Evaluation of Dike Safety and Flood Risks in the Vidå River System including Future Climate Change

Kreis Nordfriesland

and

Tønder Kommune

Deich-und Hauptsielverband Südwesthörn-Bongsiel

Final Report
September 2012

Evaluation of Dike Safety and Flood Risks in the Vidå River System including Future Climate Change

Prepared for	**Kreis Nordfriesland, DHSV Südwesthörn-Bongsiel and Tønder Kommune**
Represented by	**Martin Matzdorf, Thies Horn and Joergen Nicolaisen**

Project No	11804467
Classification	Restricted

Authors	Mads N. Madsen
	Henrik Madsen
	Bo Møller (external consultant)
Reviewed	Mads N. Madsen
Approved	Ian Sehested Hansen

Contents

1 Introduction

This report provides a technical description of the hydrologic and hydraulic model applications carried out during the Danish-German EU-Interreg project "Interreg4A – Grenzwasser/ *Grænse-vand* - Fælles sikkerhed mod oversvømmelse i lyset af klimaændringer".

1.1 Background and objective

In order to assess the dike safety in Tøndermarsk along the Vidå River and associated streams an integrated modelling system was established in 1997 (Ref. /1/). The modelling system was based on MIKE 11 within the MIKE by DHI software. The system included a hydrologic model of the Vidå catchment and a hydraulic model of the Vidå River system including the Vidå River from St. Emmerske to the outlet at the Vidå sluice as well as the Grønå River from the confluence with Vindtved Canal. Furthermore, the hydraulic model included minor tributaries such as Sønderå, Sejersbæk, Galgestrøm, Lindskov and Møllestrøm as well as a description of the sea water lake in Margrethe Kog. The hydraulic model was established based on measured cross section profiles during the period 1990 to 1996, and the model was calibrated on the basis of measurements during the period 1989 to 1995. The hydrologic model was calibrated based on the flow data from the two catchments at St. Emmerske and Rørkær, respectively. For the remaining sub-catchments the model parameters were estimated. However, this part was subject to some uncertainty, in particular with respect to the two catchments drained by pumping stations.

The integrated modelling system was used to simulate the water level over a period from 1965 to 1995 and based on these water level calculations an extreme value analysis for selected stations along the Vidå River system was carried out, and the risk of overtopping of the dikes was estimated.

In connection with the houting project in Hestholm Kog and Nørresø in 2007 (Ref./2/) the existing MIKE 11 model was updated with the last 10 years of runoff data. Also the stream profiles in Grønå were updated on the basis of the latest measurements in 2003. This update was carried out to evaluate the local effect of the different suggested solutions for restoring the area around Hestholm Kog and Nørresø.

During the last 10 years considerable focus has been on future climate changes, in particular on the changes in rainfall and sea water levels. Naturally, this implies that the dike safety must be re-evaluated in Tøndermarsk on both the German and the Danish sides of the Vidå River system (see Figure 1-1 The overall river system in the Danish German border region of the Tønder marsh).

Thus, based on an updated MIKE modelling system covering the German and Danish part of the Vidå system the overall objective with this project is to:

- Re-evaluate the dike safety along the German and Danish part of the Vidå river system under the present (2010) conditions.
- Re-evaluate the dike safety under future climate scenarios in the form of water level increases in the Wadden Sea (caused by changes in both the mean water level and storm surges) as well as the changes in rainfall patterns and rainfall amount and other hydrological conditions.
- Assessment of the effect of pullback of existing dikes and the effect of increasing the storage capacity during extreme events on both sides of the German Danish border.

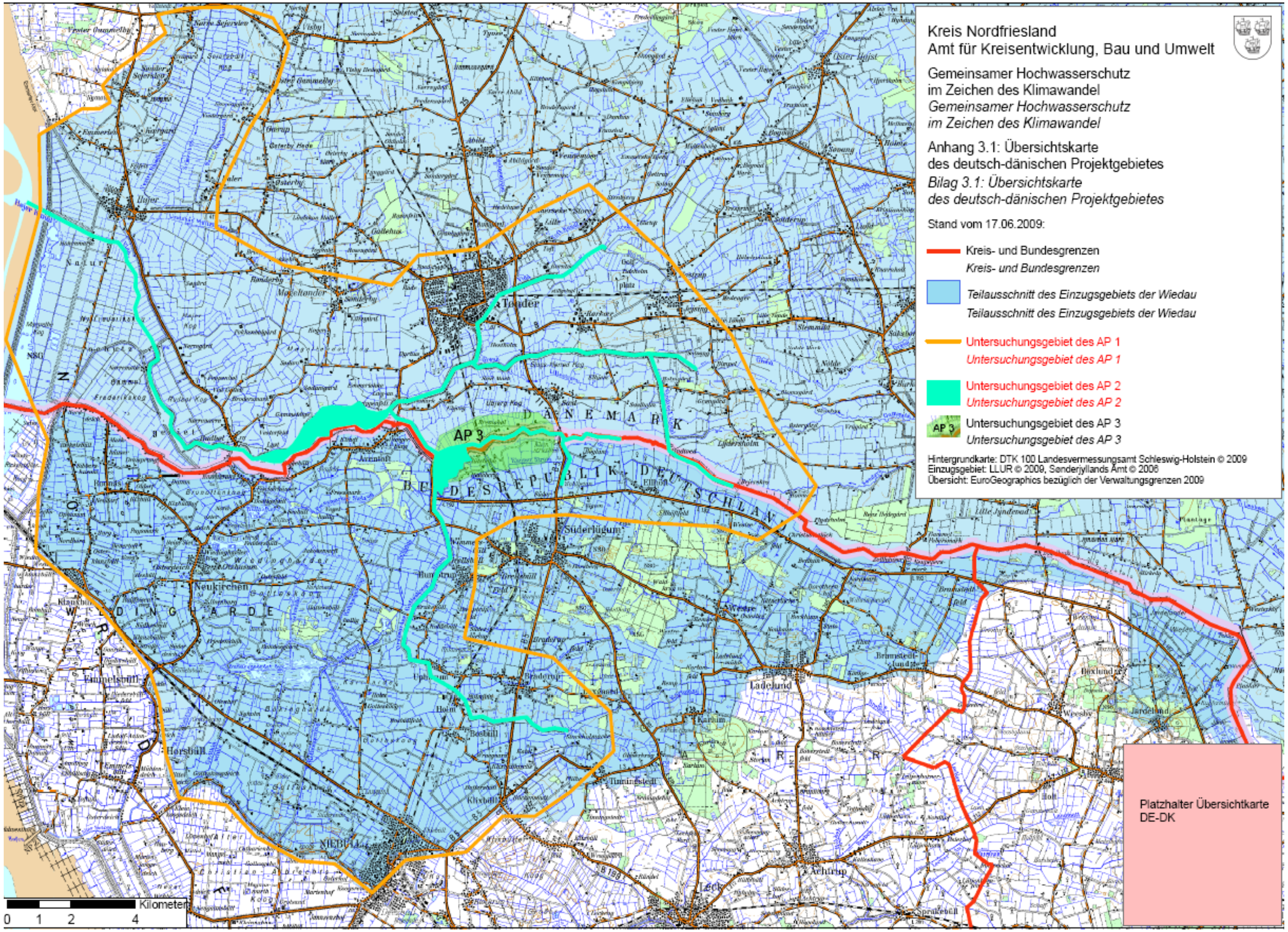


Figure 1-1 The overall river system in the Danish German border region of the Tønder marsh

2 Approach and Methodology

The platform for evaluation of dike safety is the existing MIKE11 model established in 1996 as part of a large project on extreme value analysis of the water levels in the entire Vidå River system (Ref./1/) and later updated in connection with the houting larvae project (Ref./2).

In this context the existing hydrological model has been updated to provide a much more comprehensive description of the runoff from catchments on the German side. In addition, the delineation of the river basin in sub-catchments has been revised. Upstream catchments have been recalibrated with new data, and the downstream ungauged sub-catchments have been calibrated jointly using discharge measurements at the Vidå sluice, which were not used in the previous works.

The existing MIKE 11 model has been updated and recalibrated to reflect the changes since 1995. Furthermore, the existing model complex has been extended to include all relevant river reaches (see Figure 1-1) on the Danish and German sides.

With the use of hydrological data and water level data at the Vidå sluice for the period 1981 to 2009 the integrated modelling system has been applied to simulate water levels in the Vidå River system. Statistical extreme value models of water levels have been established at selected locations for estimation of extreme water levels. These estimates have been used (compared with the latest information on the embankment levels) to determine the dike safety. The safety is expressed as the return period of embankment overtopping.

Subsequently, simulations using the future hydrological conditions and water level conditions in the Wadden Sea have been carried out. In this regard the latest projections of climate change have been be used. The climate model projections from an ensemble of regional climate models have been downscaled for determination of the future time series of rainfall, temperature and potential evapotranspiration to be used in the hydrological model. The future water level in the Wadden Sea includes changes in the mean water level caused by climate change, isostatic changes, and changes in storm surges. For determination of changes in storm surges model simulations with a hydrodynamic model forced with regional climate model projections have been applied.

The downscaled hydrological time series and time series of the water level at the Vidå sluice have been used as boundary conditions in the integrated modelling system for simulating the future water levels in the Vidå River system. The model simulations have formed the basis for an extreme value analysis at selected locations for estimating the future risk of embankment overtopping. The risk has been evaluated for climate change projections for the years 2050 and 2100.

3 Data and Data Analysis

Extensive data collections have been carried out as a part of the present project. Table 3-1 through Table 3-5 provide a list of all data applied in the MIKE 11 updating and subsequent model simulations. The names applied are those utilized within the MIKE 11 data base system. Furthermore, reference is made with respect to the organization providing/owing the data.

For the MIKE 11 simulations, boundary conditions and meteorological forcing data (i.e. sea water level at the Vidå sluice, precipitation, temperature and potential evapotranspiration) are available for the entire period from 1 Jan1981 to 31 Dec 2009.

Table 3-1 Data overview- River cross-sectional data

MIKE 11 River Name	MIKE 11 Topo-ID	MIKE 11 Chainage up	MIKE 11 Chainage down	Data source	Comment
BORG_LANDGROEFT	TOPO-2009DVR	839	1099	Tønder Kommune	River surveys after 1997
DREIHARDER_GOTTESKOOGSTROM	TOPO-2010NN	29	12600	DHSV Sudwesthorn-Bongsiel	River surveys after 2010
FRISLUSE_KANAL2	TOPO-2010DVR	0	60	Regulations for Tønder marsh	Constructed from regu-lation design
FRISLUSE_KANAL4	TOPO-2010DVR	0	60	Regulations for Tønder marsh	Constructed from regu-lation design
GALGESTROM	TOPO-1996DVR	20	2540	MIKE 11 1996 model	River surveys before 1997
GEESTABLEITER	TOPO-2010NN	13	1949	DHSV Sudwesthorn-Bongsiel	River surveys 2010
GRØNÅ_TM	TOPO-2003DVR	25	5563	Tønder Kommune	River surveys after 1997
HAASBERGER_SEE1	TOPO-2010NN	0	1170	DHI	Constructed from DTM model
HAASBERGER_SEE2	TOPO-2010NN	0	840	DHI	Constructed from DTM model
HAASBERGER_SEE3	TOPO-2010NN	0	100	DHI	Constructed from DTM model
KANAL10	TOPO-2010DVR	10	500	Regulations for Tønder marsh	Constructed from regu-lation design
KANAL12	TOPO-2010DVR	0	1035	Regulations for Tønder marsh	Constructed from regu-lation design

MIKE 11 River Name	MIKE 11 Topo-ID	MIKE 11 Chainage up	MIKE 11 Chainage down	Data source	Comment
KANAL122	TOPO-2001DVR	18	6251	Tønder Kommune	River surveys after 1997
KANAL2	TOPO-2010DVR	0	5524	Regulations for Tønder marsh	Constructed from regu-lation design
KANAL3	TOPO-2010DVR	0	3324	Regulations for Tønder marsh	Constructed from regu-lation design
KANAL33	TOPO-2000DVR	0	4290	Tønder Kommune	River surveys after 1997
KANAL4	TOPO-2010DVR	0	2970	Regulations for Tønder marsh	Constructed from regu-lation design
KANAL40	TOPO-2010DVR	0	3935	Regulations for Tønder marsh	Constructed from regu-lation design
KANAL44	TOPO-2000DVR	53	2164	Tønder Kommune	River surveys after 1997
KANAL46-34	TOPO-2000DVR	16	2447	Tønder Kommune	River surveys after 1997
KANAL66	TOPO-2000DVR	5	890	Tønder Kommune	River surveys after 1997
KANAL75	TOPO-2001DVR	5	5380	Tønder Kommune	River surveys after 1997
KANAL81	TOPO-2001DVR	18	1706	Tønder Kommune	River surveys after 1997
KANAL92	TOPO-REGDVR	1	2210	Regulations for Tønder marsh	Constructed from regu-lation design
KANAL96	TOPO-2001DVR	12	3572	Tønder Kommune	River surveys after 1997
KANAL98	TOPO-REGDVR	1485	2870	Regulations for Tønder marsh	Constructed from regu-lation design
LILLEVADE	TOPO-2010DVR	0	400	DHI	Constructed from DTM model

MIKE 11 River Name	MIKE 11 Topo-ID	MIKE 11 Chainage up	MIKE 11 Chainage down	Data source	Comment
LINDSKOV_MOLLESTROM	TOPO-2003DVR	7	4495	Tønder Kommune	River surveys after 1997
MARGRETHE_KOG	TOPO-1990DVR	0	5899	MIKE 11 1996 model	Constructed from terrain measurements
MARGRETHE_KOG_PUMPESYD	TOPO-2010DVR	0	5620	DHI	Constructed from DTM model
MOLLESO	TOPO-2008DVR	0	400	Danish Nature Agency	From houting Restoration project – riffle at Bachmanns Mølle
MOLLESTRYG	TOPO-2008DVR	0	510	Danish Nature Agency	From houting Restoration project – riffle at Bachmanns Mølle
NORRESO_OST_LINK1	TOPO-PRODVR	0	100	Danish Nature Agency	From houting Restoration project –Nørre Sø og Hestholm Kog
NORRESO_OST_TER	TOPO-PRODVR	155	2085	Danish Nature Agency	From houting Restoration project –Nørre Sø og Hestholm Kog
NORRESO_OST_VLB	TOPO-PRODVR	0	2246	Danish Nature Agency	From houting Restoration project –Nørre Sø og Hestholm Kog
NORRESO_VEST_LINK1	TOPO-PRODVR	0	100	Danish Nature Agency	From houting Restoration project –Nørre Sø og Hestholm Kog
NORRESO_VEST_TER	TOPO-PRODVR	354	1891	Danish Nature Agency	From houting Restoration project –Nørre Sø og Hestholm Kog

MIKE 11 River Name	MIKE 11 Topo-ID	MIKE 11 Chainage up	MIKE 11 Chainage down	Data source	Comment
NORRESO_VEST_VLB	TOPO-PRODVR	0	2500	Danish Nature Agency	From houting Restoration project –Nørre Sø og Hestholm Kog
OSTRE_RANDKANAL	TOPO-2008DVR	2111	6281	Tønder Kommune	River surveys after 1997
RUDBOL_SO	TOPO-1992DVR	0	1650	MIKE 11 1996 model	River surveys before 1997
SCHMALE	TOPO-2010NN	800	6700	DHI	Constructed from DTM model
SEJERSBEK_NEDRE_LOB	TOPO-2003DVR	0	1744	Tønder Kommune	River surveys after 1997
SEJERSBEK_PUMPEKANAL	TOPO-2008DVR	15	7027	Tønder Kommune	River surveys after 1997
SEJERSBEK_PUMPERES	TOPO-2010DVR	0	6200	DHI	Constructed from DTM model
SØNDERÅ	TOPO-2010NN	34	9800	DHSV Sudwesthorn-Bongsiel	River surveys 2010
SØNDERÅ_1993	TOPO-1993DVR	3140	3700	Model 1996	River surveys before 1997
SØNDERÅ_DK	TOPO-2010DVR	25540	25935	Tønder Kommune	River surveys after 1997
SØNDERÅ_RES1	TOPO-2010DVR	0	942	DHI	Constructed from DTM model
SYDOSTRE_RANDKANAL	TOPO-2003DVR	13	1391	Tønder Kommune	River surveys after 1997
VESTRE_RANDKANAL	TOPO-2008DVR	7	8116	Tønder Kommune	River surveys after 1997
VIDÅ	TOPO-1996DVR	45	4588	MIKE 11 1996 model	River surveys before 1997

MIKE 11 River Name	MIKE 11 Topo-ID	MIKE 11 Chainage up	MIKE 11 Chainage down	Data source	Comment
VIDÅ	TOPO-1992DVR	8720	25920	MIKE 11 1996 model	River surveys before 1997
VIDÅ	TOPO-1996DVR	8288	8712	MIKE 11 1996 model	River surveys before 1997
VIDÅ	TOPO-1996DVR	5098	6072	MIKE 11 1996 model	River surveys before 1997
VINDTVED_KANAL	TOPO-2010DVR	14	2841	Tønder Kommune	River surveys after 1997

Table 3-2 Data overview- Weirs

MIKE 11 River Name	MIKE 11 Chainage	MIKE 11 Name Id	Data source	Comment
MOLLESO	250	Overløb til Stryg H=2.60 m	Danish Nature Agency	From houting Restoration project – riffle at Bach-manns Mølle
DREIHARDER_GOTTESKOOGSTROM	6030	Wier	DHSV	River survey 2010
MARGRETHE_KOG	4100	Udløb fra Saltvandsøen	MIKE 11 1996 model	Constructed from terrain measurements
MARGRETHE_KOG_PUMPESYD	5595	Overløb reservoir diget	Tønder Kommune	Constructed from DTM model
SEJERSBEK_PUMPERES	6130	Overløb terræn	DHI	Constructed from DTM model
HAASBERGER_SEE1	1150	Overløb fra Sønderå til Haasberger See	DHSV	Constructed from meas-urements 2010
SØNDERÅ_RES1	50	Overløb over Terræn	Tønder Kommune	Constructed from DTM

MIKE 11 River Name	MIKE 11 Chainage	MIKE 11 Name Id	Data source	Comment
				model
LILLEVADE	25	Overløb over Dige	Regulations for Tønder marsh	

Table 3-3 Data overview- Culverts

MIKE 11 River Name	MIKE 11 Chainage	MIKE 11 Name ID	Data source	Comment
VIDÅ	24235	Højer sluse, sideporte	MIKE 11 1996 model	
VIDÅ	24235	Højer sluse, midtport	MIKE 11 1996 model	
MARGRETHE_KOG_PUMPESYD	5595	Frisluse ved pumpestation	Tønder Kommune	Fictive culvert
VIDÅ	25735	Vidåslusen	MIKE 11 1996 model	
SØNDERÅ_1993	3300	Møllehusslusen ved indløb til Magisterkog	MIKE 11 1996 model	
LILLEVADE	25	Klapsluse	Regulations for Tønder marsh	Constructed from regula-tion design
LILLEVADE	375	Culvert under Rudbøl Di-get	Regulations for Tønder marsh	Constructed from regula-tion design
HAASBERGER_SEE1	1150	Udløb1 Haasberger See ID1879	DHSV	Constructed from regula-tion design
HAASBERGER_SEE3	50	Udløb2 Haasberger See ID 2298	DHSV	Constructed from regula-tion design
KANAL33	1	Rør under Rudbølvej	Tønder Kommune	River survey
KANAL122	6060	Dykker under Vidå	Tønder Kommune	River survey

MIKE 11 River Name	MIKE 11 Chainage	MIKE 11 Name ID	Data source	Comment
KANAL10	470	Frisluse i kanal 10	Regulations for Tønder marsh	Constructed from regulation design
FRISLUSE_KANAL2	30	Frisluse i kanal 2	Regulations for Tønder marsh	Constructed from regulation design
FRISLUSE_KANAL4	30	Frisluse i kanal 4	Regulations for Tønder marsh	Constructed from regulation design

Table 3-4 Data overview- Pumps

MIKE 11 River Name	MIKE 11 Chainage	MIKE 11 Name ID	Data source	Comment
SEJERSBEK_PUMPEKANAL	7000	Sejersbæk Pumpe 1	Regulations for Tønder marsh	Tabulated Characteristic
SEJERSBEK_PUMPEKANAL	7000	Sejersbæk Pumpe 2	Regulations for Tønder marsh	Tabulated Characteristic
KANAL75	5335	Lægan Pumpe 1	Regulations for Tønder marsh	Tabulated Characteristic
KANAL75	5335	Lægan Pumpe 2	Regulations for Tønder marsh	Tabulated Characteristic
KANAL75	5335	Lægan Pumpe 3	Regulations for Tønder marsh	Tabulated Characteristic
KANAL75	5335	Lægan Pumpe 4	Regulations for Tønder marsh	Tabulated Characteristic
KANAL46-34	2370	Nørremølle Pumpe 2	Regulations for Tønder marsh	Tabulated Characteristic
KANAL46-34	2370	Nørremølle Pumpe 1	Regulations for Tønder	Tabulated Characteristic

MIKE 11 River Name	MIKE 11 Chainage	MIKE 11 Name ID	Data source	Comment
			marsh	
KANAL12	985	Højer Pumpe 1	Regulations for Tønder marsh	Tabulated Characteristic
KANAL12	985	Højer Pumpe 2	Regulations for Tønder marsh	Tabulated Characteristic
SCHMALE	6500	Verlath 1	DHSV	Fixed Discharge 4 m3/s
SCHMALE	6500	Verlath 2	DHSV	Fixed Discharge 4 m3/s
SCHMALE	6500	Verlath 3	DHSV	Fixed Discharge 5 m3/s
SCHMALE	6500	Verlath 4	DHSV	Fixed Discharge 5 m3/s
SCHMALE	6500	Verlath 5	DHSV	Fixed Discharge 3 m3/s

Table 3-5 Data overview- Time series data

Type of data	Location	Period	MIKE 11 ID	Data source
Water level	Vidå, St. Emmerske	1989-2006	H4210010_1989-2006.dfs0	Tønder Kommune
Water level	Vidå, St. Emmerske	1989-2010	H4210010_1989-2010.dfs0	Tønder Kommune
Water level	Vidå, upstream Bachmanns Mølle	1991-2007	H4210030_1991-2007.dfs0	Tønder Kommune
Water level	Vidå, Upstream Bachmanns Mølle	2009-2010	H4210030_2009-2010.dfs0	Tønder Kommune
Water level	Vidå, confluence with Grønå	1989-2007	H4210040_1989-2007.dfs0	Tønder Kommune
Water level	Vidå, confluence with Grønå	2008-2010	H4210040_2008-2010.dfs0	Tønder Kommune

Type of data	Location	Period	MIKE 11 ID	Data source
Water level	Kanal 75 at Lægan pumping station	1990-2007	H4210049_1990-2007.dfs0	Tønder Kommune
Water level	Vidå, Lægan pumping station	1989-2007	H4210050_1989-2007.dfs0	Tønder Kommune
Water level	Vidå, Lægan pumping station	2007-2010	H4210050_2007-2010.dfs0	Tønder Kommune
Water level	Vidå, Lyst in Magisterkogen	1990-2007	H4210065_1990-2007.dfs0	Tønder Kommune
Water level	Vidå, Lyst in Magisterkogen	2007-2010	H4210065_2007-2010.dfs0	Tønder Kommune
Water level	Vidå, at Nørremølle	1992-2007	H4210080_1992-2007.dfs0	Tønder Kommune
Water level	Vidå, at Nørremølle	2007-2010	H4210080_2007-2010.dfs0	Tønder Kommune
Water level	Vidå, at Højer sluice	1989-2007	H4210090_1989-2007.dfs0	Tønder Kommune
Water level	Vidå, at Højer sluice	2007-2010	H4210090_2007-2010.dfs0	Tønder Kommune
Water level	Vidå, Vidå sluice inside.	1989-2007	H4210098_1989-2007.dfs0	Tønder Kommune
Water level	Vidå, Vidå sluice inside.	2007-2010	H4210098_2007-2010.dfs0	Tønder Kommune
Water level	DreiharderGotteskoogstrom at confluence with Sønderå		H_DreihardersGotteskoogstrom.dfs0	DHSV
Water level	Udløb fra Haasberger See	2002-2004	H_HaasbergerSee2002-2004.dfs0	DHSV
Sea water level	Vidå sluice outside	1980-2010	H_VidåslusenKystdirektoratet1980-2010.dsf0	Kystdirektoratet
Discharge	Vidå, St. Emmerske	1978-2009	Q4210010_1978-2009.dfs0	Tønder Kommune
Discharge	Nørremølle pumping station Estimated discharge based on measured energy consump-tion at pumping station	2002-2010	Q4210080-Pumpesation_2002-2009.dfs0	Tønder Kommune

Type of data	Location	Period	MIKE 11 ID	Data source
Discharge	Borg Landgrøft		Q4221948_2003-2008.dfs0	Tønder Kommune
Discharge	Grønå, at Rørkær	1960-2009	Q4240080_1960-2009.dfs0	Tønder Kommune
Discharge	Vidå, Vidå sluice	2000-2007	QVidåSlusen_2000-2007.dfs0	Tønder Kommune
Wind speed	Measurements at Vidå sluice		Skryds-trup+VidåSlusen+Jyndevad_vindhastighed.dfs0	DMI
Wind direc-tion	Measurements at Vidå sluice		Skryds-trup+VidåSlusen+Jyndevad_vindretning.dfs0	DMI
Precipitation	Grid precipitation (10x10 km)	1981-2009	GridXXXXX_1981-2010.dfs0 XXXXX refers to DMI grid ID	DMI
Potential evapotran-spiration	Climate grid (40x40 km)	1981-2009	PotEvapClimateGridVidå_Ext.dfs0	DMI
Temperature	Skrydstrup	1981-1988	T_Skrydstrup.dfs0	DMI
Temperature	St. Jyndevad	1989-2009	Temperatur-SJA1989-2009.dfs0	DMI

3.1 Climate projections

To assess the impacts of future climate change changes in both the meteorological forcing (precipitation, temperature and potential evapotranspiration) and changes in sea water level are considered. The project has used regional climate model (RCM) projections from the ENSEMBLES data archive (van der Linden and Mitchell, 2009) to estimate the changes in hydrological variables in the Vidå River basin for two projection horizons, 2050 and 2100. The ENSEMBLES data archives include a number of projections for the A1B emission scenario using different RCMs forced by different general circulation models (GCMs).

It is generally recommended to use an ensemble of climate model projections for impact assessments in order to take the uncertainties in the projections into account. In this project, 15 RCM/GCM model projections from the ENSEMBLES data archive were used for estimating the changes in precipitation, temperature and potential evapotranspiration. Weighted average changes were calculated where weights for the 15 different RCM/GCM models were determined based on the skills of the models for simulation of the present climate, considering the monthly variability of mean precipitation, variance of daily precipitation, and mean temperature. The RCM/GCM model projections used in the project are listed in Table 3-6.

Table 3-6 RCM/GCM projections applied in the project. The Hadley Centre RCM and GCM models include three model versions with different climate sensitivity: reference (Q0), high sensitivity (Q16) and low sensitivity (Q3).

Model No.	Institution	RCM	GCM
1	Danish Meteorological Institute	HIRHAM5	ECHAM5
2	Danish Meteorological Institute	HIRHAM5	ARPEGE
3	Danish Meteorological Institute	HIRHAM5	BCM
4	Max Planck Institute for Meteorology	REMO	ECHAM5
5	Swedish Meteorological and Hydrological Institute	RCA3.0	ECHAM5
6	Swedish Meteorological and Hydrological Institute	RCA3.0	BCM
7	Swedish Meteorological and Hydrological Institute	RCA3.0	HadCM3Q3
8	UK Met Office, Hadley Centre for Climate Prediction and Research	HadRM3Q0	HadCM3Q0
9	UK Met Office, Hadley Centre for Climate Prediction and Research	HadRM3Q3	HadCM3Q3
10	UK Met Office, Hadley Centre for Climate Prediction and Research	HadRM3Q16	HadCM3Q16
11	Royal Netherlands Meteorological Institute	RACMO2	ECHAM5
12	Swiss Federal Institute of Technology	CLM	HadCM3Q0
13	Centre National de Recherches Météorologique, Meteo France	RM5.1	ARPEGE
14	Community Climate Change Consortium for Ireland	RCA3.0	HadCM3Q16
15	Abdus Salam International Centre for Theoretical Physics	REGCM3	ECHAM5

The variability in the estimated changes in mean precipitation and temperature of the 15 RCM/GCM models in 2050 and 2100 is shown in Figure 3-1 together with the estimated weighted average values. The estimated changes are based on 30-year periods of climate model data, 1980-2009 representing the present climate, 2035-2064 representing the future climate in 2050, and 2070-2099 representing the future climate in 2100, respectively.

Most models estimate an increase in precipitation during winter and a decrease during summer, but for all months, and especially in summer, a large variability is apparent showing both decreases and increases in mean precipitation. For temperature all models project an increase, but with a large variability. The figure illustrates the importance of considering an ensemble of climate projections in the impact assessment in order to take the variability in the estimated changes into account.

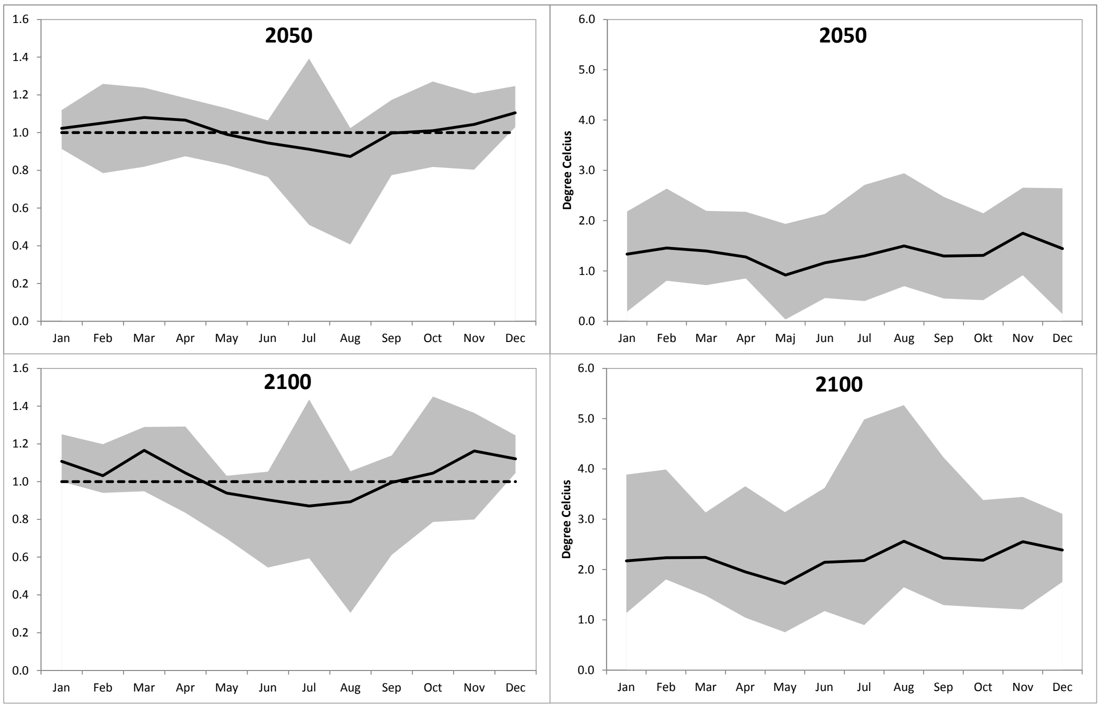


Figure 3-1 Estimated variability of the relative change in mean monthly precipitation (left) and absolute change in mean monthly temperature (right) in 2050 (top) and 2100 (bottom) from the 15 RCM/GCM models (grey shaded area) and the weighted average (black line).

The weighted average changes of mean and daily variance of precipitation, mean temperature and mean potential evapotranspiration for 2050 and 2100 are shown in Figure 3-2. Potential evapotranspiration data for the future climate are obtained from the relative change in temperature from the RCM/GCM projections using the temperature-based method of calculation of potential evapotranspiration by Kay and Davies (2008). The temperature increase is about 1-1.5 degrees in 2050 and 2-2.5 degrees in 2100. In general, precipitation increases during winter and decreases during summer and a larger variance is expected in all months, with changes being more pronounced in 2100. The increase in potential evapotranspiration follows the changes in temperature with larger relative changes during winter than during summer.

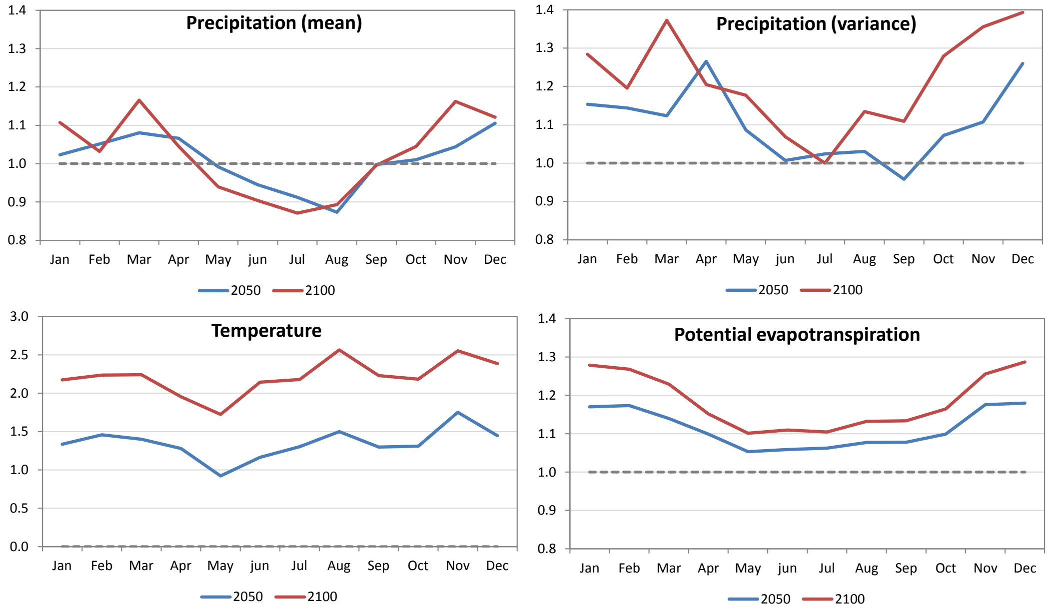


Figure 3-2 Relative change in mean and variance of precipitation and mean potential evapotranspiration, and absolute change in temperature (degree Celsius) for future (2050 and 2100) climate.

