponential increase of average water-level between return periods of 10 years and 1000 years. From then the flood depth increases gradually.

Observations 2100
For the 2100 situation the figures show the area averaged flood depth increases from around 180 cm for water-levels with a return period of 10 years to around 255 cm for water-levels with a return period of 10.000 years. This is an increase of about 48%.

Initially there is a strong exponential increase between return periods of 10 years and 2000 years. From then the flood depth increases gradually.

Observations closable but open variants
The closable but open variants show only slightly smaller average flooding depths 2050 and 2100. Until return periods of 1000 years the difference increases. From return periods of 1000 years the difference remains constant at about 10 centimetres for both 2050 and 2100. This is a reduction in average flood depth of up to 5%.

Interpretation

From the figures it can be concluded that the effects of the variant closable but open on average flood depth are small: order of magnitude 10 cm average flood depth reduction in 2050 compared to 2050 without measures. This is related to average water level reduction of the variant, which is small in the Rotterdam area and somewhat more in the Dordrecht region. However, the Rotterdam area has because of its large area of unembanked areas a much bigger weight in the calculation of the average value.

Flooding during a 10 years event in the present situation relates to natural floodplains. Events with a repeat time of 10 years in 2050 or 2100 show increased average flood depths of 30 and 60 cm over the present situation. This is strongly related to the increase of calculated average water levels in the study area.

The flood depth for a return period of 10 years in 2050 is identical to the flood depth with a return period 100 years of in 2010. The average flood depth in 2100 with a return period of 10 years is identical to a return period of 2000 years in 2010. This is about a factor 10 in the return period for both the period 2010 – 2050 and the period 2050 – 2100. This seems in congruence with the observations regarding flood extent.

The various years and variants all show a trend break at a flooding depth of around 200 cm. This may originate from two possible effects:

- Shallow flooding after an average flooding depth of 200 cm over large areas, or
- Deep flooding over limited areas.

If also the flood extent is considered, it may be concluded that the increase of flooded area with increasing return period remains large. This is an observation in favour of the first assumption that the trend break after 200cm flooding depth can be assigned to shallow flooding of large areas in the Rotterdam port area.

3.8 Flooding of embanked and unembanked floodplains

Flooding is simulated for the unembanked areas in this study. However, the adjacent areas protected by primary defenses may also suffer from flooding. Their protection levels (return period) vary from 2000 to 4000 and even 10.000 years (dike ring South Holland) in the observed study area. If these primary defenses fail, the flooding depth and flooding extent surpass the figures from unembanked areas. Failure of one or more primary defenses also reduces water levels on the river. This results in lower flooding rates in the adjacent unembanked areas.

4. Synthesis

The previous chapters provide an overview of the methods and results. The main findings are summarized here.

4.1 Flood maps

Flood maps were made from available calculated probabilistic water levels from 1D hydraulic models and Hydra-B and a newly processed and very detailed Digital Elevation Model ($5x5m^2$) based on even more detailed LiDAR data. These flood maps cover the delta area up to the Maeslant storm surge barrier.

4.2 Dataset resampling for damage assessment calculations

Data resampling proved to have a profound effect on the flood extent and depth. In this study the effect of resampling (average) of a $5x5m^2$ grid to a $25x25m^2$ grid was investigated. Resampling increased flood extent by approximately 20% for various return periods in 2010. In addition to the change in flood extent, also the average flooding depth changes during the resampling. It was found that the resampling had profound effects in the port areas depending on the flooding pattern. Especially very narrow flooding zones along the quays (ca 5m wide) showed strong effect. Deviations between flood depth datasets for various return periods of up to of 1 meter plus were observed. The effects of resampling on average flooding depth in the more natural floodplains were limited and independent of flooding pattern. Based on these observations it was decided to perform the flood damage assessment on the original $5x5m^2$ dataset, in spite of the larger computational demands.

4.3 Sensitivity analysis flooding

Reducing the failure rate of the Maeslant storm surge barrier from 1/100 to 1/1000 has effects on the water levels. Especially just behind the barrier levels are reduced. Farther from the barrier in upstream direction the effects level out. The effect on the flood extent is that flood extent and flood depth is reduced near the Maeslant barrier, while near Dordrecht the effect is small.
The original water level calculations for 2100 without measures and with a storm duration of 35 hours were compared to identical calculations with a storm duration of only 29 hours. It turns out that shorter storm durations shows water level reductions of up to several centimetres. This is especially the case for short return periods If the return periods increase the effect becomes even smaller. The effect of storm duration on flood extent en depth is small. Most effects can be seen near Dordrecht with short return periods.

4.4 Flooding animation

Based on the inundation maps for the present situation (2010) a flooding animation is made using Google Earth as backdrop images. Each consecutive image in this animation has a return period indicator. Adjacent areas within the primary dike rings having a protection level lower than the indicated return period are denoted by an exclamation mark.
The film visualizes the increase and the decrease of flooding. The decrease of flooding is the reverse of the increased flooding for visualisation purposes only. This may not represent a correct physical process because of possible occurrence of backwater effects behind dikes or elevated terrains.

4.5 Flooding ratio per function in the port of Rotterdam

For the Port of Rotterdam is interesting to know the amount of flooded area for various types of goods. For this reason flood maps were combined with maps depicting goods type distribution in the ports. For each type of goods the ratio of flooded against total area was calculated.
The categories ‘rest’ and ‘non-bulk’ experience most relative flooding for any return period. The reason is that they are mainly located in the eastern part of the port. This location suffers from somewhat higher water levels than average in the port and the terrain has a relatively low elevation, because these ports are relatively old.
The relative flooding of the category ‘liquid bulk’ increases in 2050 and 2100 until it equals the categories ‘rest’ and ‘non-bulk’. The category ‘dry – bulk’ suffers relatively the least from flooding. The reason for this is that these port areas are located in the western part of the port, on terrains being more elevated.

The difference in relative flooding between situation with – and the situation without the closable but open variant for 2050 and 2100 is small.

4.6 Flood Map Atlas

All flood maps are collected in electronic Flood Map Atlases. These Atlases are incorporated in separate documents in Adobe PDF-format. The atlases show on each page a map of the flooded area. Each map represents one unique combination of a measure (reference versus lockable/open), a climate scenario (current climate, KNMI G+ scenario or Veerman scenario) and specific return periods (all: 10, 50, 100, 1000, 2000, 4000, 10.000 plus specific for the current situation in 2010: 25, 250, 500, 750, 1250, 2500, 5000, 7500 years).

4.7 Flood extent analysis

Flooding during a 10 years event in the present situation relates to natural floodplains. Events with a repeat time of 10 years in 2050 or 2100 show increased flood extents of 1000 and 1600 ha over the present situation. These areas can be addressed as ports or industrial areas.
The flood extent for a return period of 10 years in 2050 is identical to the flood extent with return period 200 years of in 2010. The flood extent in 2100 with a return period of 10 years is identical to a return period of 2000 years in 2010. This is about a factor 10 in the return period for both the period 2010 – 2050 and the period 2050 – 2100.
The various years and variants all show a trend break at a flooding amount of around 11.000 ha. Any further return period increase results in a stronger increase. This is related to flooding of large areas in the port of Rotterdam.
Effects of the variant closable but open on flood extent seem small: around 2% reduction in total observed area.

4.8 Area averaged flood depth analysis

Flooding during a 10 years event in the present situation relates to natural floodplains. Events with a repeat time of 10 years in 2050 or 2100 show increased average flood depths of 30 and 60 cm over the present situation.
The flood depth for a return period of 10 years in 2050 is identical to the flood depth with a return period 100 years of in 2010. The average flood depth in 2100 with a return period of 10 years is identical to a return period of 2000 years in 2010. This is about a factor 10 in the return period for both the period 2010 – 2050 and the period 2050 – 2100. This is in congruence with the observations regarding flood extent.
The various years and variants all show a trend break at a flooding depth of around 200 cm. This is the effect of initial shallow flooding over large port areas.
From the figures it can be concluded that the effects of the variant closable but open on flood depth are small: order of magnitude 10 cm (or 5%) average water level reduction.

4.8 Flooding of embanked and un embanked floodplanes

Areas protected by primary defenses (dikes) may also suffer from flooding. Their protection levels (return period) vary from 2000 to 4000 and even 10.000 years (dike ring South Holland) in the observed study area. For the observed return periods these primary defenses might fail. After failure flooding depth and flooding extent surpass the figures from unembanked areas, because the terrain elevation of the protected areas is generally lower. Failure of a primary dike ring reduces flooding in the adjacent unembanked areas.

5. Conclusions

From the study the following conclusions can be drawn:

- The effects of the closable but open variant are small for flood extent and flood depth;
- Flooding increases significantly in the climate scenarios for 2050 and 2100;
- Resampling using an averaging algorithm of flood depth and extent maps should be avoided, because it increases extent and flooding depth; use of detailed data reduces overestimation in damage estimation;
- Reduction of the failure rate of the Maeslant storm surge barrier show significant effects on the flood extent and flood depth in the Rotterdam area; the effect is less in the Dordrecht area;
- Decreasing storm duration on the North Sea has little effect on water-levels and thus on flooding extent and depth;
- Flooding is normal at low return periods for natural floodplains; port areas and industrial areas suffer from flooding only during higher return periods. This is the result of the higher terrain elevation in the man-made areas;
- If flooding in Rotterdam port area starts, large areas are flooded shallow;
- From east to west the port areas in the Rotterdam area are newer and therefore more raised above the original terrain elevation. These newer port areas suffer less from flooding;
- Increase of flood extent and area averaged flood depth show quite similar behavior. The flooding properties for a 10 years event in 2050 are about equal to a 100 years event in 2010. The flooding properties of a 10 years event in 2100 are about equal to a 100 years event in 2050 or a 1000 years event in 2010. This is roughly an increase by a factor of 10 in return period.
- Flooding is simulated for the unembanked areas in this study. However, the adjacent areas protected by primary defenses may also suffer from flooding. Their protection levels (return period) vary from 2000 to 4000 and even 10.000 years (dike ring South Holland) in the observed study area. If these primary defenses fail, the flooding depth and flooding extent surpass the figures from unembanked areas. Such a failure of a primary dike ring reduces flooding in the adjacent unembanked areas.

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Appendix 1 GIS processing schemes

Elevation data processing

Reduction of the cellsize of the original LiDar datasets was performed using the ArcGIS command 'Aggregate'. This command generates a reduced resolution version of a rasterdataset. All resampling has been done to a grid-size of 5m and an extent that is a multiply of 5 to ensure a correct fit during the join of the separate datasets.

The example code is written in commandline language for ArcGIS.

Example: Aggregate_sa s_cmv1 F:\HK\min\scmv5 20 MINIMUM EXPAND DATA

Resampled datasets have been joined using the ArcGIS command 'WorkspaceToNewMosaic'.

Example: WorkspaceToNewMosaic_samples F:\HK\min F:\HK al5 # MEAN FIRST # # # # 0

The whole procedure is time demanding due to the large amount of grids and the large area covered.

To reduce the size of the final DEM, the gridvalues are converted from meters to centimetres by multiplying the elevation values by a factor 100. This result is an integer grid representing elevation as cm+NAP instead of m+NAP.

Flooding data processing

Generating flood depth and extent maps requires multiple steps. These steps are outlined below. The example code is written in AML, the scripting language of ArcInfo.

Step 1:
Subtracting the DEM from a water-level map for a given return period, year and measure gives a 'raw' flooding map.

Example: wdiep_a25 = waterlevel_a25 – K4C_dtm_2010

Step 2:
Using a landmask (containing 'nodata'-values for rivers and the value 1 for land) the flooded and non-flooded areas are discriminated. The result is a map containing the value 1 for rivers and flooded areas and 'nodata' for dry areas

Example: a25NAT = con (IsNull(landmask2010), 1, con (wdiep_a25 > 0, 1))

Step 3:
After the flooded area is determinated, a check is made on the physical 'connection' of the flooded areas to the river. Non-connected areas are removed, connected areas are preserved.

*Example: a25cost = int((costdistance(\nwb_vaarweg21, a25NAT) * 0) + 1)*

Step 4:
The connected areas are filtered from the flood depth and extent maps. This results in the final flood depth and extent maps

Example: mwdiep_a25 = con (wdiep_a25 > 0, a25cost * wdiep_a25)

Step 5:
The final flooding maps are resampled from 5*5m^2 tot 25*25m^2 to make damage calculations less demanding.

Example: tmpgrid1 = blockmean(%ingrid%, rectangle, 5, 5, DATA)
Example: %ingrid% = resample(tmpgrid1, 25, NEAREST)

Appendix 2 Coding scheme for datasets

The datasets showing flood extent and depth have been coded according to the following scheme:

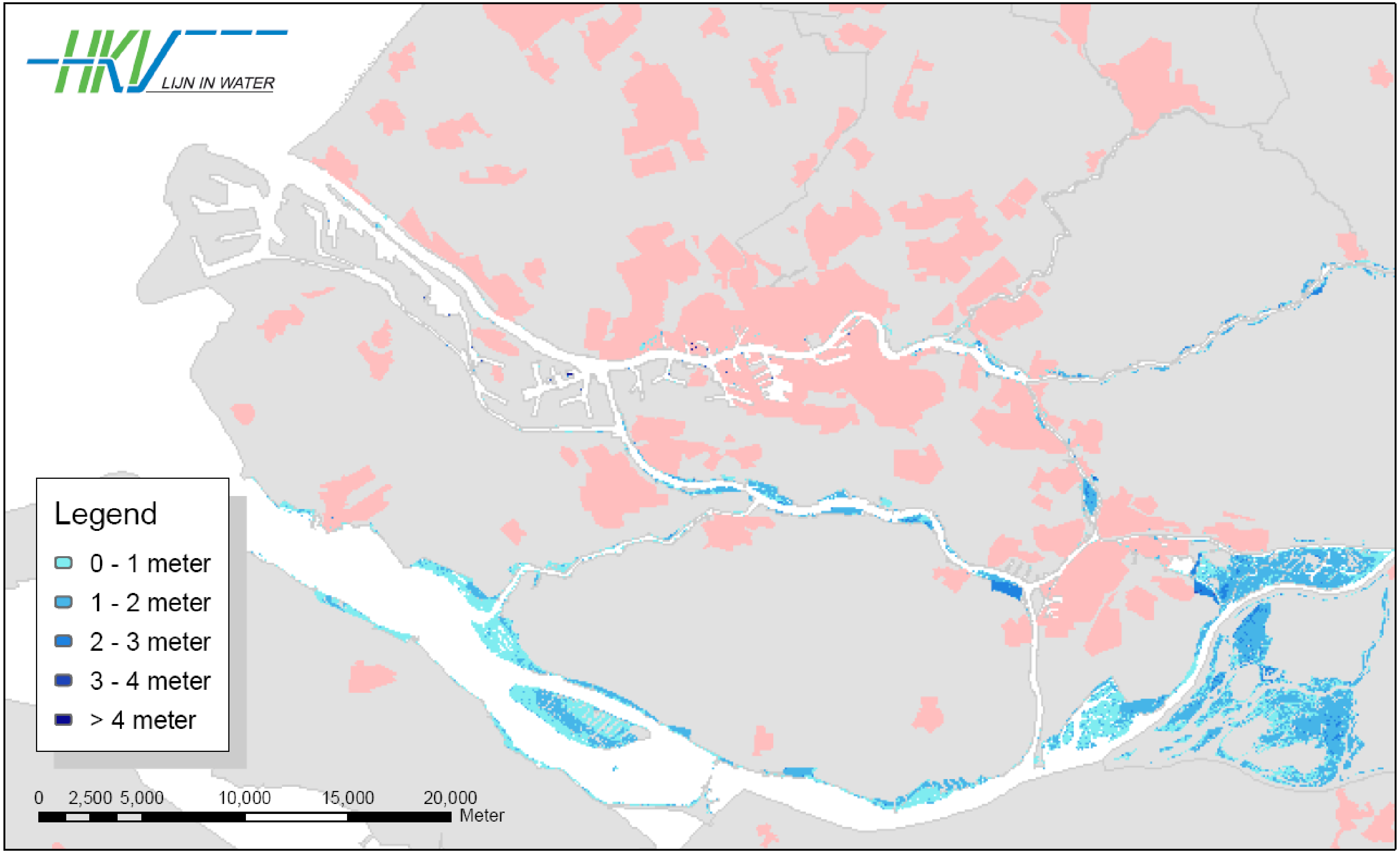
Code	Year	Measures	Return period [years]
A10	2010	Reference	10
A100	2010	Reference	100
A1000	2010	Reference	1000
A…	2010	Reference	…
B10	2050	Reference	10
B…	2050	Reference	…
C10	2100	Reference	10
C…	2100	Reference	…
E10	2050	Lockable/open	10
E…	2050	Lockable/open	…
F10	2100	Lockable/open	10
F…	2100	Lockable/open	…

Appendix 3 Flood depth maps

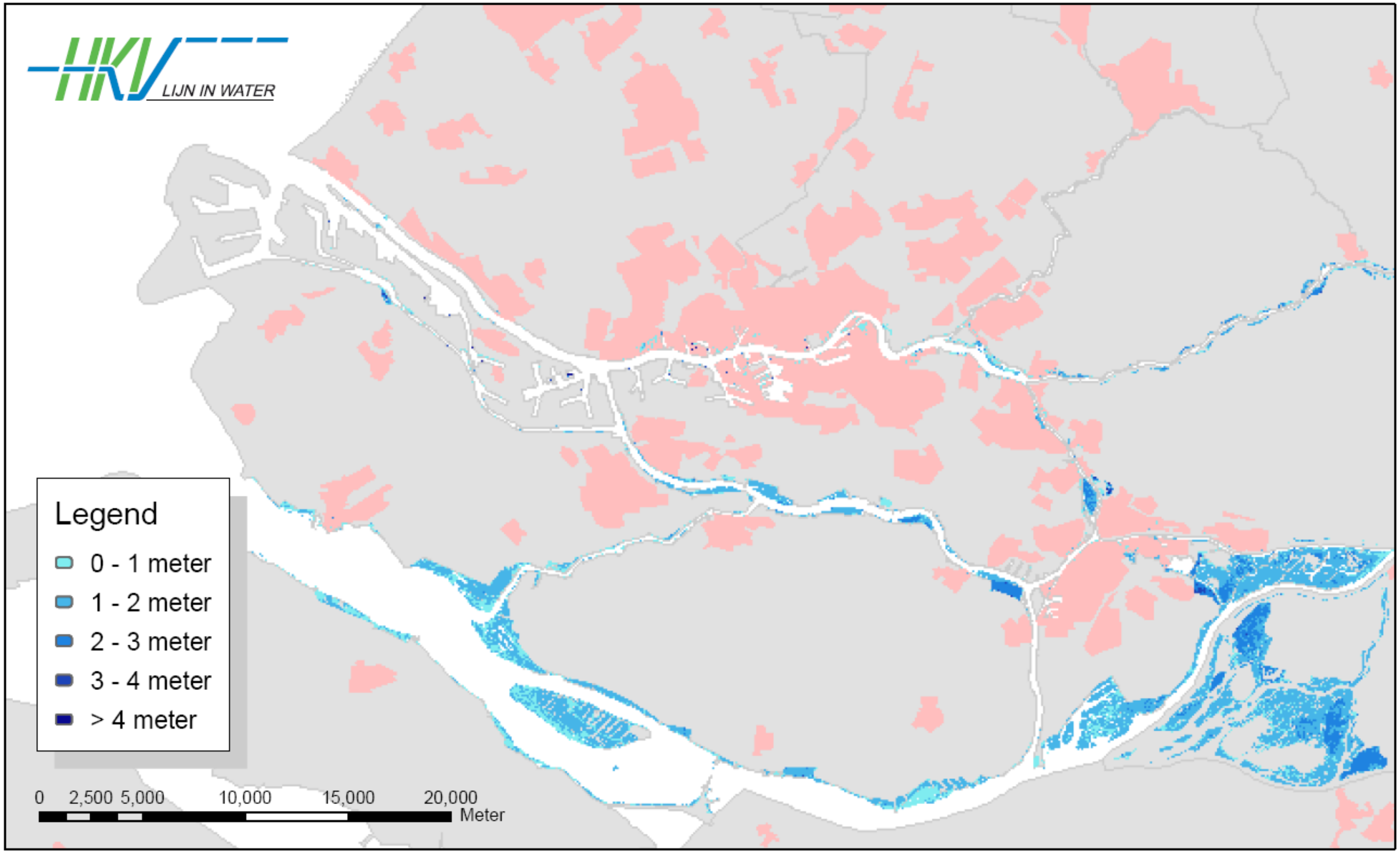
This appendix shows all flood depth maps that have been compiled. Each map represents one unique combination of a measure (reference (no measures) versus closable but open variant), a climate scenario: current climate (2010), KNMI G+ scenario (2050) or Veerman scenario (2100) and specific return periods: 10, 50, 100, 1000, 2000, 4000, 10.000 years.

