Chapter 38
Climate Change Impact Assessment of Dike Safety and Flood Risk in the Vidaa River System

Henrik Madsen, Maria Sunyer, Jacob Larsen, Mads N. Madsen, Bo Møller, Tobias Drückler, Martin Matzdorf and Jørgen Nicolaisen

Abstract The impact of climate change on the flood risk and dike safety in the Vidaa River system, a cross-border catchment located in the southern part of Jutland, Denmark and northern Germany, is analysed. The river discharges to the Wadden Sea through a tidal sluice, and extreme water level conditions in the river system occur in periods of high sea water levels where the sluice is closed and increased catchment run-off take place. Climate model data from the ENSEMBLES data archive are used to assess the changes in climate variables and the resulting effect on catchment run-off. Extreme catchment run-off is expected to

H. Madsen (✉) · M. Sunyer · J. Larsen · M. N. Madsen · B. Møller
DHI, AgernAllé 5, 2970 Horsholm, Denmark
e-mail: hem@dhigroup.com

M. Sunyer
e-mail: masu@env.dtu.dk

J. Larsen
e-mail: jla@dhigroup.com

M. N. Madsen
e-mail: mm@dhigroup.com

B. Møller
e-mail: ebm@mail.tele.dk

T. Drückler
DHI-WASY, Max-Planck-Str. 6, 28857 Syke, Germany
e-mail: tdr@dhi-wasy.de

M. Matzdorf
Kreis Nordfriesland, Marktstraße 6, 25813 Husum, Germany
e-mail: martin.matzdorf@nordfriesland.de

J. Nicolaisen
Tønder Kommune, Rådhusstræde 2, 6240 Løgumkloster, Denmark
e-mail: jn@toender.dk

W. Leal Filho (ed.), *Climate Change and Disaster Risk Management*,
Climate Change Management, DOI: 10.1007/978-3-642-31110-9_38,

increase about 8 % in 2050 and 14 % in 2100. The changes in sea water level is assessed considering climate projections of mean sea level rise, isostatic changes, and changes in storm surge statistics. At the Vidaa sluice a mean sea level rise of 0.15–0.39 m in 2050 and 0.41–1.11 m in 2010, and increases in storm surge levels of up to 0.8 m in 2100 are estimated. The changes in extreme catchment run-off and sea water level have a significant effect on the flood risk in the river system. While most parts today have a low risk of dike overtopping with annual exceedance probabilities of 0.1 % or less, the worst case scenario in 2100 show annual exceedance probabilities of 5 % or more in the downstream part of the river system.

Keywords Climate change · Flood risk · Extreme precipitation · Sea level rise · Storm surge

Introduction

The Vidaa River catchment is a cross-border catchment located in the southern part of Jutland, Denmark and northern Germany. The Vidaa River discharges into the Wadden Sea through a tidal sluice. Extreme water levels in the lower part of the river system occur during storm surges where the sluice is closed over a prolonged period, and at the same time increased run-off from the catchment takes place due to heavy precipitation. The low-lying part of the catchment is protected by river dikes. Changes in flood risk and dyke safety in the Vidaa River system in the light of climate change with anticipated sea level rise, more severe storm surges and heavier extreme rainfalls have been evaluated in an EU INTERREG project (INTERREG 4A Syddanmark-Schleswig-K.E.R.N).

To assess the impacts of future climate change both changes in the meteorological forcing (precipitation, temperature and potential evapotranspiration) and changes in sea water level are considered. Changes in meteorological forcing data are estimated from regional climate model projections included in the ENSEMBLES data archive. Future sea water levels are estimated from current projections of the mean sea level rise in the area, estimated isostatic changes, and changes in storm surge statistics predicted from a hydrodynamic model run forced with a regional climate model (Rugbjerg and Johnsson in press).

To estimate the changes in flood risk in the Vidaa River system an integrated hydrological and hydraulic model has been set up and calibrated. This model forms the basis for simulation of water levels in the river system using meteorological forcing and sea water level data for the current (using observed records) and the future climate (using projected records), considering two projection horizons, 2050 and 2100. Extreme value analysis is applied to estimate the risk of dike overtopping at different locations.