Changes in the sea water level at the Vidå sluice are a combination of:

1. Global increase in mean water level due to thermal expansion and melting of glaciers and ice caps.
2. Regional and local change in mean water level due to changes in water density and circulation patterns.
3. Local change in mean water level due to isostatic change.
4. Local change in storm surge levels due to changes in extreme storm intensities and changes in mean water level.

According to the results published in IPCC's 4th Assessment Report (IPCC, 2007) a global increase in mean sea water level of 0.18-0.59 m is expected by 2100, with an additional local increase in the waters around Denmark of about 0.15 m. New results, however, show that the global sea level rise will be larger than reported in IPCC's 4th Assessment Report (e.g. Grindsted et al., 2009). Based on the new results, the Danish Meteorological Institute has estimated an increase in mean sea water level for Danish waters in the range 0.3 to 1.0 meters in 2100 (Danish Climate Change Adaptation Portal, 2011). Due to the large uncertainties in the projected increase in the mean sea water level, two scenarios have been applied in the analysis corresponding to an increase of 0.3 and 1.0 meter in 2100, respectively. For estimation of the mean sea level rise in 2050 the temporal development reported in Grindsted et al. (2009) was used.

Due to isostatic changes there is a continuous relative increase in the mean sea water level in the area. According to the Danish Coastal Authority (2007) there has been an increase in the mean sea water level at the Vidå sluice due to isostatic changes of 11 cm during the period 1891-1990. This relative increase is assumed to continue up to 2100, i.e. an annual increase of 0.11 cm per year has been applied.

For estimation of changes in storm surges, model simulations based on a hydrodynamic model covering the North Sea, Baltic Sea and inner Danish waters was used. The model was forced by projections of wind and atmospheric pressure fields from the HIRHAM5-ARPEGE model from the ENSEMBLES data archive (Rugbjerg and Johnson, 2012). From the hydrodynamic model simulations time series of sea water levels at the Vidå sluice were extracted. From this time series extreme water level statistics were calculated for 2010 (based on simulation results for the period 1980-2009), 2050 (2035-2064) and 2100 (2070-2099). Future extreme value statistics for 2050 and 2100 were then estimated by superimposing the changes in extreme value statistics to the current statistics (Danish Coastal Authority, 2007) and adding the projected mean sea level rise and isostatic changes, see Figure 3-3.

The changes in extreme value statistics caused by changes in the storm surge signal (i.e. without considering climate-induced mean sea level rise and isostatic changes) are in the order of 0.04 - 0.05 m for 2050 and 0.5 - 0.8 m for 2100 for annual exceednce probabilities ranging between 0.5 and 5%. This corresponds well with results from other studies in this area (Woth et al., 2006; Madsen, 2009). When adding the climate-induced mean sea level rise and isostatic changes, the extreme value statistics become much more severe. For instance, a 5 m water level has an annual excedance probability of about 0.5% according to the current statistics (corresponding to an event which is expected once every 200 years on average), but in 2100 in the case of the high sea level rise scenario will have an annual exceedance probability of about 30% (1 in 3-year event).

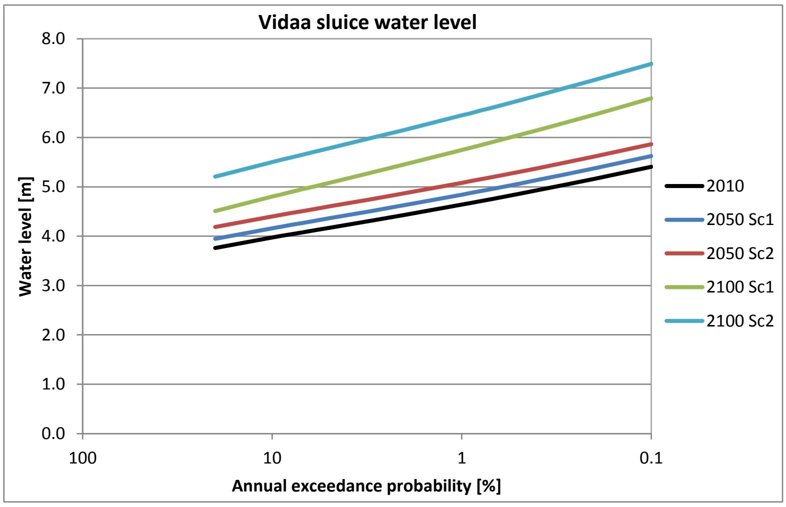


Figure 3-3 Estimated extreme sea water level statistics at the Vidå sluice for current (2010) and future (2050 and 2100) climate. Sc1 and Sc2 correspond to, respectively, the low and high scenario of mean sea level rise.

The duration of the high sea water level at the Vidå sluice is critical for storage of water in the river system. An increase in mean sea level will result in an increase of the duration of high sea water level above a given datum. However, there may also be an additional increase in the duration of high sea water level caused by changes in the storm surge patterns. This is analysed from the hydrodynamic model simulations representing current (2010) and future (2050 and 2100) conditions. To compare the changes in the duration of high water levels caused by changes in storm surge patterns, the rise in mean sea level has been subtracted from the hydrodynamic model simulations. Figure 3-4 shows the number of events with prolonged periods of high water level at the Vidå sluice above 0.5 m relative to mean sea level, representing 2010, 2050 and 2100. As opposed to the increase in extreme storm surge peak level caused by changes in storm surge patterns, the durations of high water levels are not expected to increase in future climates relative to mean sea level. Thus, the increase in the duration of high water levels at the Vidå sluice is due to the increase in mean sea level only.

The four different climate change scenarios applied in the risk analysis (in section 5.5) are summarised in Table 3-7.

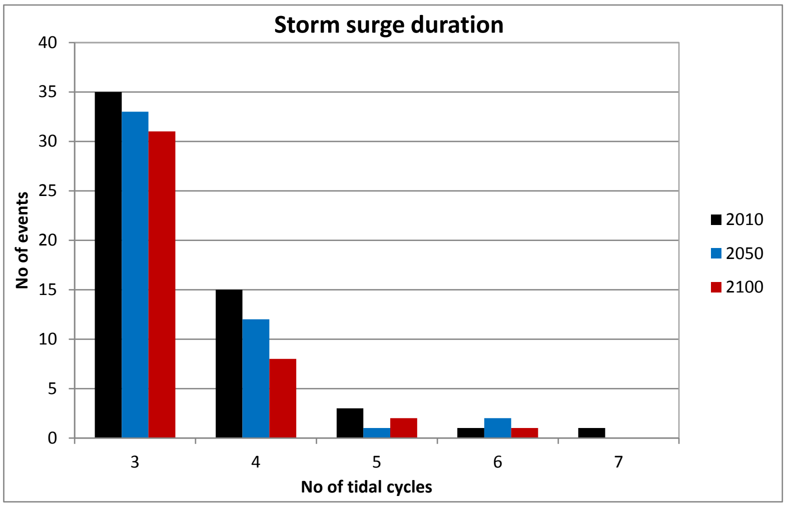


Figure 3-4 Distributions of duration of storm surge water level (over a 30 year period) above 0.5 m relative to mean sea level in terms of No. of tidal cycles from the hydrodynamic model simulations for current (2010) and future (2050 and 2100) climate.

Table 3-7 Summary of applied climate change scenarios.

Scenario	Projection Horizon	Change in mean sea water level		Change in storm surge statistics	Change in precipitation, temperature and potential evapotranspiration
		Climate change	Isostatic change		
1	2050	+10 cm	+5 cm	Based on hydrodynamic model run (Figure 3-3 and Figure 3-4)	Based on weighted averages from ENSEMBLES data archive (Figure 3-2)
2	2050	+34 cm	+5 cm		
3	2100	+30 cm	+11 cm	Based on hydrodynamic model run (Figure 3-4)	Based on weighted averages from ENSEMBLES data archive (Figure 3-2)
4	2100	+100 cm	+11 cm		

4 Model update, calibration and verification

4.1 Model update

The model established in 1996/97 has been updated and extended on both sides of the Danish/ German border. The model now comprises the majority of the Tønder marsh with respect to streams, wetlands and major drainage canals (the part controlled by "Digelaget for the Tøndermasken"). Furthermore, the model has been extended with the two streams "Geestableiter" and " Dreiharder-Gottetskoogstrom".

In order to comply with the DVR90 datum, the original model based on DNN has been converted into DVR90. The conversion was simply done by lowering all levels by 11cm.

The most significant change to the original model is the establishment of the wetlands projects in Nørresø and Hestholm Kog, where parts of Vidå and Grønå have been relocated and dikes were withdrawn, thereby producing an approximate 115 ha wetland/lake. In Vidå near Tønder city the former regulation at Bachmanns Mølle has been replaced by a model description of the stone ripple constructed in 2008 (as a part of the houting project).

Grønå has been extended from Rørkær to Jejsing and Vindtved Kanal and Sydøstre Randkanal have been added to the river network. The downstream part of Sejersbækken and Lindskov-Møllestrøm has been updated with more recent cross-sectional surveys.

Sejersbækken has been extended with Sejersbæk Kog (Vester Randkanal, Øster Randkanal, Sejersbækkens Pumpekanal and Borg Landgrøft). In order to include the reservoir capacity of Sejersbæk Kog, an additional "reservoir" canal has been added to the river network along Sejersbækken Pumpekanal.

An updated digital terrain model has been used to improve the description of the freshwater reservoir and the saltwater lake in Margrethe Kog.

The border river Sønderå has been updated with the new cross-sectional surveys from 2010. Furthermore, the river has been extended upstream until the sluice gate at Vindtved Kanal. The tributaries Dreiharder-Gottetskoogstrom and Geestableiter have likewise been added based on the 2010 survey. In addition, a description of the Haasberger See and the wetland constructed in 2004 on the Danish side of the Sønderå has been included in the model.

Figure 4-1provides an overview map showing the river in the original model (blue) and the updated and new rivers added to the model (Magenta).

The drainage of Tønder marsh takes place via a complex interconnected canal network and pumping stations. From the pumping stations water is pumped from the drainage canals and into the Vidå. The pumping starts whenever the water level in the drainage canals exceeds a certain threshold level. The location of the pumping stations is marked by the green dots in Figure 4-1. Whereas the old model included the pumped water as pre-described time series of inflow at the appropriate locations, the updated model comprises a description of the pumping rules and associated pumping rates as well as the major canals behind the pumping stations. However, due to lack of data, the canals behind Verlath pumping stations have been described in a simplified manor with the sole purpose of representing a reservoir behind the pumping station.

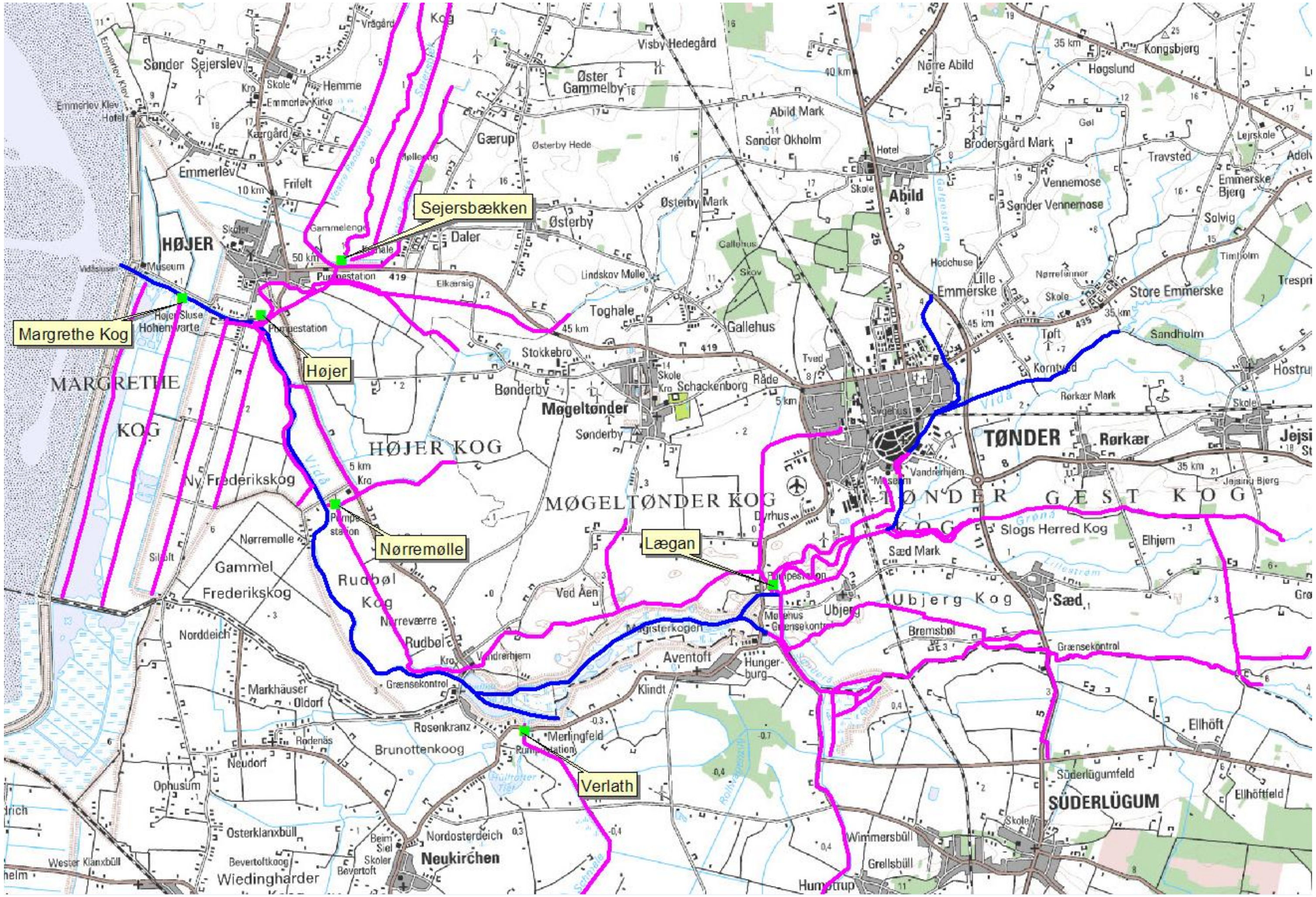


Figure 4-1 Overview showing the original model from 1996 (blue) and the updated model system (magenta)

4.2 Calibration and verification

4.2.1 The NAM catchment model

The Vidå River basin has a total catchment area of 1342 km^2, see Figure 4-2 . The German part of the Vidå catchment amounts to approximately 260 km^2 (19%). The most western part of the marsh (approximately 282 km^2 or 21% of the catchment area) is drained by pumping stations.

Table 4-1 Catchment distribution in the Vidå river basin

Catchment distribution	**Area (km^2)**
Catchments in Germany	111.8
Catchments in Germany	948.0
Pumped catchments in Germany	148.3
Pumped catchments in Denmark	133.8
Total Catchment area	**1341.9**

In the German part of the marsh all pumping takes place at Verlath where water is pumped into Rudbøl Sø. On the Danish side pumping takes place at 5 stations (see Figure 4-1 for a complete overview).

Table 4-2 Pumping stations in the marsh

Pumping stations in the marsh	**Area (km^2)**
Lægan	70.4
Nørremølle	31.7
Højer	15.4
Sejersbæk	9.0
Margrethe Kog	7.2
Verlath	148.3
Total pumped catchment area	**282.1**

For rainfall-runoff modelling the basin has been divided into 18 sub-catchments; four large upstream catchments with a total area of 864 km^2 that drain to Vidå, Grønå and Sønderå, and 14 downstream catchments with a total area of 478 km^2. Of the 14 downstream sub-catchments, four catchments are drained by pumping. The sub-catchment delineation is shown in Figure 4-3, and the different sub-catchments are listed in Table 4-3.

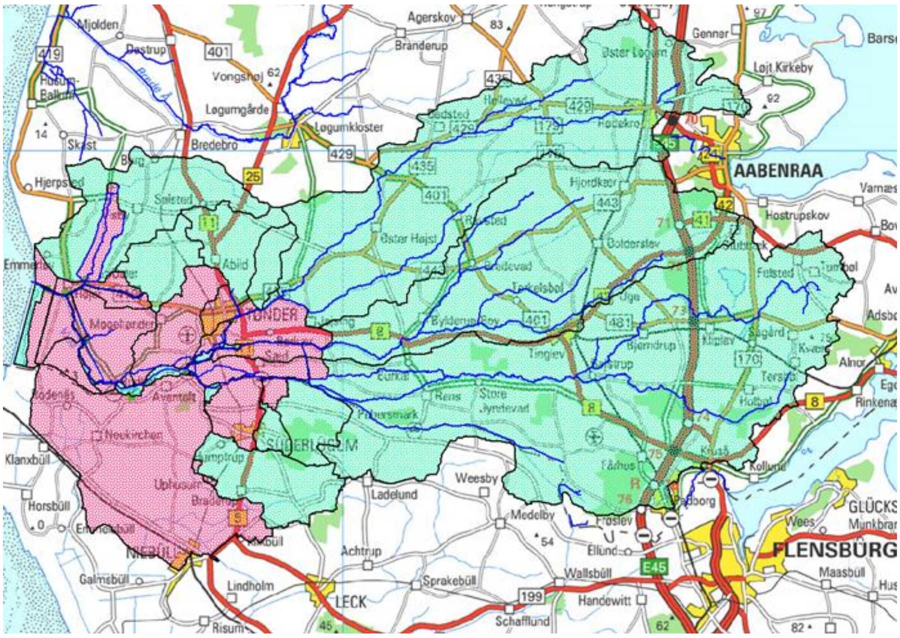


Figure 4-2 Total catchment area of the Vidå river basin. Only the red area is comprised by the river network model

Table 4-3 Definition of sub-catchments for the NAM rainfall-runoff modelling.

Sub-catchment	Area [km²]	Comment
LEGAN_PUMPE_MARK	64.6	Drained by pumping
LINDSKOV_MOLLESTROM	20.9	
TOFT_KANAL_MM	11.3	
MARGRETHEKOG	10.6	
SEJERSBEK_PUMPE	9.0	Drained by pumping
SEJERSBEK	62.9	
NORREMOLLE_PUMPE	31.7	Drained by pumping Estimated discharge
SØNDERÅ_DE	25.9	
GALGESTROM	24.7	
HOJER_PUMPE	15.9	Drained by pumping
LEGAN_PUMPE_BY	8.1	
VERLATH_PUMPE	148.9	
DREIHARDER_GOTTESKOOGSTROM	39.0	
INTERNE_OPLANDE	4.8	
VIDÅ	252.4	Gauged Vidå, St. Emmerske (Q4210010)
GRØNÅ	207.2	Gauged, Combined catchment Grønå, Rørkær (Q4240080)
GRØNÅ-SØNDERÅ_1 (SØNDERÅ_DK)	312.3	Gauged, Combined catchment Grønå, Rørkær (Q4240080)
GRØNÅ-SØNDERÅ_2 (ALTE_AU)	91.5	Gauged, Combined catchment Grønå, Rørkær (Q4240080)
Total Vidå River Basin	1341.6	Gauged, Vidå sluice

Figure 4-3 Sub-catchments delineation.

NAM rainfall-runoff models were set up and calibrated for the 18 sub-catchments. Time series of runoff measurements were available for calibration of the four upstream sub-catchments. The Vidå sub-catchment was calibrated against discharge measurements at Vidå, St. Emmerske (Q4210010). The Grønå, Grønå_Sønderå_1 and Grønå_Sønderå_2 sub-catchments were combined into one catchment and calibrated against measurements at Grønå, Rørkær (Q4240080). Data in the period from 1 Jan 2000 to 31 Dec 2009 were used for the calibration, and the remaining data from 1 Jan 1981 to 31 Dec 1999 were kept for validation.

No runoff measurements were available for individual calibration of the downstream sub-catchments. For Nørremølle Pumpe sub-catchment a runoff time series was estimated based on measured energy consumption at the pumping station. This time series was used together with the discharge measurements at the river basin outlet at the Vidå sluice for joint calibration of the downstream catchments. Since the NAM model simulates the total catchment runoff at the basin outlet (without considering the hydraulic processes in the river), the NAM simulations cannot be compared directly with the measured time series but are compared with the accumulated discharge at the basin outlet for validation of the simulation of the total water balance of the river basin.

Calibration results are shown in Table 4-4 and Figure 4-4 -Figure 4-9. Both the rainfall-runoff dynamics (Nash-Sutcliffe coefficients of 0.89-0.91) and the water balance (water balance error of -3.1 – 2.1%) for the two upstream sub-catchments are simulated satisfactorily (Figure 4-4 - Figure 4-7). The water balance for the entire river basin is simulated well (Figure 4-8) with a total water balance error of only 0.6%. With respect to the extreme runoff events the simulations are acceptable with no general tendency of under- or overestimation (Figure 4-9).

Table 4-4 Performance statistics of the NAM calibration. The Nash-Sutcliffe coefficient is an overall measure of the goodness-of-fit of the simulations, with a maximum value of 1 indicating a perfect fit. The water balance error is calculated as the difference between the average observed and simulated runoff divided by the average observed runoff.

Catchment / simulation period	Nash-Sutcliffe coefficient	Average observed runoff [mm/year]	Average simulated runoff [mm/year]	Water balance error [%]
Vidå 1 Jan 2000 - 31 Dec 2009 (calibration)	0.89	423	417	1.5
Vidå 1 Jan 1981 - 31 Dec 2009	0.89	428	419	2.1
Grønå, combined 1 Jan 2000 - 31 Dec 2009 (calibration)	0.91	370	369	0.3
Grønå, combined 1 Jan 1981 - 31 Dec 2009	0.90	377	389	3.1
Vidå River Basin 1 Jan 2000 – 30 Sep 2005 (calibration)	-	388	385	0.6

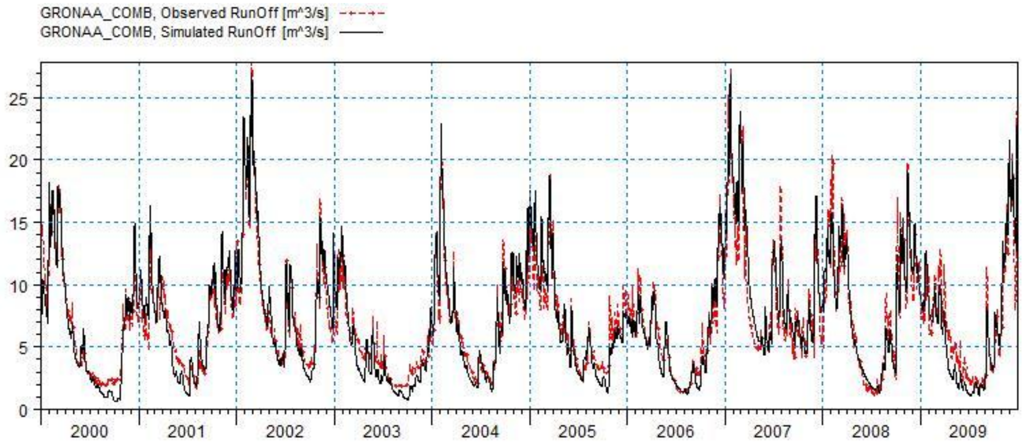


Figure 4-4 Observed and simulated runoff for the Grønå combined sub-catchment for the calibration period 1 Jan 2000 – 31 Dec 2009.

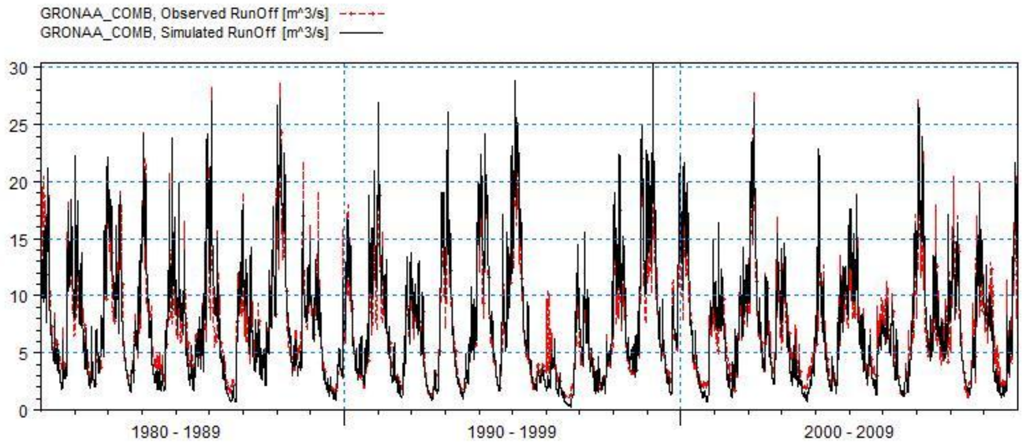


Figure 4-5 Observed and simulated runoff for the Grønå combined sub-catchment for the entire simulation period 1 Jan 1981 – 31 Dec 2009.

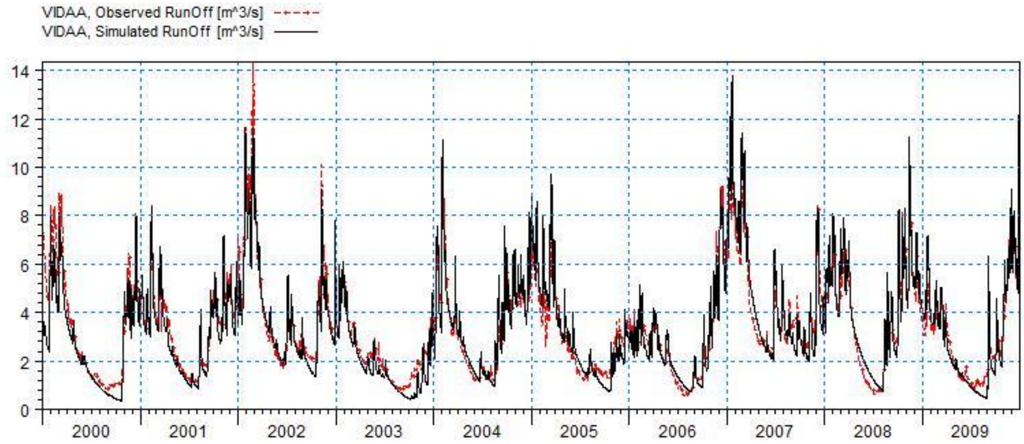


Figure 4-6 Observed and simulated runoff for the Vidå sub-catchment for the calibration period 1 Jan 2000 – 31 Dec 2009.

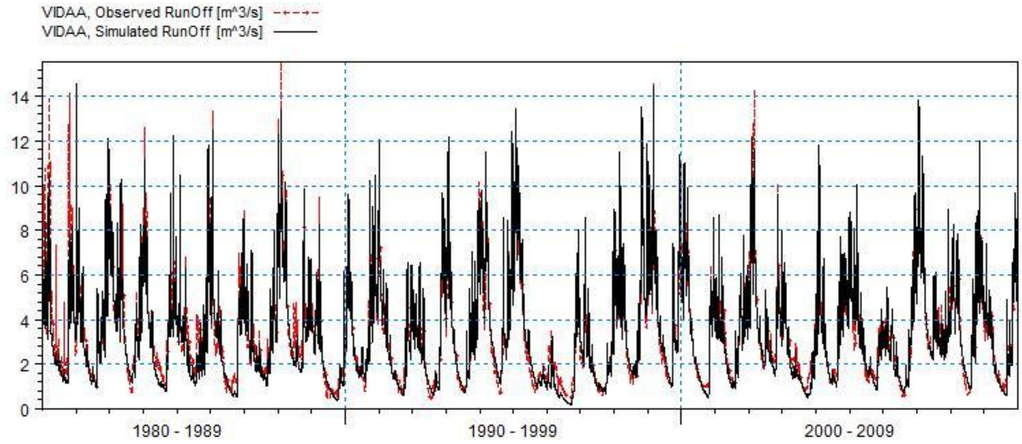


Figure 4-7 Observed and simulated runoff for the Vidå sub-catchment for the entire simulation period 1 Jan 1981 – 31 Dec 2009.

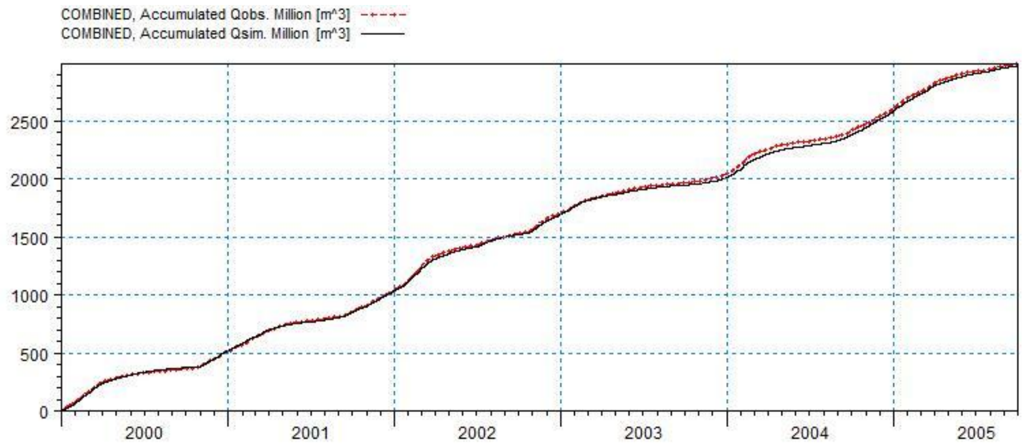


Figure 4-8 Observed and simulated accumulated runoff for the Vidå River Basin for the calibration period 1 Jan 2000 – 30 Sep 2005.

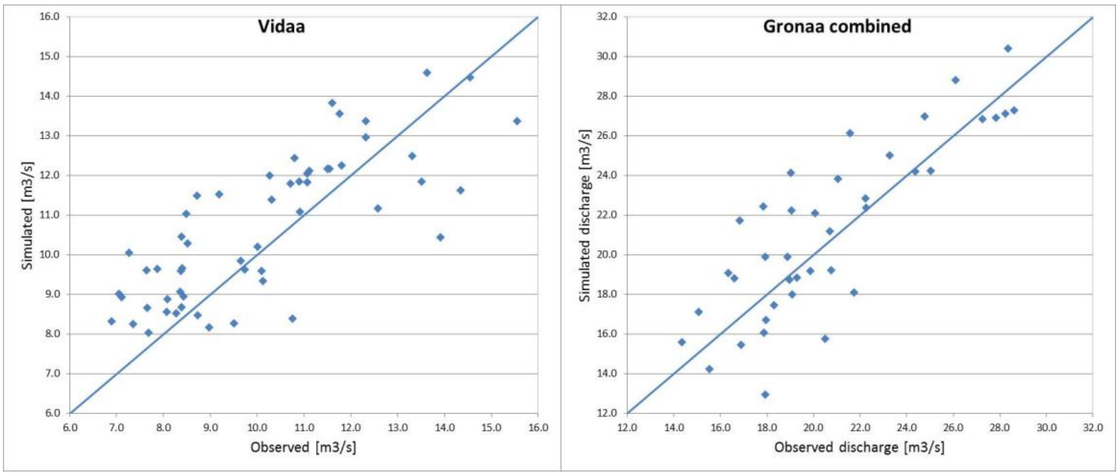


Figure 4-9 Comparison of observed and simulated extreme runoff events for the Vidå and Grønå combined sub-catchments for the simulation period 1 Jan 1981 – 31 Dec 2009.

4.2.2 The river network MIKE 11 model

The most significant changes from the 1996/1997 model are the addition of the two streams ”Geestableiter” and ” Dreiharder-Gottetskoogstrom” in the Sønderå and the Hassberger See and the houting restoration project comprising the wetlands in Nørresø and Hestholm Kog and the constructed stone ripple at Bachmanns Mølle.

4.2.2.1 Sønderåen and Haasberger See

Haasberger See acts as a reservoir being filled by dike overflows during high water levels in the Sønderå, see Figure 4-10. The dike spill occurs over a distance of 50 m only where the dike crest has been lowered locally. At lower water levels water is discharged from the Hassberger See via two pipes equipped with a regulating valve allowing outflow only.

Figure 4-11 shows observed and simulated water levels in the Sønderå in a situation with increasing water levels and dike spilling over the 50 m of the dike allocated for inflows. The simulated water level in Haasberger See increases from approximately 0.35 m to 0.95 m. As seen there is a good agreement between simulated and observed water levels at the Møllehus Sluice. This agreement also holds during the approximately 24 hours when the observed water level at the Møllehus Sluice does not increase due to filling of the Hassberger See reservoir. After filling the observed water level is roughly 3-5 cm higher than the simulated water levels. This discrepancy can be due to uncertainties in either the reservoir volume or the simulated catchment run-off in the actual period.