All maps depict the situation with a failure rate of the Maeslant storm-surge barrier of 1/100.

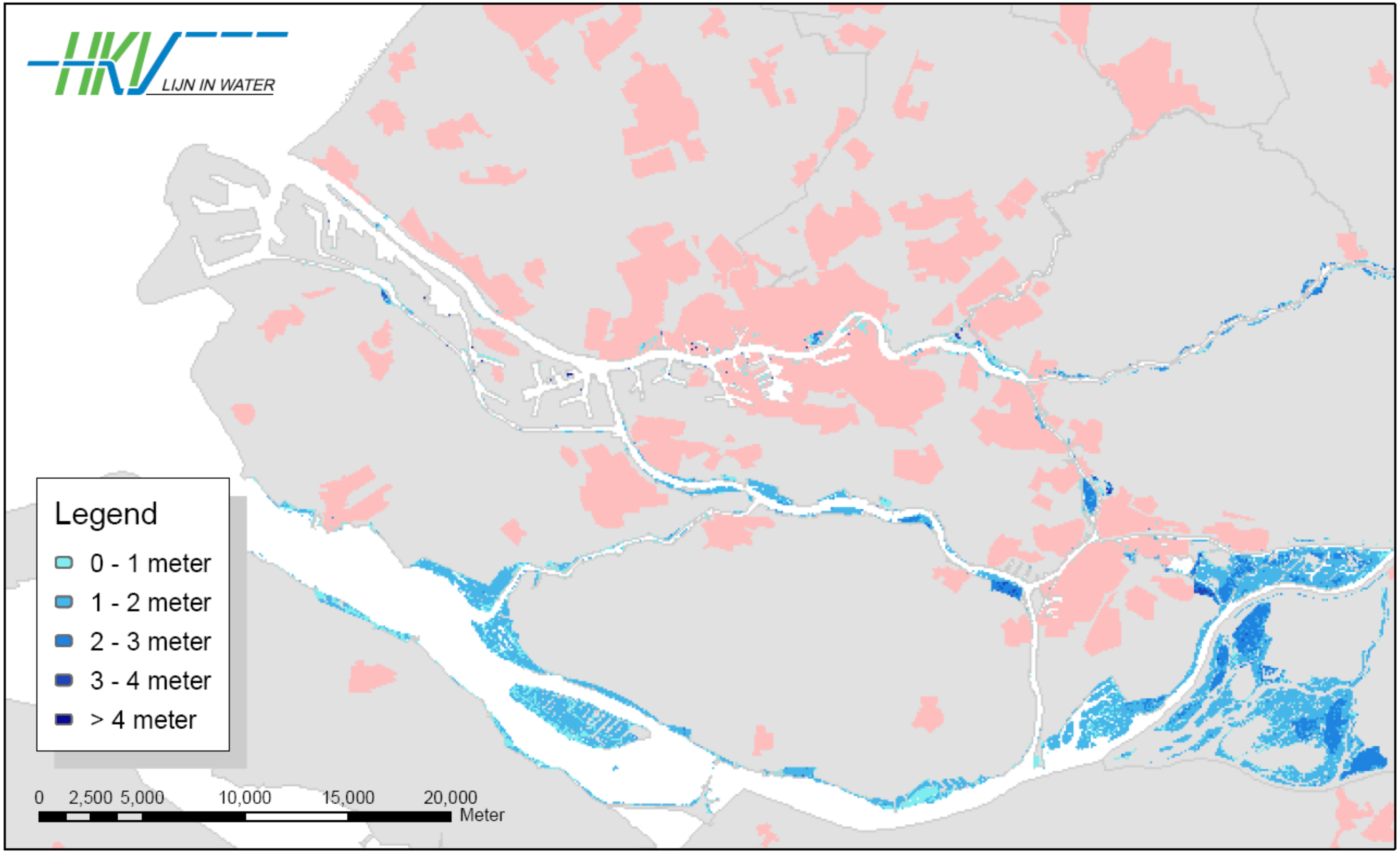
Flood depth 2010 - return period 10 years - reference



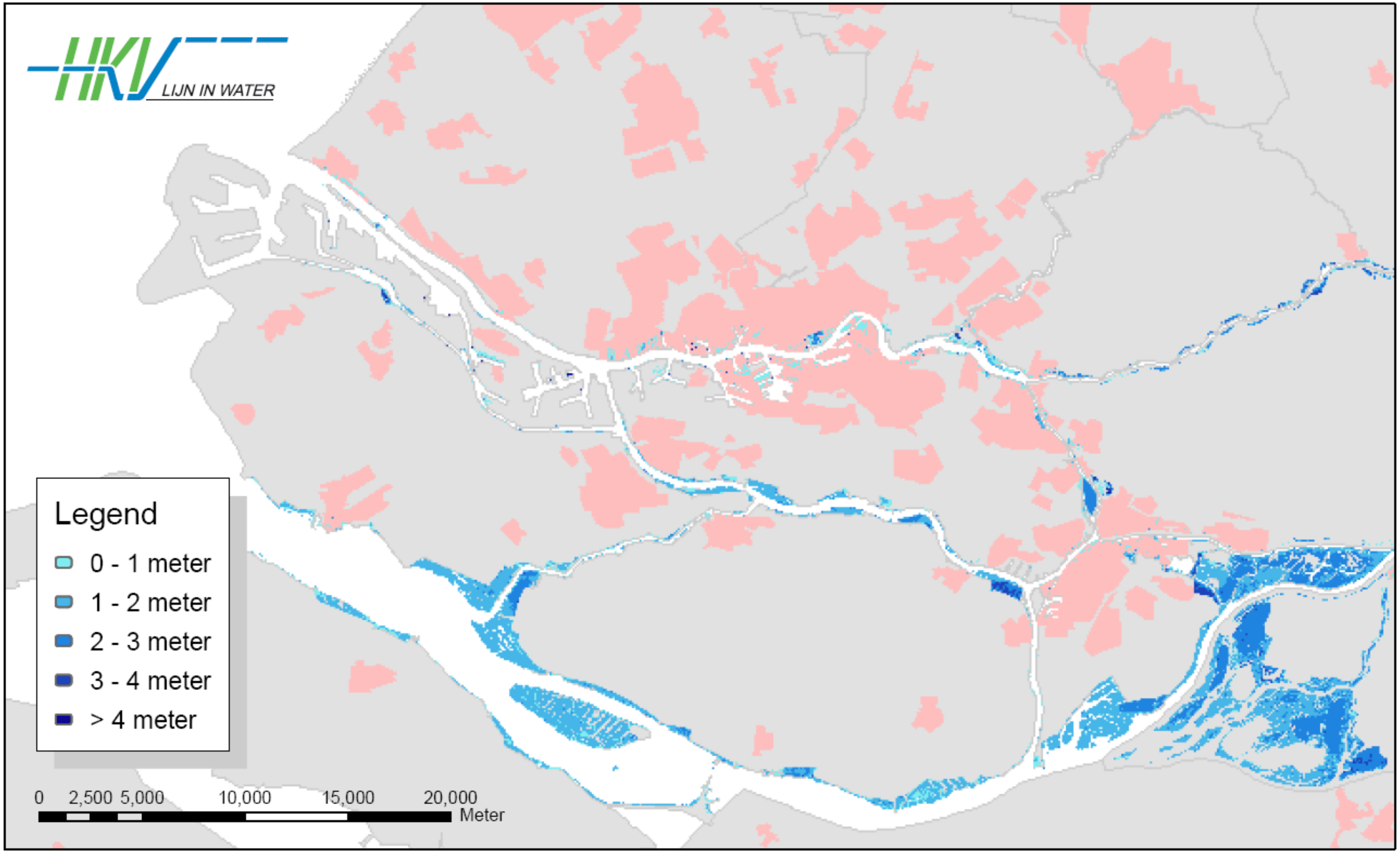
Flood depth 2010 - return period 50 years - reference



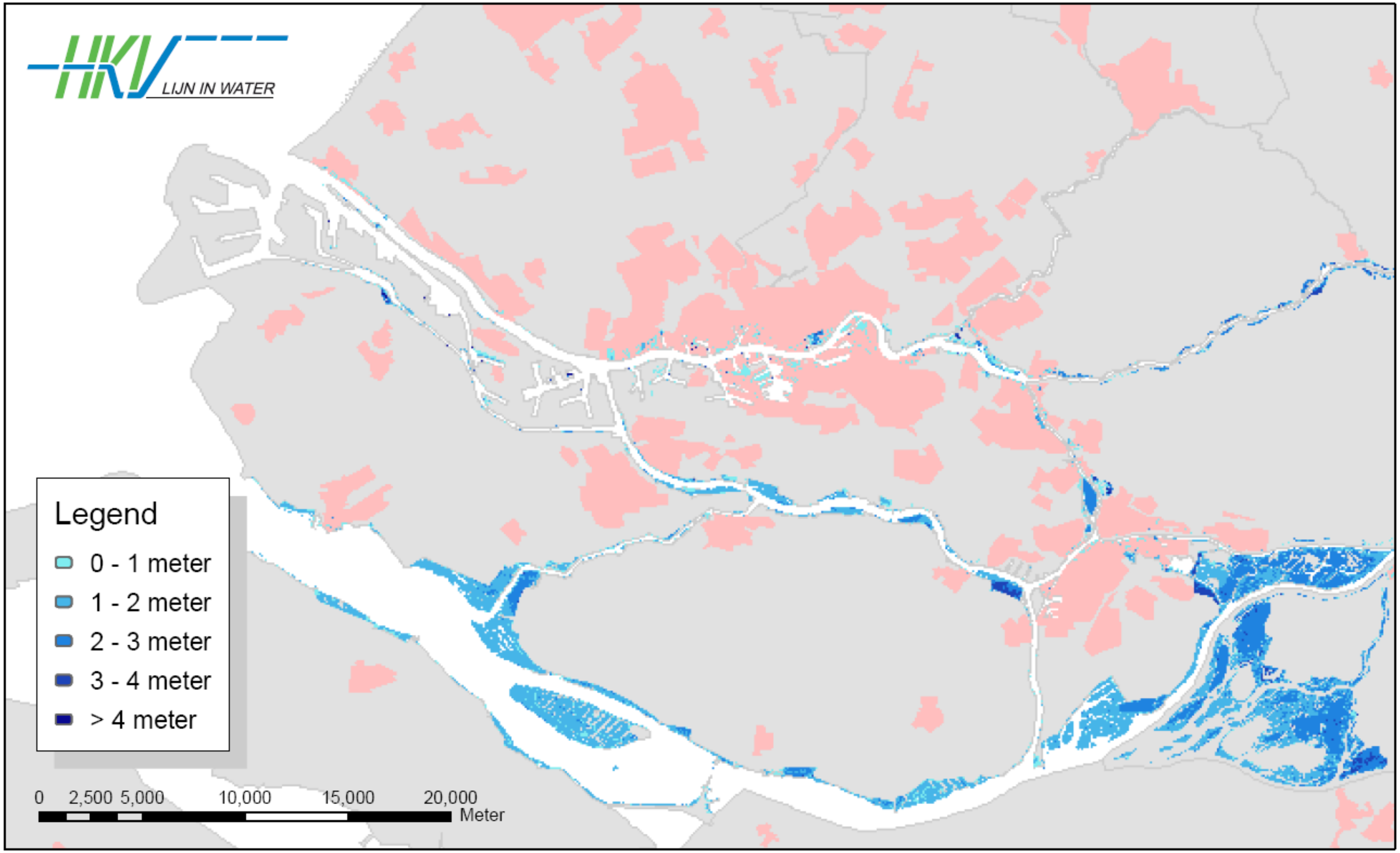
Flood depth 2010 - return period 100 years - reference



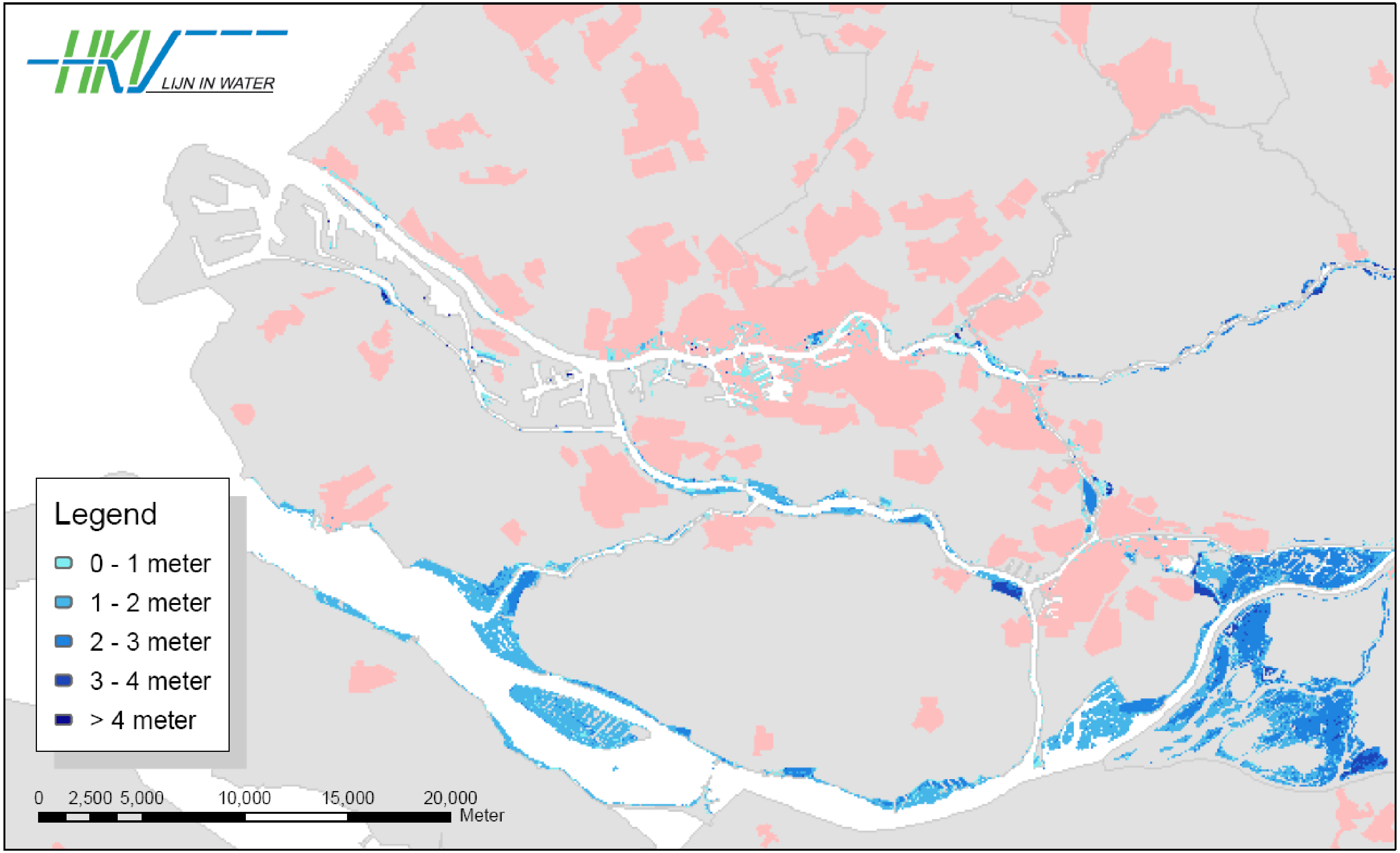
Flood depth 2010 - return period 1000 years - reference