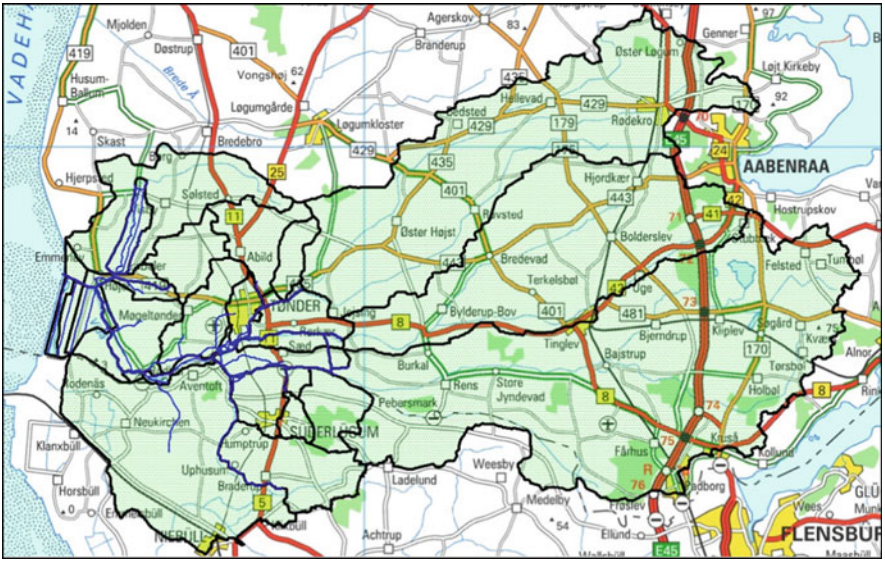

Fig. 38.1 MIKE 11 model setup. River basin (*green shaded area*), river network (*blue line*), and sub-catchments (*black line*)

Hydrological and Hydraulic Model Set-up

A MIKE 11 model (DHI 2009a) has been set up and calibrated for the Vidaa River basin (Fig. 38.1). The river network includes the Vidaa River and the major tributaries Gronaa, Sonderaa and Dreiharder Gotteskoogstrom as well as major drainage canals. The Vidaa River basin has a total catchment area of 1,342 km^2. For rainfall-run-off modelling the basin has been divided into 18 sub-catchments; four larger upstream catchments with a total area of 864 km^2 that drain to Vidaa, Gronaa and Sonderaa, and 14 downstream catchments with a total area of 478 km^2. Of the 14 downstream sub-catchments, four catchments are drained by pumping.

Rainfall-run-off models have been set up and calibrated for the 18 sub-catchments. Time series of run-off measurements were available for calibration of the four upstream catchments. No sub-catchment run-off measurements were available for calibration of the downstream catchments. These catchments were calibrated jointly against run-off measurements at the river basin outlet at the Vidaa sluice. Calibration results for one of the upstream sub-catchments and total catchment run-off are shown in Fig. 38.2. Both the rainfall/run-off dynamics and the catchment water balance are simulated satisfactorily.

Seasonal varying bed resistance has been adopted for the calibration of the MIKE 11 river model, in order to account for riverbed vegetation growth and cutting. Wind setup was included in the model and was shown to provide improved simulations of extreme events.

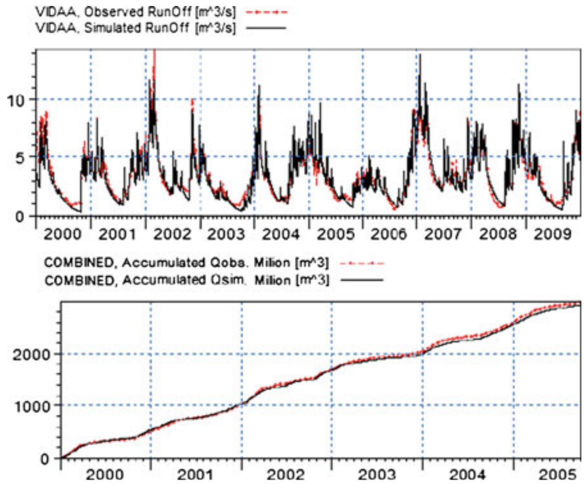

Fig. 38.2 Rainfall-run-off calibration results. *Top*: simulated (*black*) and observed (*red*) run-off at the Vidaa sub-catchment. *Bottom*: simulated (*black*) and observed (*red*) accumulated run-off at the Vidaa sluice