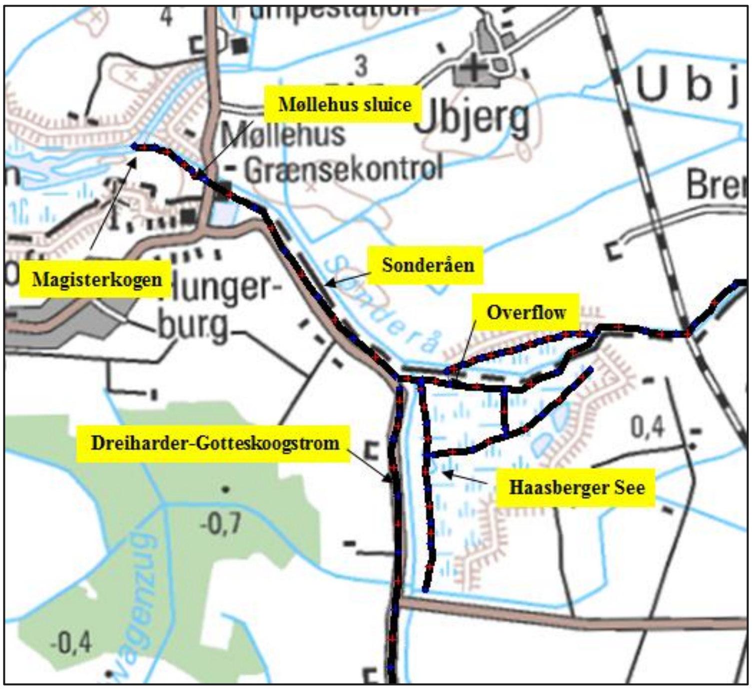


Figure 4-10 The Hassberger See, Sønderå and Dreiharder-Gottetskoogstrom

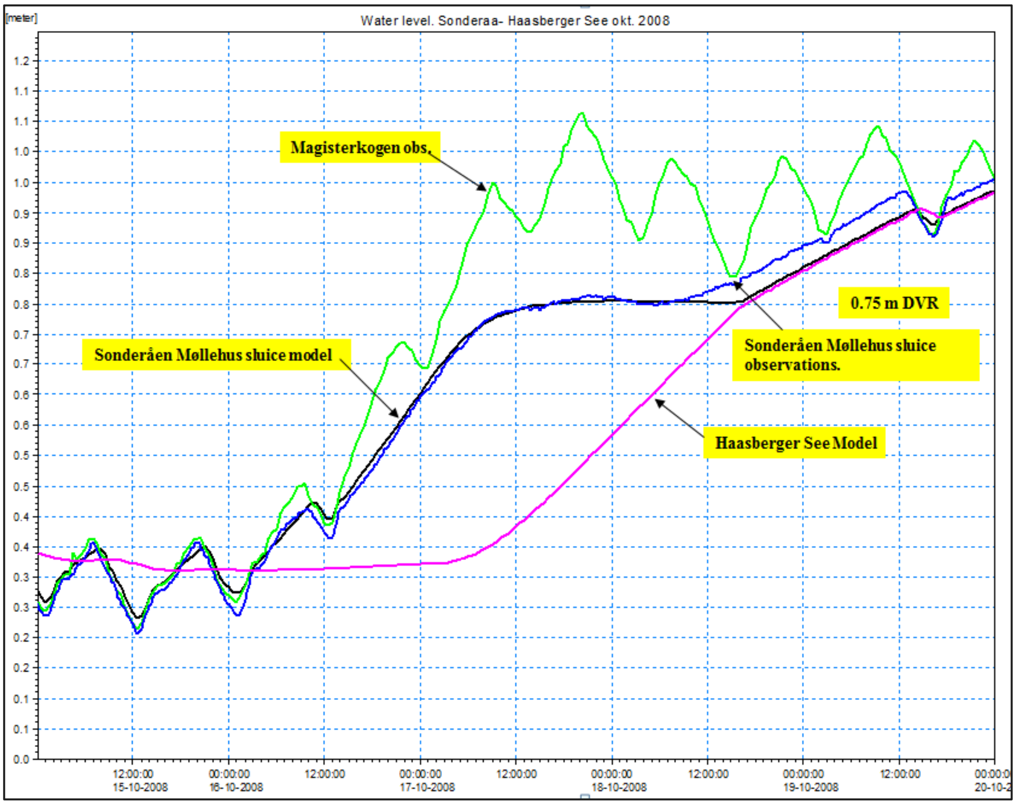


Figure 4-11 Observed and simulated water levels in the Sønderå during spilling into Hassberger See. The observed water levels in Magisterkogen are represented by recordings at SJA station no. 4210050

4.2.2.2 The wetland restoration projects in Nørresø and Hestholm Kog

During the Nørresø and Hestholm wetland restoration projects parts of Vidå and Grønå were relocated and dikes withdrawn, thereby producing an approximate 115 ha wetland/lake.

In the model Nørresø and Hestholm two MIKE 11 branches are represented where one describes the meandering stream at low flows and the other represents the inundated area during higher flows as illustrated in Figure 4-12.

Figure 4-13 shows measured and simulated water levels at the railway bridge after opening of inflows into the meandering part of Nørresø in September 2009. As seen there is generally a good agreement at high water levels. At low water levels the model results are, however, significantly higher (10-15 cm) than those observed. The large difference between the model simulation (1.40 m) and the measured water level (1.30 m) on 30December 2009 is mainly due to the fact that the water level recorder by mistake was not able to measure water levels larger than 1.30, see Figure 4-14.

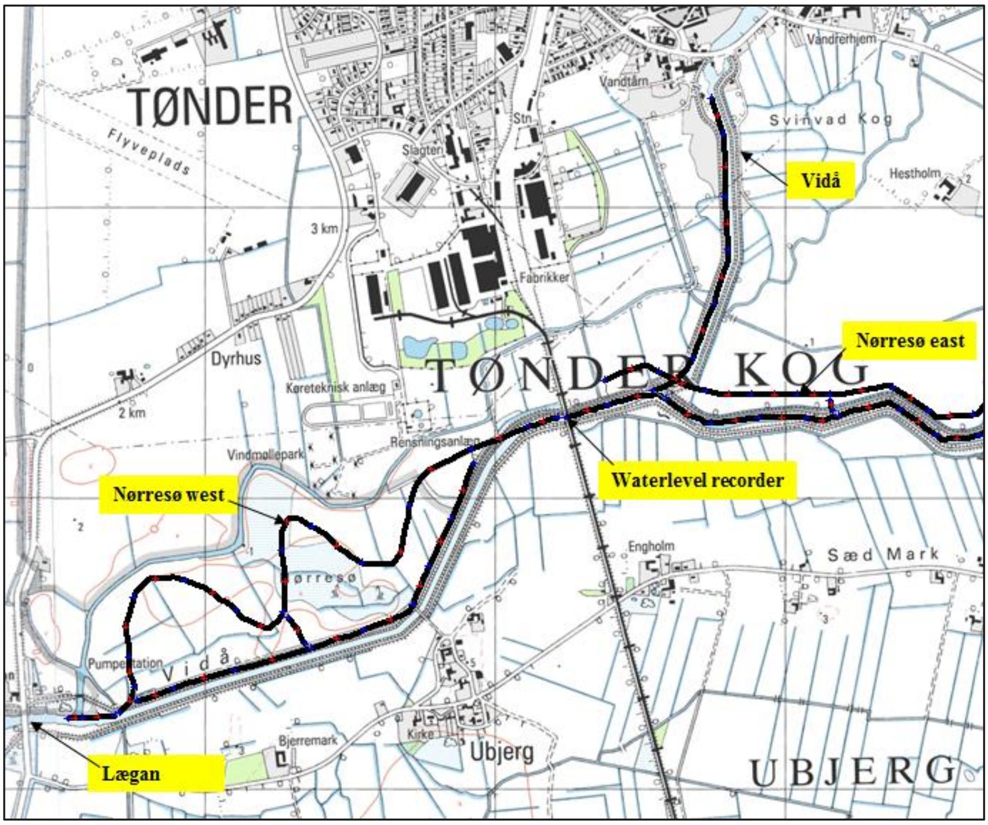


Figure 4-12 The Nørresø and Hestholm wetland restoration project

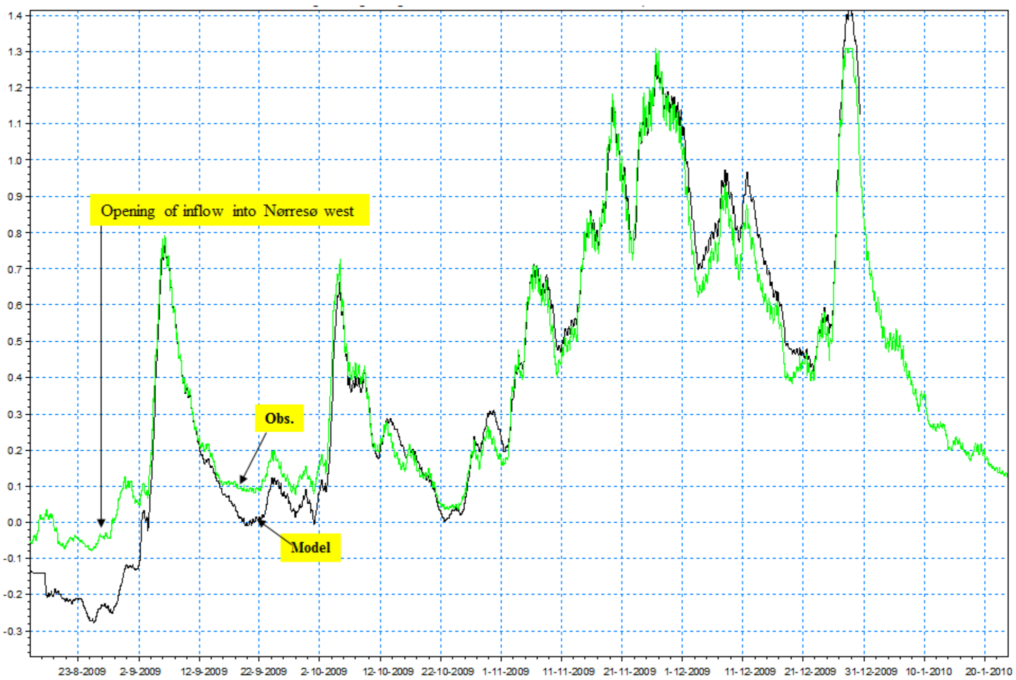


Figure 4-13 Simulated and observed water level at the railway bridge

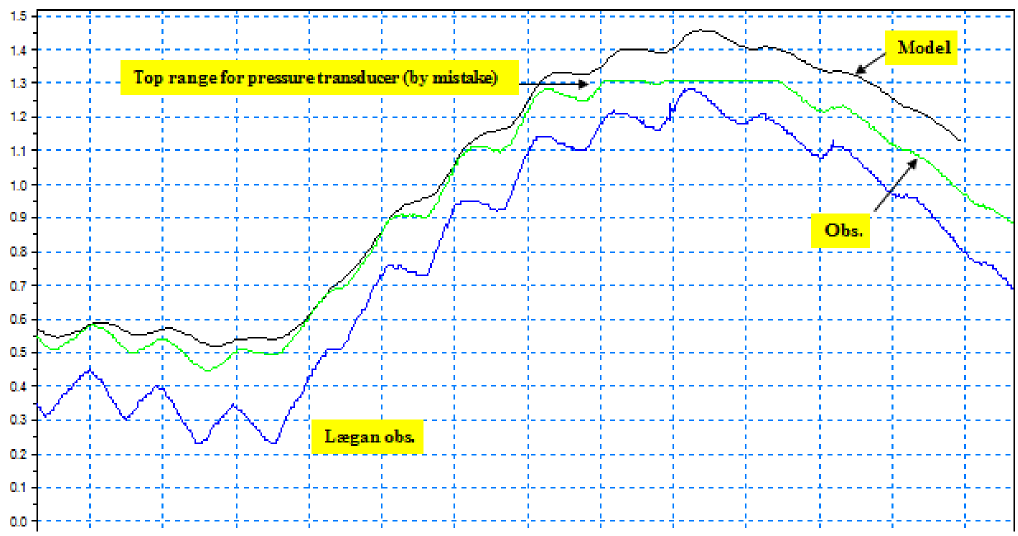


Figure 4-14 Simulated and observed water levels at the railway bridge, 24 Dec 2009 through 31 Dec 2009

4.2.2.3 Bachmanns Mølle

The former regulation of Vidåen at Bachmanns Mølle near Tønder city (Figure 4-15) has been replaced by a 500 m long stone ripple in 2008/2009. Water from the reservoir/lake at Bachmanns Mølle may during high runoff spill into the constructed ripple via a 190 m long overflow weir (crest elevation of 2.60 m DVR90). In the MIKE 11 model the lake and the ripple are two parallel branches connected via an overflow weir.

The model setup has been tested based on dedicated flow and water level measurements conducted upstream of the ripple in the period September 2009 –February 2011, see Figure 4-16. As seen the difference between model simulations and observations are within 3 - 5 cm.

Figure 4-17 shows simulated and measured Q/H relations. In the flow range 2.0 to 4.0 m^3/s the measured discharges are lower than those simulated. One explanation for the observed difference may be due to differences in the actual flow cross-sections and those applied in the model set-up. The cross-sections in the model are based on design drawings; however, erosion or subsidence during high flows after the construction may have altered the constructed river profiles.

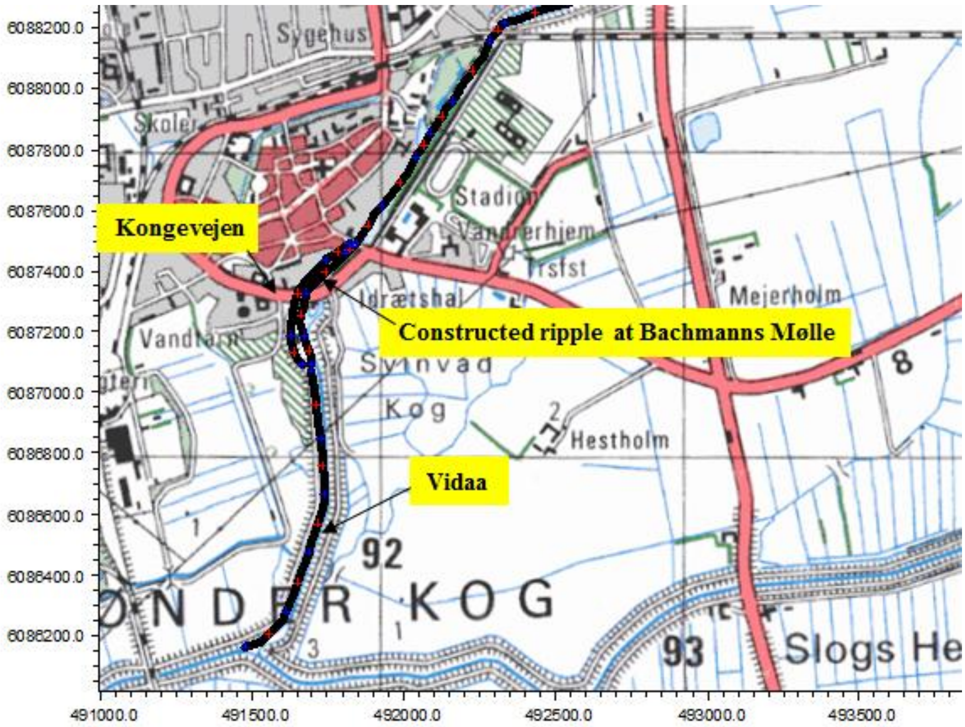


Figure 4-15 Bachmans Mølle and the 500 m long constructed ripple

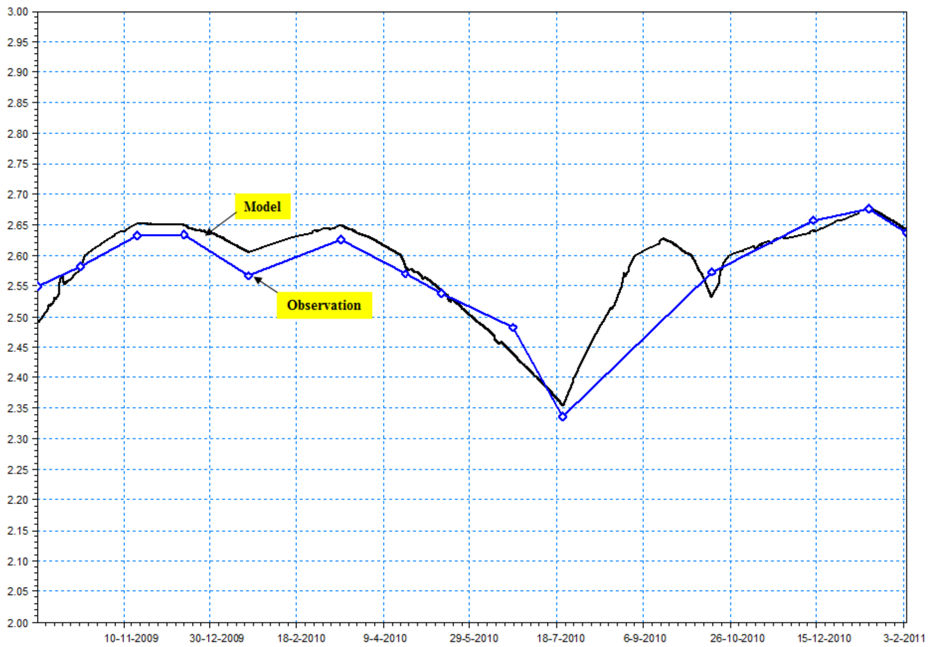


Figure 4-16 Measured and simulated water levels upstream of the constructed ripple

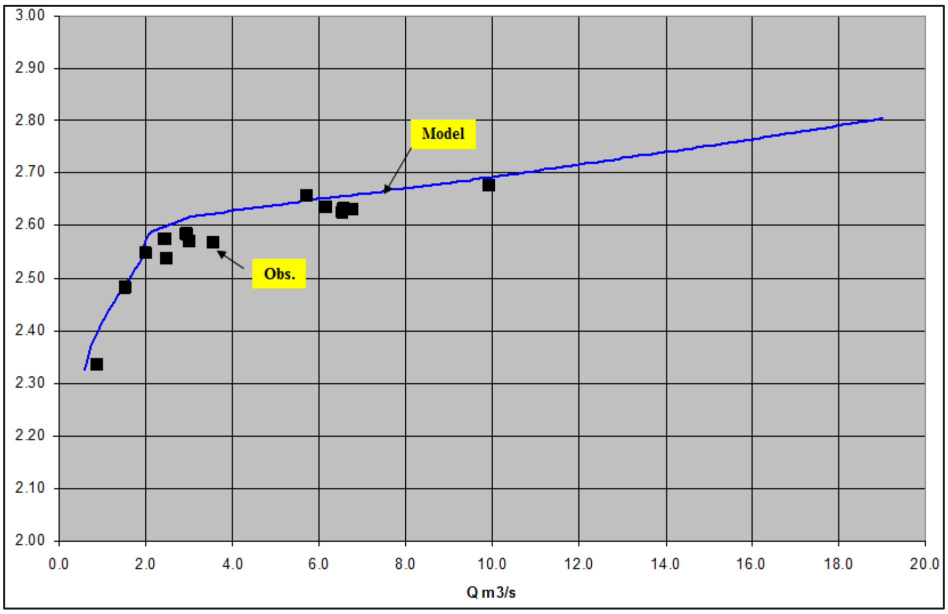


Figure 4-17 Simulated and measured Q/H relations

4.2.2.4 Hydraulic resistance to vegetation

Due to the seasonal variation in vegetation the streams will experience a similar variation in hydraulic resistance. Thus, a less severe runoff event during the summer period (with extensive vegetation) may lead to more severe flooding due to a larger hydraulic resistance. In the model the bed resistance is comprised by the Manning number. Weed cutting is carried out in most streams, however, with different intensity and frequency.

Based on the measurements of water level and discharge in Grønå/Vidå (Rørkær to Lægan) a calculation of the Manning Number has been performed as depicted in Figure 4-18. As seen there is a large seasonal and yearly variation in the computed Manning Number.

Based on the these calculations of the Manning Number for Grønå/Vidå, four different time series describing the different yearly average variation of the Manning Number for the different types of rivers were constructed, see Figure 4-19:

1. Large streams with no weed cutting
2. Smaller streams with no weed cutting
3. Streams and canals with **one** yearly weed cutting
4. Streams and canals with **two** yearly weed cuttings
5. Surface waters without yearly variation of Manning Number (lakes and reservoirs)

Figure 4-20 shows the final model distributions of the various Manning Numbers.

It should be noted that the Manning Numbers are average numbers and have the main purpose of describing the differences between major and minor streams and the differences between the different weed cutting practices. When comparing measured and calculated water levels some discrepancies can be expected mainly during the summer seasons. The Manning numbers used during the winter seasons (M= 20-28) are consistent with the Manning Number used in the model from 1997, where a calibration on periods with extreme high water levels and discharge was carried out.

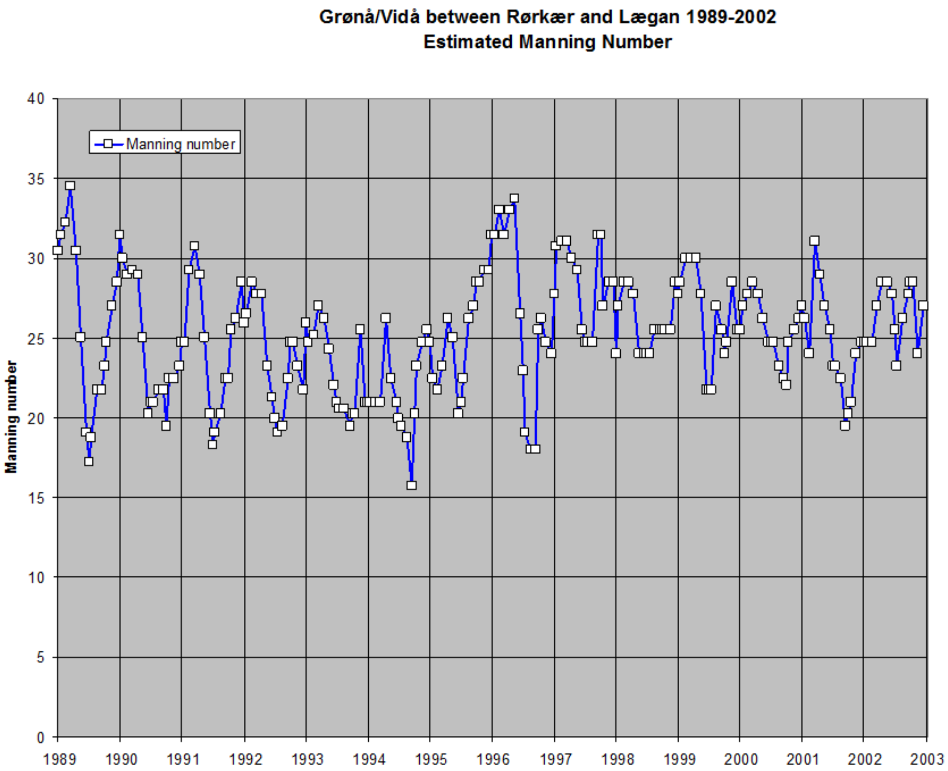


Figure 4-18 Estimated Manning Number for Grønå/Vidå between Rørkær and Lægan

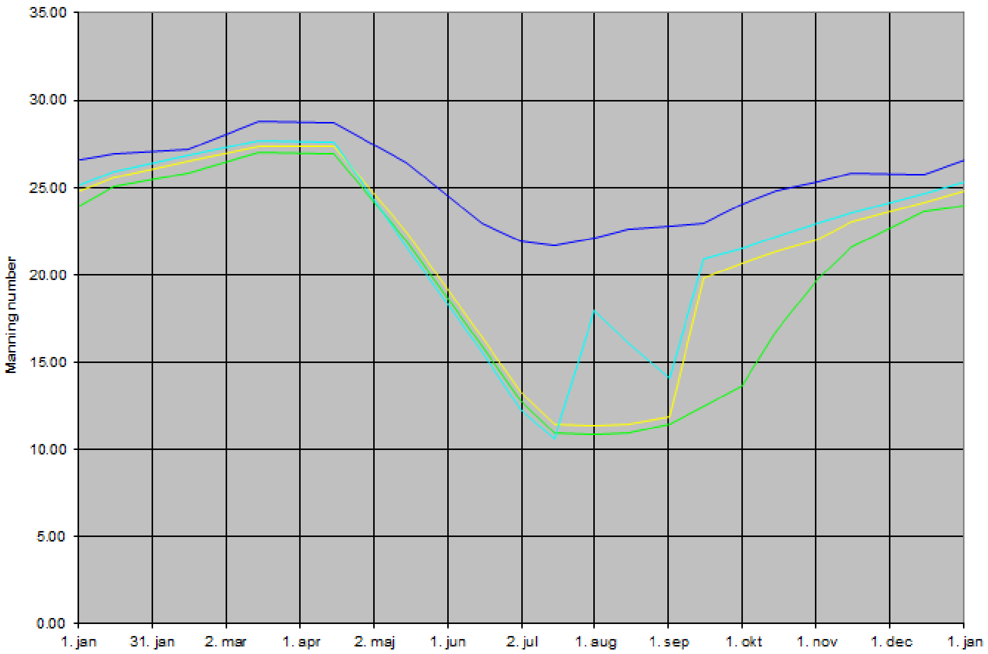


Figure 4-19 Constructed yearly Manning Number variation. Larger stream (blue curve), Smaller stream (green curve), one yearly cutting (yellow curve), two yearly cuttings (light blue curve)

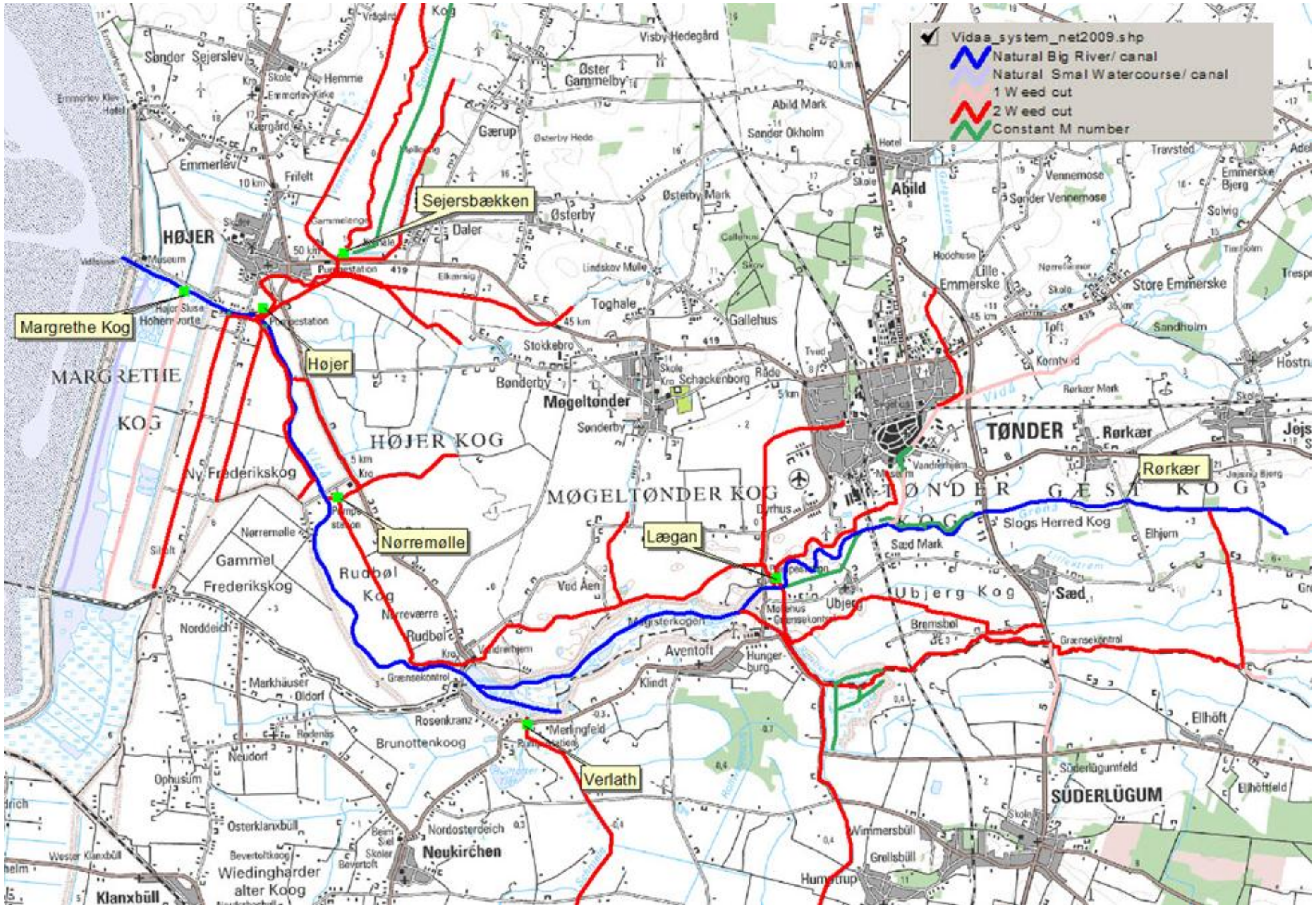


Figure 4-20 Overview map displaying art which rivers the different Manning Number variations are applied

4.2.2.5 Validation of high water extreme events

Generally, the model is capable of describing the recorded high water events quite accurately. Two particular events have been selected for further validation of the model.

October 1998:

At the end of October 1998 (October 28-31) extreme high water levels were recorded in the lower part of the Vidå system (at Lægan 2.0 meter DVR and 1.75 -1.80 m DVR at the Vidå sluice gate). These levels were the highest ever recorded.

The simulated and recorded water levels at different locations are shown in Figure 4-21 through Figure 4-24.

February 2002:

At the end of February 2002 snow melting combined with heavy precipitation and runoff caused high water levels in the lower part of Vidå with water levels at Lægan reaching 1.82 m DVR. This level was the third highest level ever recorded.

The simulated and recorded water levels at different locations are shown in Figure 4-25 through Figure 4-30.

As seen the agreement between simulations and observations is not as good as during the October 1998 event. The maximum water levels are underestimated by the model by up to 15 cm.

The main reason for the underestimation in water levels is due to the fact that the catchment runoff and hence the simulated discharges are too low as can be seen in Figure 4-31 .