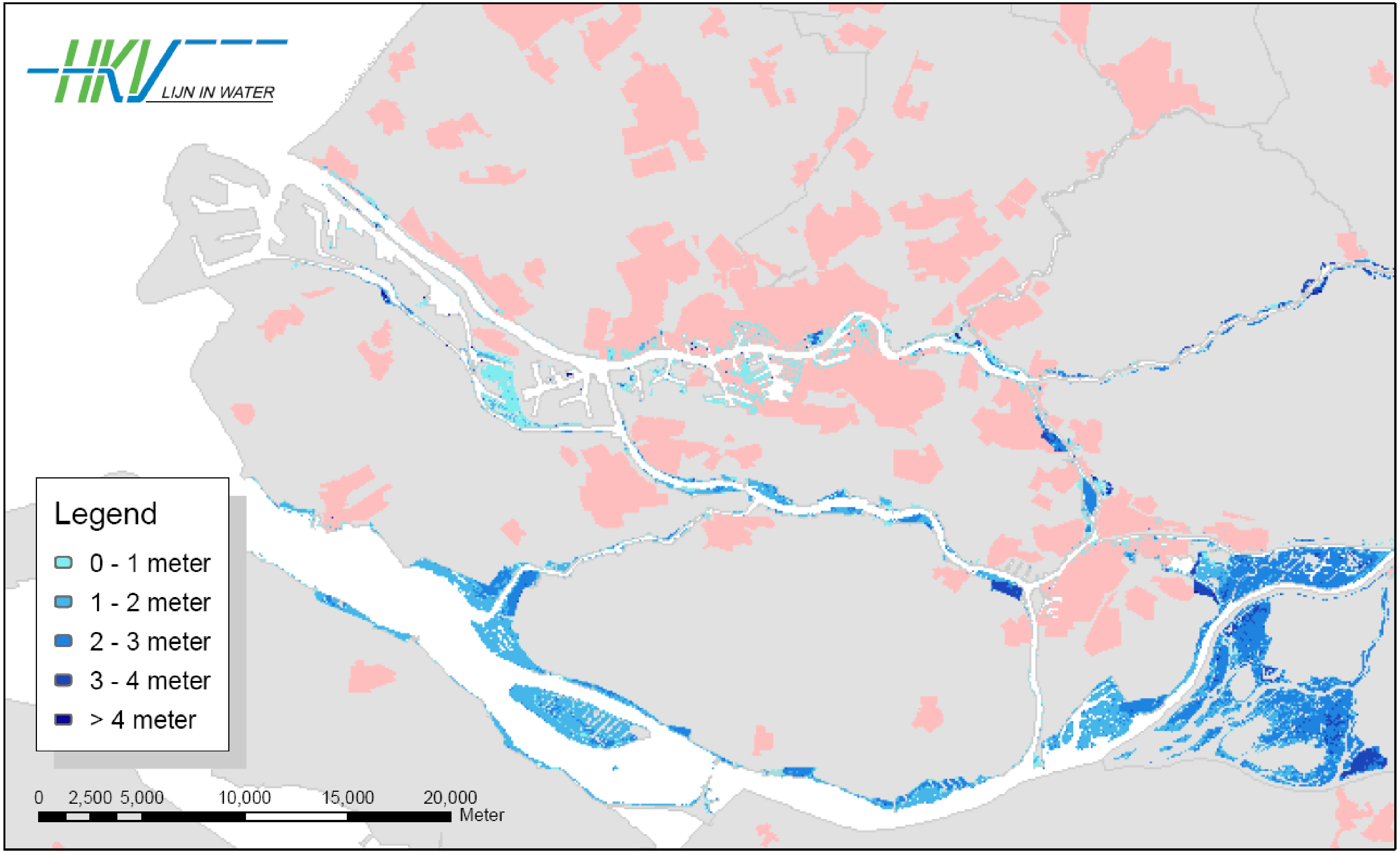
Flood depth 2010 - return period 2000 years - reference



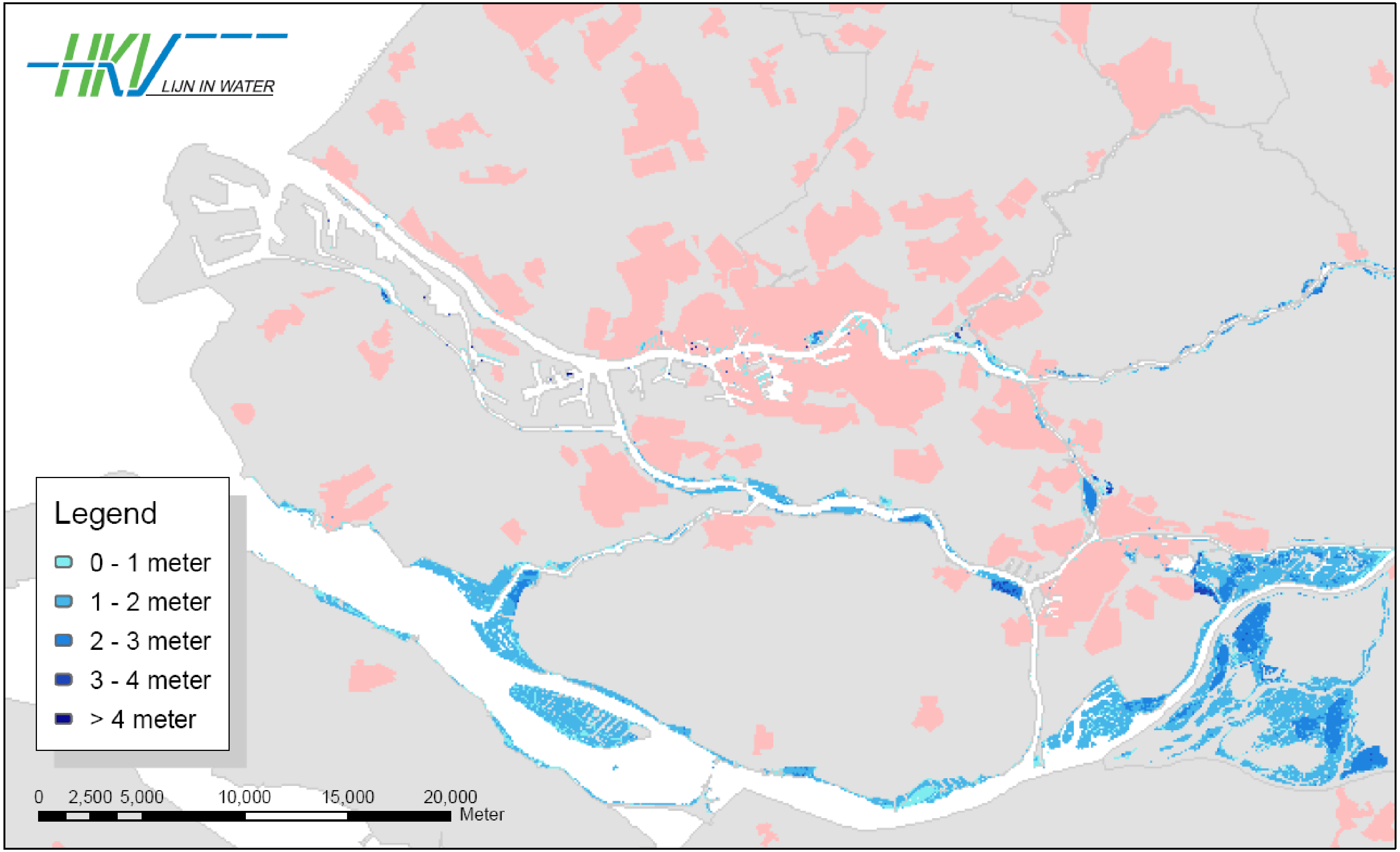
Flood depth 2010 - return period 4000 years - reference



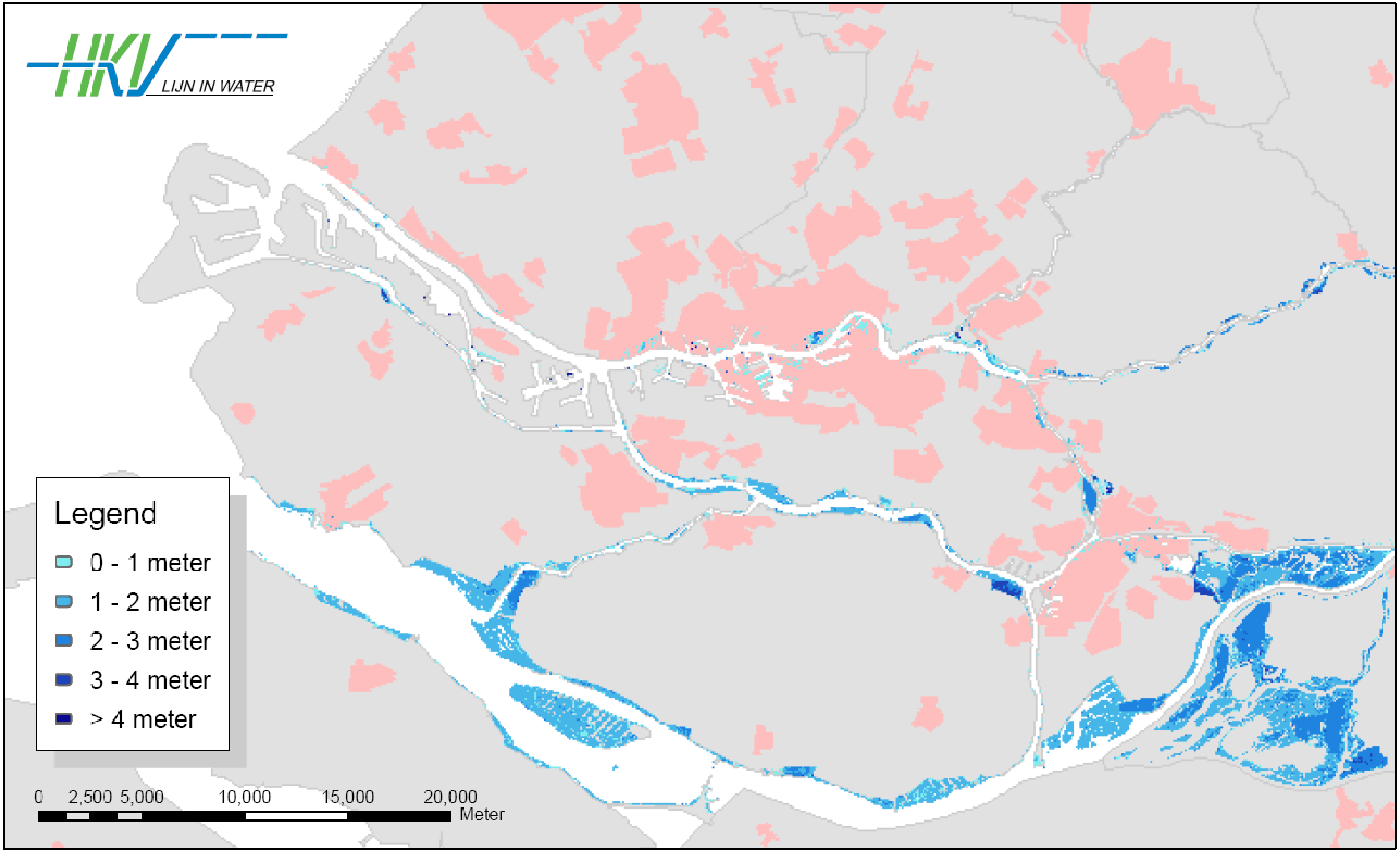
Flood depth 2010 - return period 10.000 years - reference



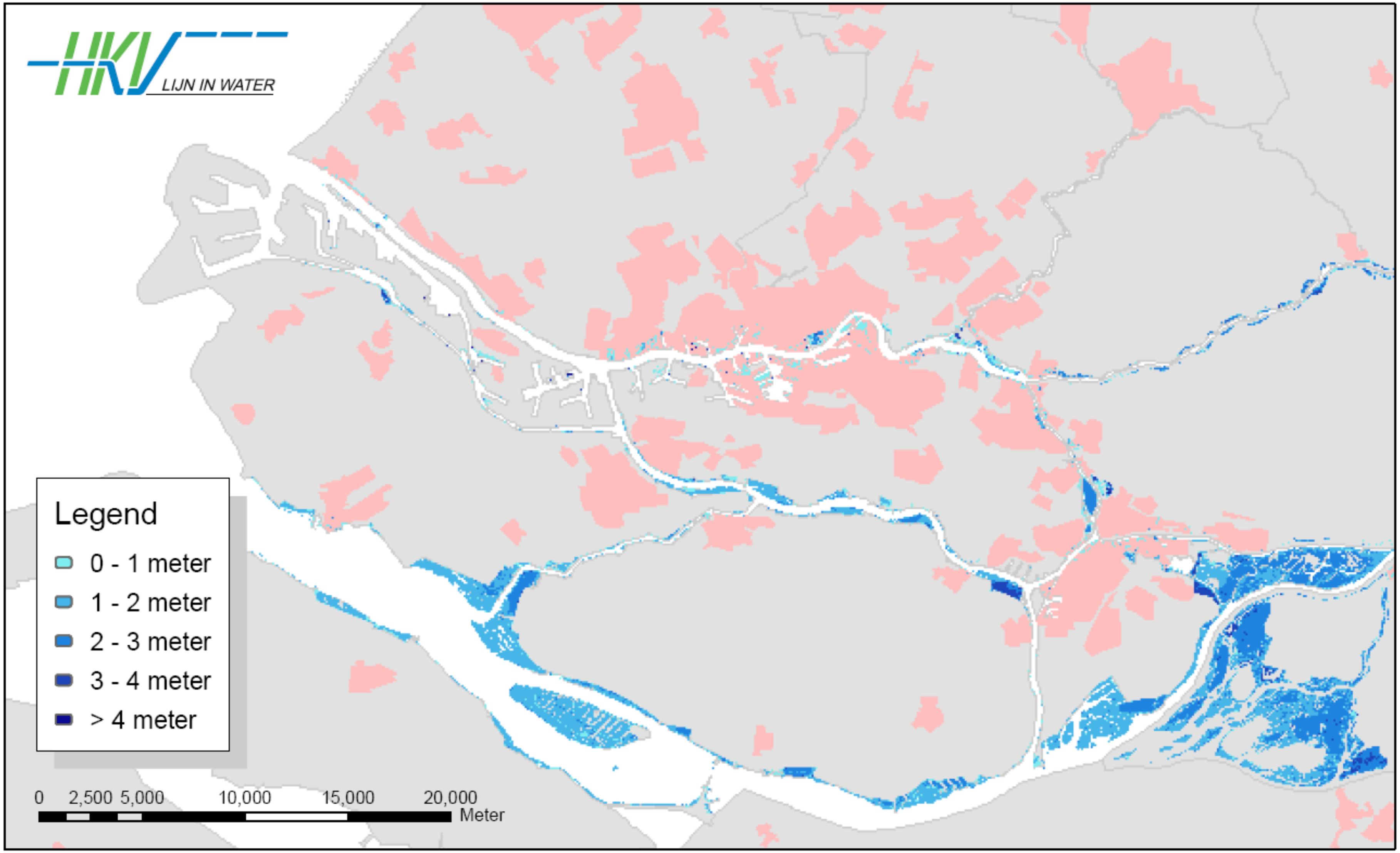
Flood depth 2050 - return period 10 years - reference



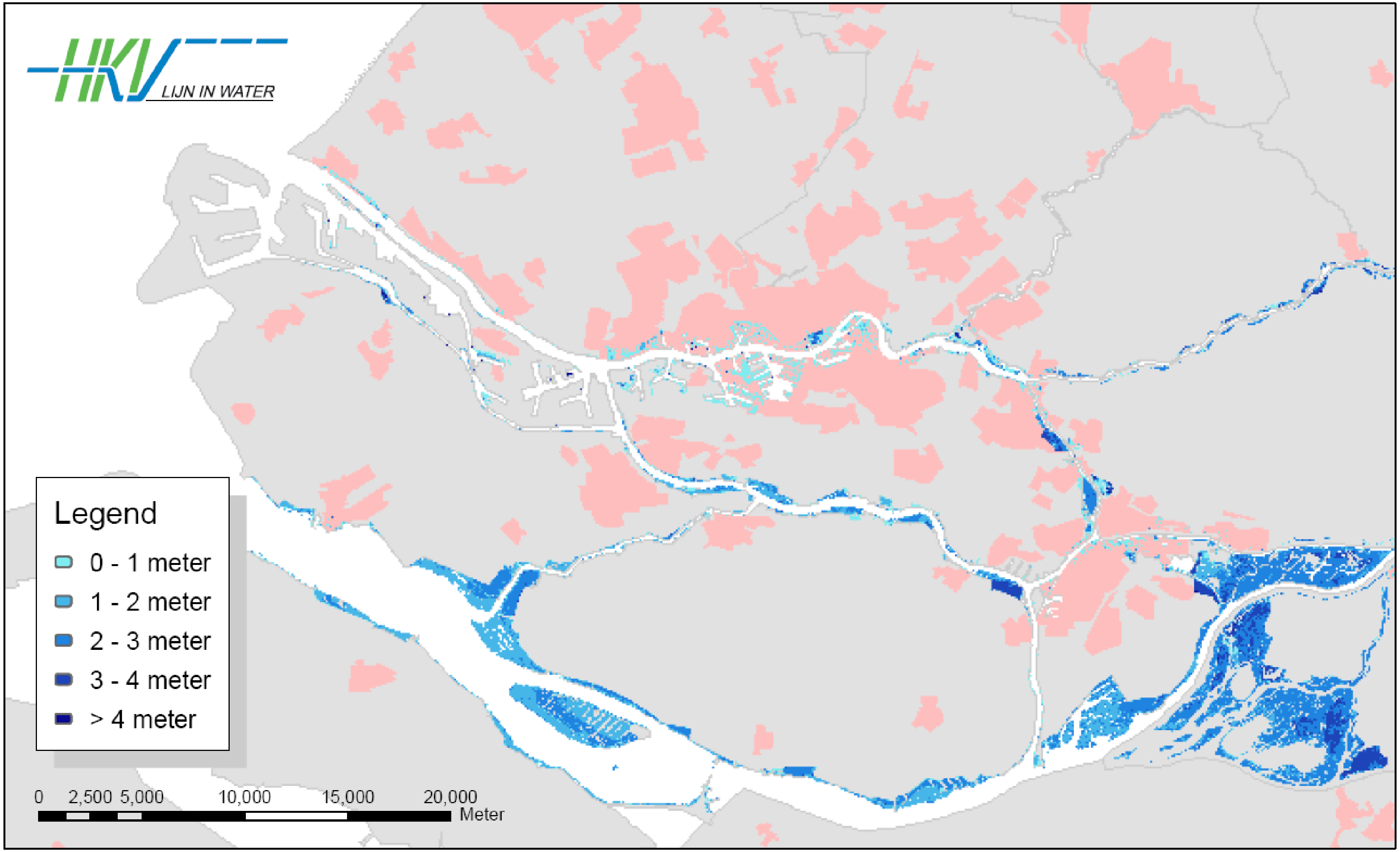
Flood depth 2050 - return period 50 years - reference



