Projected Change—Hydrology

12

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Abstract

This chapter reviews studies on projected hydrological changes within the Baltic Sea catchment area published since the first assessment of climate change in the Baltic Sea region in 2008. Hydrological impact studies have been carried out in almost all countries in the area. The large differences in hydrological conditions (present and projected) from northern Scandinavia to the southern Baltic Sea area are addressed. The chapter considers the impacts of snow accumulation and melt, river discharge and flooding. Water resources with studies on dry periods and groundwater resources are also covered. In contrast to the first assessment, uncertainty has received significant attention. In contrast to traditional hydrological studies, projections of climate impacts on hydrology are associated with uncertainties related to the models and greenhouse gas (GHG) emission scenarios used. In several studies, individual uncertainty sources are quantified and compared.

Keywords

Hydrological change • Hydrological modeling • Climate model projection uncertainty • Impact model uncertainty

12.1 Introduction

This chapter reviews studies on projected hydrological changes within the Baltic Sea catchment area published since the first assessment of climate change in the Baltic Sea region (BACC Author Team 2008). The majority of the studies have been performed at a national level. This chapter is therefore structured by country within the Baltic Sea catchment area. Impact assessments associated with the changes in climate and hydrology are found in Chaps. 15–22.

12.2 Country-Specific Projections

12.2.1 Belarus

No separate studies on catchments in Belarus were found. However, the river Neman/Nemunas covers part of Belarus and is addressed under Lithuania (Sect. 12.2.7).

12.2.2 Denmark

Thodsen et al. (2008) analysed the impacts of direct and indirect effects of climate change on suspended sediment transport in Danish rivers. Two lowland catchments were examined, an alluvial catchment dominated by sandy soils and a moraine catchment dominated by clay soils. Both catchments were modelled using a rainfall-run-off model for discharge and a regression model for the relation between discharge, precipitation and suspended sediment transport. Climate input from the Danish regional climate model (RCM)

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The BACC II Author Team, *Second Assessment of Climate Change for the Baltic Sea Basin*, Regional Climate Studies,
DOI 10.1007/978-3-319-16006-1_12

HIRHAM representing the SRES A2 scenario for 2071–2100 was used. The effect of climate change appeared to be more important than the change in length of the growing season. While changes in mean annual precipitation of 6–7 % were projected, the mean annual river discharge was projected to increase by 11–14 %, and the sediment transport by 24–27 % in the moraine catchment and 9–17 % in the alluvial catchment, depending on the growing season scenario used. Hence, the study indicates that the climate change effect increases down the chain—from precipitation to discharge to sediment transport—presumably because of strong seasonal changes.

Jeppesen et al. (2009) used the NAM rainfall-run-off model at ten small catchments in Denmark to quantify the effects of the climate projection provided by the ECHAM4/OPYC general circulation model (GCM) (SRES A2 scenario) downscaled by the Danish HIRHAM RCM (25-km grid). Annual discharge for the period 2071–2100 was projected to increase by 9–34 % compared to the control period 1961–1990. Strong seasonal changes were observed in response to seasonal changes in precipitation, with monthly run-off generally increasing in winter and decreasing in late summer. The projected discharge was used with a statistical phosphorus loading model. This resulted in an increase in phosphorus loading of 3.3–16.5 % and a decrease in phosphorus concentration of −2.2 to −13.4 %.