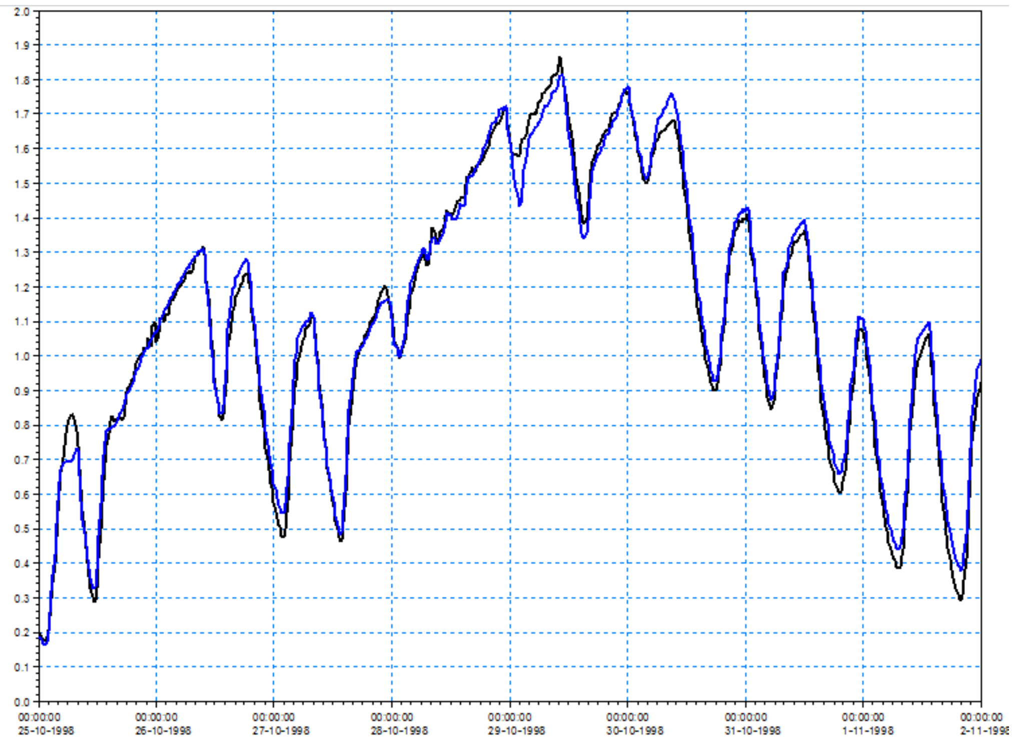


Figure 4-21 Simulated (black curve) and measured (blue curve) water level in Vidå at the Højer sluice- October-1998

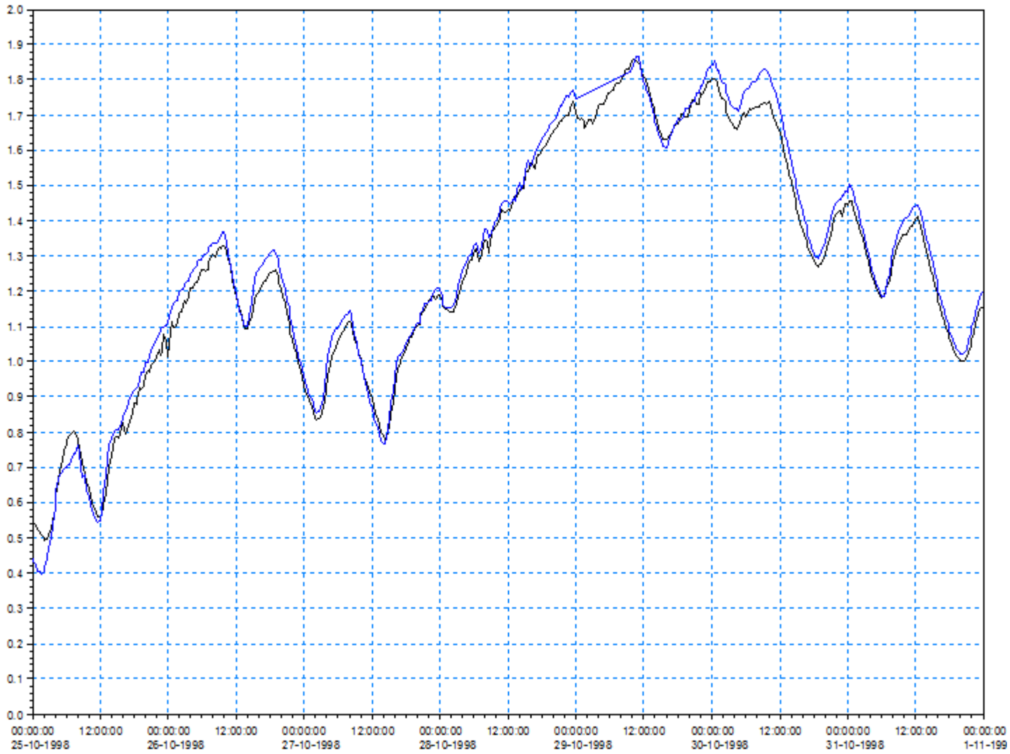


Figure 4-22 Simulated (black curve) and measured (blue curve) water level in Vidå at the Nørremølle pumping station- October-1998

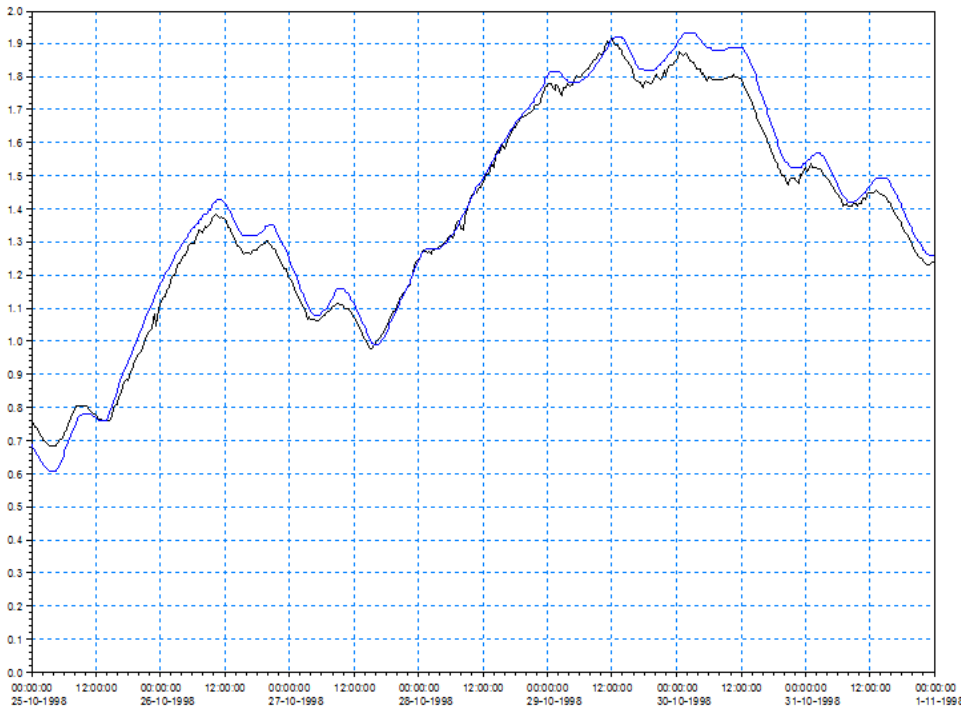


Figure 4-23 Simulated (black curve) and measured (blue curve) water level in Vidå at Lyst in the Magister Kog- October-1998

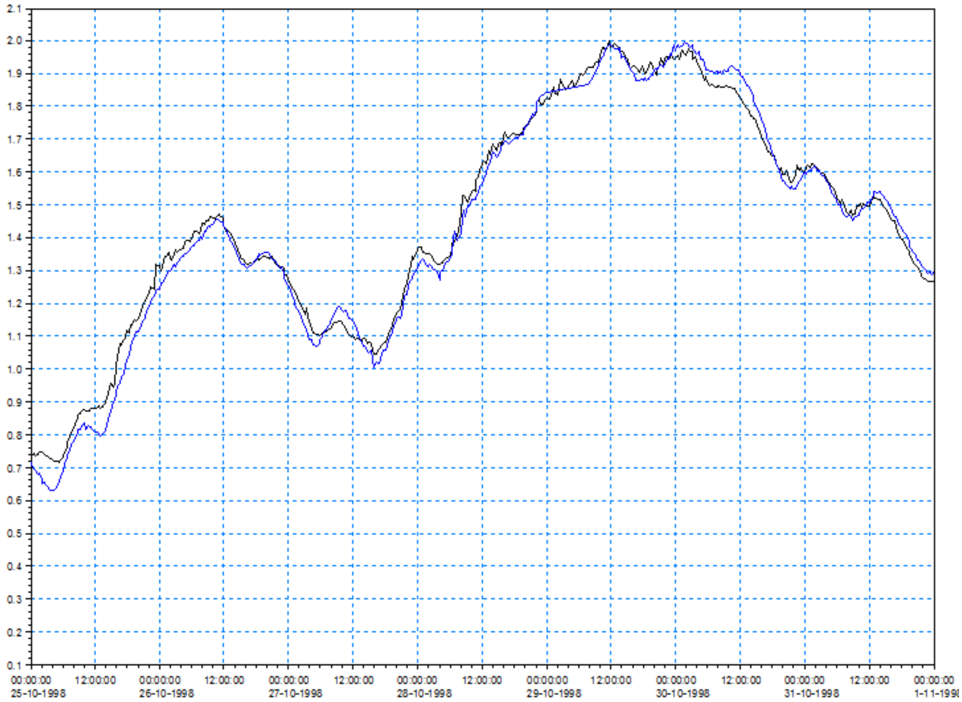


Figure 4-24 Simulated (black curve) and measured (blue curve) water level in Vidå at Lægan pumping station-October-1998

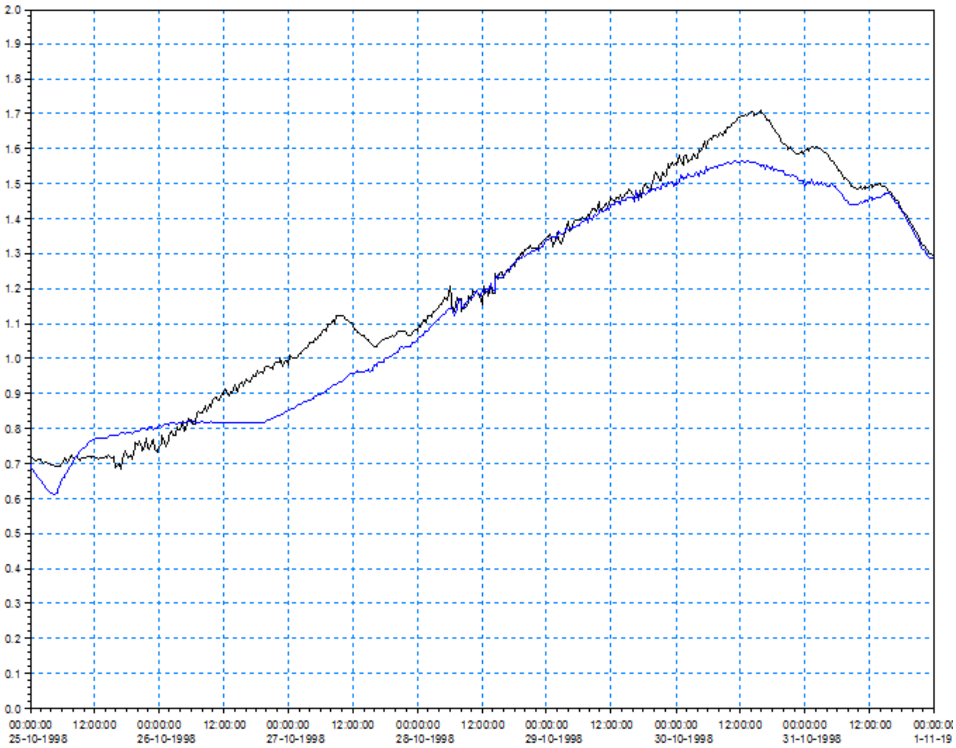


Figure 4-25 Simulated (black curve) and measured (blue curve) water level in Sønderå at the Møllehus sluice-October-1998

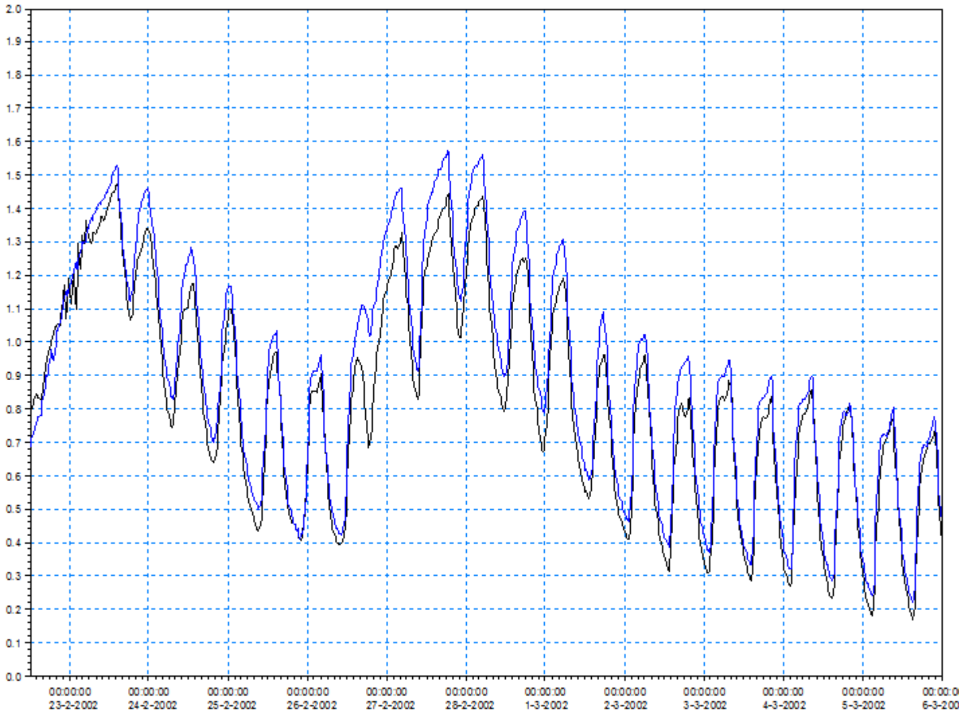


Figure 4-26 Simulated (black curve) and measured (blue curve) water level in Vidå at the Højer sluice- February-2002

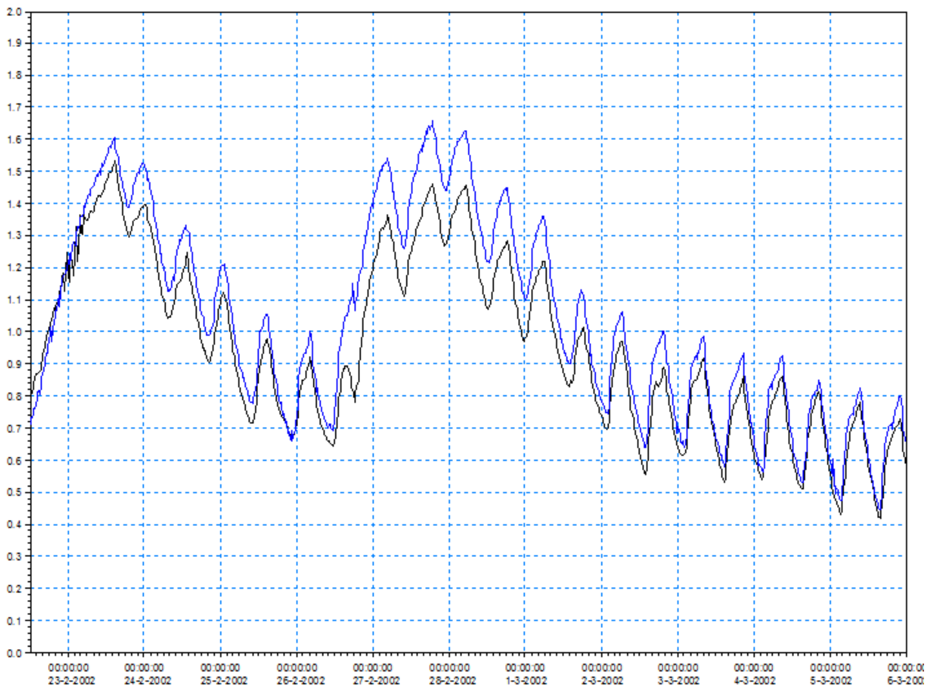


Figure 4-27 Simulated (black curve) and measured (blue curve) water level in Vidå at the Nørremølle pumping station- February-2002

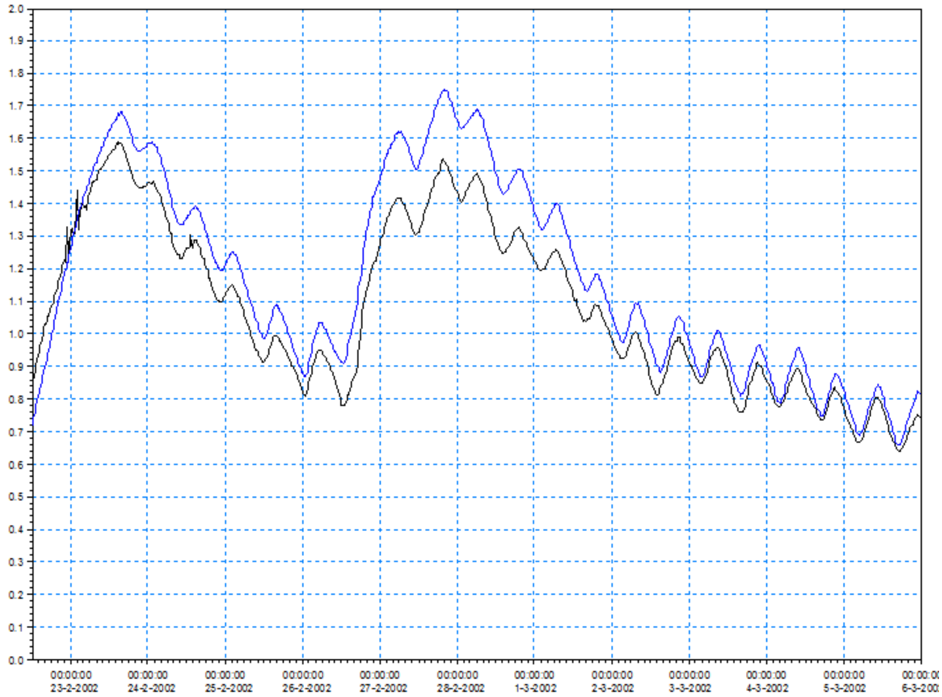


Figure 4-28 Simulated (black curve) and measured (blue curve) water level in Vidå at Lyst in the Magister Kog- February-2002

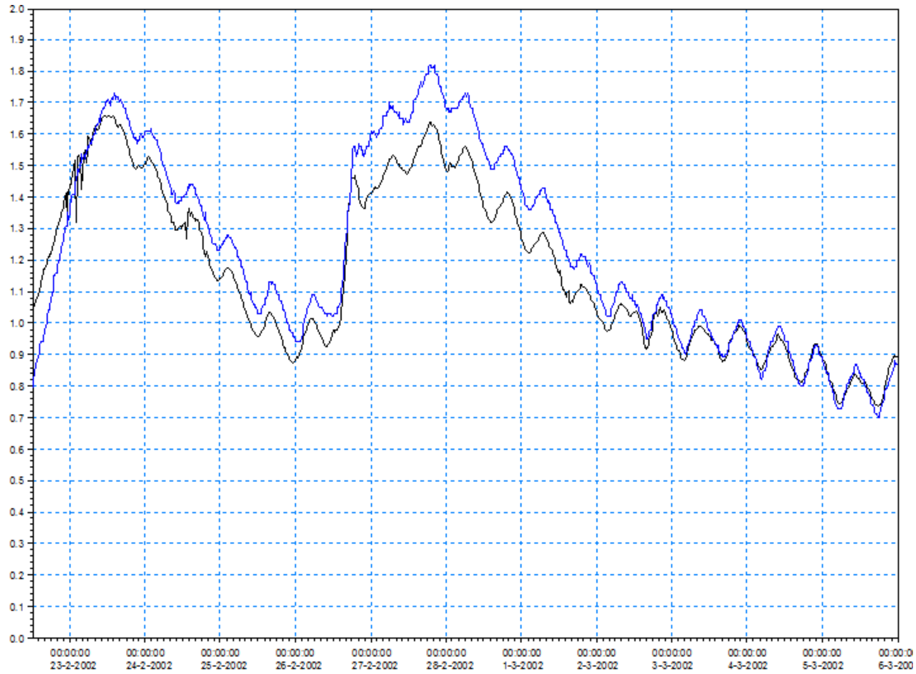


Figure 4-29 Simulated (black curve) and measured (blue curve) water level in Vidå at Lægan pumping station- February-2002

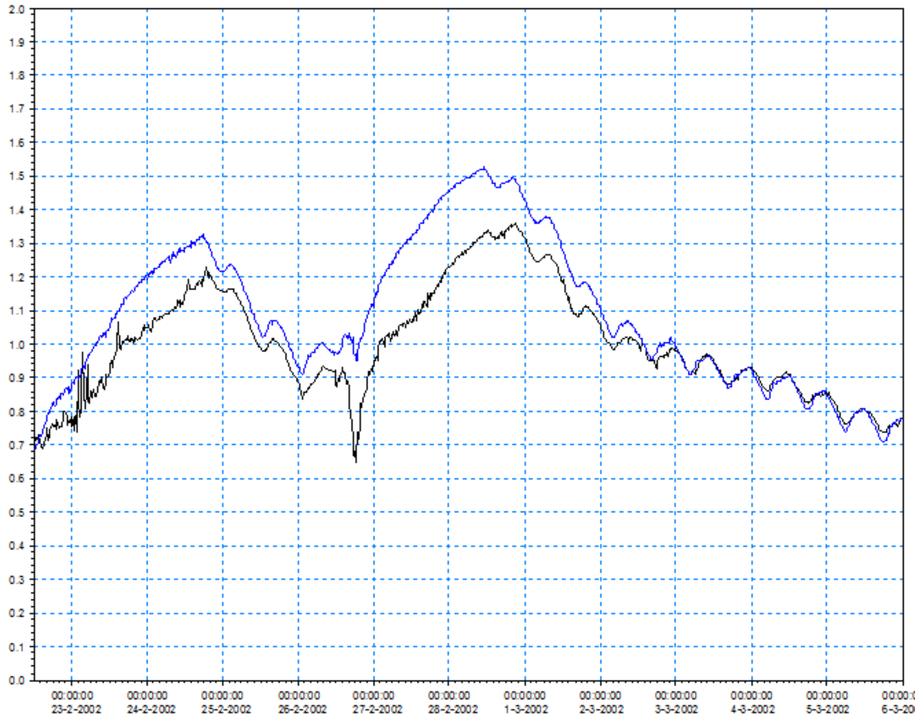


Figure 4-30 Simulated (black curve) and measured (blue curve) water level in Sønderå at the Møllehus sluice- February-2002

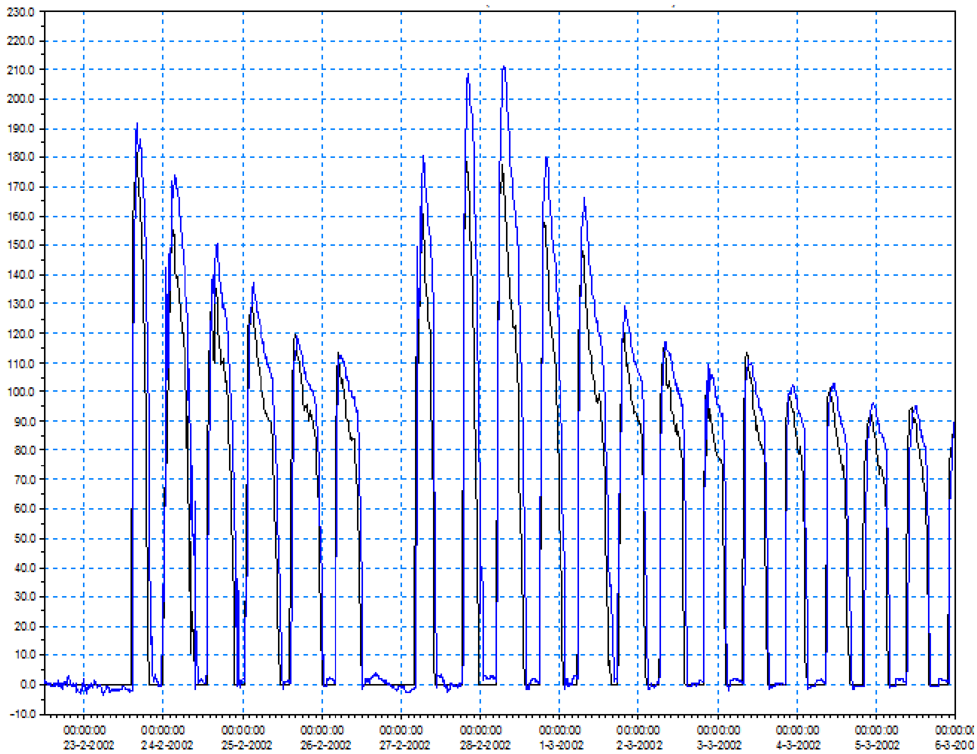


Figure 4-31 Simulated (black curve) and measured (blue curve) discharge at the Vidå sluice. - February-2002

5 Results

5.1 Identification of storm events and related river flows where high water levels in the Wadden Sea prevent outflow

In general, extreme conditions with high water levels in the river system occur during periods with high sea water levels at the Vidå sluice and large runoff from the catchment. The 10 events that cause the most extreme water levels in the downstream part of the river system during the simulation period 1981-2009 are listed in Table 5-1. The most extreme event on record (29/10/1998) is mainly caused by extreme conditions of high sea water level at the Vidå sluice (the most extreme duration on record) and less so on catchment runoff (rank 19 on record). Also the second (26/01/1993) and third (12/01/2007) largest events are mainly caused by extreme durations of high sea water levels. On the other hand, the event 11/02/1988 (rank 6) is mainly due to extreme runoff conditions (rank 2) and less affected by the sea water level conditions. The table shows the complex nature of extreme conditions in the river system, which emphasises the need for integrated hydrological and hydraulic modelling for proper flood risk assessment.

Table 5-1 Water level (H) at Rudbøl Lake, total catchment runoff (Q) and peak sea water level (H) and duration of high water level (above 0.5 m) at the Vidå sluice for the 10 most extreme events in the downstream part of the river system

Date	Water level Rudbøl Lake		Total catchment runoff		Sea water level Vidå sluice			
	H [m]	Rank	Q [m3/s]	Rank	H [m]	Rank	Duration [h]	Rank
29/10/1998	1.79	1	71.5	19	2.39	> 60	70.25	1
26/01/1993	1.70	2	69.8	21	3.33	15	58.50	4
12/01/2007	1.66	3	70.5	20	3.28	18	58.25	5
14/01/1984	1.65	4	66.4	29	2.71	56	44.50	18
29/01/1994	1.63	5	55.0	> 60	3.77	5	34.00	43
11/02/1988	1.61	6	85.0	2	2.73	53	33.00	52
21/01/2007	1.58	7	71.5	18	2.70	> 60	22.00	> 60
29/01/2002	1.56	8	67.4	26	3.64	8	22.25	> 60
04/01/1988	1.56	9	76.8	8	2.32	> 60	34.50	35
04/01/1984	1.55	10	53.5	> 60	3.29	16	45.50	14

5.2 Assessment of potentially restricted outflow from the old Højer Sluice gate

It has been questioned whether the old Højer Sluice gate could act as restriction for outflows during high catchment runoff and hence high river discharges. Figure 5-1 provides measured water levels up-and downstream of the old Højer sluice during a high runoff event in November 1998. As can be seen there are only minor differences in up-and downstream high water levels. It should be noted that the downstream water level is measured at the Vidå sluice gate (inside), and whenever the gate is open the water level is entirely controlled by the outside conditions in the Wadden Sea.

In order to assess the potential restriction in more detail, model simulations were carried out with and without the old Højer Sluice. The results are shown at two locations in Figure 5-2 (just upstream of the Højer Sluice and in Rudbøl Sø). The simulations covered a period of high flow in 2002. As seen the maximum observed difference does not exceed 5 cm.

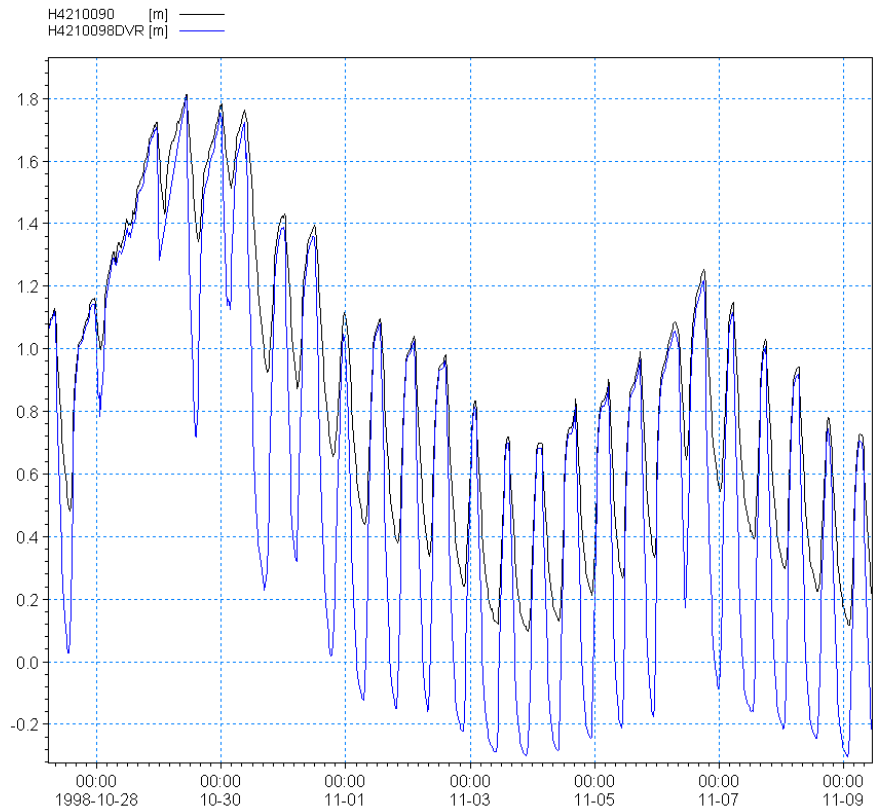
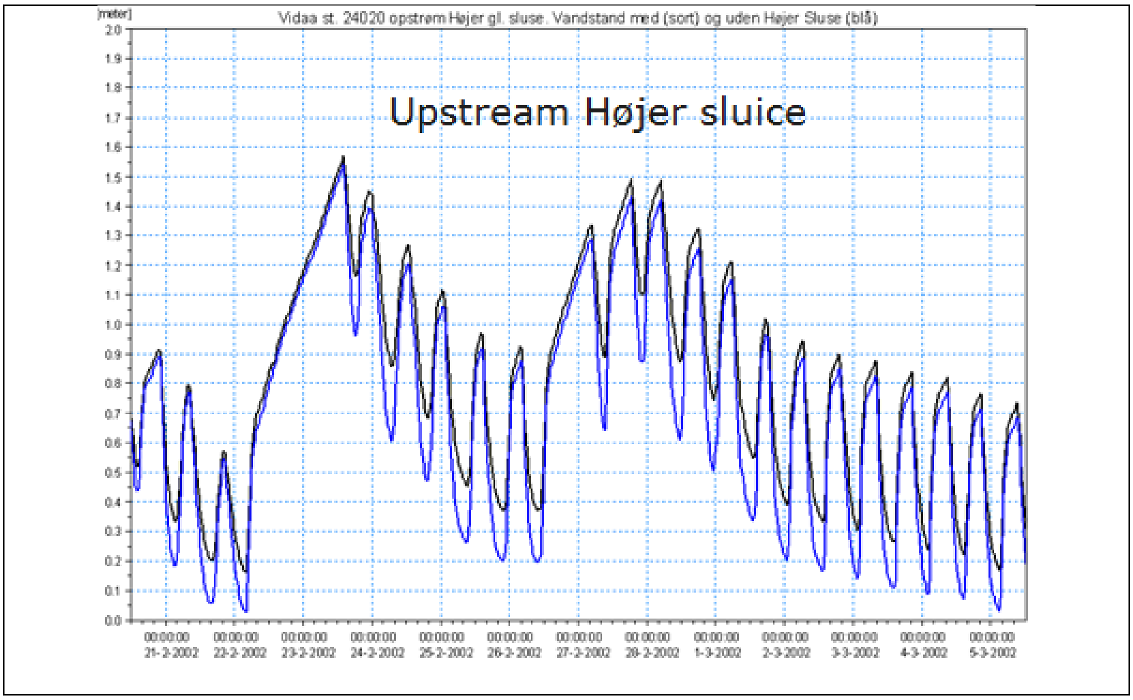


Figure 5-1 Measured water level up (black curve) - and downstream (blue curve) of the old Højer Sluice



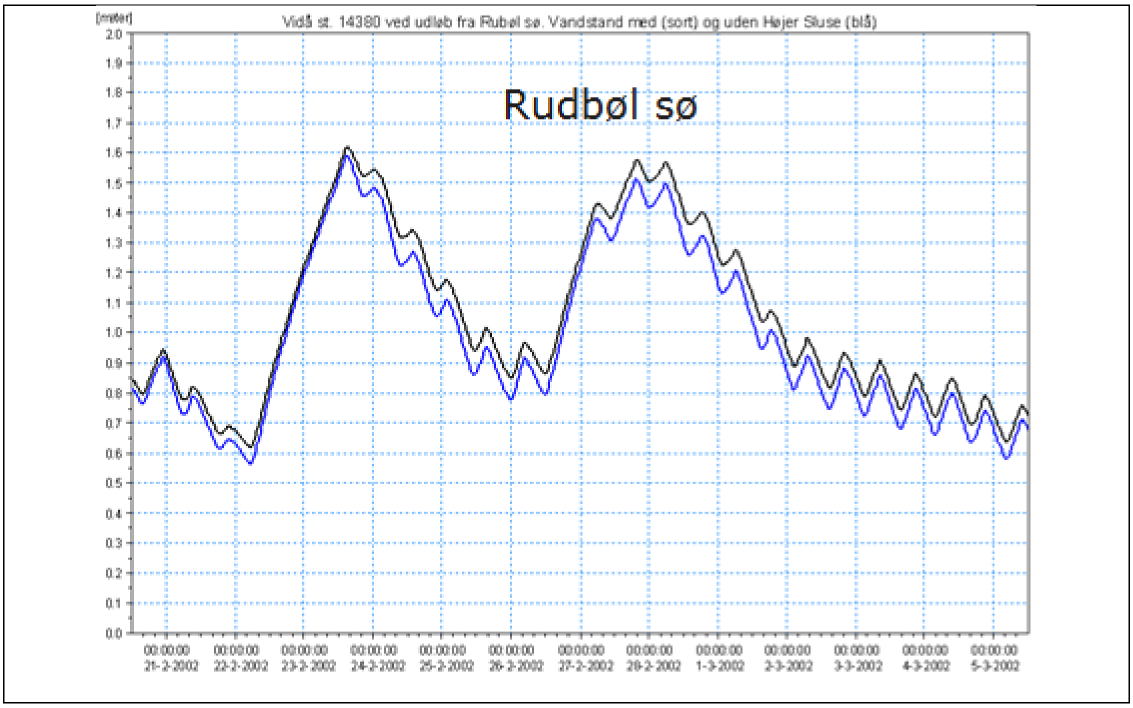


Figure 5-2 Simulated water level with (black curve) and without (blue curve) the old Højer Sluice gate

5.3 Assessment of the outflow flap gate system from the Sønderå into the Vidå system in relation to flood control

The function of the sluice in Sønderå – called the Møllehus sluice (Figure 5-3) – is to prevent inflow during high water levels in the Magisterkogen. The sluice has three openings. The middle gate has a width of 4.0 m and two horizontal hinged self-closing gates. The other two openings each having a width of 2.0m are equipped with underflow gates, which have to be operated manually.

According to regulations for Tøndermasken it is the responsibility of Digelaget to remove the underflow gate in case the inflowing water cannot pass through the middle opening. Normally, the side-openings are closed and it is extremely rare that the underflow gates are removed with the purpose of lowering the water level at inside of the sluice. Thus, under normal conditions the water level upstream of Møllehus sluice is regulated entirely by the capacity of the middle opening.

At several occasions it has been argued that the capacity of the sluice is too small and an increase of the flow area would decrease the risk of unwanted high water levels in Sønderå. The capacity of the sluice could be increased by reconstructing the side-openings so that they are identical with the middle opening, e.g. remove the manually operated underflow gate and equip them with self-closing gates.

To investigate the above an extreme high water situation is modelled with two different scenarios:

- Existing conditions, e.g. a 4.0m wide middle opening equipped with a gate
- Existing conditions (like above) + the 2 side openings equipped with gates, e.g. the flow area is approximately doubled

The results of the calculations can be seen in Figure 5-4.