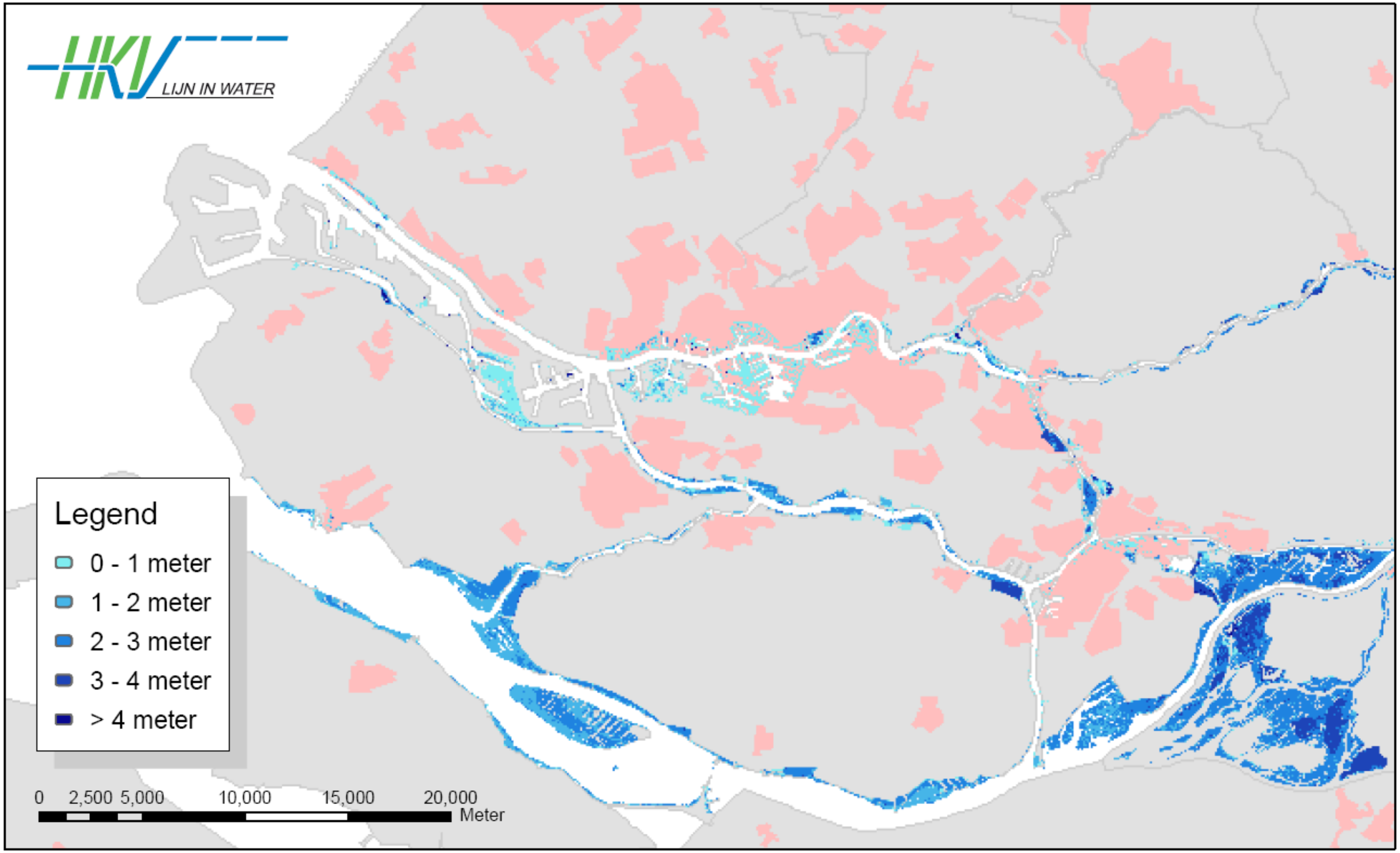
Flood depth 2050 - return period 100 years - reference



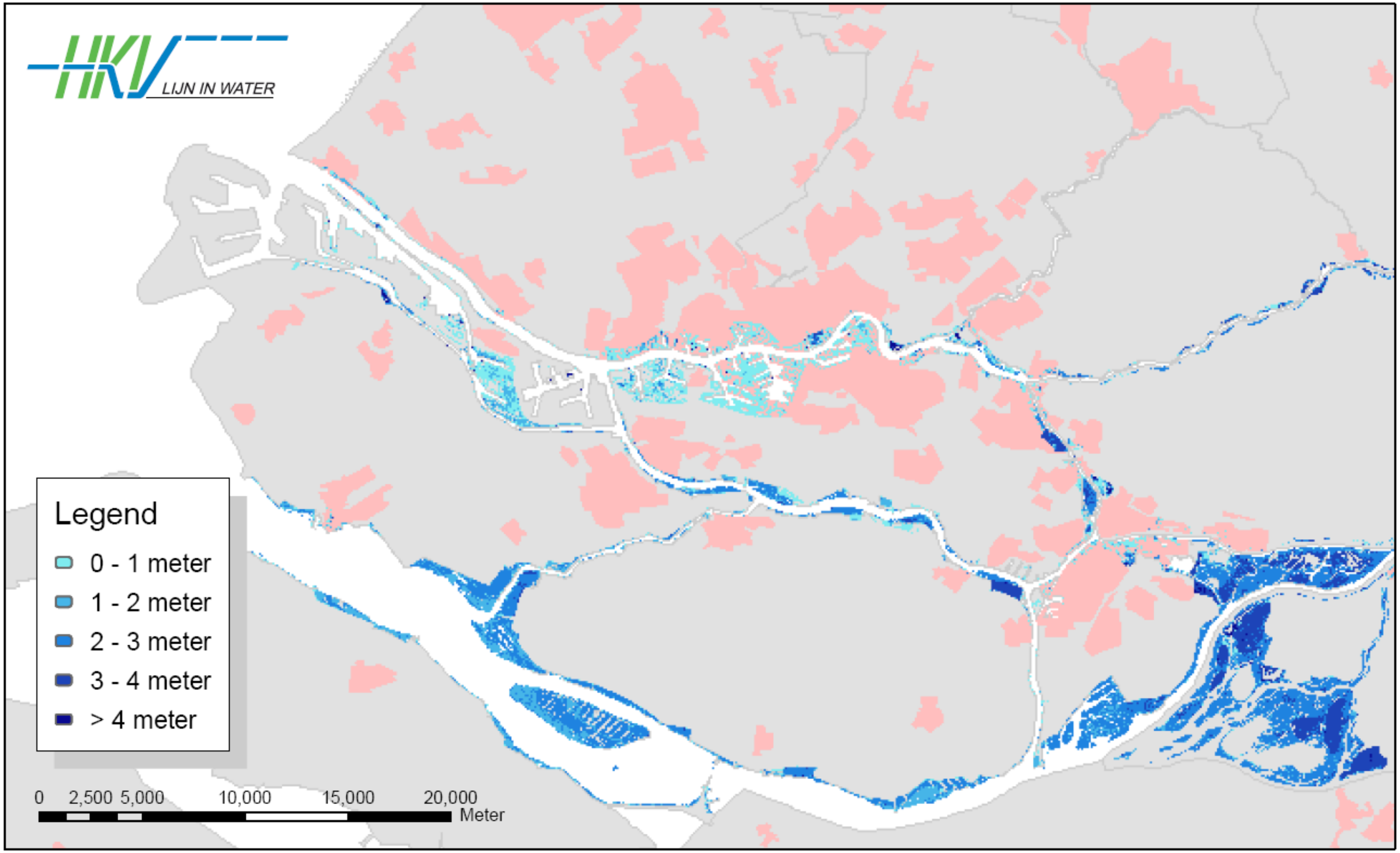
Flood depth 2050 - return period 1000 years - reference



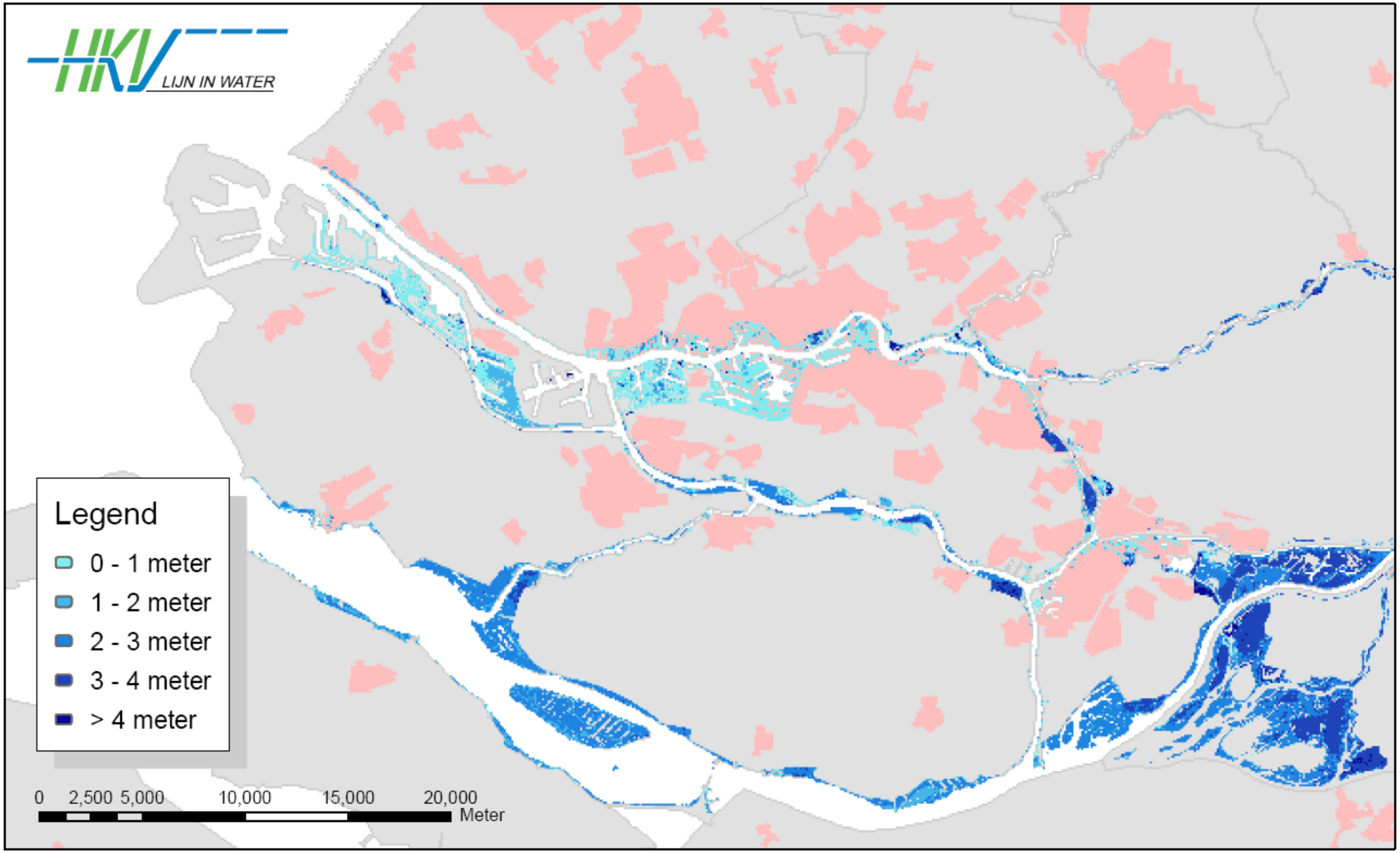
Flood depth 2050 - return period 2000 years - reference



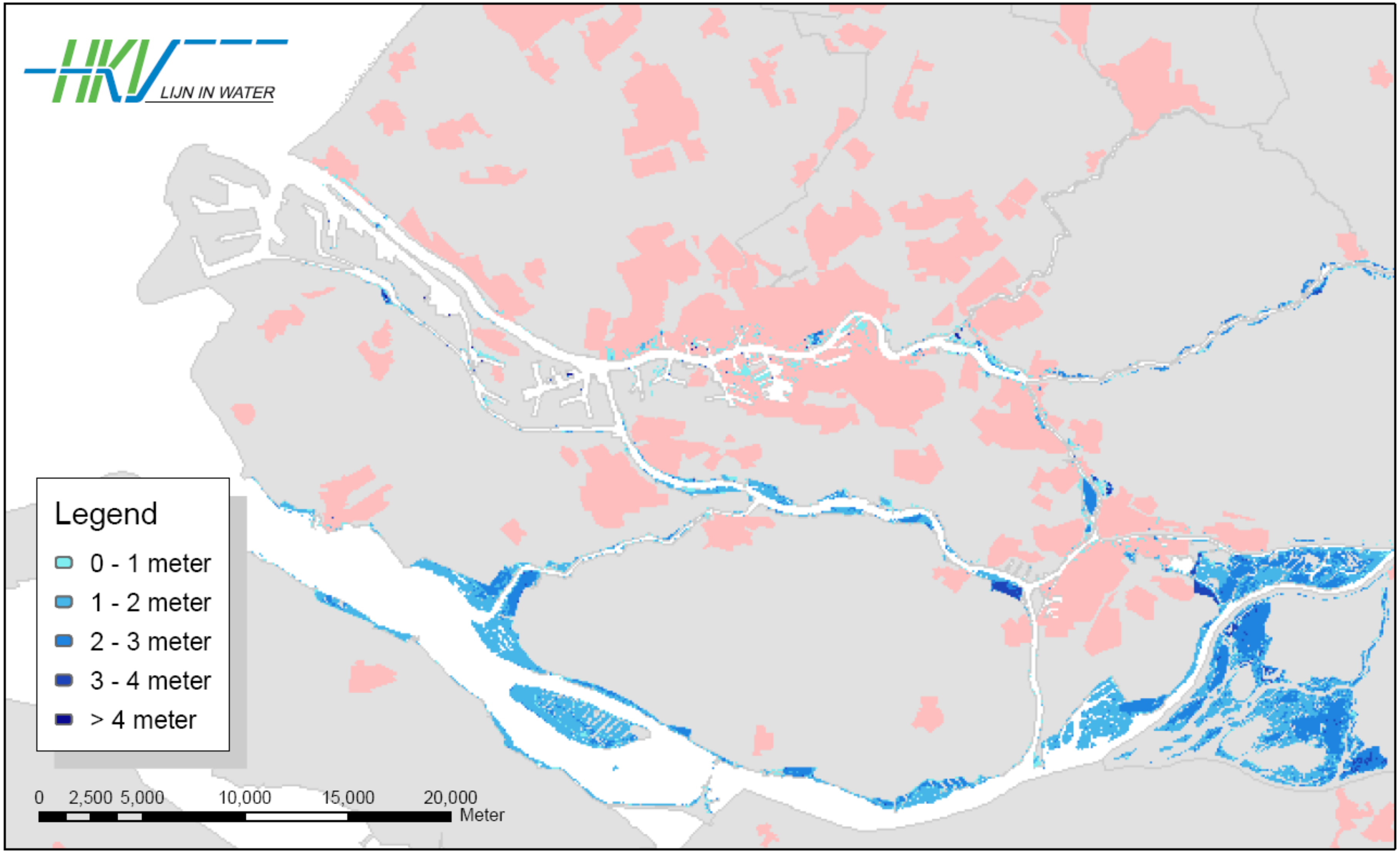
Flood depth 2050 - return period 4000 years - reference



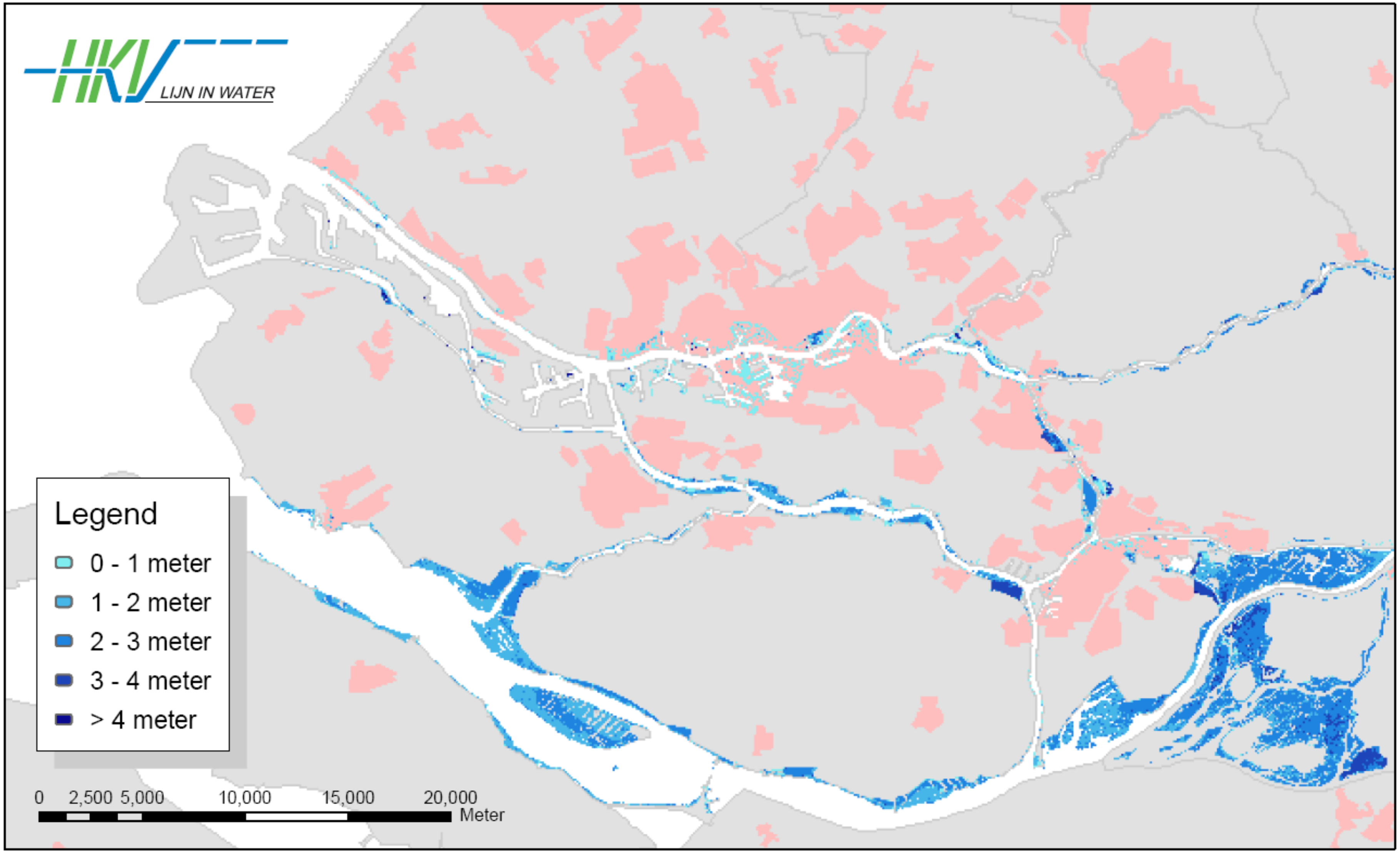
Flood depth 2050 - return period 10.000 years - reference