The integrated hydrological and hydraulic model was used for simulation of water levels in the river system, which was subsequently used in the extreme value analysis and flood risk assessment. For the long-term simulations, meteorological forcing data (precipitation, temperature and potential evapotranspiration) and sea water level at the Vidaa sluice are available for the period 1981–2009. The 10 events that cause the most extreme water levels in the downstream part of the river system are listed in Table 38.1. In general, extreme conditions with high water levels in the river system occur in periods with high sea water level at the Vidaa sluice and large run-off from the catchment. The most extreme event on record (29/10/1998)is mainly caused by extreme conditions of high sea water level at the Vidaa sluice (the most extreme duration on record) and less so on catchment run-off (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 level. On the other hand, the event 11/02/1988 (rank 6) is mainly due to extreme run-off conditions (rank 2) and less affected by sea water level. The table shows the complex nature of extreme conditions in the river system, which emphasises the need for integrated hydrological and hydraulic models for proper flood risk assessment.

Climate Change Projections

Hydrological Data

This project has used regional climate model (RCM) projections from the ENSEMBLES data archive to estimate the changes in hydrological variables in the Vidaa River basin for two projection horizons, 2050 and 2100. The ENSEMBLES

Table 38.1 Water level (H) at Rudbol Lake, total catchment run-off (Q) and peak sea water level and duration of high water level (above 0.5 m) at the Vidaa sluice for the 10 most extreme events in the downstream part of the river system

Date	Water level Rudbol lake		Total catchment run-off		Sea water level Vidaa sluice			
	H [m]	Rank	Q [m^3/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

data include a number of projections for the A1B emission scenario using different RCMs forced by different general circulation models (GCMs).

To correct for biases introduced by the RCM/GCM 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/GCM 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.

A mean correction methodology (also known as the Delta change approach) was applied for statistical downscaling of temperature. Temperature data for the future climate are obtained by adding absolute changes in temperature from the RCM/GCM projections to the observed temperature record. In order to estimate changes in potential evapotranspiration a temperature-based method was used (Kay and Davies 2008). Potential evapotranspiration data for the future climate is obtained from the relative change in temperature from the RCM/GCM projections. For statistical downscaling of precipitation a method that uses both changes in the mean and changes in the variance was applied as seen elsewhere in the literature. In this case, the future precipitation is given by (Leander and Buishand 2007): $P_{fut} = aP^{b}_{obs}$, where P_{obs} is the observed precipitation, and a and b are estimated from the changes in mean and variance.

For the calculation of change factors, catchment averages of daily precipitation and temperature from the RCM/GCM have been used. The changes are based on 30-year periods of climate model data, with 1980–2009 representing the present climate, 2035–2064 representing the future climate in 2050, and 2070–2099 representing the future climate in 2100.

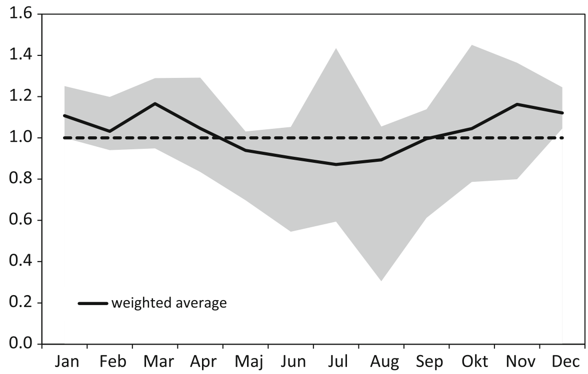

Fig. 38.3 Estimated variability of the change in mean precipitation in 2100 from the 15 RCM/GCM models (*grey shaded area*) and the weighted average

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 (Fowler et al. 2007). In this project, 15 RCM/GCM projections from the ENSEMBLES data archive were used for downscaling precipitation, temperature and potential evapotranspiration. Weighted average change factors were applied where weights for the 15 different RCM/GCM models were determined based on the skills of the models for simulation of present climate, considering the monthly variability of mean precipitation, variance of daily precipitation, and mean temperature.

A large variability in the estimated changes is seen for all statistics. As an example, the variability of the change in mean precipitation in 2100 of the 15 RCM/GCM models and the weighted average are shown in Fig. 38.3. Most models estimate an increase in precipitation in winter and a decrease in summer, but for all months, and especially in summer, a large variability is apparent. The weighted average change factors for 2050 and 2100 are shown in Fig. 38.4. The temperature increase is about 1–1.5° in 2050 and 2–2.5° in 2100. In general, precipitation increases in winter and decreases in summer and a larger variability is expected in all months, with the changes being more pronounced in 2100. The increase in potential evapotranspiration follows the changes in temperature with larger relative changes in winter than in summer.