The effect of increasing the flow area is a lowering of the water level of 2-3cm, when the sluice is open. The effect gradually declines in upstream direction. At the Dreiharder-Gotteskoogstrom junction with Sønderå the effect is 1-2cm. As clearly illustrated in Figure 5-4 , there will be no outflow from Sønderå as long as the downstream water level is higher than the upstream water level in the Sønderå.

Thus, it can be concluded that it will not be possible to obtain reasonable lowering of the up-stream water level of the Møllehus sluice by increasing the flow area.

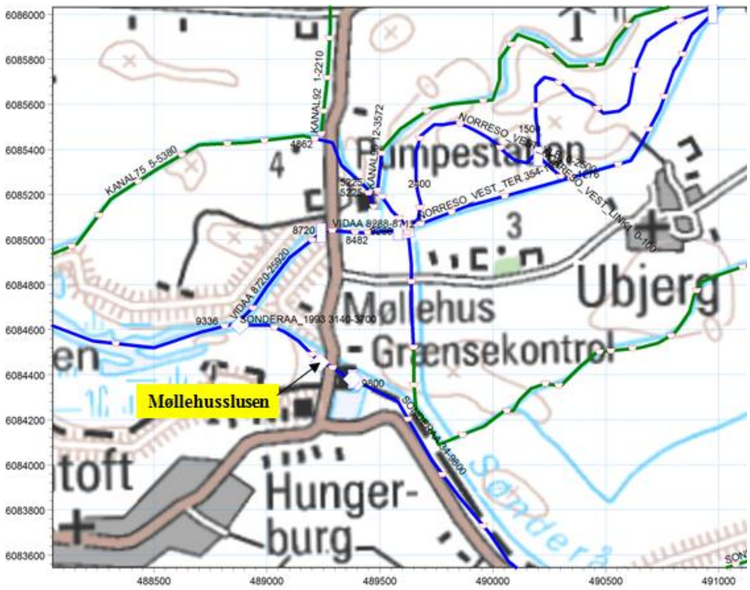


Figure 5-3 Location of the Møllehus sluice

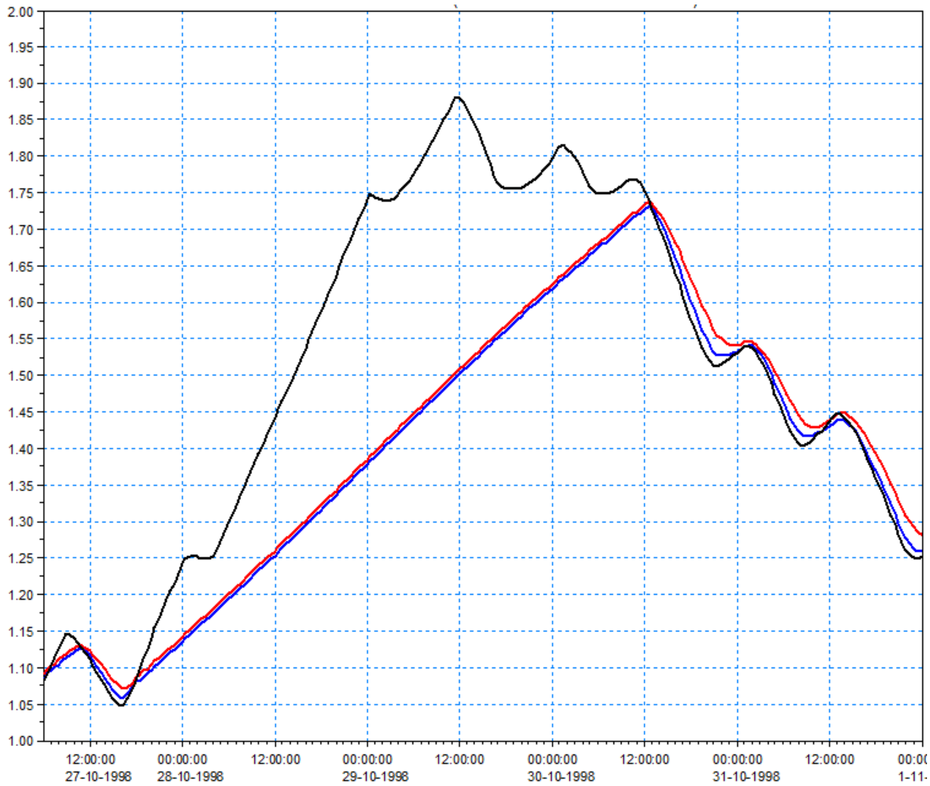


Figure 5-4 Simulated water levels in Sønderå near the Møllehus sluice, October 1998. Downstream water level (black curve), upstream water level present condition (red curve) and upstream water level with increased flow area (blue curve)

5.4 Assessment of increased storage capacity

5.4.1 Assessment of the effect of pullback of existing dikes along the Sønderå on both sides of the German Danish border and extension of the storage of the Haasberger See

A reduction in extreme high water levels can potentially be achieved by increasing the upstream storage capacity. In this context the potential effect of pullback of existing dikes along the Sønderå on both sides of the German Danish border and extension of the storage of the Haasberger See have been investigated.

The basis for model updating was maps describing the proposed location of the new dike lines (see Figure 5-5) in combination with a DEM (digital elevation model) with a resolution of 1m. The latter has been provided by the "Landesamt fuer Landwirtschaft, Umwelt und laendliche Raeume" in Schleswig-Holstein.

Using the October 1998 extreme event model simulations were carried out to assess the impact of dike relocation. The results are shown in Figure 5-6 through Figure 5-8 as longitudinal profiles along the Sønderå, Dreiharder-Gotteskoogstrom and Geestableiter respectively. While the red curve represents the riverbed profile the two upmost curves represent the maximum water level occurred during the simulations, with and without the increased storage. As illustrated only minor reductions in maximum water levels can be expected during the 1998 extreme event. The maximum simulated reductions relative to the existing conditions were as follows:

Sønderå: 3.5 cm

Dreiharder-Gotteskoogstrom: 3.4 cm

Geestableiter: 3.3cm

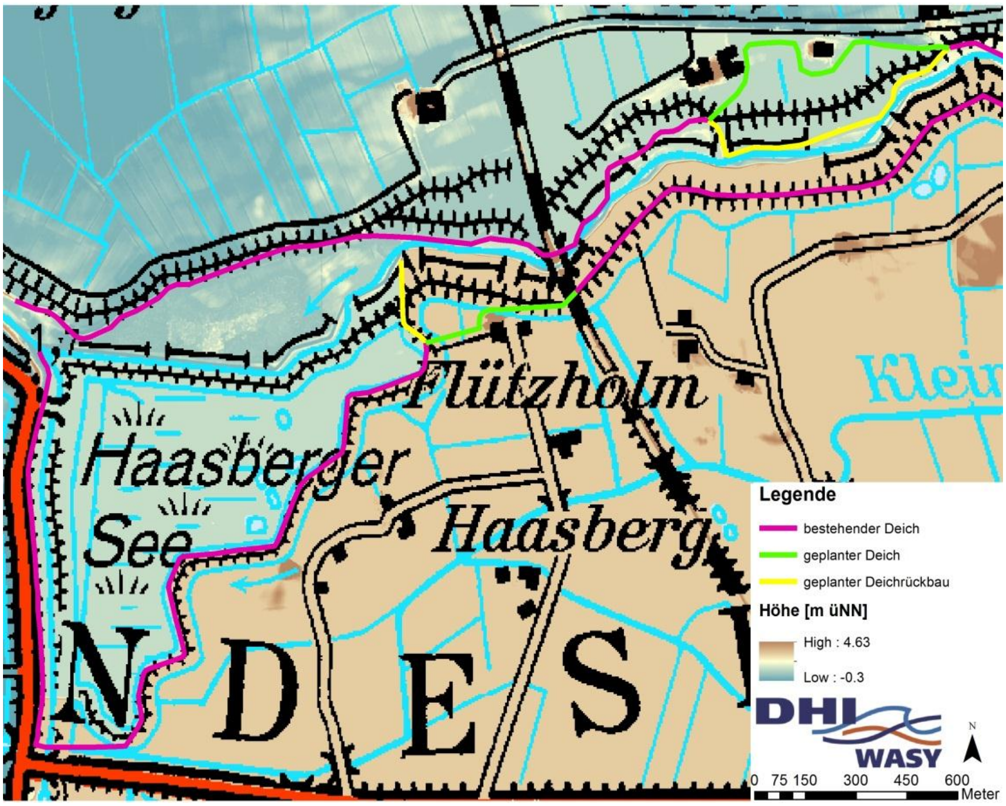


Figure 5-5: Investigation area with existing dike line (red) and planned dike line (green)

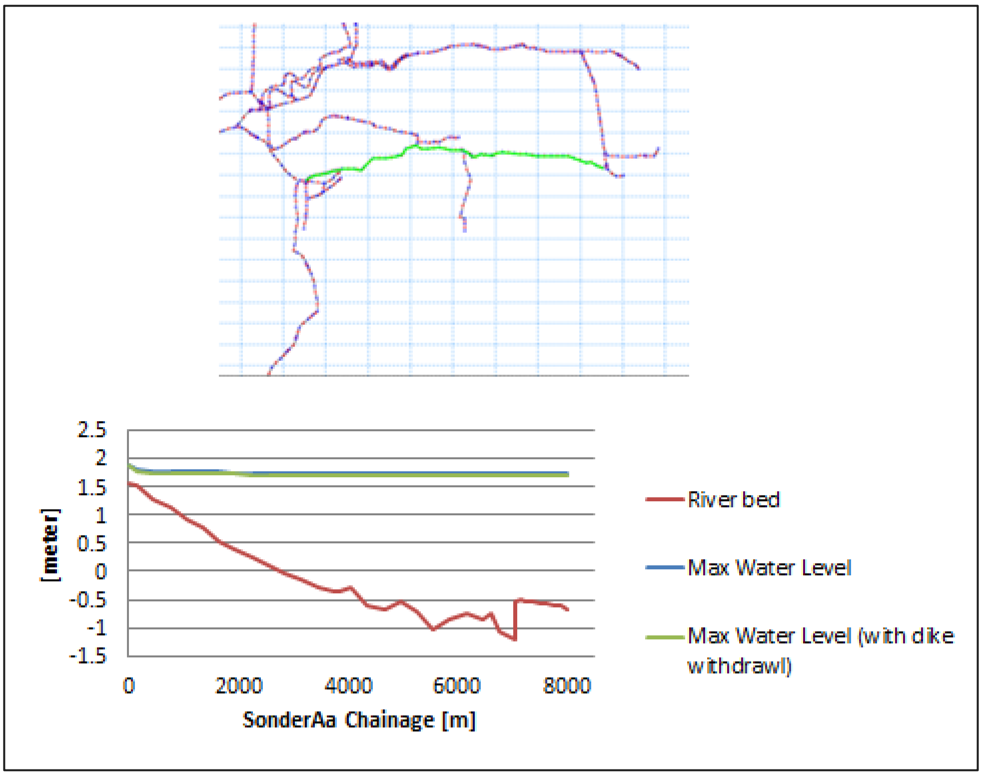


Figure 5-6 Longitudinal profile of maximum simulated water level along Sønderå with and without dike relocation

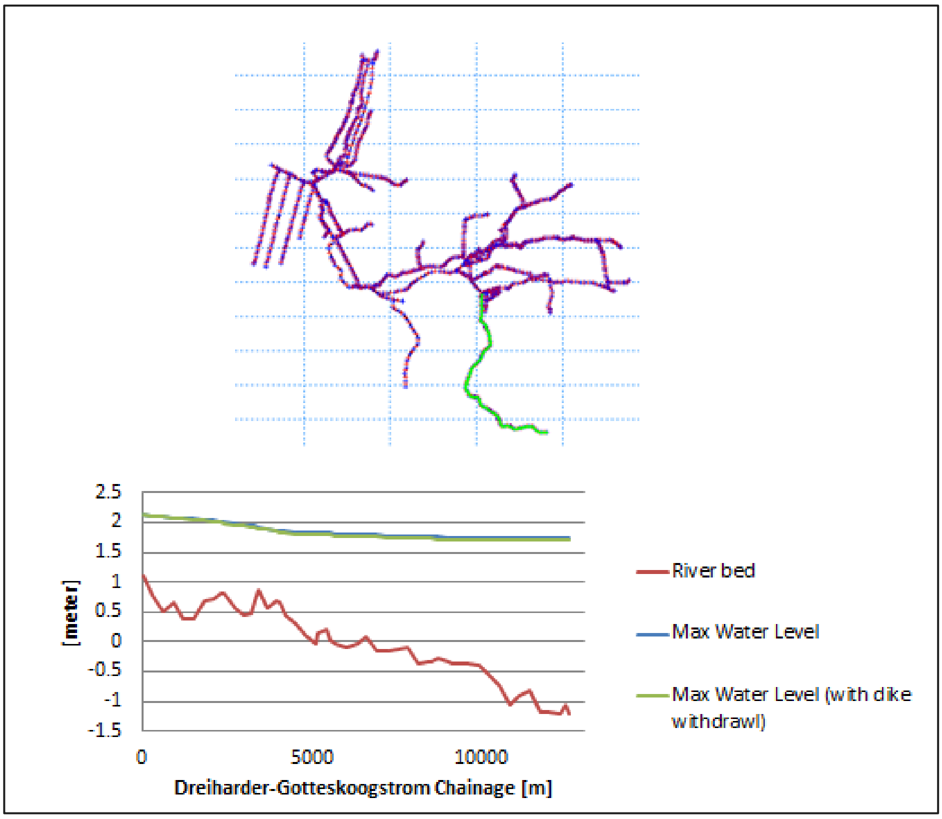


Figure 5-7 Longitudinal profile of maximum simulated water level along Dreiharder-Gotteskoogstrom with and without dike relocation

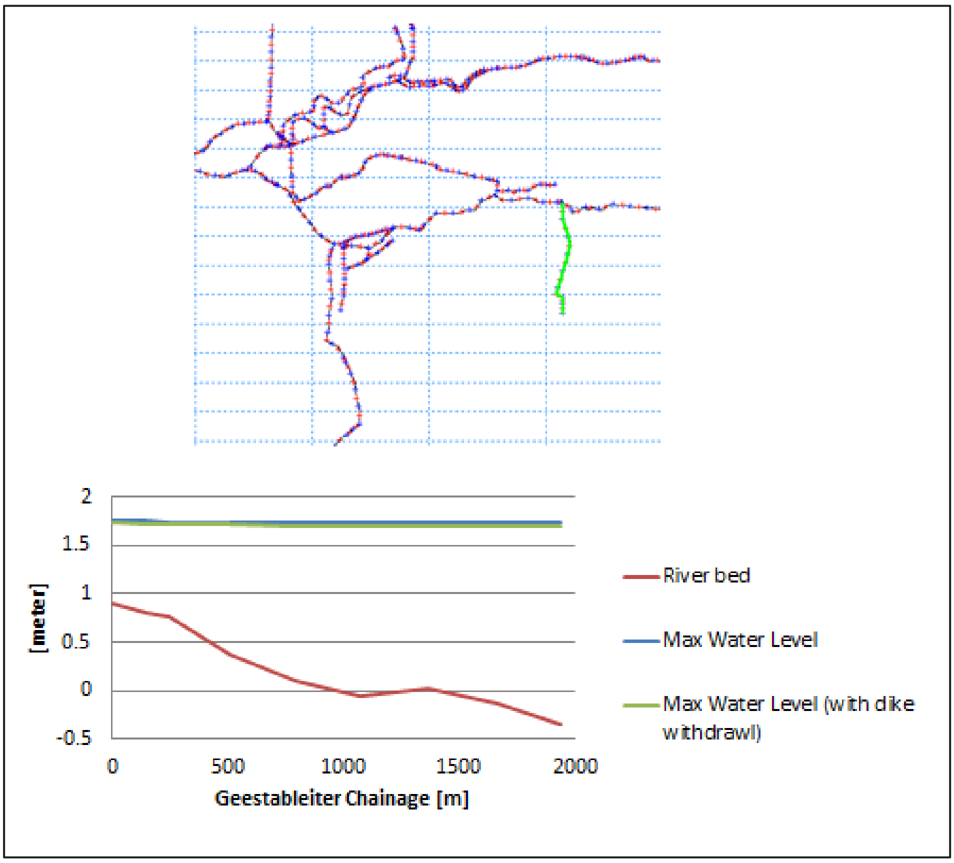


Figure 5-8 Longitudinal profile of maximum simulated water level along Geestableiter with and without dike relocation

5.4.2 Assessment of the effect of increased storage capacity in Sønderå from Møllehus to the border at Sæd

The increased storage capacity can be activated by controlled overflow of existing dikes along the Sønderå combined with a new retracted dike. The inflow to a high water reservoir could be activated by constructing an inflow weir where the weir crest elevation controls the frequency of inflows (i.e. the higher the crest elevation the less incidents of dike overflows and vice versa). Outflow from the reservoir can be established via a one-way sluice gate allowing outflow to the Sønderå whenever the water level in the river is lower than the water level in the reservoir.

Draining of the lowest lying areas of the reservoir after an overflow incident can potentially be carried out via the existing drainage system and the associated pumping stations.

Figure 5-9 provides a schematic drawing of the proposed high water reservoirs.

Using the October 1998 extreme event model simulations were carried out to assess the impact of increased storage capacity. In the modified model set-up it is further assumed that the planned expansion of the magazine capacity of Haasberger See by Flutzholm (about 7 ha) and the Bremsbøl project with a further increase in storage capacity (about 9 ha) has been implemented.

Three scenarios were investigated:

Scenario 1: The reservoir (referred to as "DHSV") is located on the German side of the border between the custom house at Sæd and the railway track Tønder – Niebøl:

- Surface area: 50 ha, Ground elevation: 0.10 DVR.
- Overflow weir: Crest elevation: 1.10 m DVR, width: 50 meter.
- Outflow sluice gate: Bottom elevation: - 0.50 m DVR, width : 1.0 m.

Scenario 2: The reservoir is located on the Danish side of the border in Udbjerg Kog.:

- Surface area: 90 ha, Ground elevation: 0.10 DVR.
- Overflow weir: Crest elevation: 1.20 m DVR, width: 50 meter.
- Outflow sluice gate: Bottom elevation: - 0.50 m DVR, width: 1.0 m.

Scenario 2: Both reservoirs are activated:

The results of the simulations are shown in Figure 5-10 through Figure 5-12, and Table 5-2 provides a summary of the simulations. Figure 5-10 and Figure 5-11 each contain three curves whereas Figure 5-12 contains four curves. The curves represent the simulated water levels upstream of the Møllehus sluice with and without the reservoir respectively. In addition the simulated water level within the reservoirs is also illustrated. As clearly demonstrated no inflow to the reservoirs takes place before the outside water level has reached the inlet crest elevation. On the other hand the reservoir water level cannot be lowered by a simple one-way sluice gate before the outside water level is lower than the water level within the reservoir. The latter is clearly demonstrated in Figure 5-11 representing the impact of the Udbjerg Kog reservoir. The effect of both reservoirs is shown in Figure 5-12. It can be noted that the potential of the Udbjerg Kog reservoir is not utilized to the same extent as shown in Figure 5-11. The main reason being the filling of the DHSV reservoir and hence reduced water levels at the inlet structure at Udbjerg Kog. Thus the combined effect of activating both reservoirs is minor compared to the effect of the individual reservoirs (see Scenario 3 in Table 5-2).

Table 5-2 Simulated maximum water levels in Sønderå (upstream of the Møllhus sluice) with high water reservoirs on the German and Danish sides of the border

	Max. Water level (DVR) in Sønderå	DHSV-reservoir Inflow volume m^3	Udbjerg Kog reservoir Inflow volume m^3
Scenario 0	1.56		
Scenario 1	1.39	562.000	
Scenario 2	1.34		706.000
Scenario 3	1.31	525.000	232.000

It is concluded that a significant reduction in high water levels can be achieved by activating the proposed high water reservoirs. Further optimization of the reservoirs with respect to size, inlet crest elevations and width of inlet structures may lead to even further reduction in water levels during extreme high waters events. The optimization can conveniently be carried out utilizing the modified model setup comprising the two reservoirs.

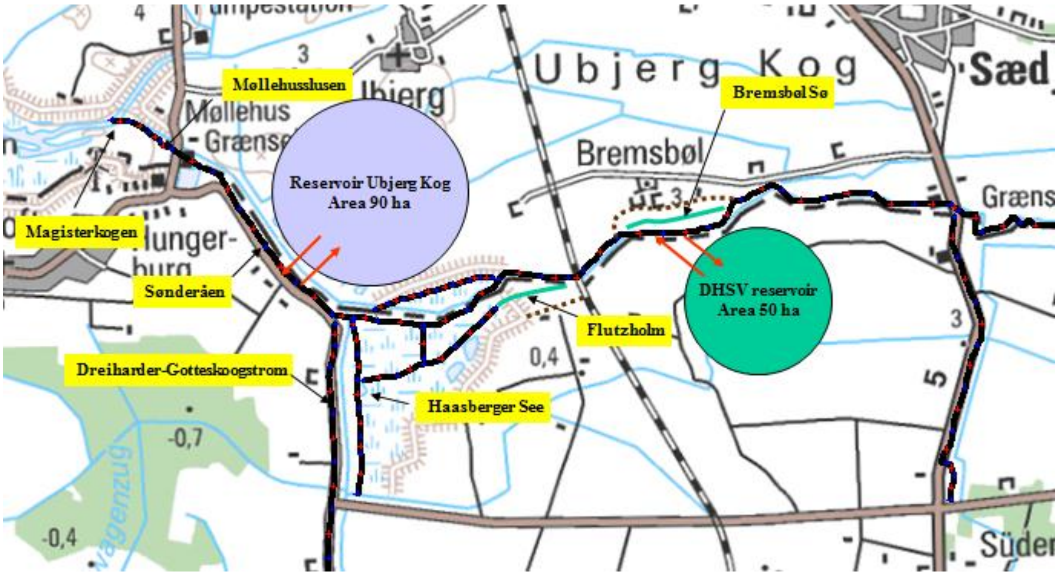


Figure 5-9 Location of proposed high water reservoirs on the German and Danish sides of the border

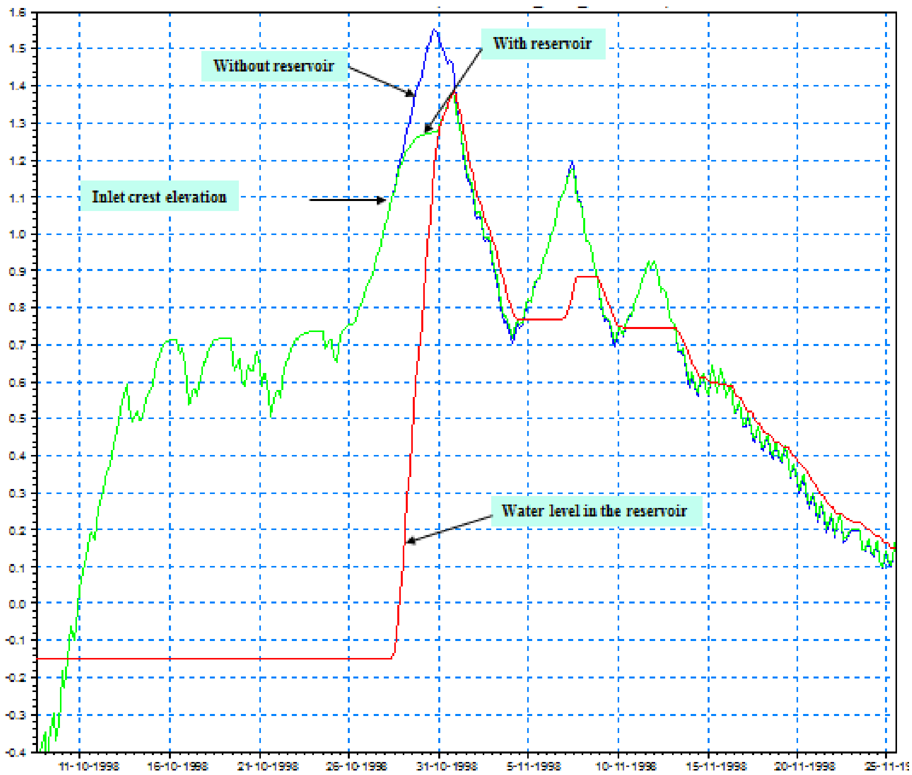


Figure 5-10 Scenario 1: 50 ha DHSV reservoir on the German side: Simulated water level in the Sønderå upstream of the Møllehus Sluice

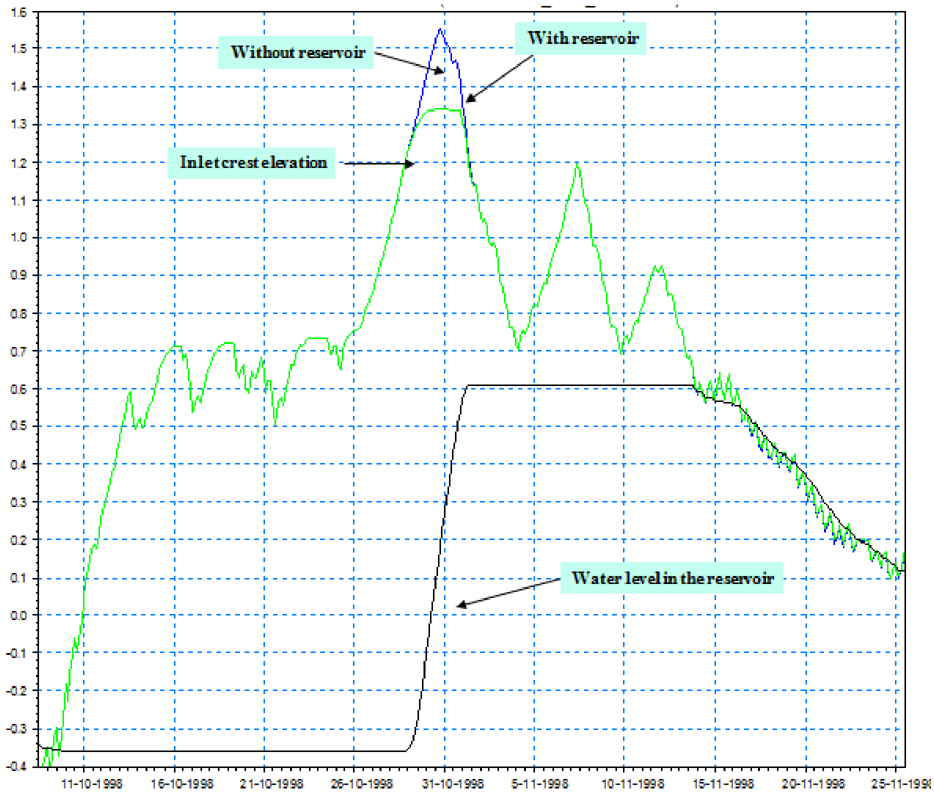


Figure 5-11 Scenario 2: 90 ha Udbjerg Kog reservoir on the Danish side: Simulated water level in the Sønderå upstream of the Møllehus Sluice.

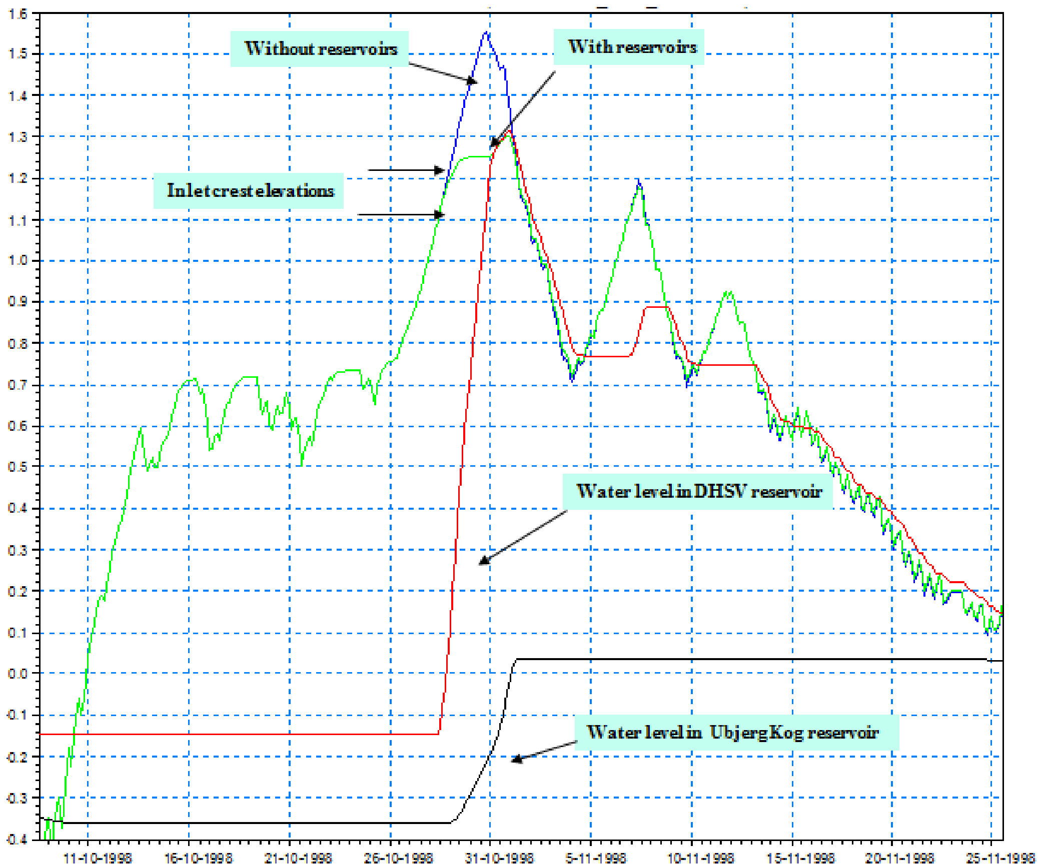


Figure 5-12 Scenario 3: Both reservoirs active

5.4.3 Assessment of the storage capacity potential of the eastern part of the Margrethe Kog

The southern part of Margrethe Kog (located between Digevej and the Danish-German border) has an area of approx. 7.1 km^2, see Figure 5-13 . The western part (the freshwater reservoir and the salt water lake) is directly connected to Vidå. The eastern part (approximately. 4.7 km^2) is surrounded by a dike with a crest elevation corresponding to approximately 2.15m DVR90. The dike protects against flooding during periods with high water levels in Vidå. Drainage is taking place through a sluice gate and a pumping station. The elevation of the Margrethe Kog varies between 1.0 and 1.5m DVR90.

The highest recorded water level in the Vidå between the Vidå sluice and the Højer Sluice is 1.82m DVR90 (29-10-1998). At this water level, the volume capacity behind the eastern reservoir dike will be close to 2.5 mill. m^3. Thus by controlled release of water into the eastern part the overall storage capacity can be increased, which in turn may lead to less critical high water levels and thereby ease the pressure on the dikes along the Vidå.

In order to investigate the additional storage potential, model simulations have been carried out utilising the extreme high water situation (29-10-1998). In the model the crest of reservoir dike facing Vidå has been lowered to ground elevation over a length of 80 m.

The result of the analysis is seen in Figure 5-14 to Figure 5-17. The result of using the additional reservoir capacity in Margrethe Kog reduces the peak water level locally by 13cm. The effect decreases gradually upstream and near Tønder – downstream Kongevej the reduction in peak water level is 6cm.

In this model analysis the capacity potential of the reservoir was not completely utilised as the maximum level in the southern part of the reservoir was 30cm lower than the peak level at the inlet in Vidå. The main reason for this difference is the routing time for water entering and leaving the reservoir.

It is envisaged that a more controlled timing of inflow (efficient design of the in- and outlet of the reservoir) may lead to further reduction of the peak high water levels in Vidå.