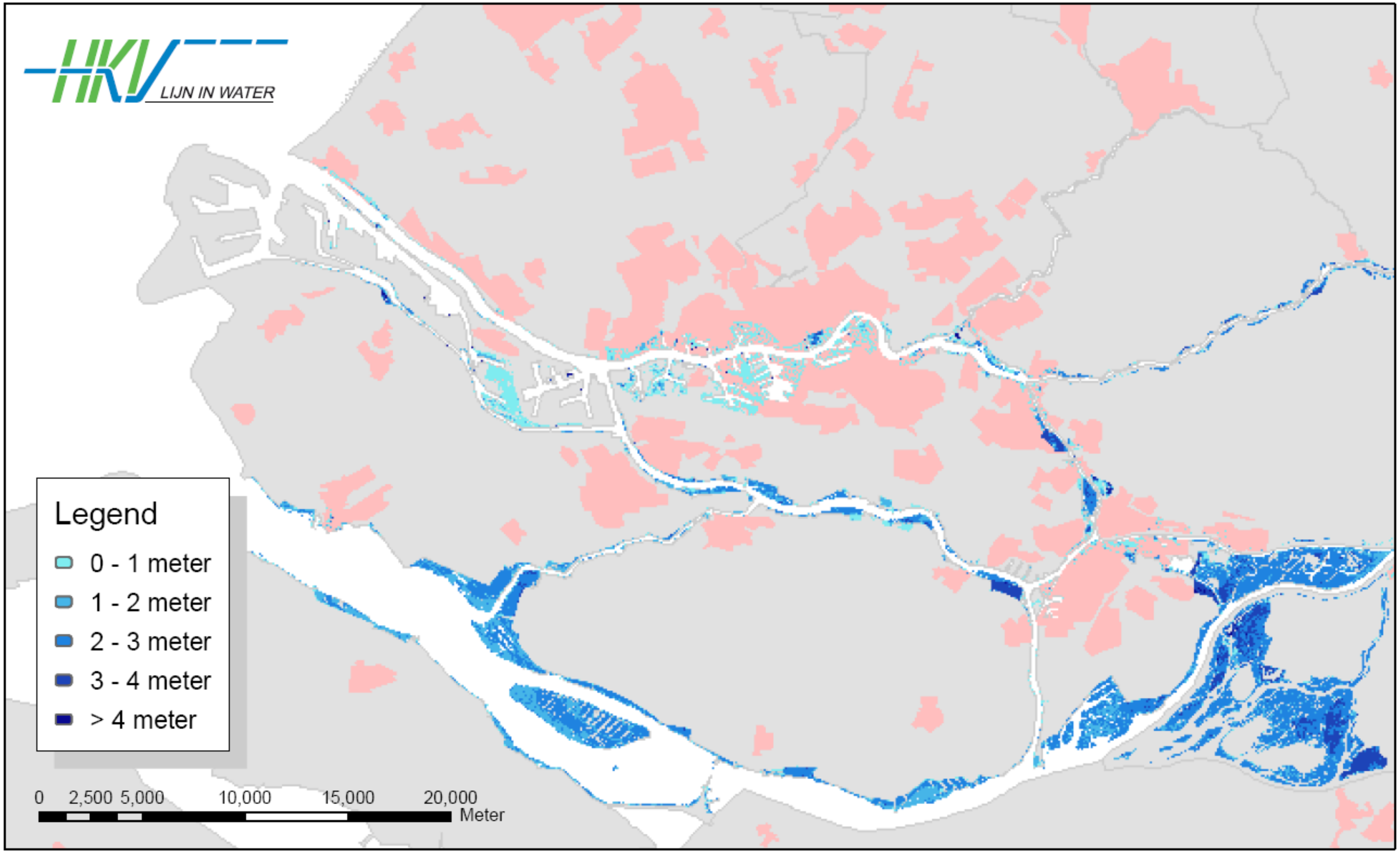
Flood depth 2100 - return period 10 years - reference



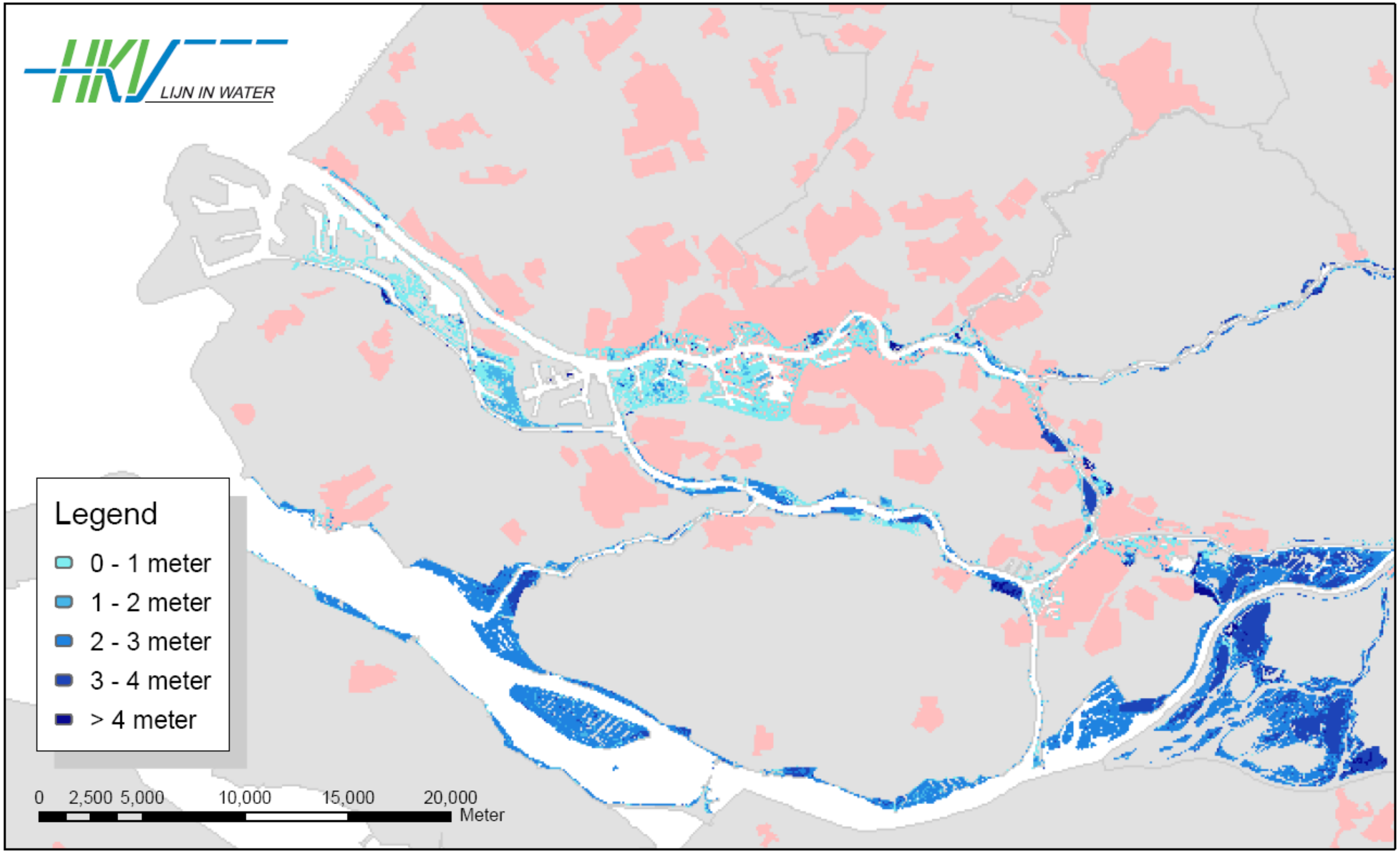
Flood depth 2100 - return period 50 years - reference



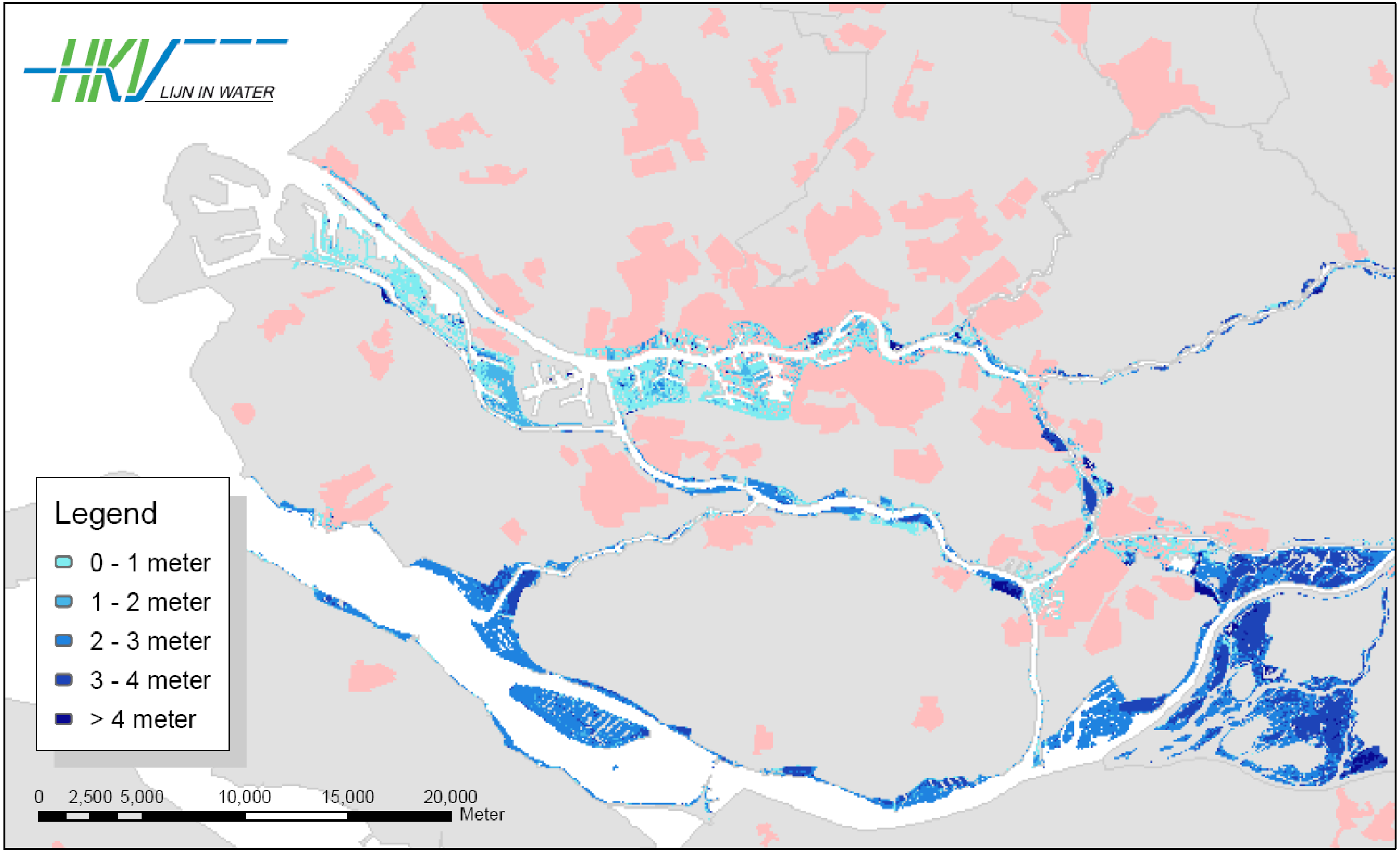
Flood depth 2100 - return period 100 years - reference



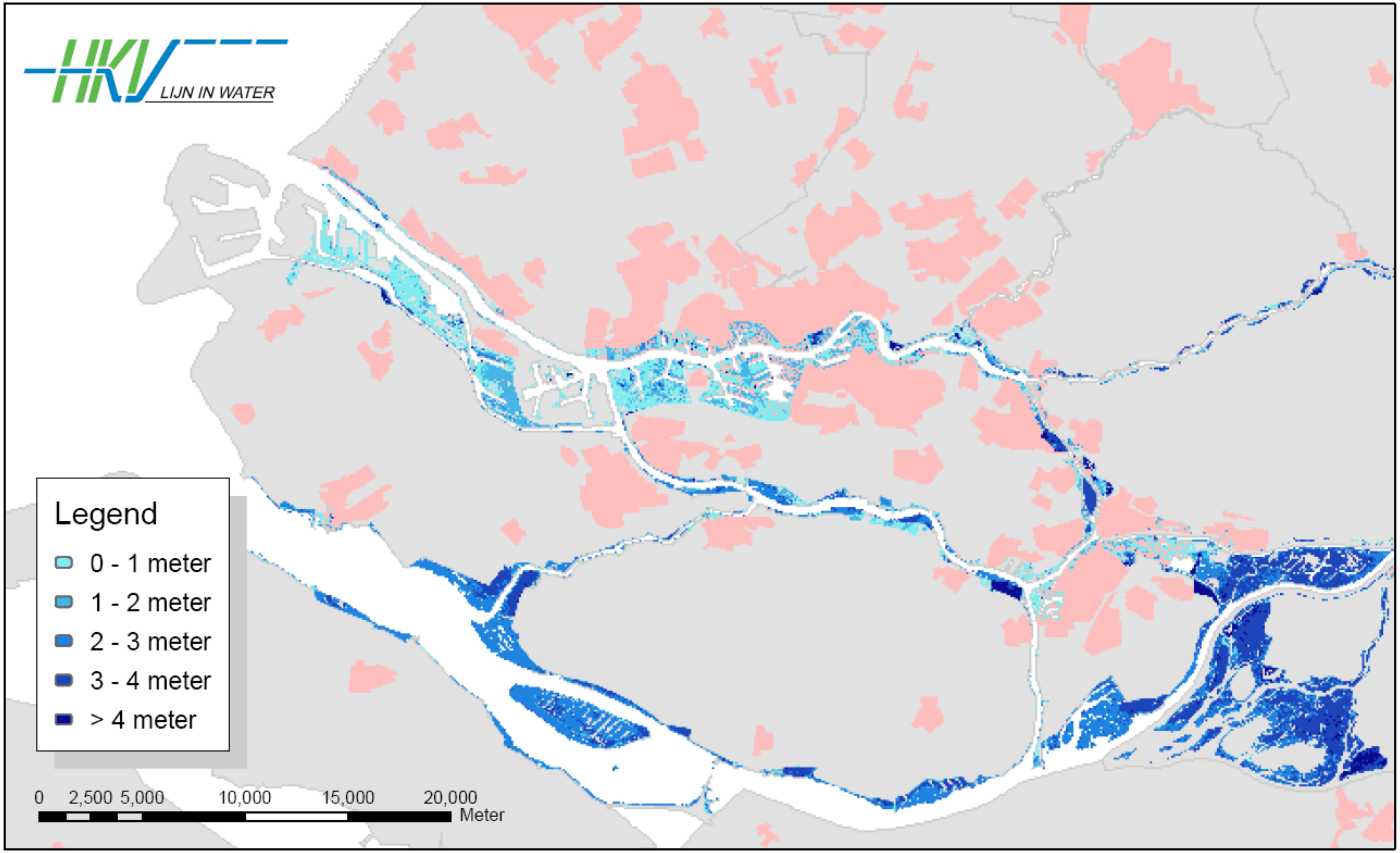
Flood depth 2100 - return period 1000 years - reference



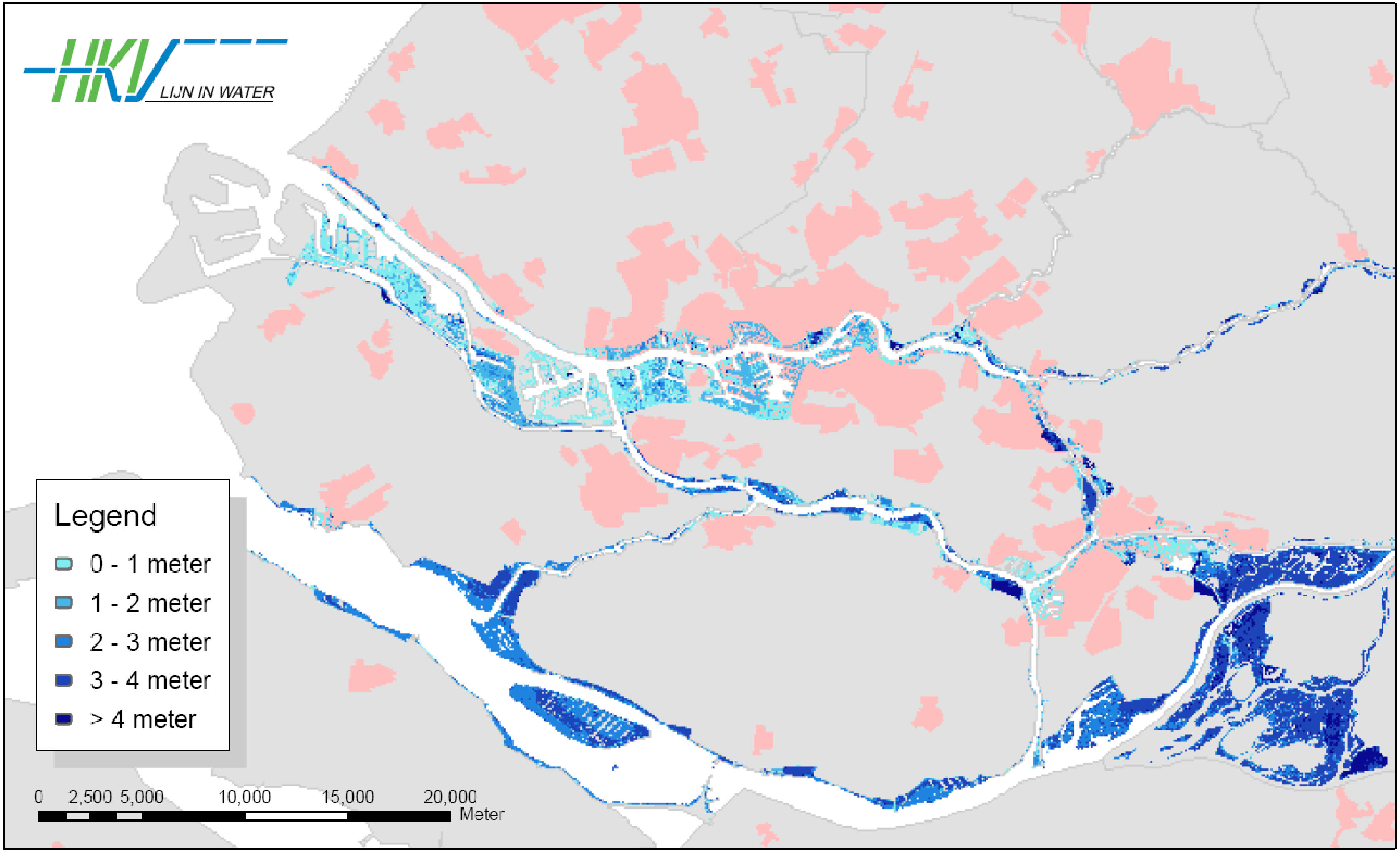
Flood depth 2100 - return period 2000 years - reference