The downscaled precipitation, temperature and potential evapotranspiration data for 2050 and 2100 have been used as input for rainfall-run-off model simulations. The changes in the estimated extreme value statistics of catchment average rainfall and total catchment run-off are shown in Fig. 38.5. The extreme daily precipitation increases about 9 % in 2050 and 15 % in 2100, and similar changes are seen in the extreme catchment run-off statistics (about 8 % in 2050 and 14 % in 2100).

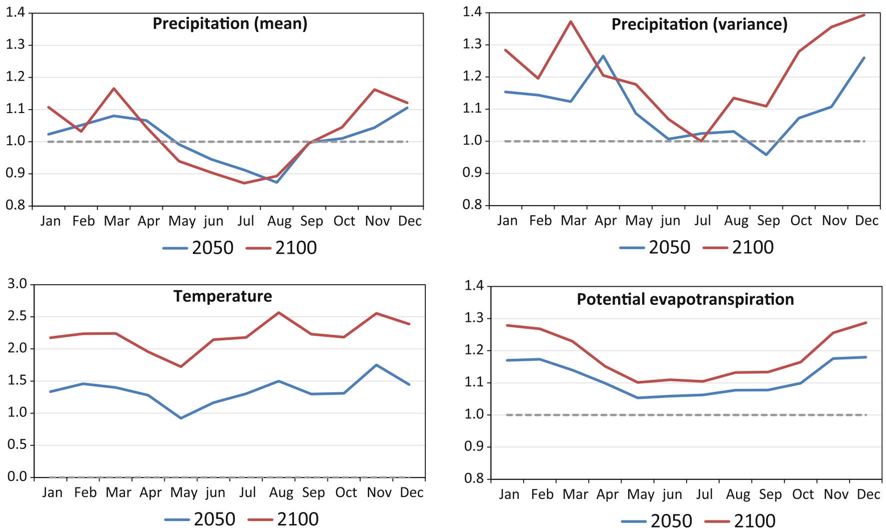

Fig. 38.4 Relative change in mean and variance of precipitation and mean potential evapotranspiration, and absolute change in temperature (degrees Celsius) for future (2050 and 2100) climate

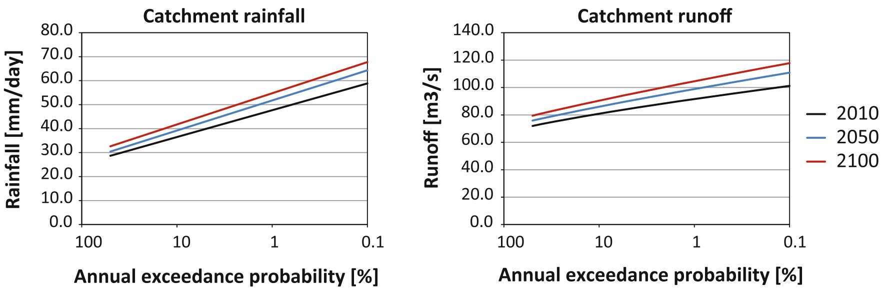

Fig. 38.5 Extreme value statistics of catchment average rainfall and total catchment run-off for current (2010) and future (2050 and 2100) climate

Sea Water Level

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

- Global increase in mean water level due to thermal expansion and melting of glaciers and ice caps;
- Local change in mean water level due to changes in water density and circulation patterns;
- Local change in mean water level due to isostatic change;
- Local change in storm surge levels due to changes in extreme storm intensities and changes in mean water level.