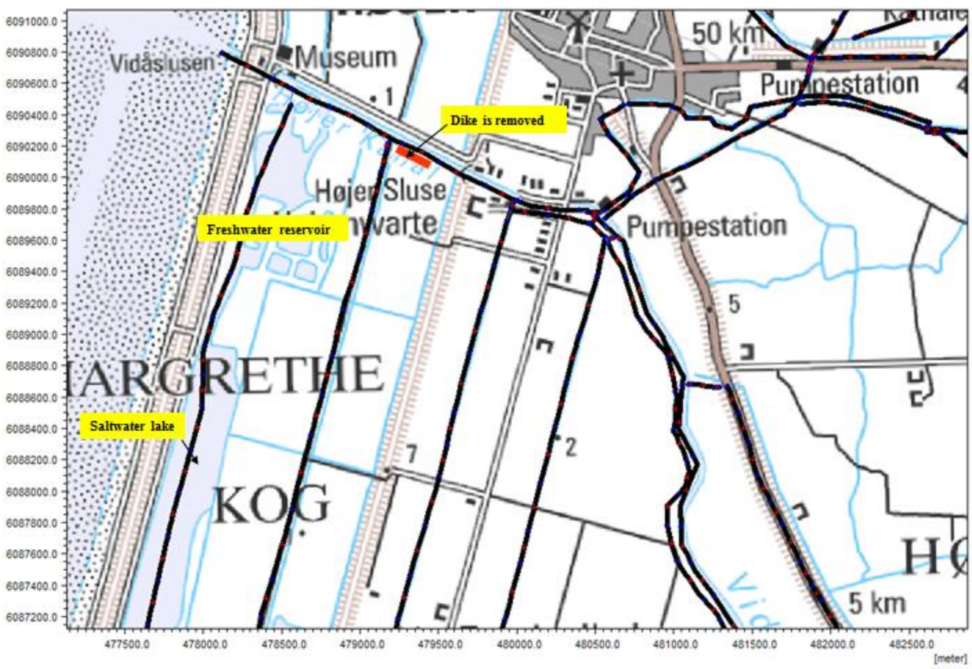


Figure 5-13 The Margrethe Kog and the freshwater reservoir

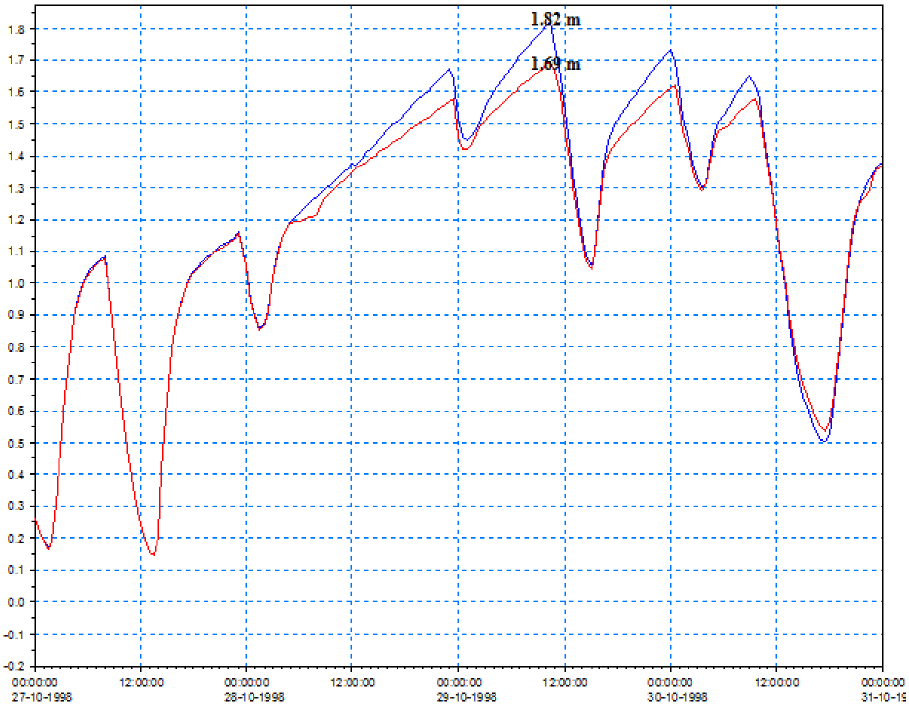


Figure 5-14 Simulated water level in the Vidå between the Vidå sluice and the Højer sluice with (red curve) and without (blue curve) dike removal

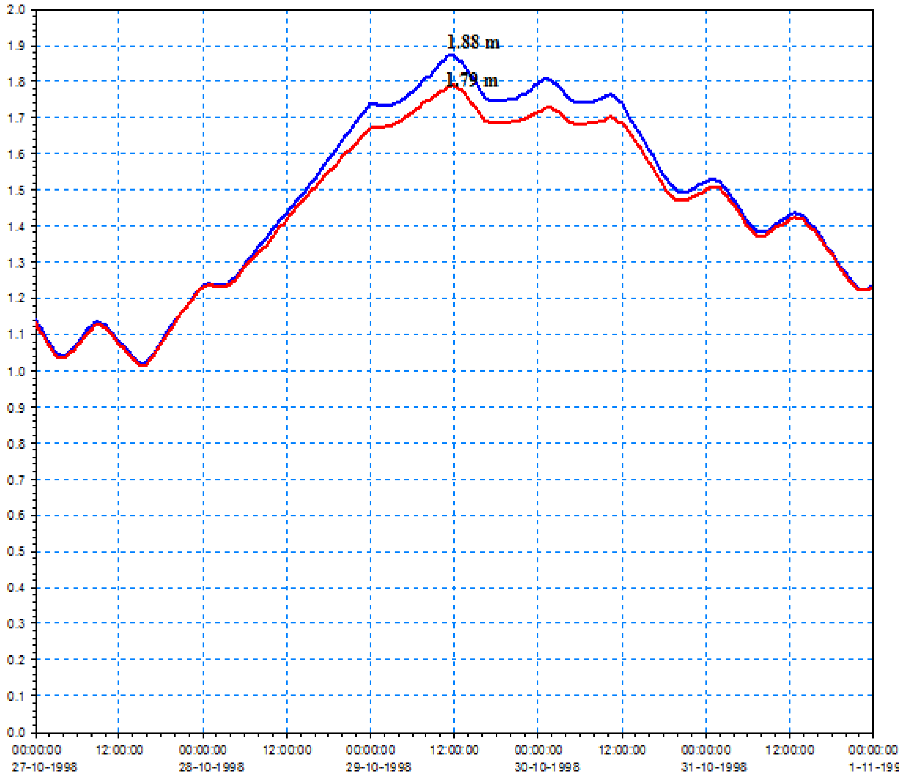


Figure 5-15 Simulated water level in the Vidå at Rudbøl Sø with (red curve) and without (blue curve) dike removal

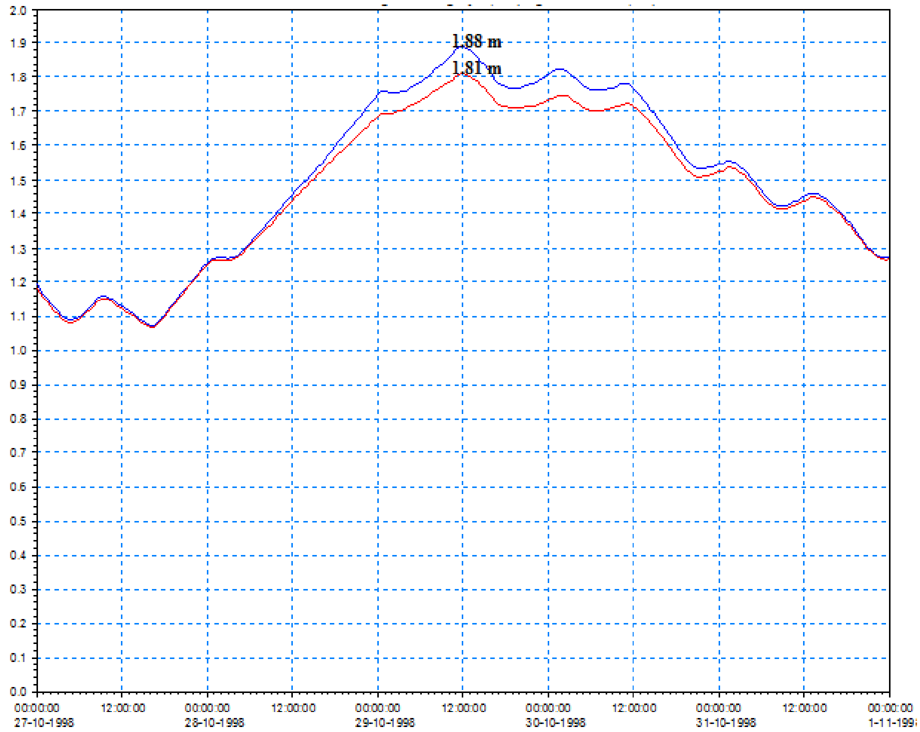


Figure 5-16 Simulated water level in the Vidå at Lægan with (red curve) and without (blue curve) dike removal

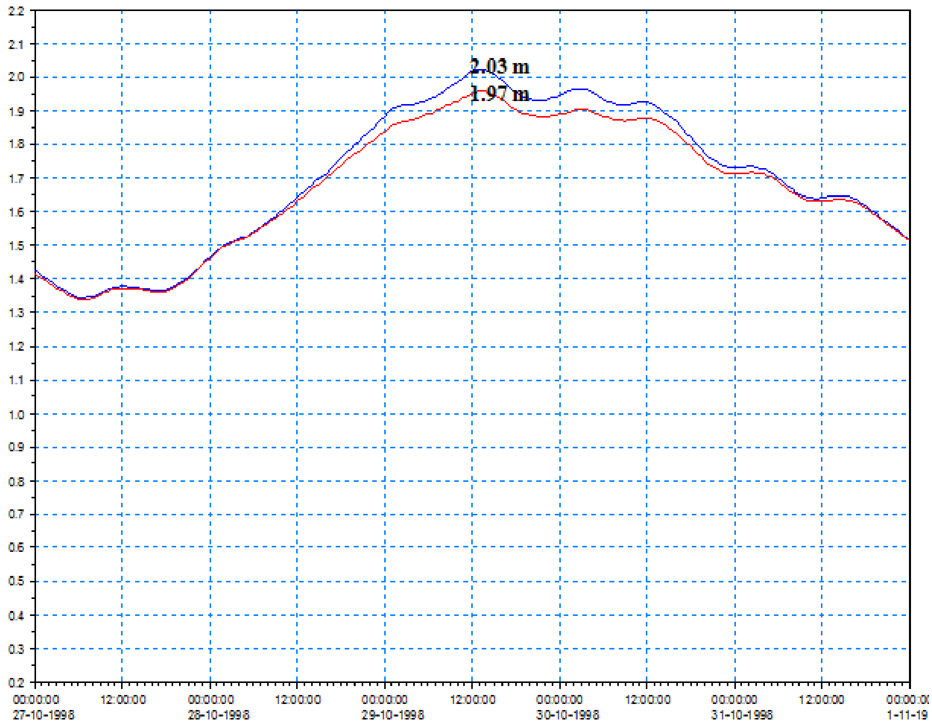


Figure 5-17 Simulated water level in the Vidå at Tønder with (red curve) and without (blue curve) dike removal

5.4.4 Summary of impacts from increased storage capacity

A summary of the effects of increased storage capacity is provided below for the various scenarios. All effects are evaluated based on the extreme October 1998 event.

Scenario A: Pullback of existing dikes along the Sønderå on both sides of the German-Danish border and extension of the storage of the Haasberger:

- The maximum reduction does not exceed 3.5 cm in the Sønderå , Dreiharder-Gotteskoogstrom and Geestableiter

Scenario B: Reservoir "DHSV" located on the German side of the border between the custom house at Sæd and the railway track Tønder – Niebøl

- The maximum reduction upstream of the Møllehus sluice is 17 cm

Scenario C: Reservoir in Udbjerg Kog

- The maximum reduction upstream of the Møllehus sluice is 22 cm

Scenario D: Combined Scenario B and C

- The maximum reduction upstream of the Møllehus sluice is 25 cm

Scenario E: Increased reservoir capacity in Margrethe Kog

- The maximum local reduction in Magrethe Kog is 13 cm. The effect decreases gradually upstream and near Tønder – downstream Kongevej the reduction in peak water level is 6 cm.

5.5 Re-evaluation of the dike safety under the existing and future climate scenarios

5.5.1 Effects of climate change in Vidå River Basin and flood protection

The calibrated MIKE 11 model is used for simulation of water levels in the river system using meteorological forcing and sea water level data for current (using observed records) and future climate (using projected records), taking the two projection horizons, 2050 and 2100 with different mean sea level rise scenarios into consideration (Table 3-7). Extreme value analysis is then applied to estimate the risk of dike overtopping at different locations in the river system. For the simulations of current conditions, meteorological forcing data (precipitation, temperature and potential evapotranspiration) and sea water level at the Vidå sluice are available for the period 1981-2009. For the simulations of 2050 and 2100 conditions projected time series of meteorological forcing and sea water level are derived by perturbing the observed time series with the projected changes described in Section 3.

To correct for biases introduced by the RCM model for simulating climate variables at the river basin scale, the climate model data are statistically downscaled. In this project, downscaling based on a general change factor methodology has been applied. In this case the RCM climate model simulations are used to extract future changes in statistical characteristics of climate variables (denoted change factors), and these changes are then superimposed on the statistical characteristics of the climate variables representing the river basin obtained from observed records. To take seasonal variations into account, monthly change factors are calculated.

For statistical downscaling of temperature a mean correction methodology (also known as the Delta Change approach) was applied. Temperature data for the future climate are obtained by adding absolute changes in temperature from the RCM projections (weighted average shown in Figure 3-2) to the observed temperature record. Potential evapotranspiration data for the future climate are obtained from the relative change in temperature from the RCM projections (changes shown in Figure 3-2). For statistical downscaling of precipitation a method that uses both relative changes in the mean and the daily variance (Figure 3-2) was applied as recommended by Sunyer et al. (2011). In this case, the future precipitation is given by: $P_{fut} = aP_{obs}^{b}$, where P_{obs} is the observed precipitation, and *a* and *b* are estimated from the changes in mean and variance.

Based on the projections of sea level rise and changes in storm surge statistics (see Section 3), time series of sea water levels at the Vidå sluice representing 2050 and 2100 climate were established from the observed time series by adding climate-induced mean sea level rise, isostatic changes, and changes in extreme water level statistics.

The projected changes in precipitation, temperature and potential evapotranspiration for 2050 and 2100 were used as input for the rainfall-runoff model simulations. The changes in the estimated extreme value statistics of catchment average rainfall and total catchment runoff are shown in Figure 5-18. The extreme daily precipitation increases about 9% in 2050 and 15% in 2100, and similar changes are seen in the extreme catchment runoff statistics (about 8% in 2050 and 14% in 2100).

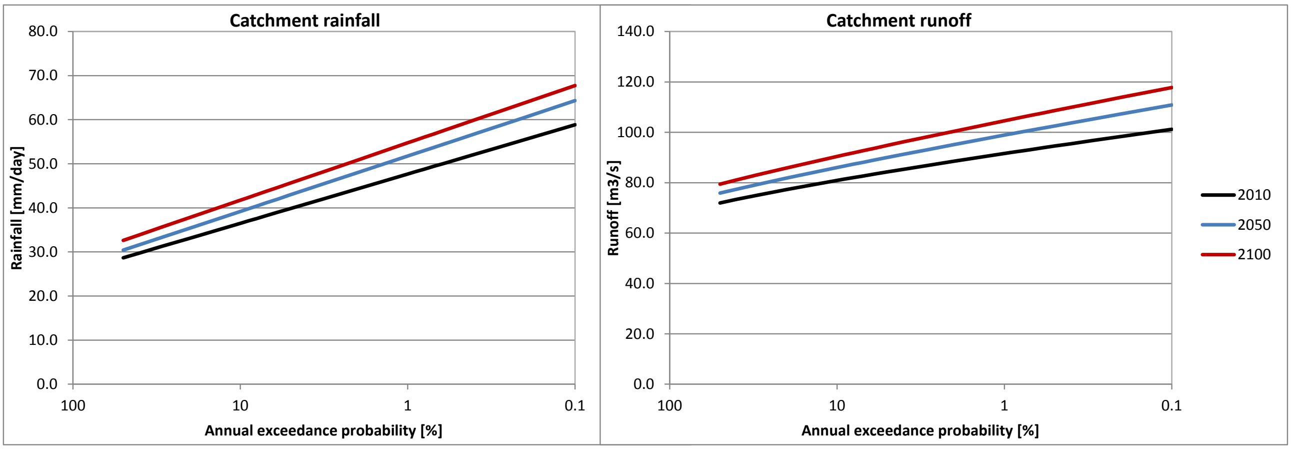


Figure 5-18 Extreme value statistics of catchment average rainfall and total catchment runoff for current (2010) and future (2050 and 2100) climate.

From the MIKE 11 simulations water level data from selected locations in the river system were extracted and analysed. In this study, the peak-over-threshold method included in the MIKE by DHI extreme value software package has been applied for analysis of the extreme water levels. The analysis showed that the Weibull distribution is preferable for fitting of the water level extremes.

An example of the results of the extreme value analysis at one of the selected locations is shown in Figure 5-19 (Appendix A provides similar figures for all locations). Figure 5-19 shows the extreme water level statistics for current conditions and the four different climate change scenarios compared to the river dike levels (see Table 5-3). A significant increase in the risk of dike overtopping is projected at this location. For the current conditions, the annual exceedance probability of the dike level is less than 0.1% (corresponding to an event that is expected less than once every 1000 years on average). In 2050, with the low mean sea level rise scenario the risk is still small (about 0.1%), but with the high mean sea level rise scenario the risk increases to about 0.7%. In 2100, the risk corresponding to the low mean sea level rise scenario is close to the risk of the 2050 high sea level rise scenario, but for the high mean sea level rise scenario the risk increases to about 10%. Thus, in the worst case scenario the risk has increased from an event that is expected less than once in 1000 years event to a 1 in 10 year event. A very pronounced increase of the flood risk at this location.

Thus, the results in Appendix A can for each MIKE 11 location (and climate scenario) be used to identify the required dike crest elevation in order to comply with a given risk for overtopping.

Table 5-3 River dike levels

X (UTM)	Y (UTM)	MIKE 11 Branch Name	MIKE 11 Chainage [m]	Critical dike level Left [m]	Critical dike level Right [m]	Comments
491703.68046	6087075.27254	VIDAA (Tønder)	3770	3.98	2.90	Right = Area without dike
489453.13418	6085035.45923	VIDAA	5098	3.03	3.03	
485772.46804	6083486.67421	VIDAA	8566	2.93	2.93	
484064.09882	6083541.91489	VIDAA	12820	2.77	2.82	
481061.40975	6088622.77885	VIDAA (Rudbøl Sø)	14620	2.38	2.38	
478501.41336	6090599.67916	VIDAA	22030	2.38	1.92	Right = Reservoir dike at Lille Vade
478501.41336	6090599.67916	VIDAA	25560	2.15	3.55	Left = Reservoir dike at Margrethe Kog
496339.80579	6083944.96727	SONDERAA	1400	2.88	3.04	
494017.65122	6084090.22980	SONDERAA	4100	2.20	2.45	
491912.36748	6083664.67196	SONDERAA	6500	2.20	2.20	
490476.10976	6083359.82523	SONDERAA	8150	1.05	2.05	Left = Reservoir dike at Haasberger See
489899.15153	6083777.19927	SONDERAA	8900	1.94	1.98	
490294.02011	6082795.14271	DREIHARDER_GOTTESKOOGSTROM	600	1.93	0.93	Right = Reservoir dike at Haasberger See
490695.02653	6076567.26738	DREIHARDER_GOTTESKOOGSTR	8400	3.11	2.98	

		OM				
494095.39736	6075257.85864	DREIHARDER_GOTTESKOOGSTROM	12600	3.22	3.08	
495551.85885	6086558.92562	GRONAA_TM	3072	3.83	3.83	
483462.84493	6096921.66824	VESTRE_RANDKANAL	1244	3.25	3.25	
497620.82696	6083745.74277	VINDTVED_KANAL	110	4.78	4.78	

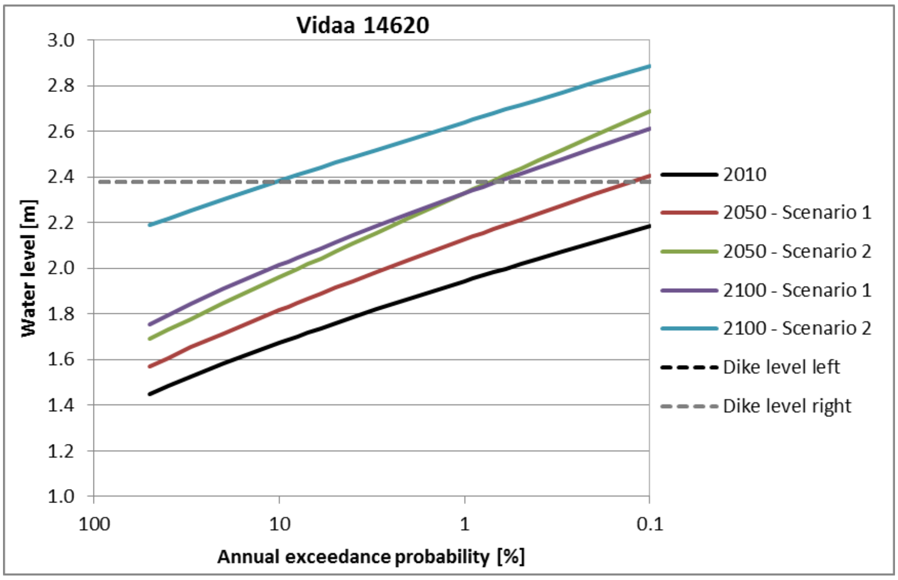


Figure 5-19 Estimated extreme water level statistics at Rudbøl Lake for current (2010) and future (2050 and 2100) climate. Scenario 1 and Scenario 2 refer to, respectively, the low and high scenario of mean sea level rise

In Figure 5-20-Figure 5-24 the flood risks for current and future climate at the selected locations are shown for the left and right bank respectively. I this context it is important to emphasize that the risk for left and right bank overtopping represents "conditional probabilities" only. The lowest probability is only meaningful provided that no overtopping takes place at other locations (i.e. under the assumption that the dike crest elevation has been increased to a level where no overtopping takes place at other locations). For the current conditions (Figure 5-20) the flood risk in most parts of the river system is less than 0.1% (a 1 in a 1000 years event). Risks exceeding 1% are seen in the downstream part of Sønderå and Dreiharder Gotteskoogstrom and downstream and upstream part of Vidå. At three locations the risk exceeds 25% (1 in 4 years event). For the 2050 climate scenarios the risk increases (Figure 5-21-Figure 5-22). The risk in the downstream part of Sønderå and Dreiharder Gotteskoogstrom and downstream part of Sønderå exceeds 5% (1 in 20 years event) with the high mean sea level scenario. Large parts of Sønderå experience flood risk levels of 1% or more. For the 2100 climate with the low mean sea level scenario (Figure 5-23) the flood risks correspond to the risks of the 2050 climate with the high mean sea level scenario. The 2100 climate scenario with high mean sea level rise (Figure 5-24) has considerably larger flood risks. In the upstream river branches the risk is still small (risks less than 0.1%), but the downstream parts of Vidå, Sønderå and Dreiharder Gotteskoogstrom have risk levels of 5% or more.

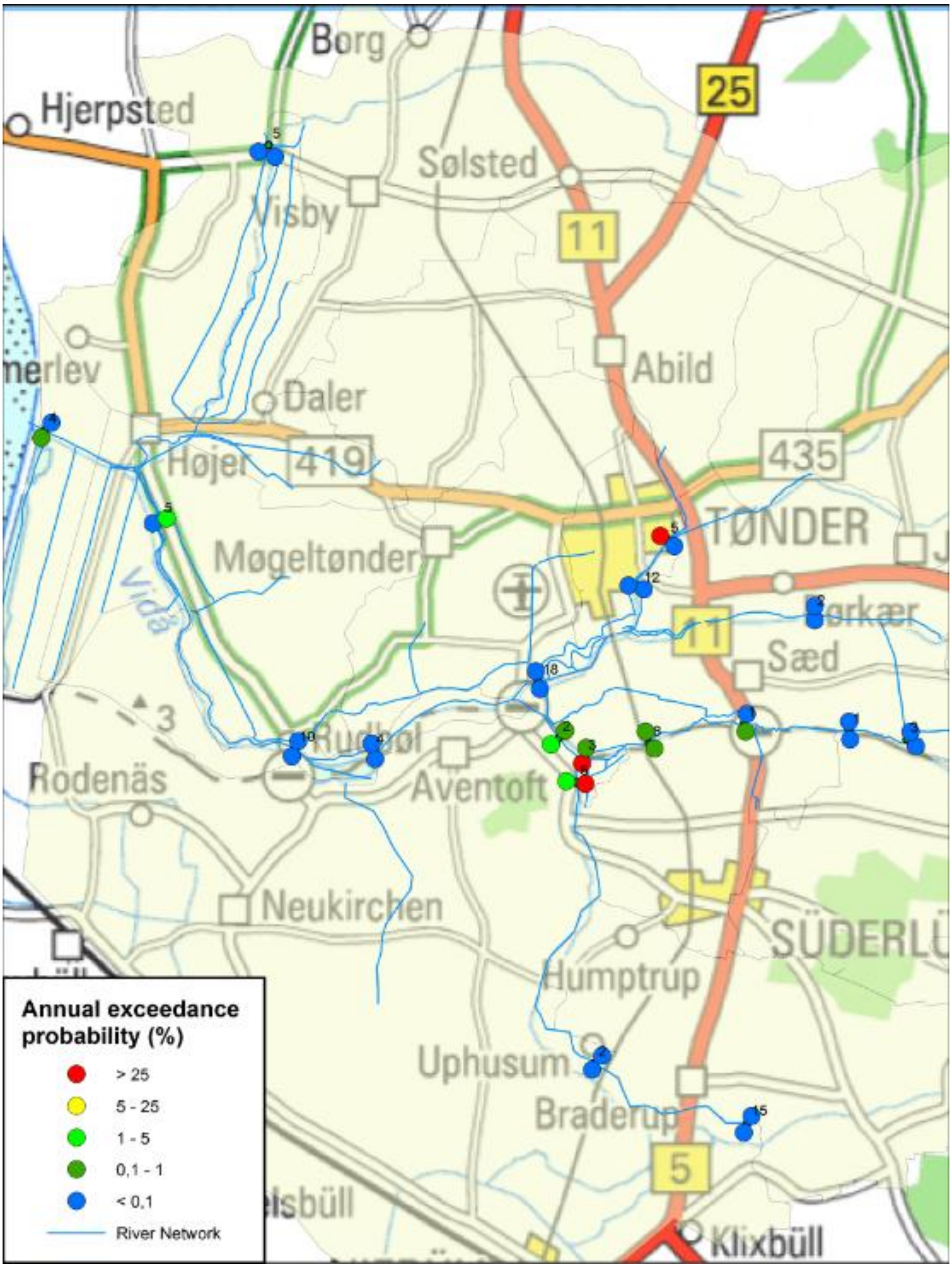


Figure 5-20 Estimated flood risk at selected locations in the Vidå River system for the current climate. For each location the annual exceedance probabilities for overtopping left and right bank are shown

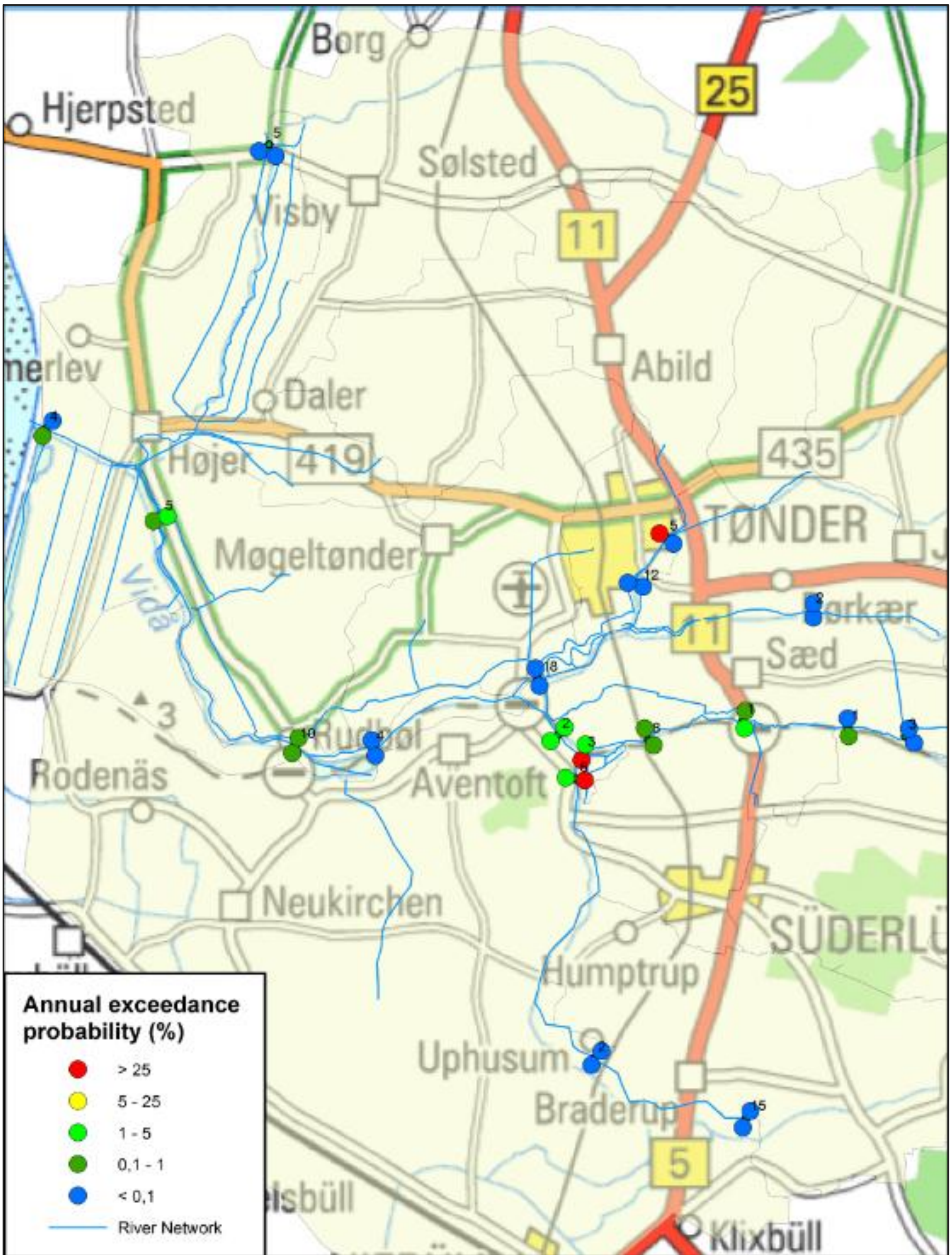


Figure 5-21 Estimated flood risk at selected locations in the Vidå River system for future 2050 climate with low mean sea level scenario. For each location the annual exceedance probabilities for overtopping left and right bank are shown

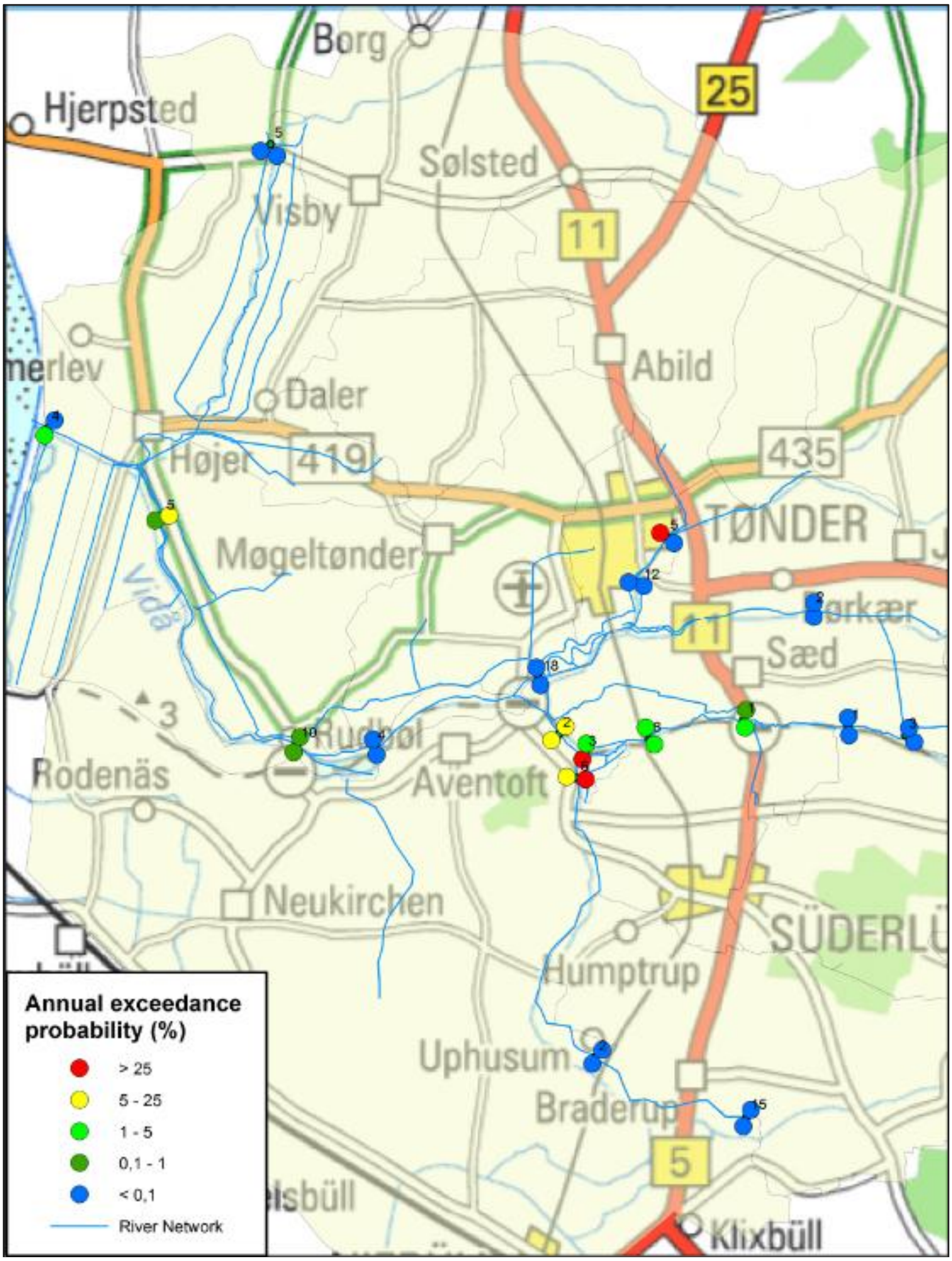


Figure 5-22 Estimated flood risk at selected locations in the Vidå River system for future 2050 climate with high mean sea level scenario. For each location the annual exceedance probabilities for overtopping left and right bank are shown