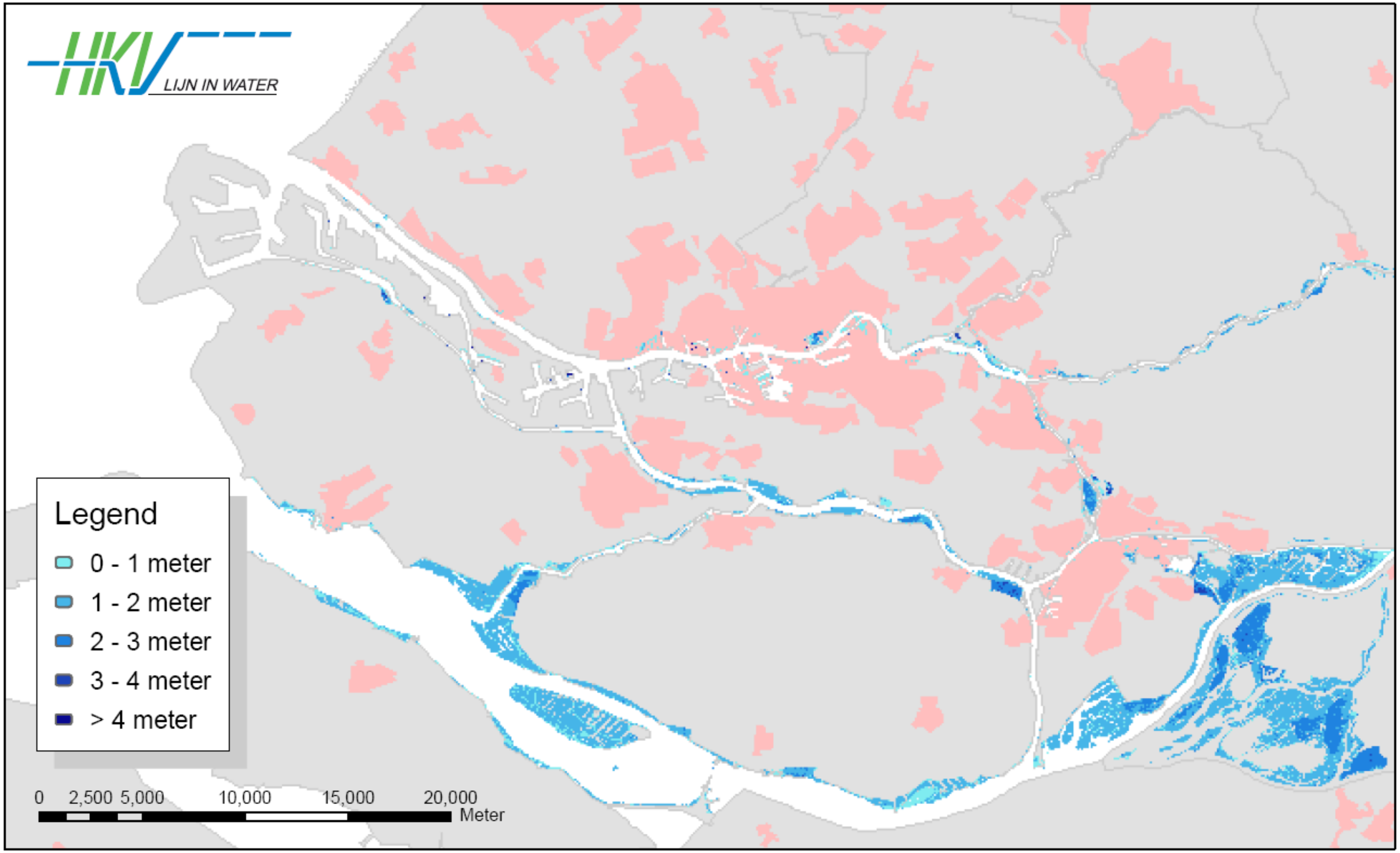
Flood depth 2100 - return period 4000 years - reference



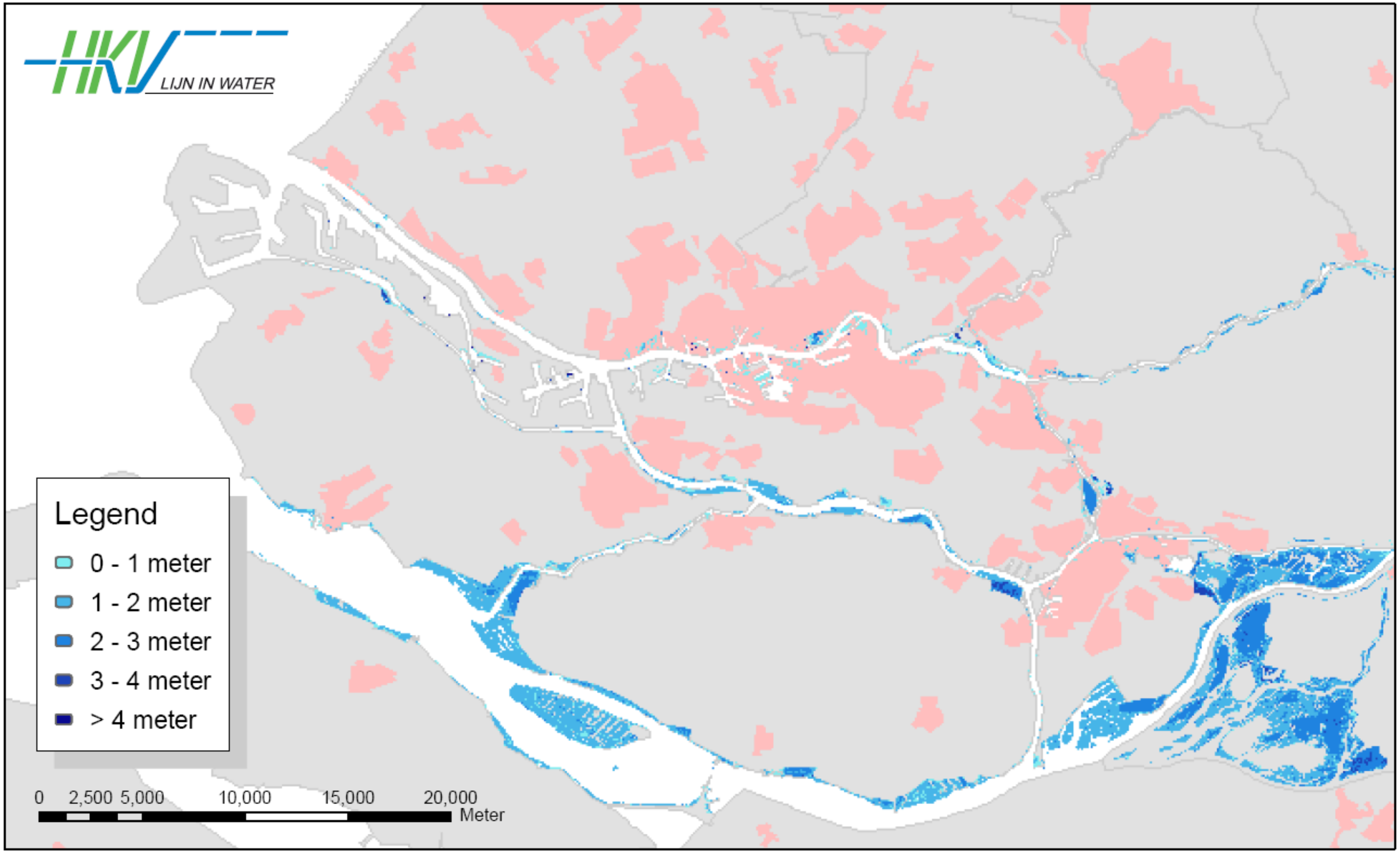
Flood depth 2100 - return period 10.000 years - reference



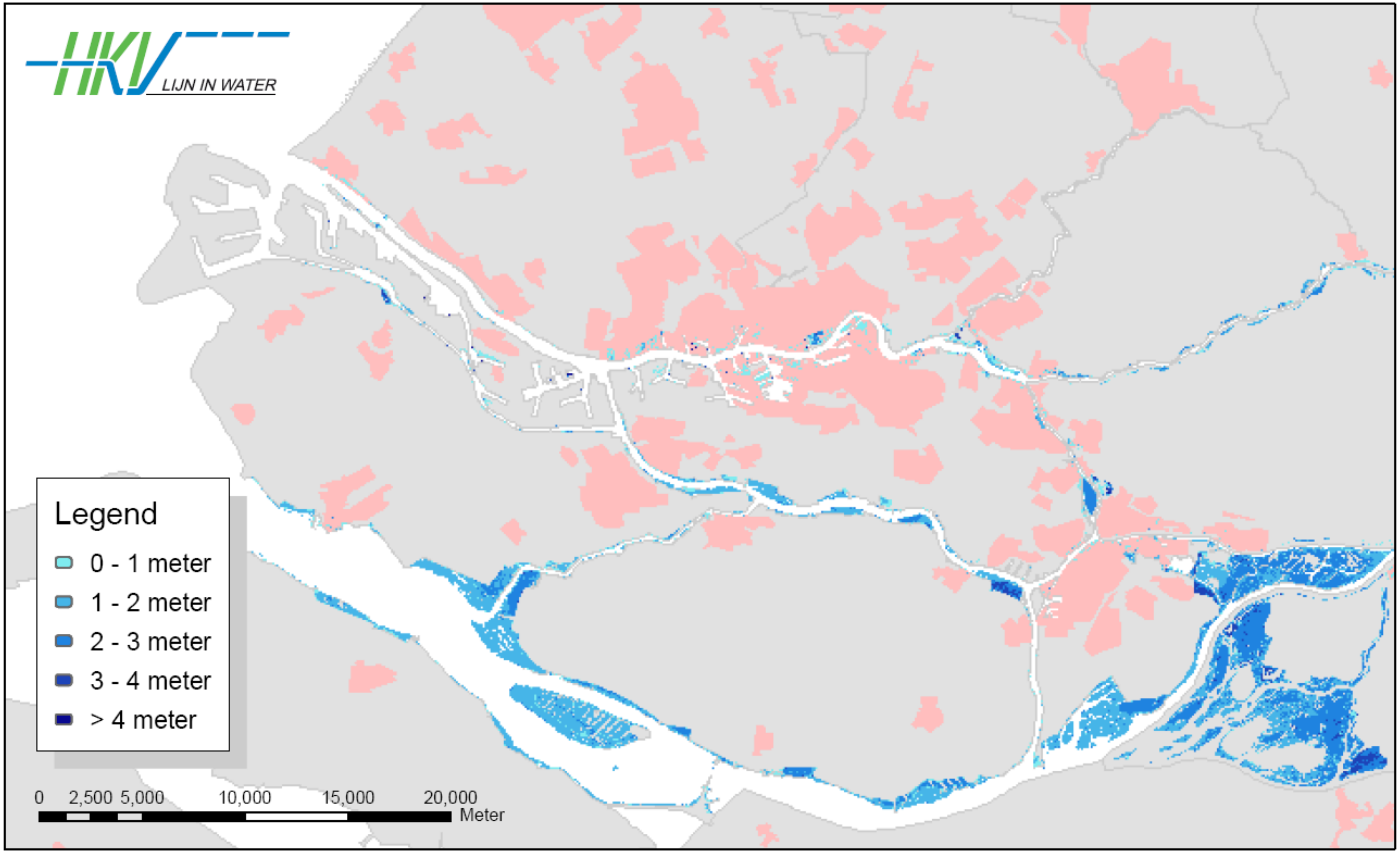
Flood depth 2050 - return period 10 years – variant closable but open



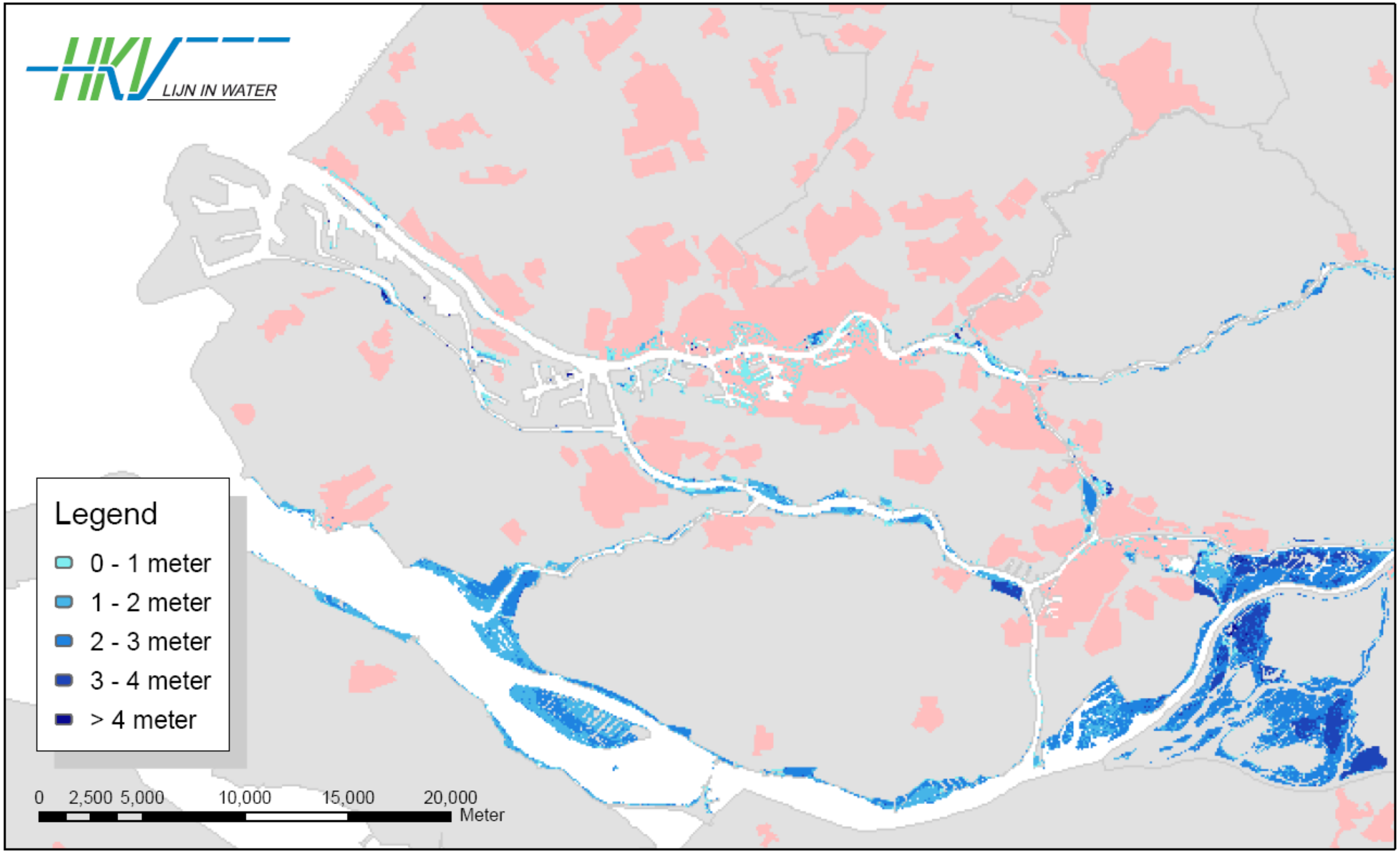
Flood depth 2050 - return period 50 years – variant closable but open