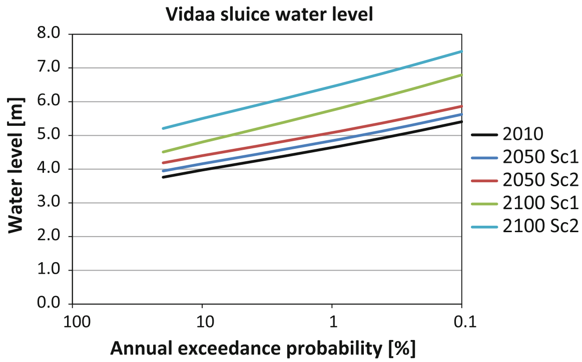

Fig. 38.6 Estimated extreme sea water level statistics at the Vidaa sluice for current (2010) and future (2050 and 2100) climate. Sc1 and Sc2 correspond to, respectively, the low and high scenario of mean sea level rise

According to the results published in the IPCC's Fourth 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 global sea level rise will be larger than reported in the IPCC's Fourth Assessment Report (e.g. Grinsted 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 0.3–1.0 m in 2100 (Danish Climate Change Adaptation Portal 2011). Due to the large uncertainties in the projected increase in mean sea water level, two scenarios have been applied in the analysis corresponding to, a respective increase of 0.3 and 1.0 m in 2100. In order to estimate 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 mean sea water level at the Vidaa sluice due to isostatic changes to the extent of 11 cm in 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 were used. The model was forced by wind and atmospheric pressure fields from one of the RCM models form the ENSEMBLES data archive (Rugbjerg and Johnsson in press). Time series of sea water levels at the Vidaa sluice were extracted from the hydrodynamic model simulations. Extreme water level statistics were calculated for 2010 using these time series (based on simulation results for the period 1980–2009), 2050 (2035–2064) and 2100 (2070–2099). Future extreme value statistics for 2050 and 2100 are 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 Fig. 38.6).

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

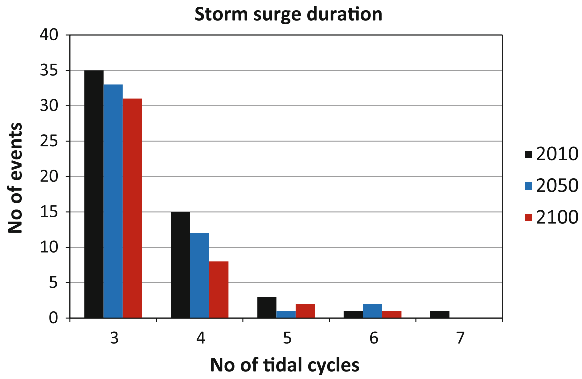

Fig. 38.7 Distributions of duration of storm surge water level above 0.5 m in terms of number of tidal cycles from the hydrodynamic model simulations for current (2010) and future (2050 and 2100) climate

annual exceedance probabilities ranging between 0.5 and 5 %. This corresponds well with results from other studies in this area (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 exceedance probability of about 0.5 % according to the current statistics (corresponding to an event which is expected once every 200 years on average) but will in 2100 in the case of the high sea level rise scenario have an annual exceedance probability of about 30 % (1 in 3-year event).

As shown above, the duration of high sea water level at the Vidaa sluice is critical for storage of water in the river system. The duration of high sea water levels have been calculated from the hydrodynamic model simulations. In Fig. 38.7 the number of events with prolonged periods of high water level at the Vidaa sluice (above 0.5 m) are shown for the three 30-year periods representing 2010, 2050 and 2100 (without changes in mean sea level). As opposed to the extreme storm surge peak level, the durations of high water levels are not expected to increase in future climate. In fact, the number of events with larger durations tends to slightly decrease towards 2100.

Based on the above results, time series of sea water levels at the Vidaa 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 four different climate change scenarios applied in the risk analysis are summarised in Table 38.2.

Risk Analysis

The integrated hydrological and hydraulic model has been used for simulations using the observed records of meteorological data and sea water level at the Vidaa sluice 1981–2009, and the projected records representing the respective climates for 2050 and 2100 (see Table 38.2). From the simulations, water levels at selected

Table 38.2 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 (cm)	Isostatic change (cm)		
1	2050	+10	+5	Based on hydrodynamic model run 2035–2064	Based on ENSEMBLES data 2035–2064
2	2050	+34	+5		
3	2100	+30	+11	Based on hydrodynamic model run 2070–2099	Based on ENSEMBLES data 2070–2099
4	2100	+100	+11		

critical locations in the river system have been extracted and used for the extreme value and risk analysis.

The MIKE by DHI extreme value analysis software package EVA (DHI 2009b) has been used for the analysis. EVA includes both annual maximum series and peak over threshold (POT) estimation procedures. Several statistical distributions are included, and EVA supports parameter estimation using maximum likelihood, method of moments and method of L-moments. Several goodness-of-fit measures are available to support selection of a proper statistical distribution. In this study, the POT method has been applied for analysis of extreme water levels. The analysis showed that the Weibull distribution is preferable for the fitting of water level extremes.