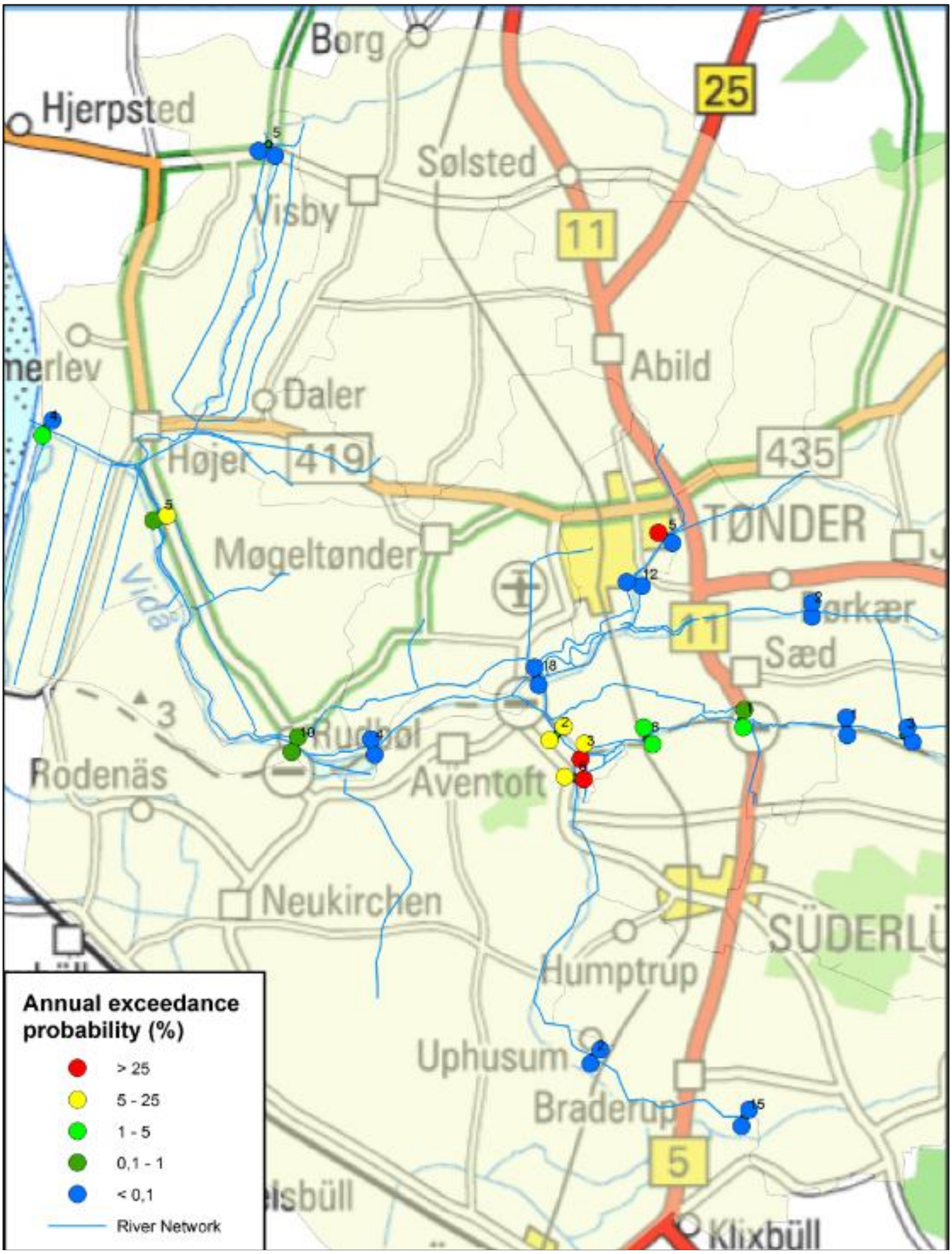


Figure 5-23 Estimated flood risk at selected locations in the Vidå River system for future 2100 climate with low mean sea level scenario. For each location the annual exceedance probabilities for overtopping left and right bank are shown

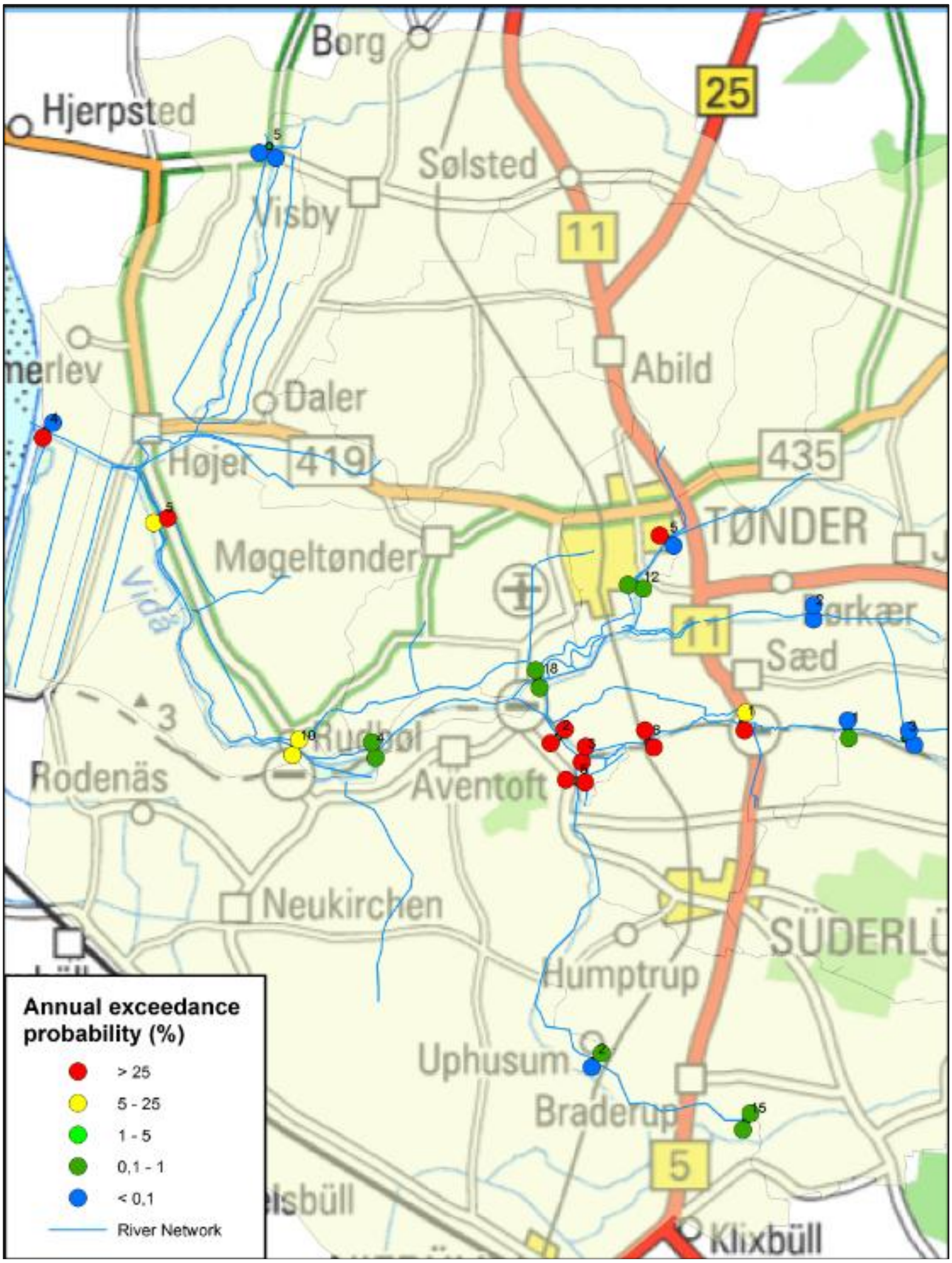


Figure 5-24 Estimated flood risk at selected locations in the Vidå River system for future 2100 climate with high mean sea level scenario. For each location the annual exceedance probabilities for overtopping left and right bank are shown

6 References

[1] Ekstremværdianalyse af Vandstande i Vidå systemet- Revurdering af digesikkerheden i Tøndermarsken, DHI, maj 1997.

[2] Modellering af de hydrauliske konsekvenser samt snæbellarveopvækstbetingelserne ved gennemførelse af snæbelprojekt i Hestholm Kog og Nørresø, DHI, oktober 2007.

[3] Strategi for tilpasning til klimaændringer i Danmark, Regeringen, marts 2008.

[4] Danish Climate Change Adaptation Portal, 2011, Future sea level rise (In Danish), http://www.klimatilpasning.dk/, assessed June 2011.

[5] Danish Coastal Authority, 2007, Extreme sea level statistics for Denmark, 2007 (In Danish).

[6] Grindsted, A., Moore, J.C. and Jevrejeva, S., 2009, Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD, Clim. Dyn., DOI 10.1007/s00382-008-0507-2.

[7] IPCC, 2007, The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

[8] Madsen, K.S., 2009, Recent and future climatic changes in temperature, salinity, and sea level in the North Sea and the Baltic Sea, Ph.d. Thesis, Niels Bohr Institute, Copenhagen University.

[9] Rugbjerg, M. and Johnsson, M., 2012, Climate change effects on marine design conditions in the North Sea, the Inner Danish Waters and the Baltic Sea, In preparation.

[10] Sunyer, M.A., Madsen, H., Ang, P.H., 2011, A comparison of different regional climate models and statistical downscaling methods for extreme rainfall estimation under climate change, Atmospheric Research, doi:10.1016/j.atmosres.2011.06.011.

[11] van der Linden, P. and Mitchell, J.F.B. (eds.), 2009, ENSEMBLES: Climate Change and its Impacts. Summary of research and results from the ENSEMBLES project, Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK, 160pp.

[12] Woth, K., Weisse, R. and von Storch, H., 2006, Climate change and North Sea storm surge extremes: an ensemble study of storm surge extremes expected in a changed climate projected by four different regional climate models, Ocean Dyn., DOI 10.1007/s10236-005-0024-3.

A P P E N D I X A

Extreme water level statistics at all selected locations

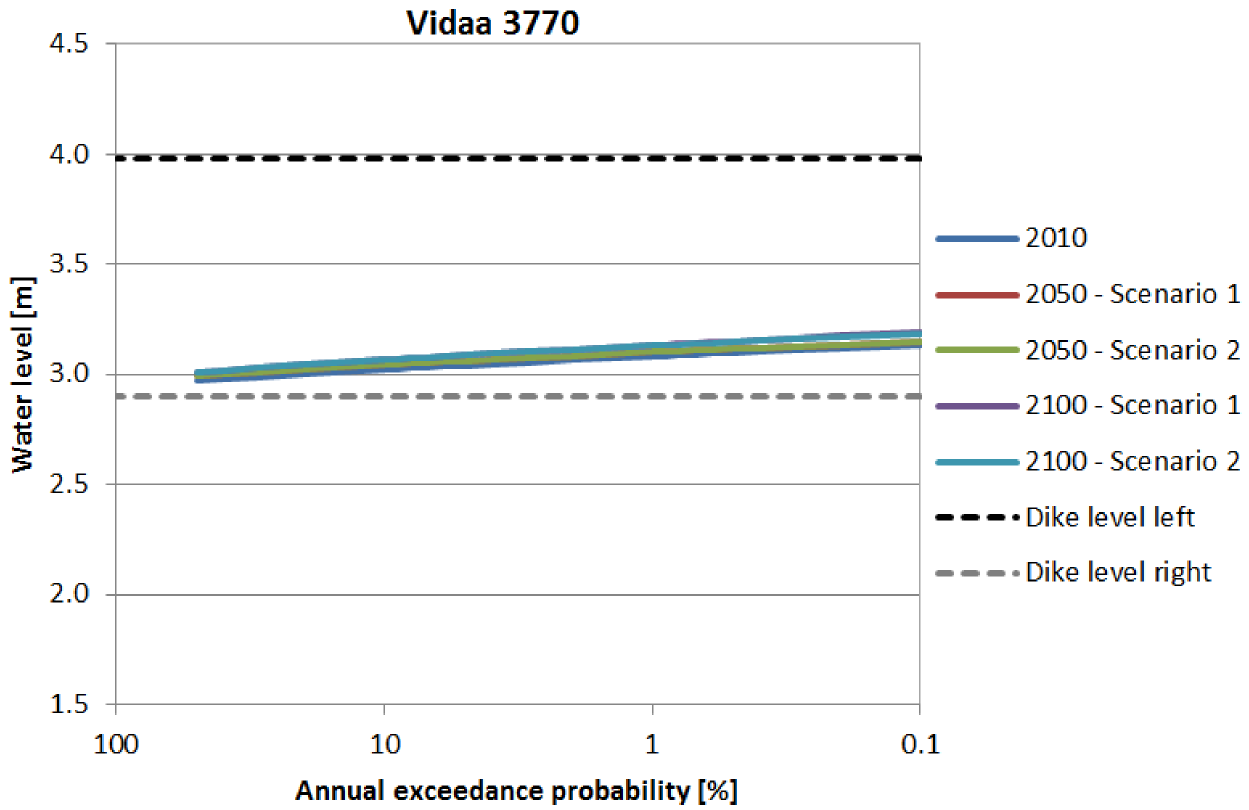


Figure A-1: Estimated extreme water level statistics at Vidaa St. 3770 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

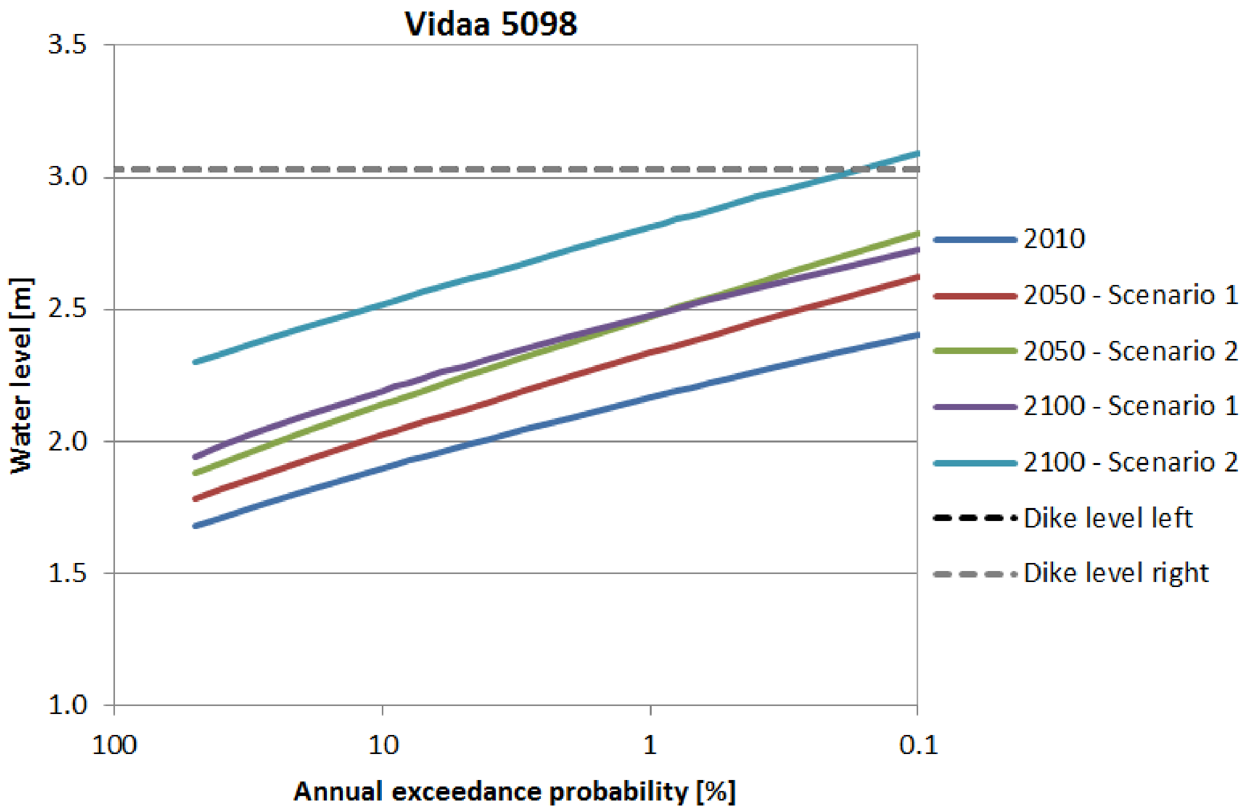


Figure A-2: Estimated extreme water level statistics at Vidaa St. 5098 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

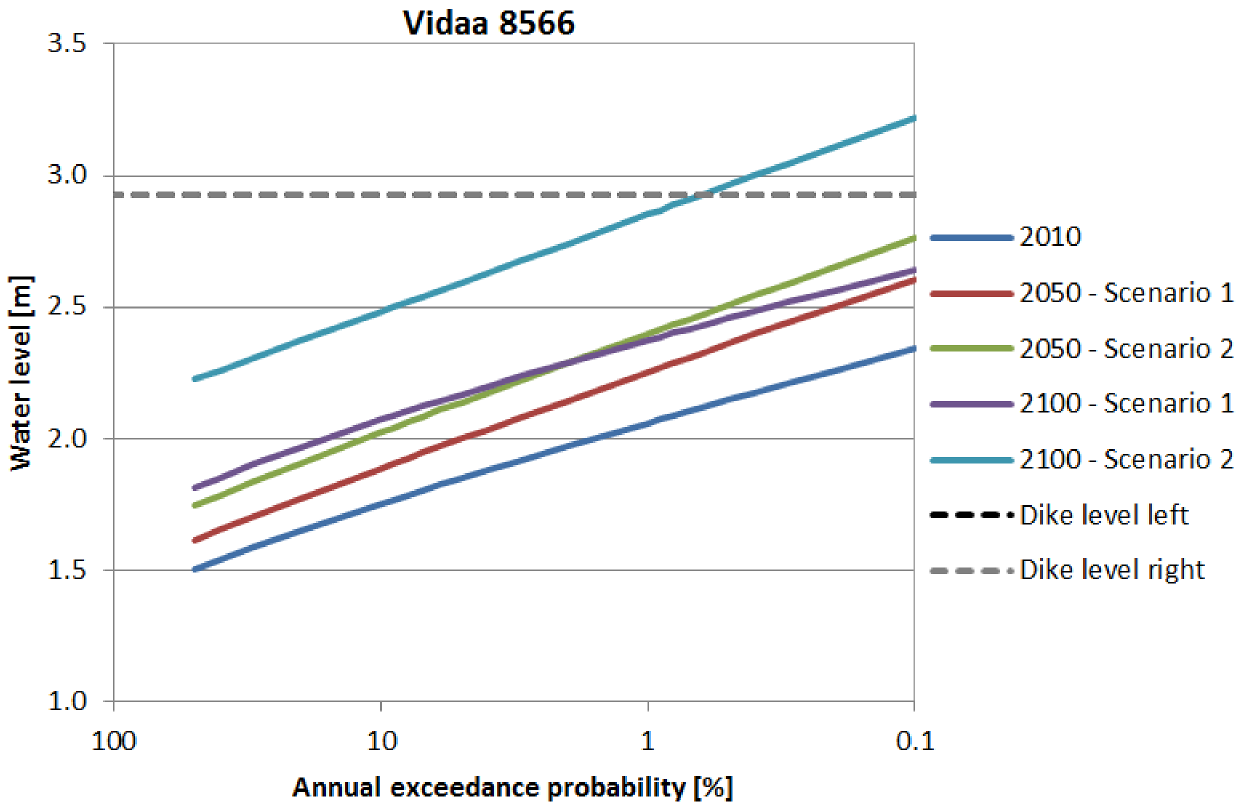


Figure A-3: Estimated extreme water level statistics at Vidaa St. 8566 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

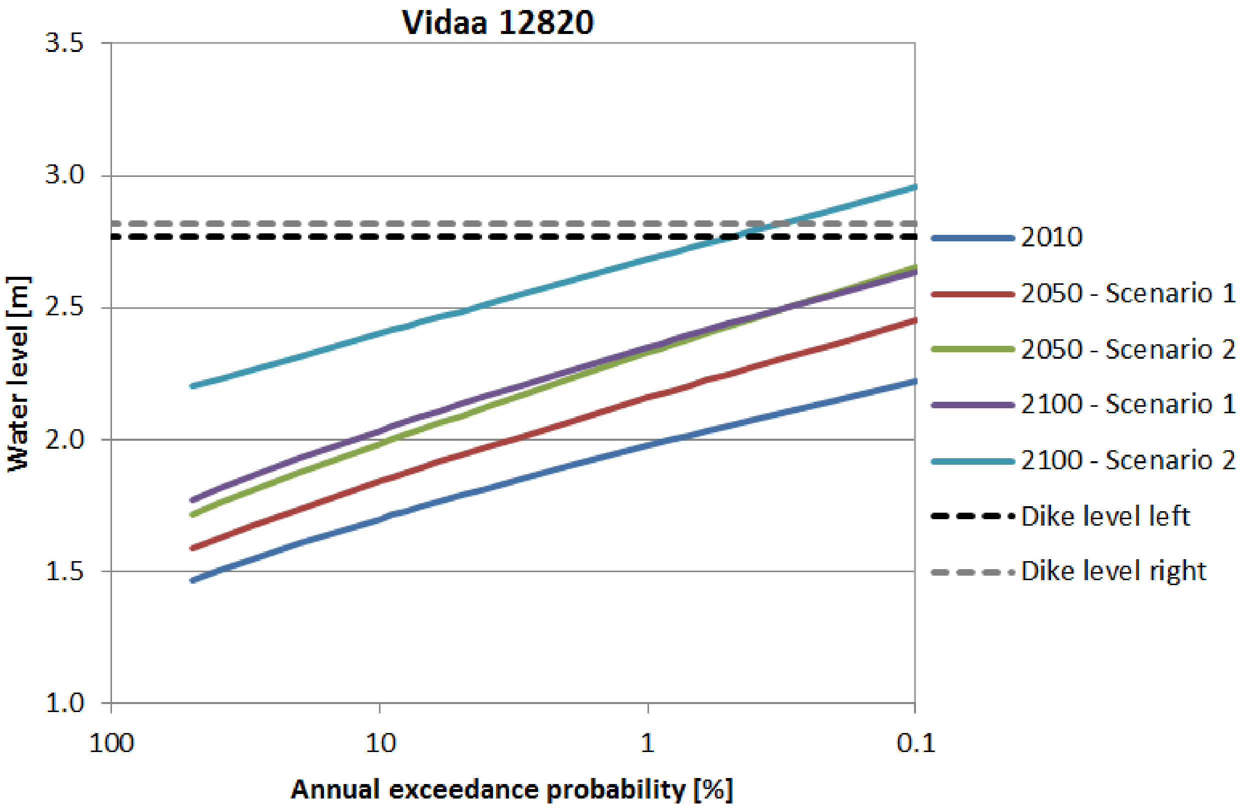


Figure A-4: Estimated extreme water level statistics at Vidaa St. 12820 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

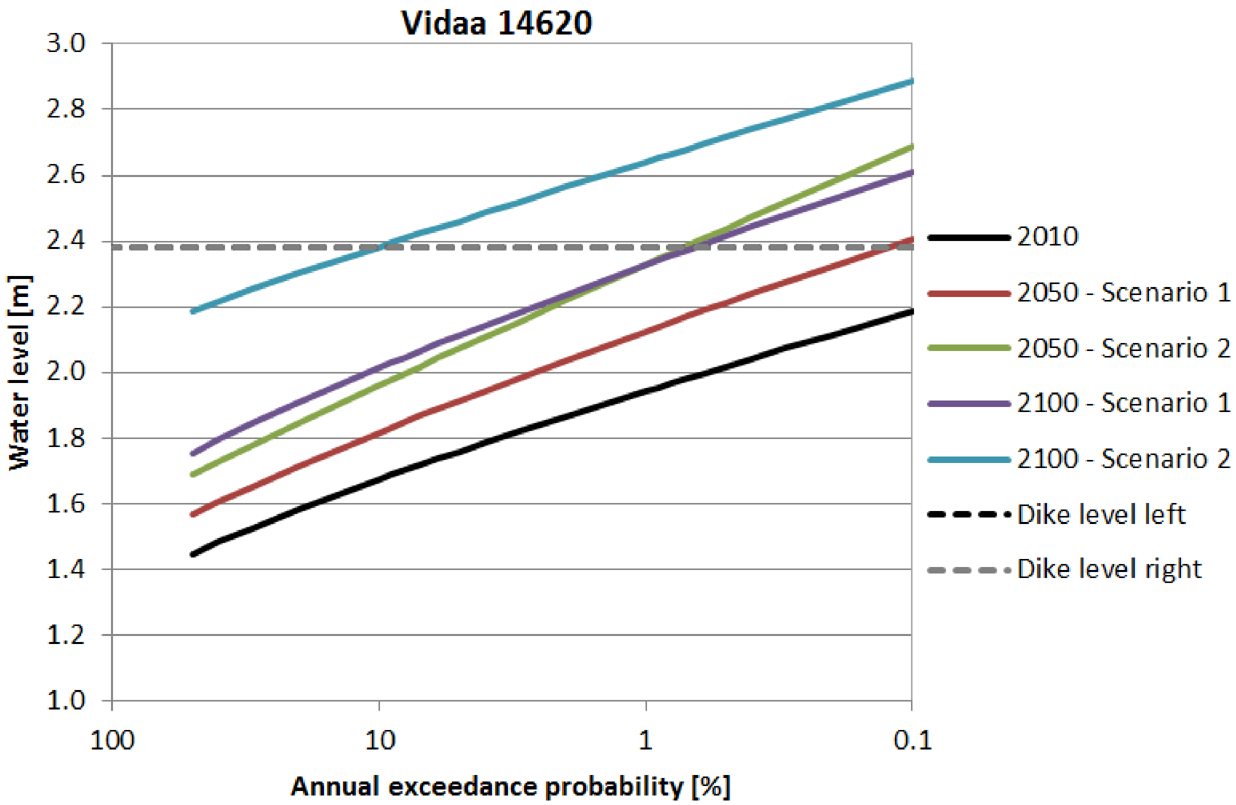


Figure A-5: Estimated extreme water level statistics at Vidaa St. 14620 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

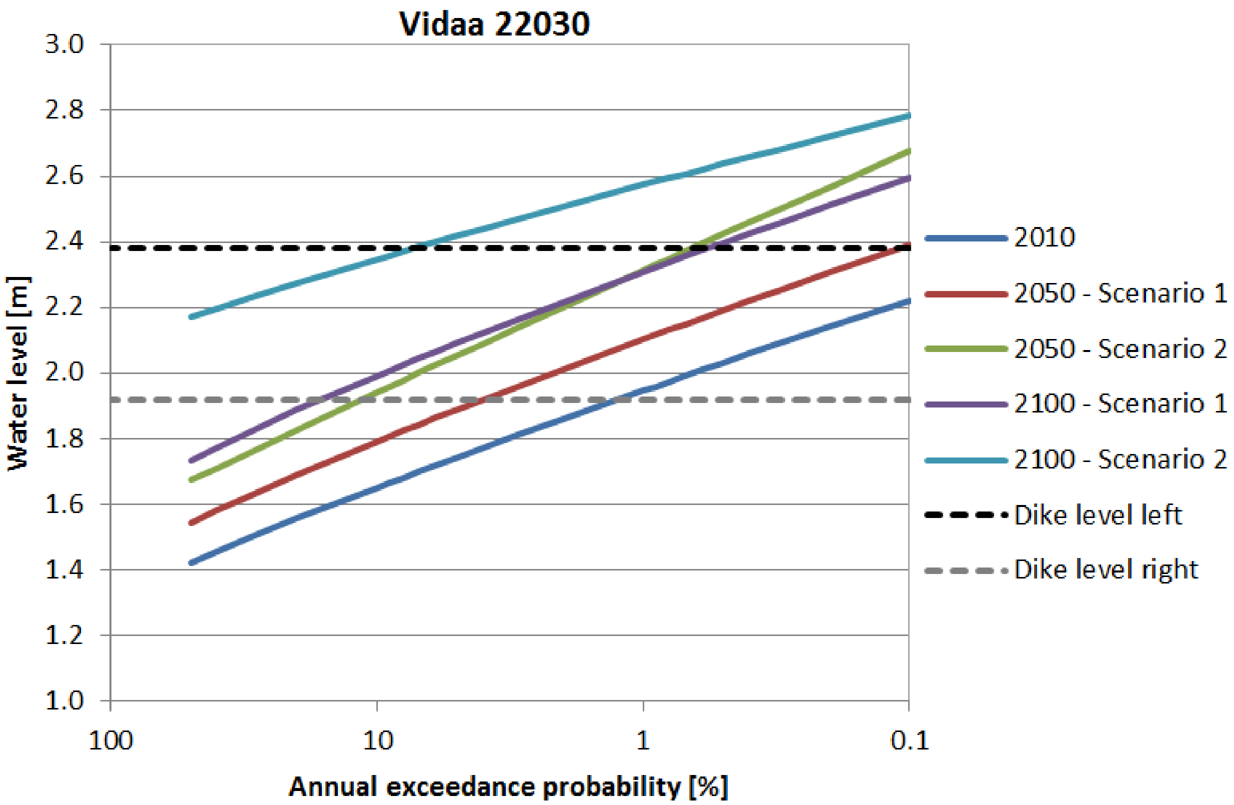


Figure A-6: Estimated extreme water level statistics at Vidaa St. 22030 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

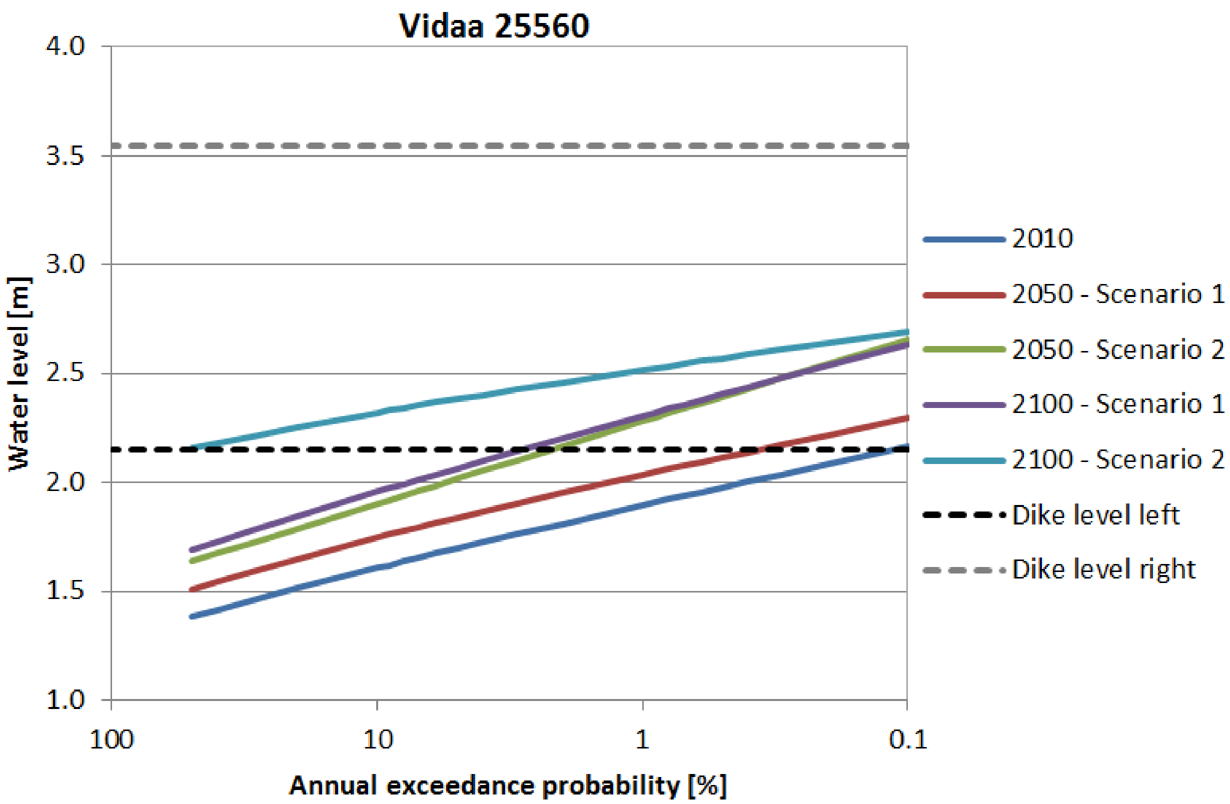


Figure A-7: Estimated extreme water level statistics at Vidaa St. 25560 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

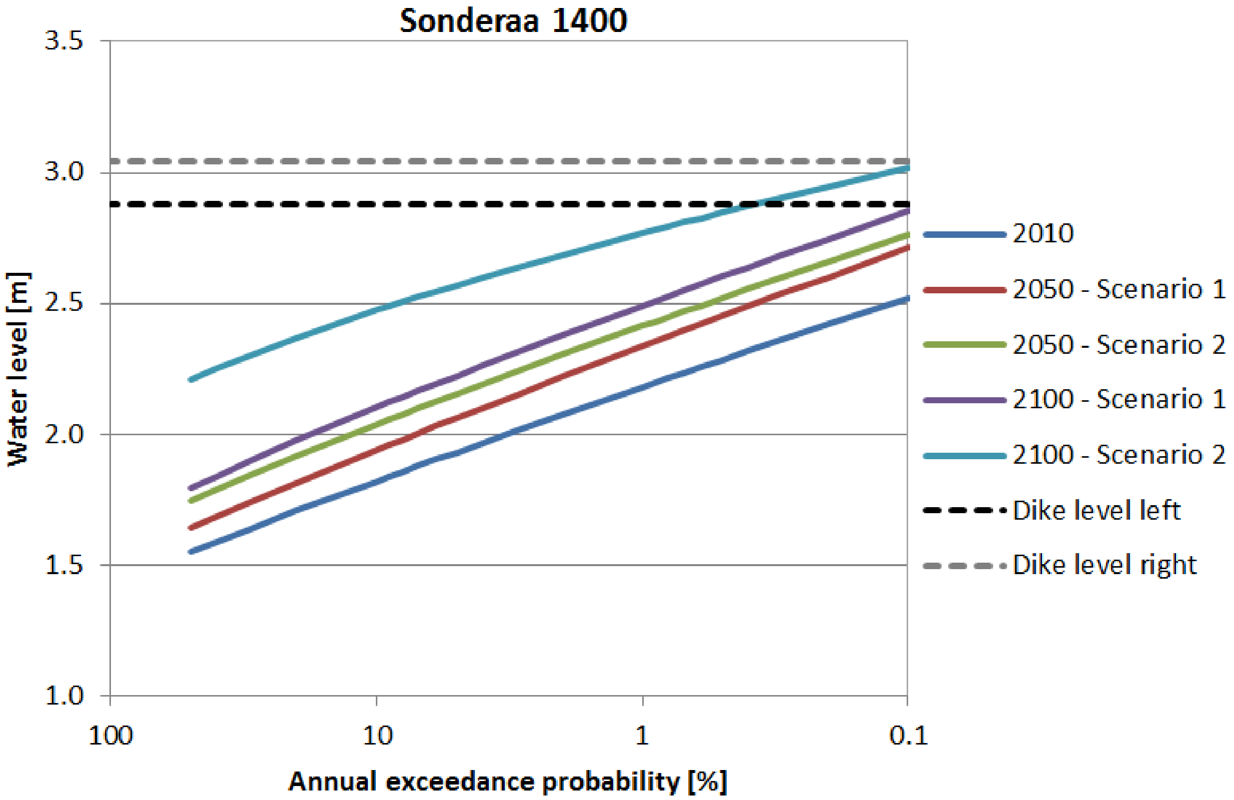


Figure A-8: Estimated extreme water level statistics at Sønderå St. 1400 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to , respectively, the low and high scenario of mean sea level rise.