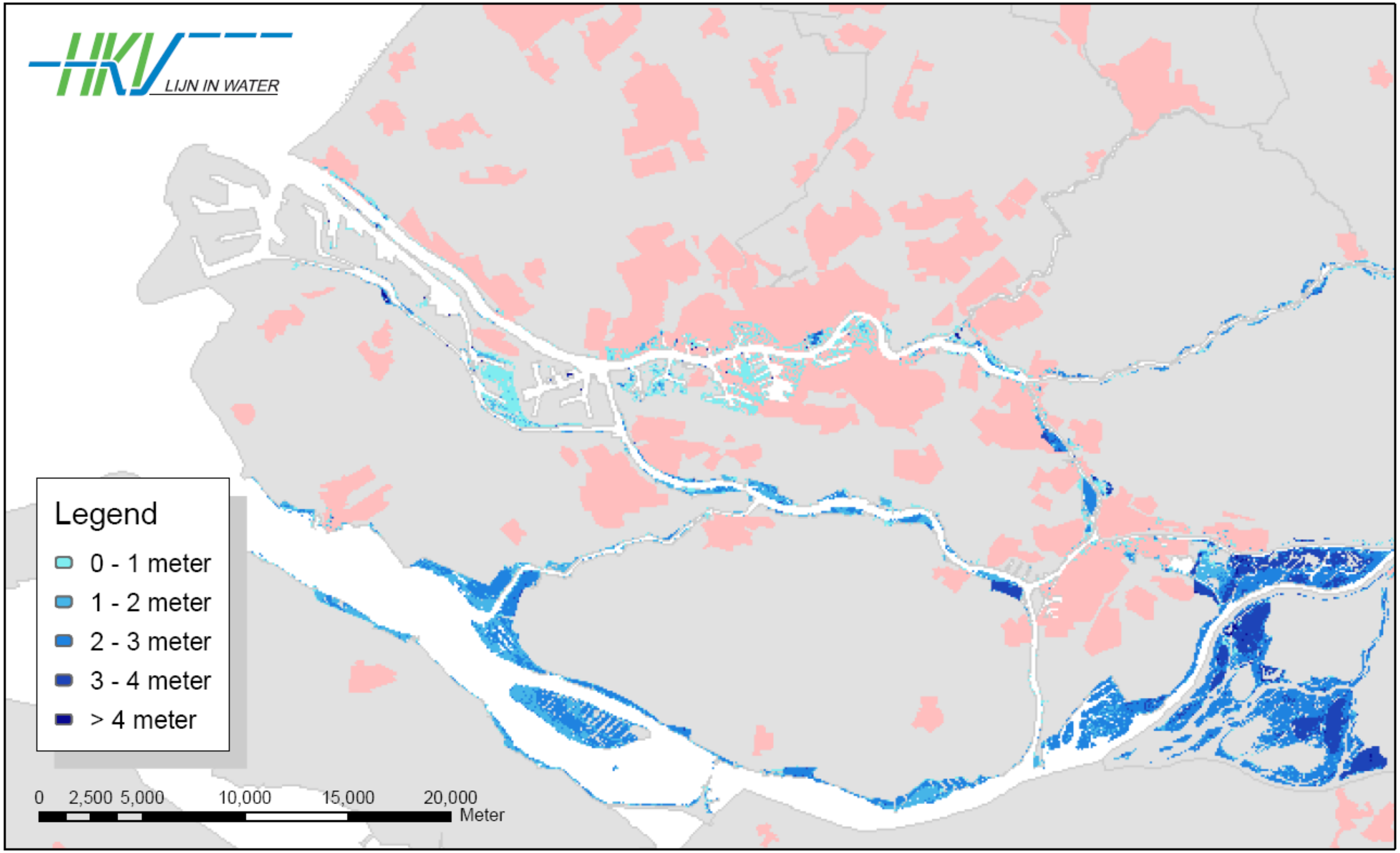
Flood depth 2050 - return period 100 years – variant closable but open



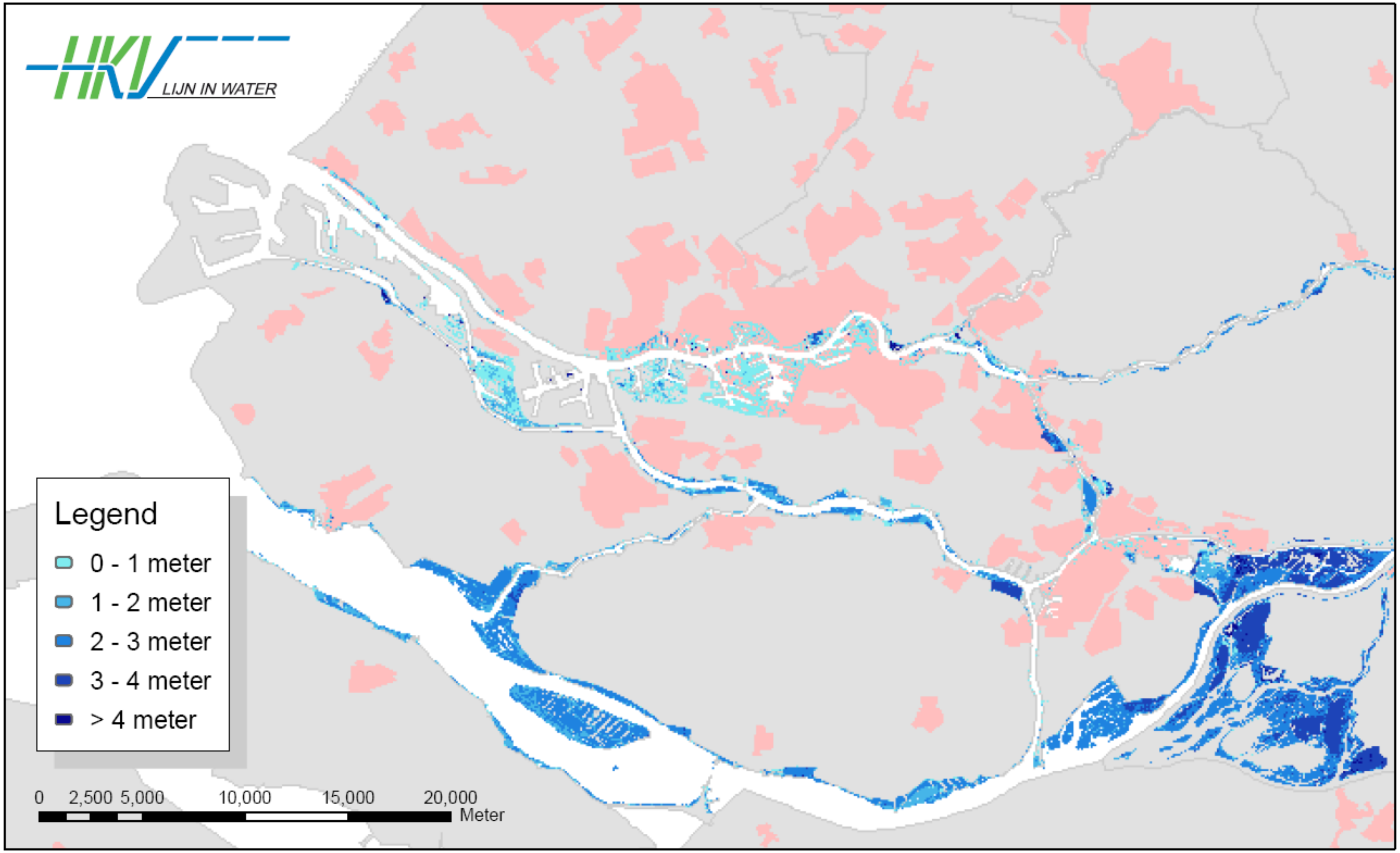
Flood depth 2050 - return period 1000 years – variant closable but open



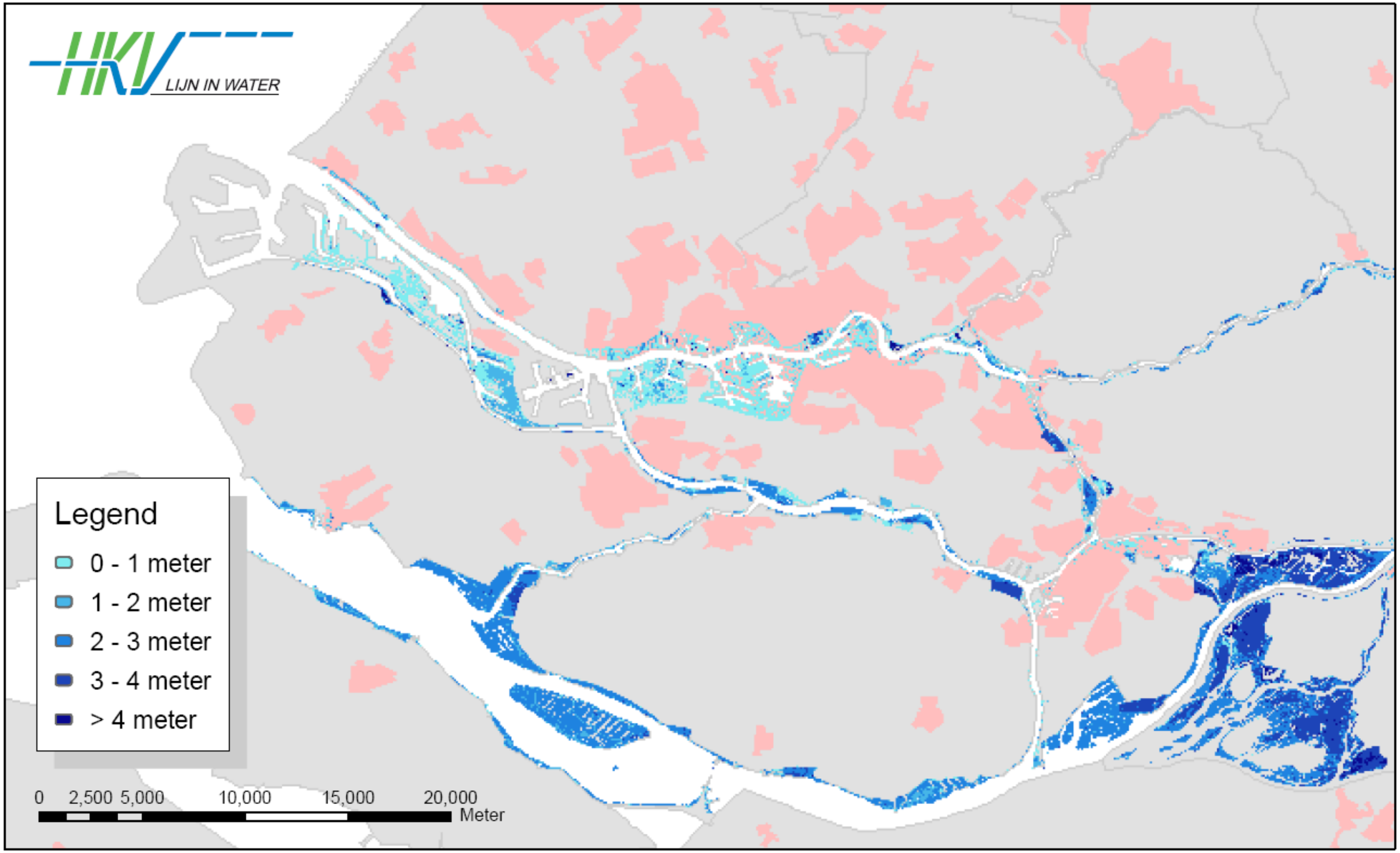
Flood depth 2050 - return period 2000 years – variant closable but open



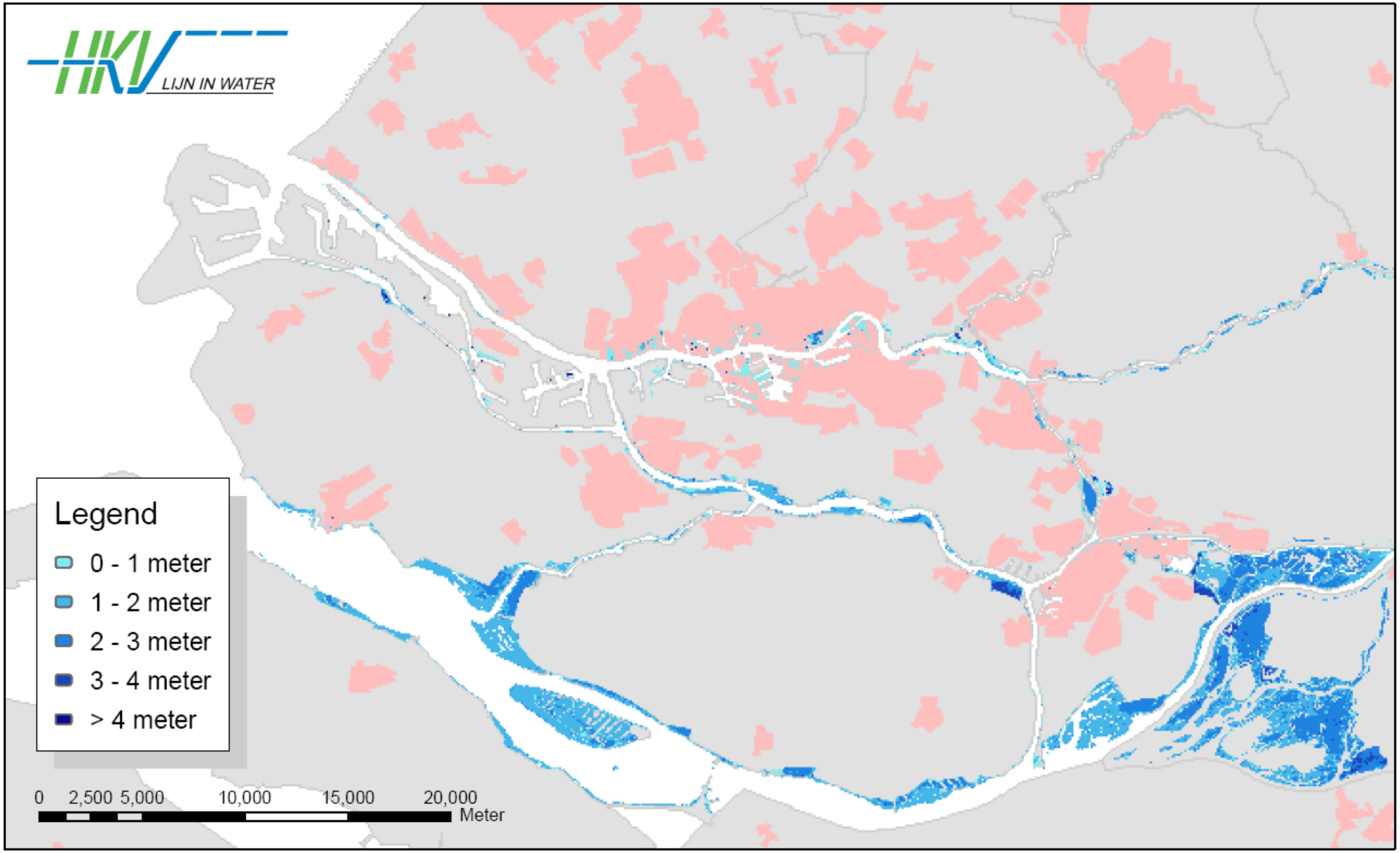
Flood depth 2050 - return period 4000 years – variant closable but open



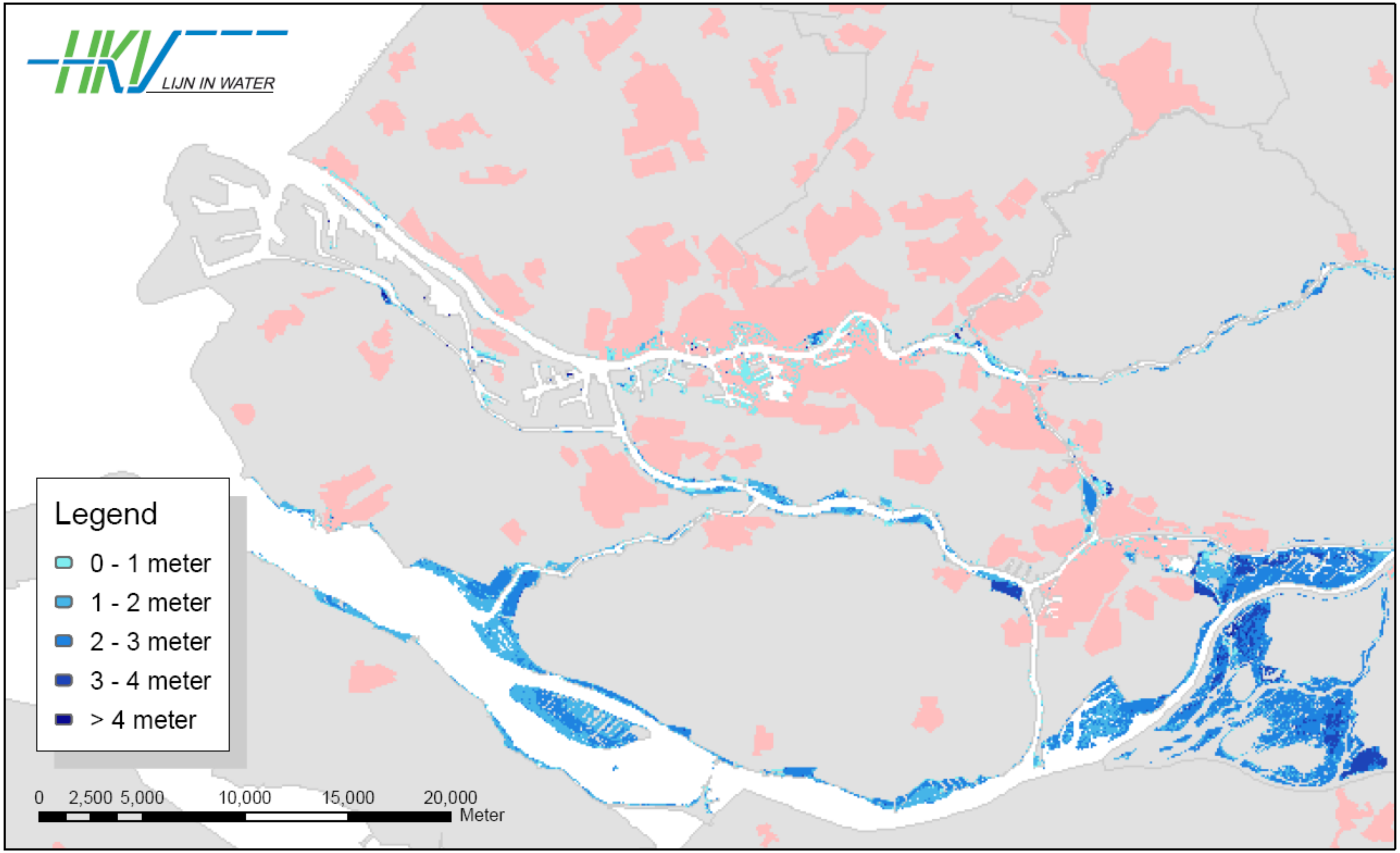
Flood depth 2050 - return period 10.000 years – variant closable but open