An example of the results of the extreme value analysis at one of the selected locations is shown in Fig. 38.8. The figure shows the extreme water level statistics for current conditions and the four different climate change scenarios compared to the river dike levels. 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 sea level rise scenario the risk increase 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 to a 1 in 10 years event, which represents a significant increase in the flood risk at this location.

In Fig. 38.9 the flood risks for current and future climate at the selected locations are shown. Current conditions indicate that the flood risk in most parts of the river system is less than 1 %. The 2100 climate with the high mean sea level scenario has a considerably larger flood risk. In the upstream river branches the

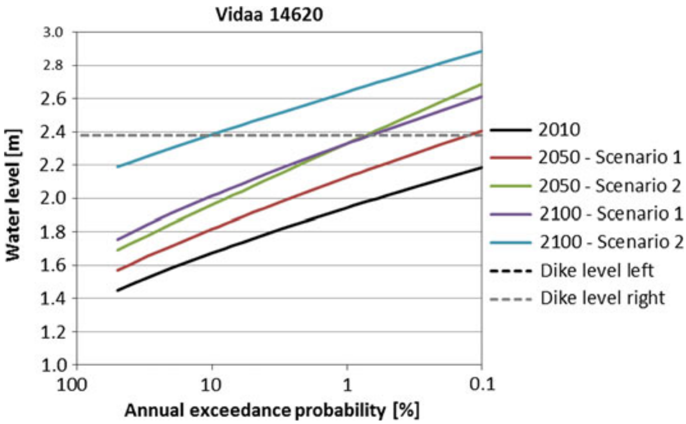

Fig. 38.8 Estimated extreme water level statistics at Rudbol Lake for current (2010) and future (2050 and 2100) climate. Scenario 1 and Scenario 2 refer to, respectively, the low and high scenario of mean sea level rise

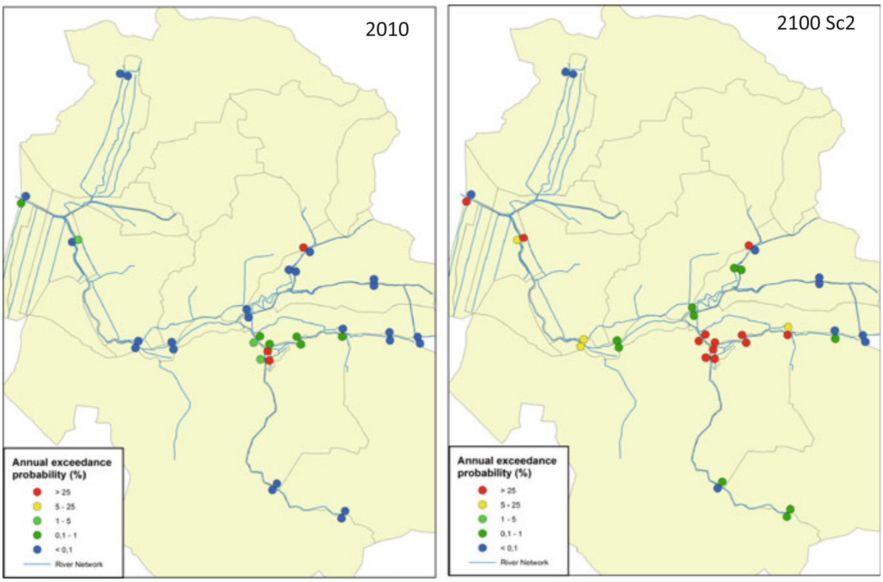

Fig. 38.9 Estimated flood risk at selected locations in the Vidaa River system for current (2010) and future (2100 with high mean sea level scenario) climate. For each location the annual exceedance probabilities for overtopping on the left and right bank are shown

risk is still small (annual exceedance probability less than 0.1 %), but the downstream parts of the Vidaa and Sonderaa Rivers have risk levels of 5 % or more.

Conclusions

The impact of climate change on the risk of dike overtopping in the Vidaa River system has been evaluated. Both changes in the meteorological forcing data (precipitation, temperature and potential evapotranspiration) and changes in sea water level have been considered. Results from 15 RCM/GCM projections from the ENSEMBLES data archive were used for estimating changes and downscaling future meteorological forcing. More extreme precipitation events are expected in the future, which will result in an increase in the extreme run-off in the Vidaa River basin of about 8 % in 2050 and 14 % in 2100.