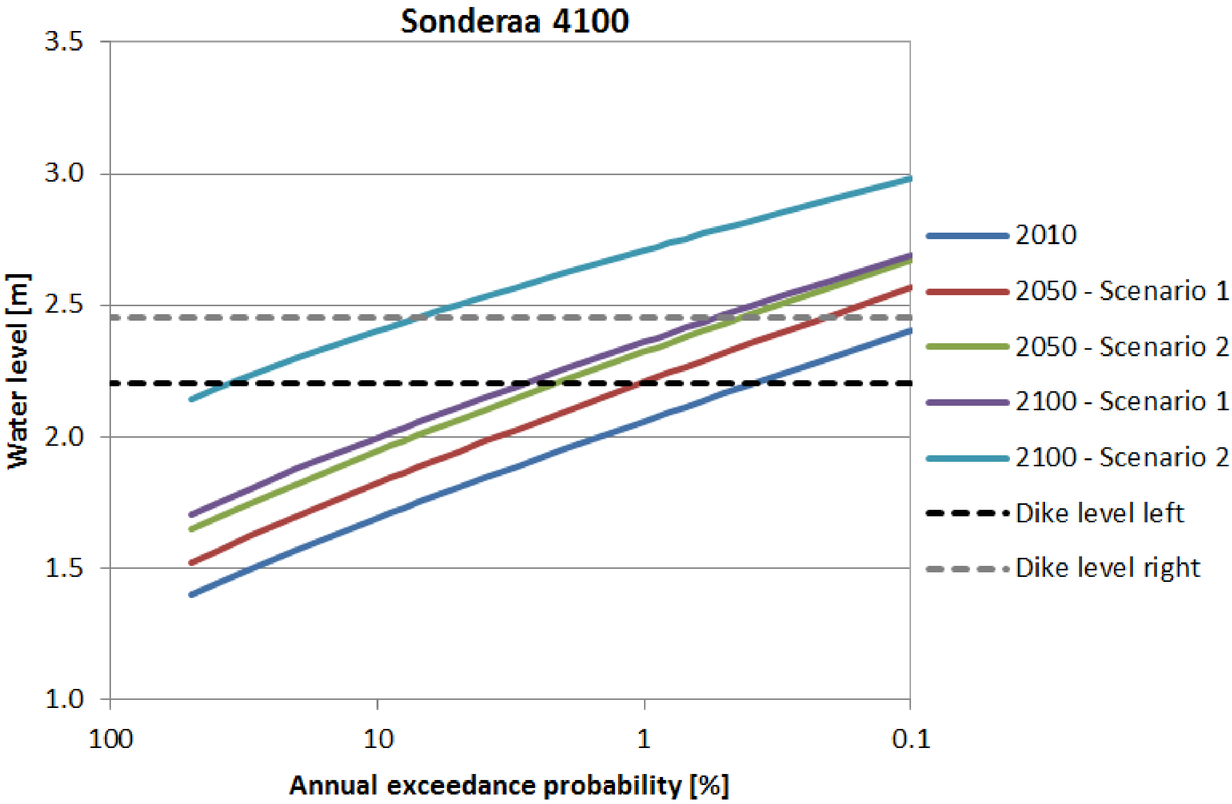


Figure A-9: Estimated extreme water level statistics at Sønderå St. 4100 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

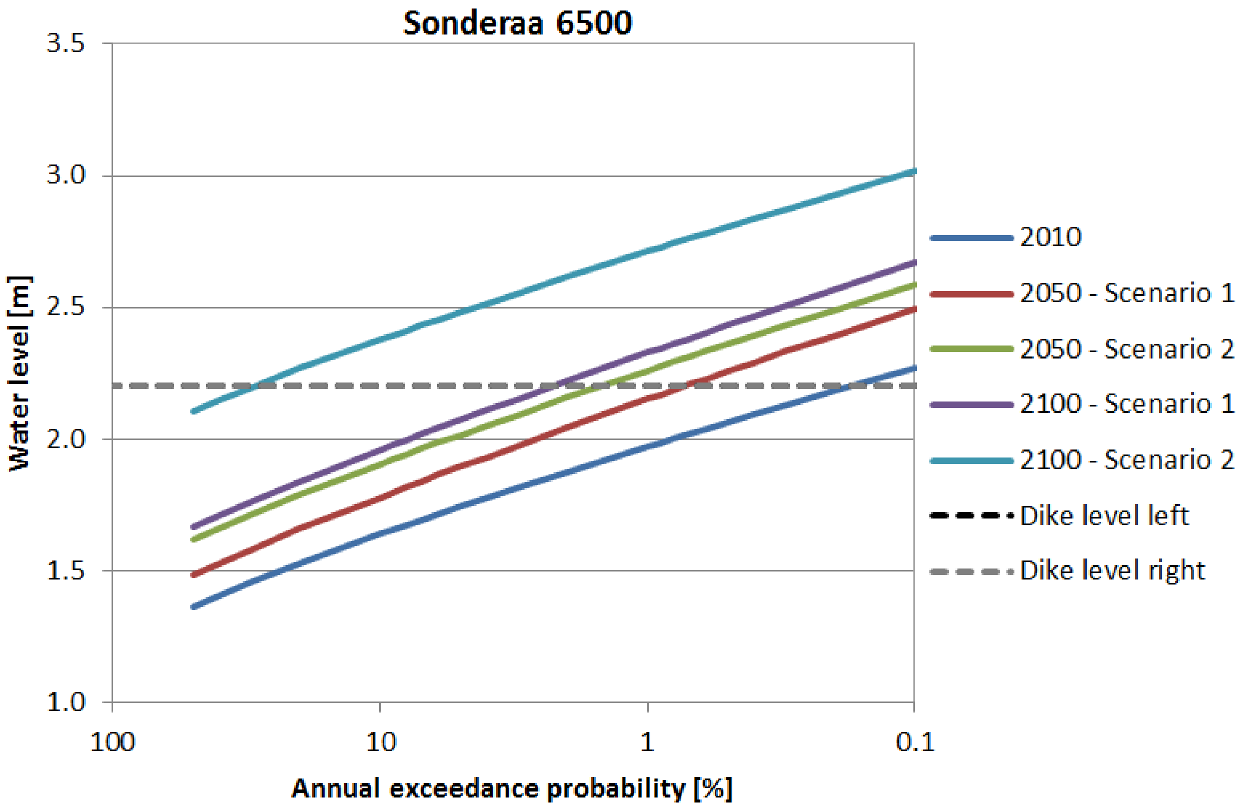


Figure A-10: Estimated extreme water level statistics at Sønderå St. 6500 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

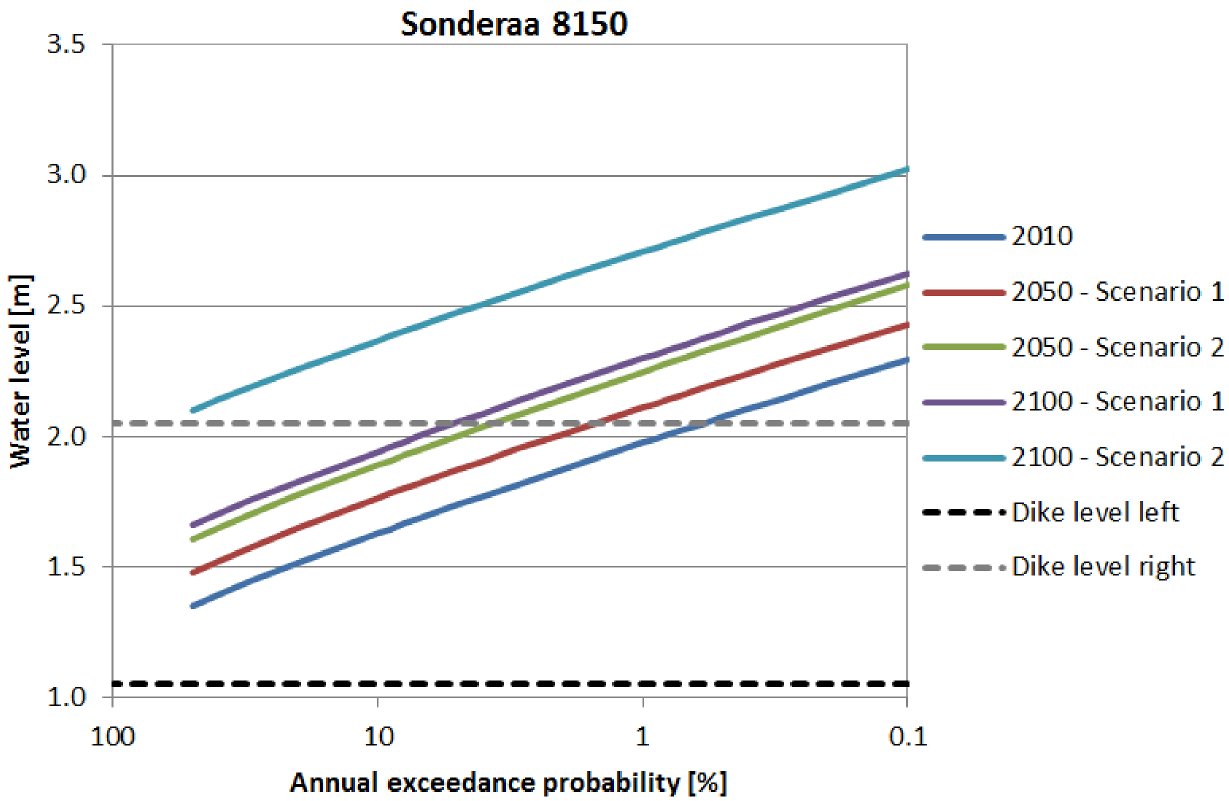


Figure A-11: Estimated extreme water level statistics at Sønderå St. 8150 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

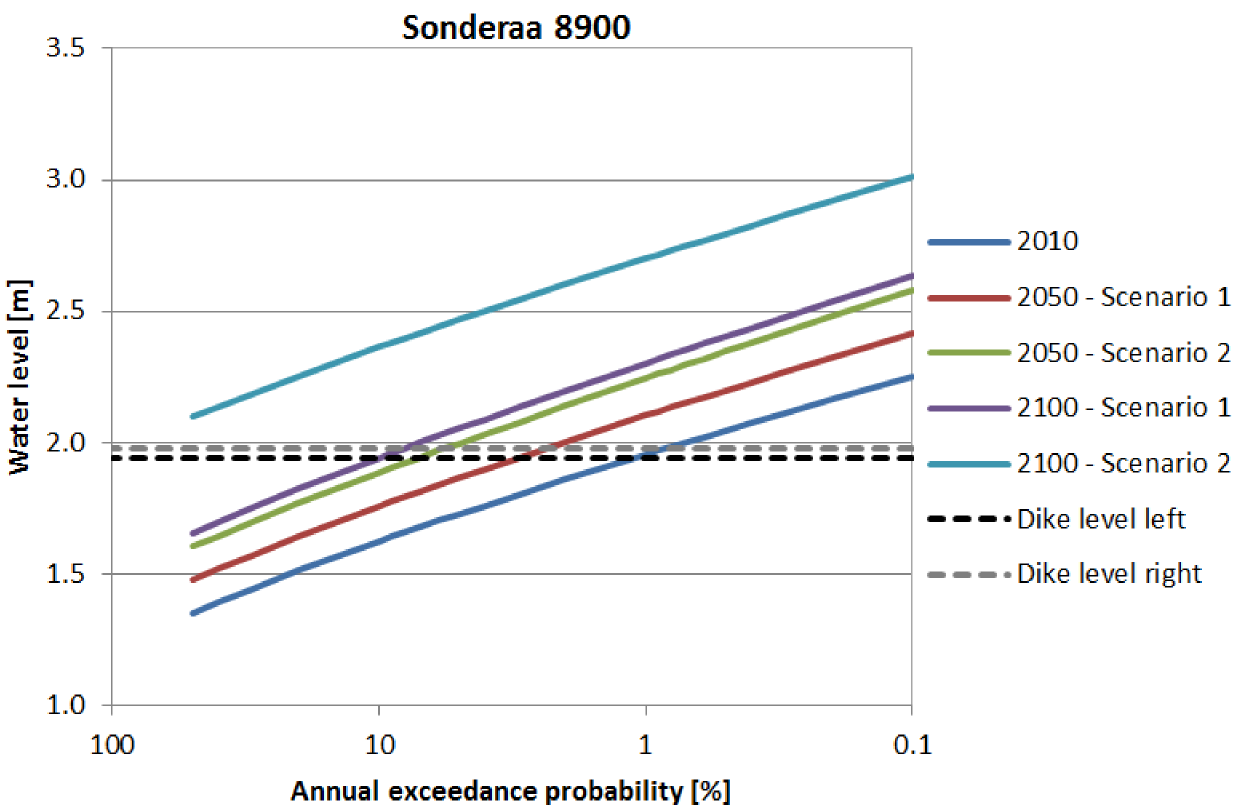


Figure A-12: Estimated extreme water level statistics at Sønderå St. 8900 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

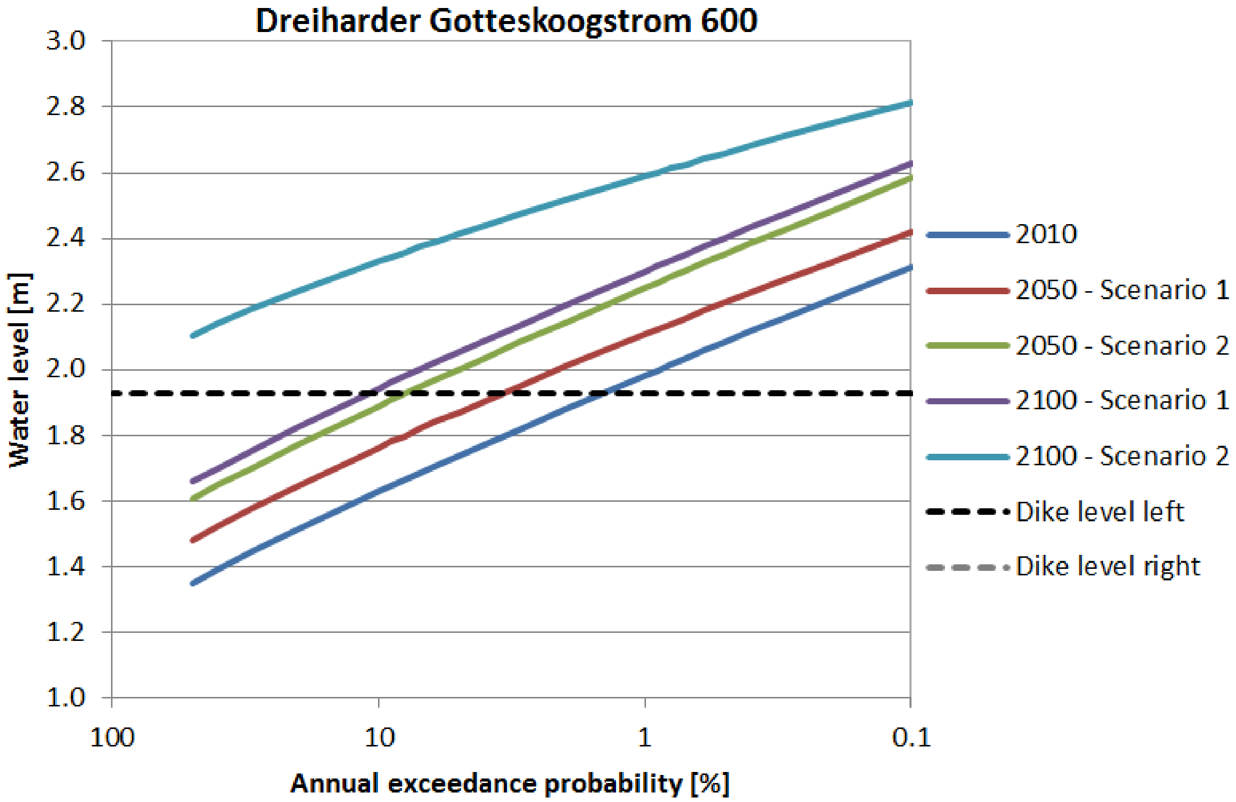


Figure A-13: Estimated extreme water level statistics at Dreiharder Gotteskoogstrom St. 600 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

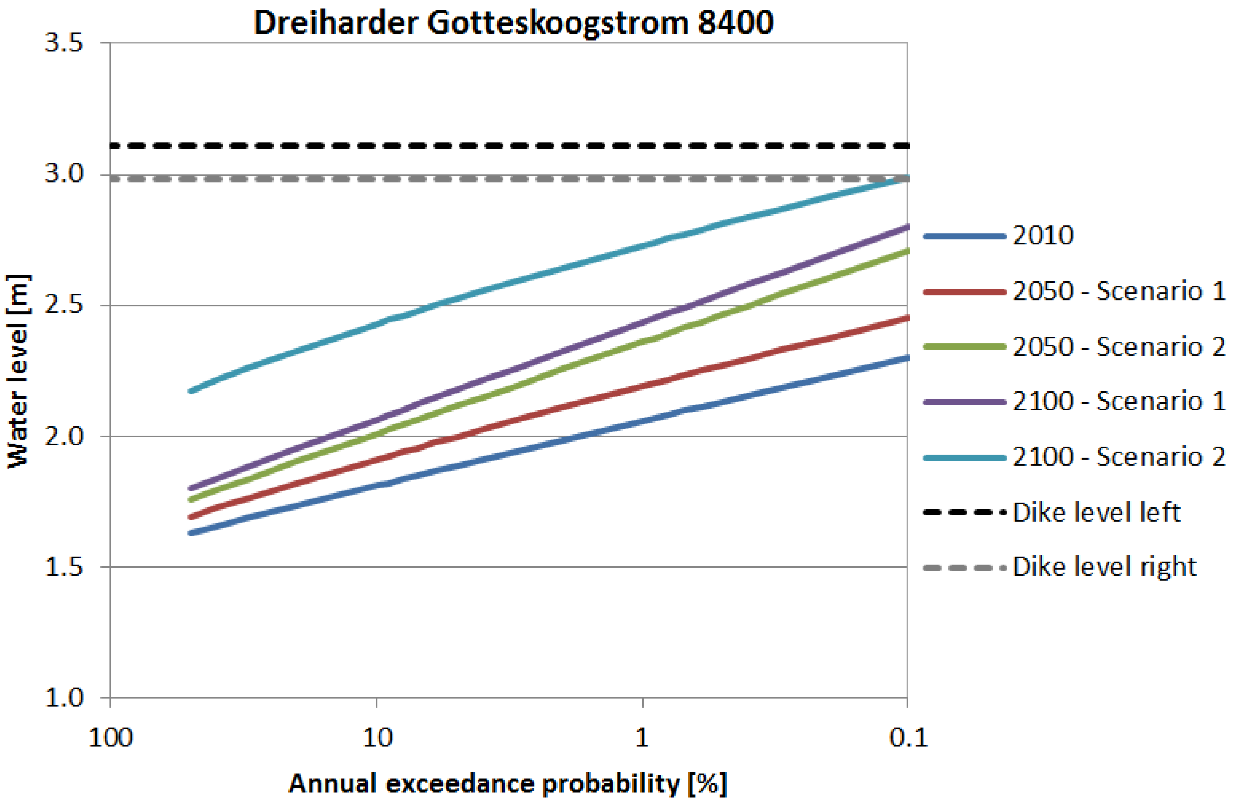


Figure A-14: Estimated extreme water level statistics at Dreiharder Gotteskoogstrom St. 8400 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

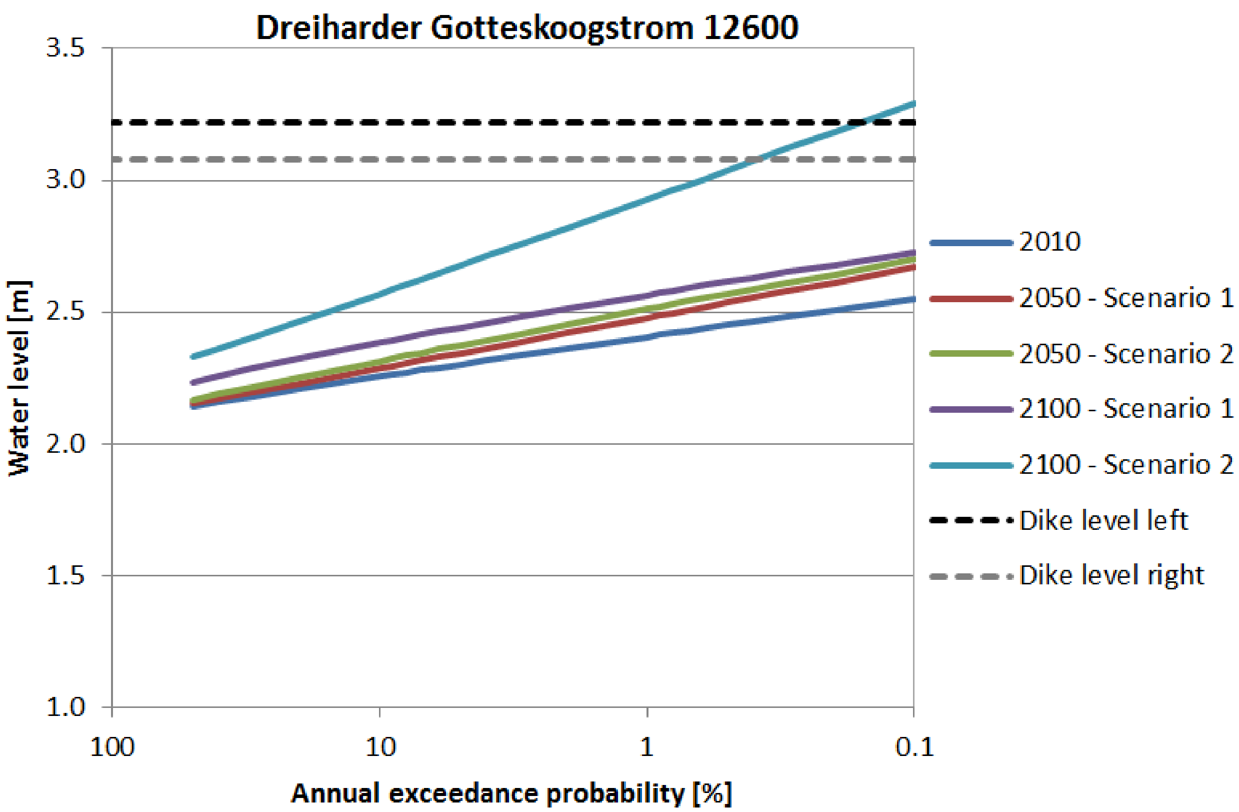


Figure A-15: Estimated extreme water level statistics at Dreiharder Gotteskoogstrom St. 12600 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

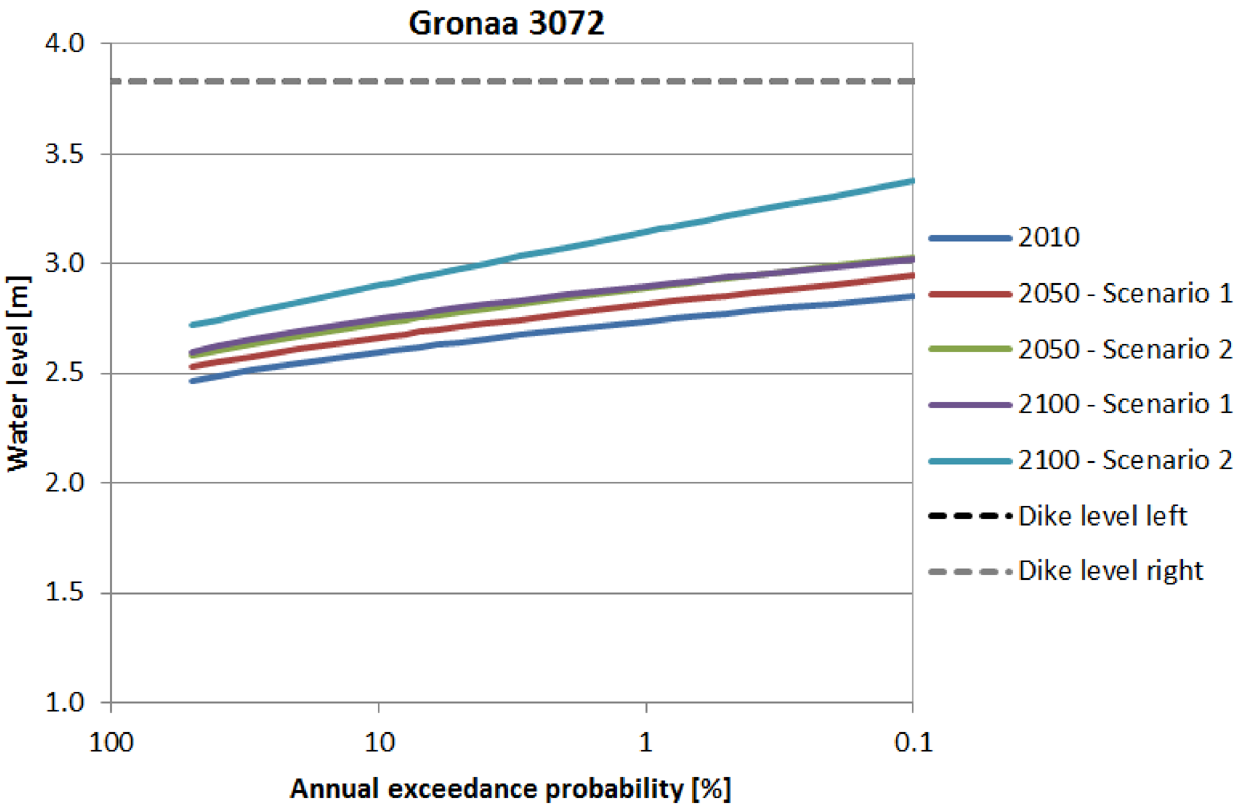


Figure A-16: Estimated extreme water level statistics at Gronaa St. 3072 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

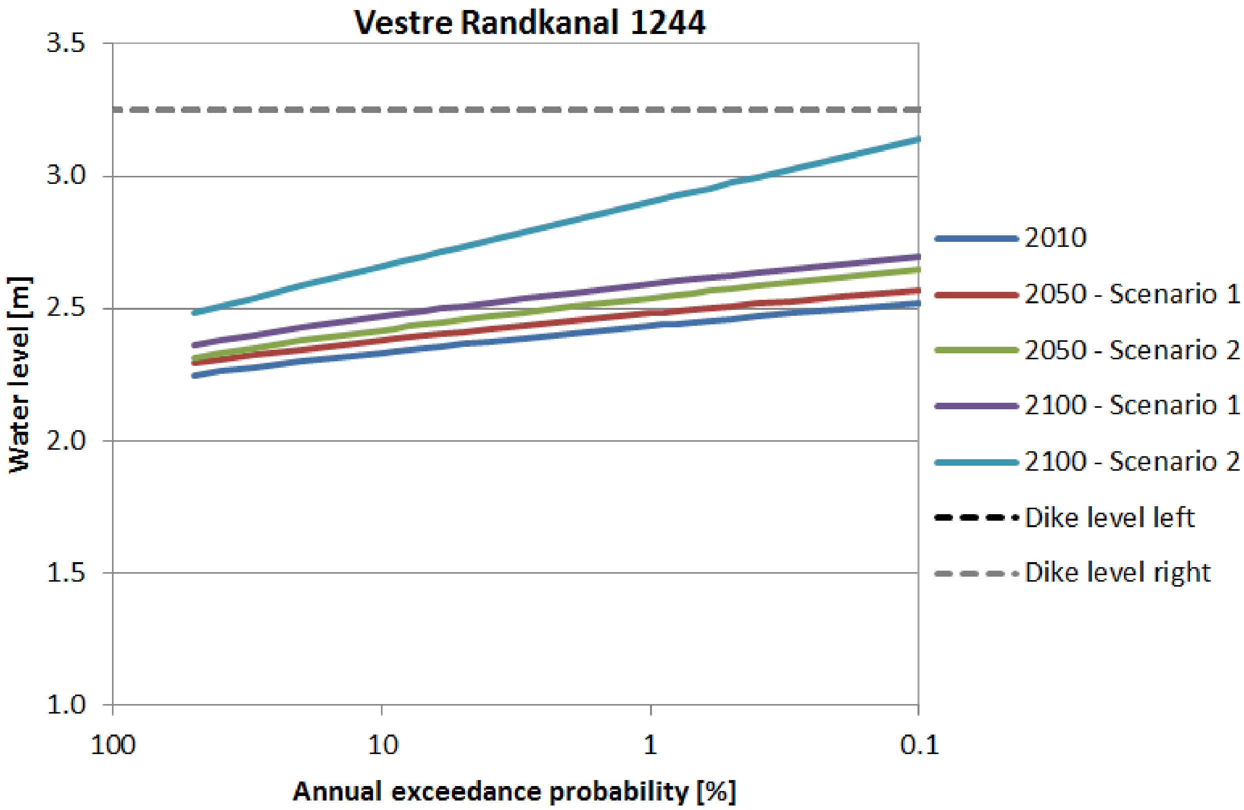


Figure A-17: Estimated extreme water level statistics at Venstre Randkanal St. 1244 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.

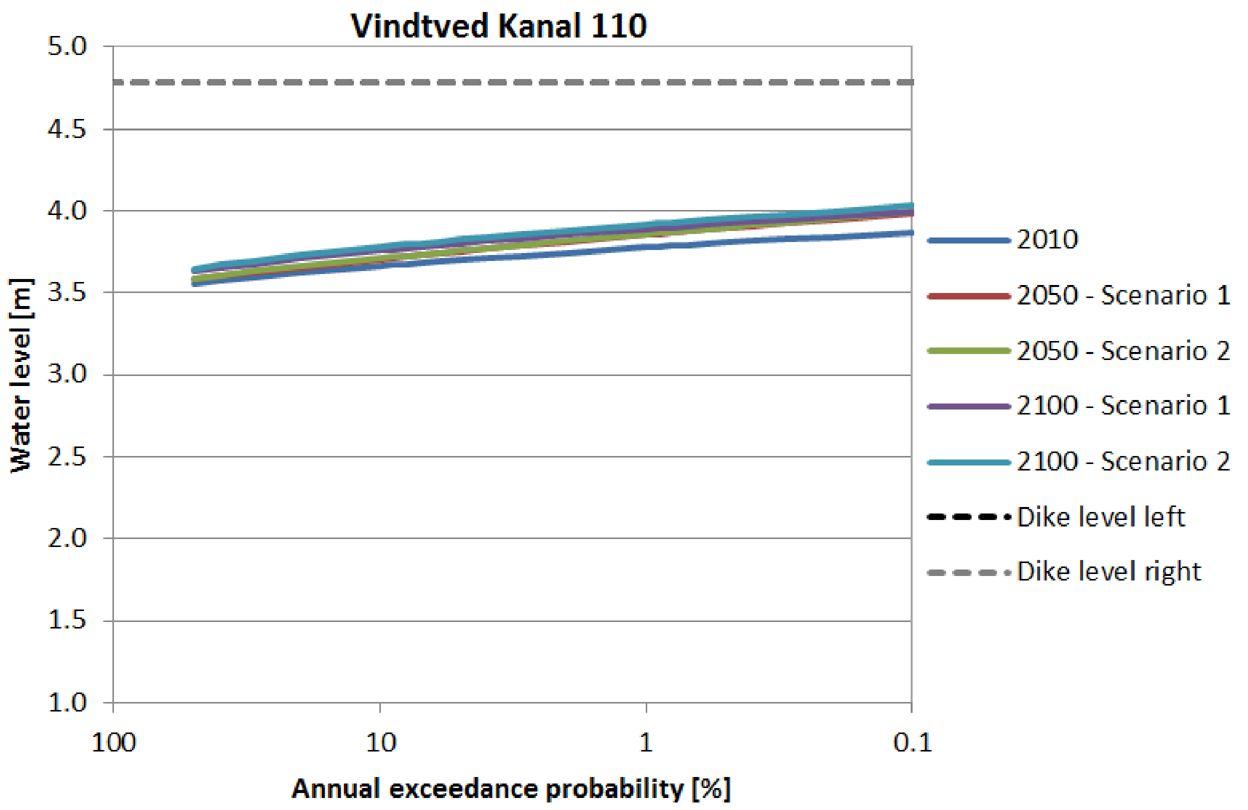


Figure A-18: Estimated extreme water level statistics at Vindtved Kanal St. 110 for current (2010) and future (2050 and 2100) climate. Scenario 1 and 2 refer to, respectively, the low and high scenario of mean sea level rise.