van Roosmalen et al. (2007) used the distributed, physically based hydrological model MIKE SHE to evaluate the impact of climate change on two large-scale catchments, a sandy area in the western part of Denmark and a clay area in the eastern part. The two models were forced by projections from the PRUDENCE project (Christensen and Christensen 2007) as simulated by the HIRHAM RCM nested in the HadAM3H GCM. The SRES A2 and B2 scenarios for the period 2071–2100 were considered, and the delta change approach was used for bias correction (see Chap. 10, Sect. 10.3.1.2). The authors found the magnitude of the hydrological response to be highly dependent on the geological settings of the model area. In the sandy catchment, groundwater recharge increased as a result of higher winter precipitation. Groundwater levels increased significantly, up to 3 m, resulting in elevated base flow and drain flow to the rivers. Significant increases in winter river discharge occurred, while summer discharge was only slightly affected. In contrast, only small changes in groundwater level occurred in the clay area since the infiltration capacity of the less permeable shallow geology was exceeded. Here, the increase in precipitation resulted in significant changes in drain flow and overland flow to rivers, with changes in mean monthly river discharge of up to +50 % in winter and −50 % in summer.

In a subsequent study, van Roosmalen et al. (2009) used the same model set-up to quantify the combined effects of climate change, sea level rise and change in land use on irrigation demand and water resources. The study showed that climate change had the most substantial effect on the hydrological system. However, indirect effects were also found to be significant. Irrigation demands were found to increase by up to 90 % for the SRES A2 scenario. Although groundwater levels generally increased with increasing mean precipitation, the water content of the root zone was found to decrease during summer in response to decreasing summer precipitation and increasing evapotranspiration. Changes in land cover from grass to forest and changes in growing season length resulted in minor effects on groundwater recharge. More significant effects were found when assuming that plant respiration became more water efficient with increasing carbon dioxide (CO_2) concentrations. A simple approach was used where future potential evapotranspiration (PET) was assumed to equal present PET and not to increase in response to the projected rise in future temperature. The resulting reduction in actual evapotranspiration was found to have a relatively large impact on groundwater recharge, groundwater levels and stream discharge. Sea level rise of 0.5 and 1.0 m was shown to have a pronounced effect on groundwater levels in coastal areas, where groundwater was affected up to 10 km inland from the coast.

van Roosmalen et al. (2011) studied the impact of the bias correction method on the response of a hydrological model. The delta change method (Chap. 10, Sect. 10.3.1.2), where the observed database of meteorological variables are perturbed according to the changes projected by the climate model, was compared to a distribution-based scaling (Chap. 10, Sect. 10.3.1.1; Piani et al. 2010), where the projected meteorological variables are corrected. In contrast to the delta change method, the distribution-based scaling method reproduced the dynamics of the climate model, for example prolonged periods of drought and possible changes in the number of days with precipitation. Comparing the hydrological simulations using both methods, only small differences in the hydrological variables were found. Only average quantities were analysed, however, such as annual groundwater recharge, mean change in groundwater level or mean monthly river discharge. The authors recommended that additional analyses are needed, addressing extremes and sensitivity to catchment characteristics, such as sandy versus clay catchments.

12.2.3 Estonia

No recent studies on the impact of climate change on basins in Estonia were found.

12.2.4 Finland

The effect of climate change on design floods was evaluated for 34 dams in Finland by Veijalainen and Vehviläinen (2008).

Design floods are hypothetical floods defined by their probability of occurrence and are used for planning and floodplain management. A 14-day design precipitation with a 1000-year return period was generated for both present-day and future climate conditions. The design precipitation, which depends on location and time of year, is defined such that the largest precipitation occurs on the 9th day of the period and corresponds to the 1000-year maximum of 1-day precipitation, while the precipitation sum of days 7–11 corresponds to the 1000-year maximum 5-day precipitation. The design storm is moved through the 40-year observation period and the 30-year future period. Results representing 2071–2100 from three GCMs, three emission scenarios and two estimates of design precipitation were applied in order to evaluate the uncertainty of the resulting change in design flood. The rainfall-run-off model WSFS was used. In northern Finland, the timing and magnitude of the floods were on average found to remain unchanged. Warmer winters with less snow accumulation were partly compensated for by increases in winter and spring precipitation. On dams in western and central Finland, the design floods increased, while the timing remained unchanged (summer and autumn). In eastern Finland, the time of the design floods changed from spring to summer, while both increasing and decreasing magnitudes of the design floods were found. The range of changes in the simulated design floods was large at most sites resulting in projections of both increasing and decreasing design floods at several dams. However, the relative contribution from the individual uncertainty sources was not quantified. The authors drew attention to the fact that additional uncertainty sources such as the impact model type or the parameters of the impact model would result in even larger uncertainty ranges.