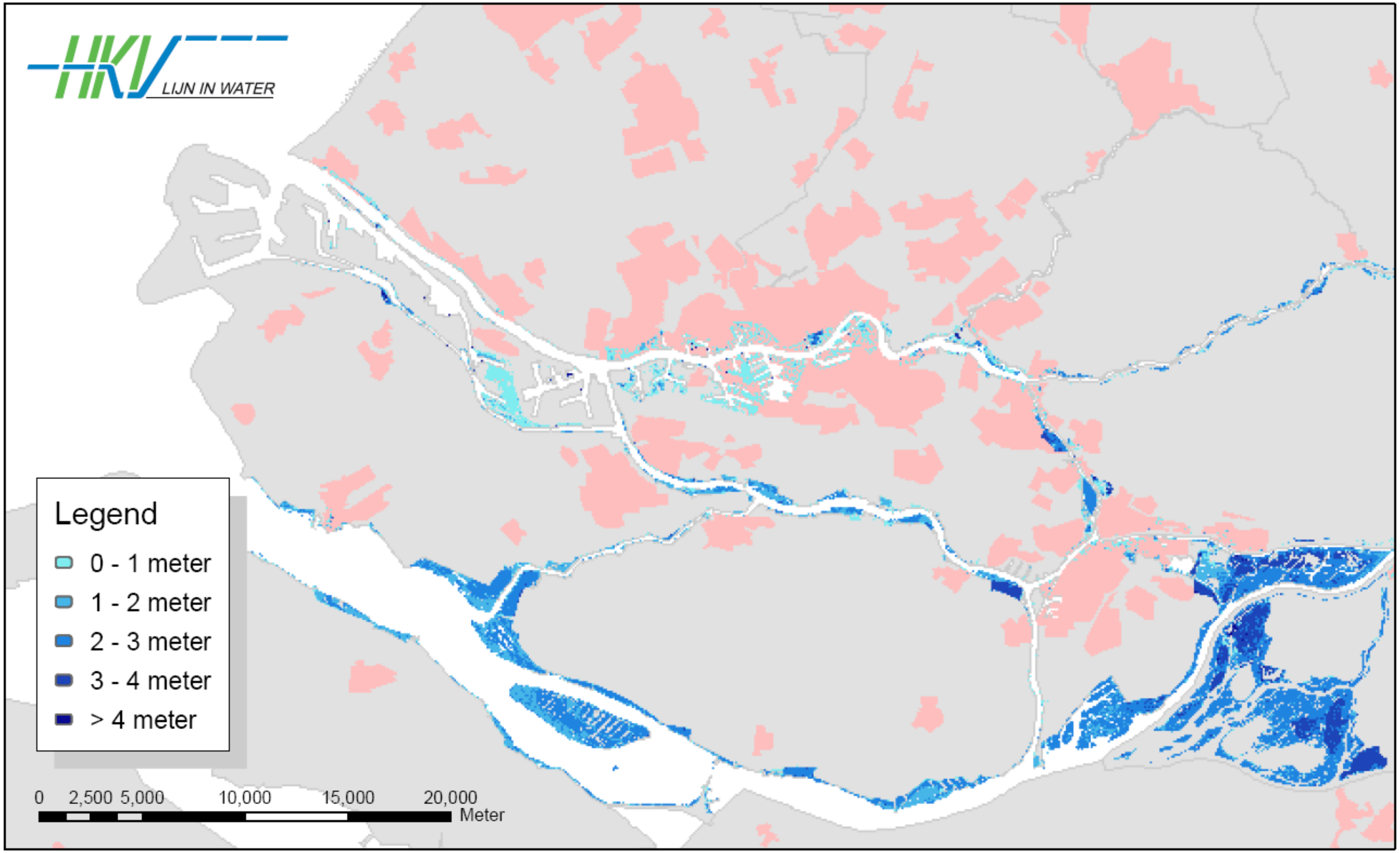
Flood depth 2100 - return period 10 years – variant closable but open



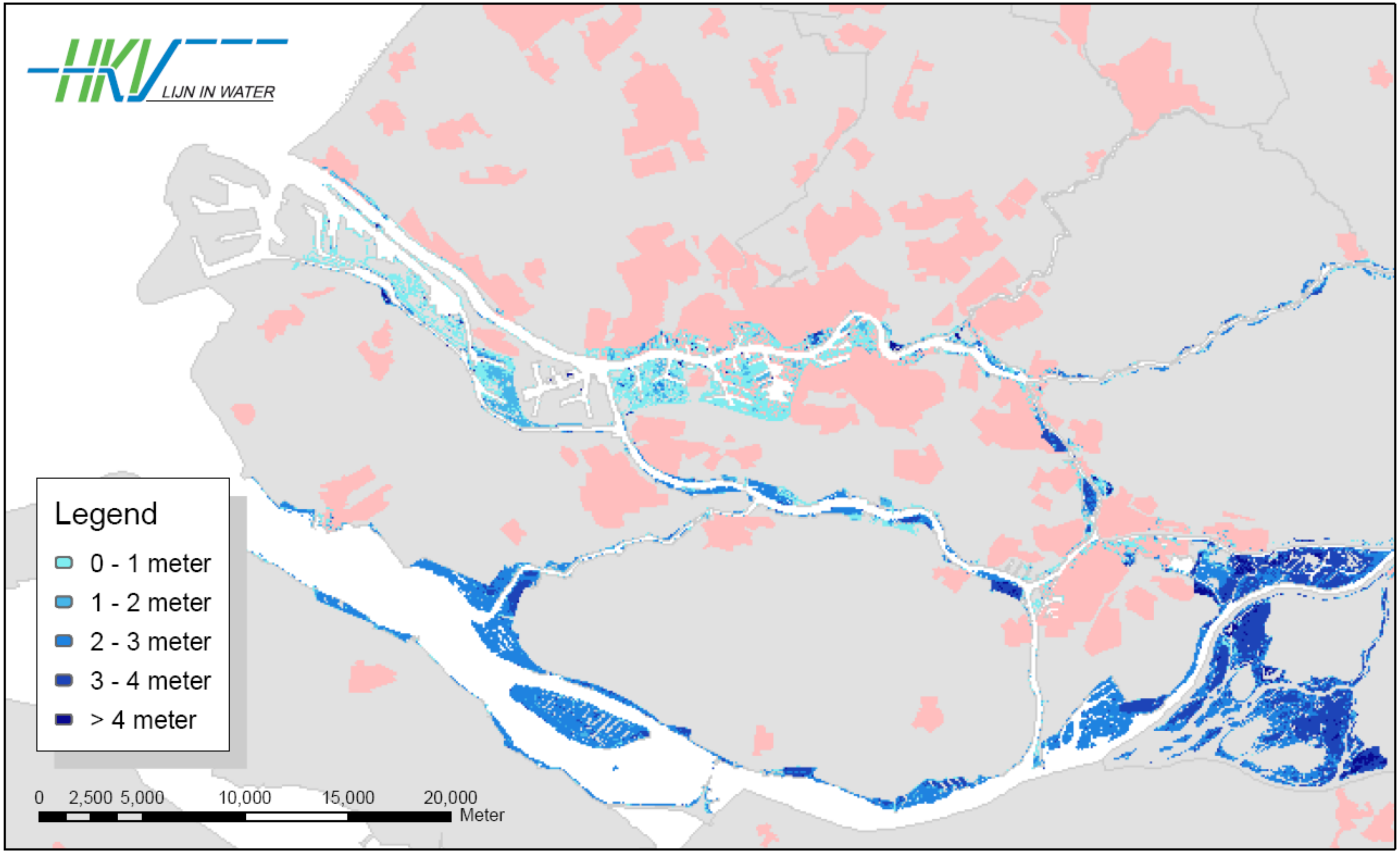
Flood depth 2100 - return period 50 years – variant closable but open



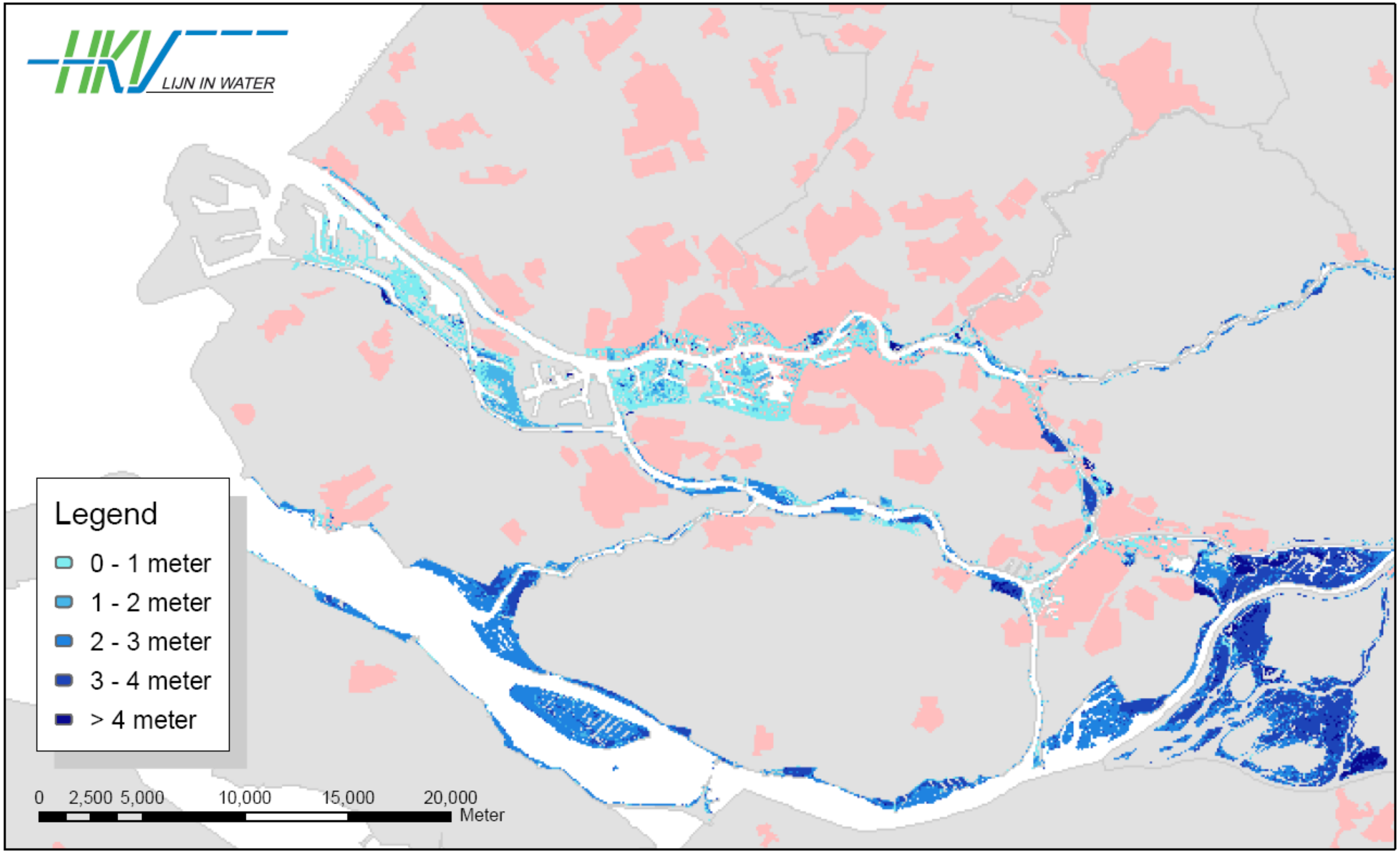
Flood depth 2100 - return period 100 years – variant closable but open



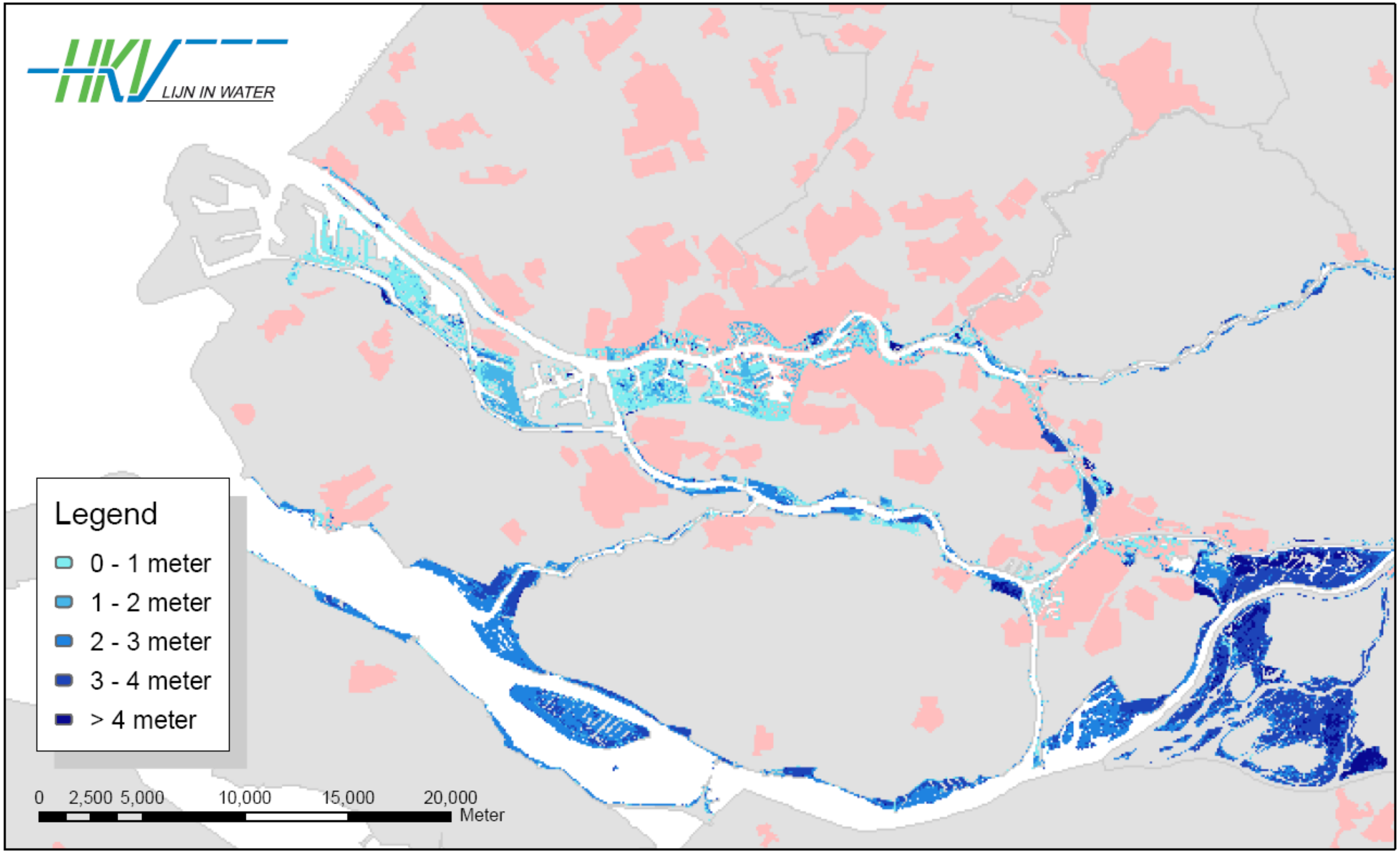
Flood depth 2100 - return period 1000 years – variant closable but open



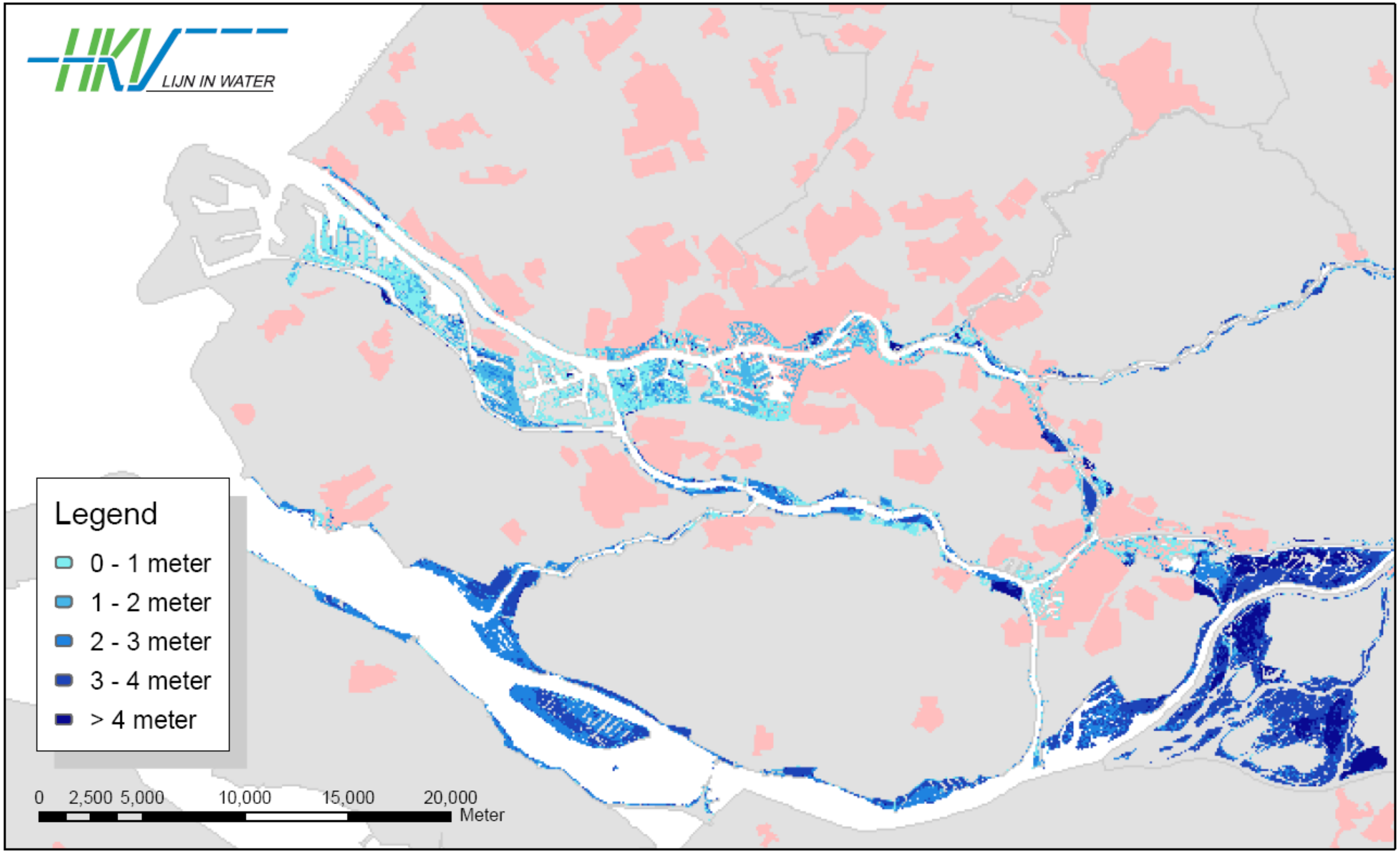
Flood depth 2100 - return period 2000 years – variant closable but open



Flood depth 2100 - return period 4000 years – variant closable but open



Flood depth 2100 - return period 10.000 years – variant closable but open



To develop the scientific and applied Knowledge required for climate proofing the Netherlands and to create a sustainable Knowledge infrastructure for managing climate change

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