Regarding changes in sea water level at the Vidaa sluice, climate projections of mean sea level rise, isostatic changes, and changes in extreme water level statistics have been included. Due to the large uncertainty in current projections of mean sea level rise, two scenarios have been considered. Hydrodynamic model results show increases in extreme storm surge levels at the Vidaa sluice of up to 0.8 m in 2100. However, durations of extreme water levels are not seen to increase.

For the projected changes in meteorological forcing and sea water level, changes in extreme conditions in the Vidaa river system have been analysed. Currently, there is a relatively low risk of dike overtopping with annual exceedance probabilities of 0.1 % or less in most parts of the river system. For the worst case scenario in 2100, pronounced changes in flood risk are seen with flood risks of 5 % or more in the downstream parts of the Vidaa and Sonderaa Rivers.

References

Danish Climate Change Adaptation Portal (2011) Future sea level rise (In Danish). Available http://www.klimatilpasning.dk/

Danish Coastal Authority (2007) Extreme sea level statistics for Denmark (In Danish)

DHI (2009a) MIKE 11. A modelling system for rivers and channels. Reference manual, MIKE by DHI 2009

DHI (2009b) EVA. Extreme value analysis. Technical reference and documentation, MIKE by DHI 2009

Fowler HJ, Blenkinsop S, Tebaldi C (2007) Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modeling. Int J Climatol 27:1547–1578

Grinsted A, Moore JC, Jevrejeva S (2009) Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. Clim Dyn. doi:10.1007/s00382-008-0507-2

IPCC (2007) The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. In: Solomon SD, Qin M, Manning Z, Chen M, Marquis KB, Averyt MT, Miller HL (eds) Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p 996

Kay AL, Davies HN (2008) Calculating potential evaporation from climate model data: a source of uncertainty for hydrological climate change impacts. J Hydrol 358:221–239

Leander R, Buishand TA (2007) Resampling of regional climate model output for the simulation of extreme river flows. J Hydrol 332:487–496

Madsen KS (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
Rugbjerg M, Johnsson M (in press) Climate change effects on marine design conditions in the North Sea. The Inner Danish Waters and the Baltic Sea (in preparation)

Author Biographies

Henrik Madsen has more than 15 years' experience in hydrological modelling, water resources management, extreme value analysis, stochastic modelling, flood forecasting, and climate change impact assessment. He is head of innovation at DHI responsible for the research and development activities within climate change adaptation. He is co-ordinator of a major research project on risk-based design in a changing climate funded by the Danish Strategic Research Council (http://riskchange.dhigroup.com/) and member of the Science Core Group of the Centre for Regional Change in the Earth System (CRES) (http://cres-centre.net/).

Maria Sunyer has experience in working with climate data and climate change issues. Her expertise covers statistical downscaling of climate model projections, climate change impact assessment of hydrological systems, and flood risk analysis. She is currently a PhD student at the Technical University of Denmark working with methods for estimation of uncertainty in climate model projections.

Jacob Larsen has 12 years of experience in the application of computational models covering both coastal and inland waters. Most of the last eight years of his career have been spent on development, maintenance, and application of major flood forecasting and flood management systems in many different countries of the world, working with local river management authorities or private organisations. He has been responsible for the customisation and installation of hydrological and hydraulic flow forecasting systems in the USA, Asia, Europe, and the Pacific.

Mads N. Madsen has more than 20 years' experience in development and application of mathematical modelling systems for simulation of flows and water quality in rivers, estuaries, and reservoirs. He has extensive experience from assignments in Europe and Asia in relation to project management, training and teaching and business development. He has published several papers in international journals with emphasis on mathematical model development and application.

Bo Møller was employed in the county of Southern Jutland between the years 1988–2006 working in river management, including dike safety and the assessment of flood risk. From 2006 he has worked as senior consultant in a number of projects related to water resources planning and management.

Tobias Drückler has worked at DHI-WASY for two years. He forms part of the flood forecast team at DHI-WASY and is an expert in hydrological and hydraulic modelling.

Martin Matzdorf is head of the Water Management Division at the Nordfriesland County, Northern Germany.

Jørgen Nicolaisen is working in the Environment Department at the municipality of Tønder, Southern Jutland, Denmark.