Veijalainen et al. (2010a) assessed the impact of climate change on the regulation of three lakes in eastern Finland. The rainfall-run-off model WSFS was forced by results from 14 projections of climate change generated by combining four GCMs, where one was found as an average of 19 GCMs (IPCC 2007) and three SRES scenarios. Two scenarios were downscaled using the RCA3 RCM. The delta change approach was used for bias correction in all cases. Clear changes occurred in the seasonality of run-off and water levels, with decreases in late spring and summer and increases in late autumn and winter. The changes were primarily due to changes in snow accumulation and melt with changes in precipitation and evaporation less important. Current regulation permits were found to be unsuited for the projected future hydrological conditions in many lakes.

The effects of climate change on discharge and fluvial erosion potential were studied by Lotsari et al. (2010) for a sub-Arctic catchment in the border area between Finland and Norway in northern Fennoscandia. Impact modelling was carried out by combining results from the rainfall-run-off model WSFS with the two-dimensional hydraulic model TUFLOW. Future scenarios using three different emission scenarios and two different GCMs were applied. Additionally, two GCM projections were downscaled using the RCA3 RCM. The period 2070–2099 was considered, and the delta change approach was applied for bias correction. Based on annual maximum discharges projected by WSFS, floods with return periods of 2 years and 250 years were estimated using an extreme value-type I distribution. The floods were used as input to the hydraulic model. For all eight scenarios, the flood with a return period of 2 years was found to decrease in a future climate, while for the 250-year flood a decrease was found in seven out of eight cases. The reason for decreasing flood discharges was found to be a decline in snowfall together with a shorter snow accumulation period and warm spells with snow melt during winter. As a result, future erosion power was reduced, that is diminishing flow velocity, bed shear stress and stream power.

Veijalainen et al. (2010b) used the same methodology as Lotsari et al. (2010) to assess the impacts of climate change on flooding in Finland. However, the number of climate change projections was increased to 20, including three emission scenarios (SRES A2, A1B and B1), five GCMs and four RCMs. The delta change approach was used for transferring the climate model results to the hydrological model. Changes in flooding were evaluated at 67 study sites covering Finland. The 100-year floods were on average found to decrease by 8–22 % in 2070–2099 compared to the reference period 1971–2000. However, considerable variation between regions was observed. In areas currently dominated by spring snowmelt floods, the 100-year flood generally decreased due to less snow accumulation. In areas where autumn and winter flooding currently occur frequently, the projected increases in temperature and precipitation result in increasing floods. For the central lakes characterised by long-lasting volume floods, a clear increase was found. The changes in discharge were not linearly reflected in flood area extent. The characteristics of the river channels and floodplains were found to greatly influence the spatial extent of flood inundation. Flat floodplains showed a larger change in inundation than the projected change in discharge, whereas floodplains with greater variation in topography experienced less change in inundation. Generalisations based on a few case studies or a few climate scenarios in countries with variable hydrological conditions should be avoided, however.

Based on a statistical relation between the elevation of the groundwater table and snowmelt, precipitation and evapotranspiration, Okkonen and Kløve (2010) projected the fluctuations in the groundwater table for the period 2010–2039. The analysis was based on a lumped conceptual water balance model and climate projections using the SRES A2 scenario (climate model unspecified). The elevation of the groundwater table for a catchment in central Finland was found to increase in winter and decrease in summer. However, the changes were small with differences in mean monthly values of up to about 20 cm.

12.2.5 Germany

No studies on German catchments areas in the Baltic Sea basin were found.

12.2.6 Latvia

Apsīte et al. (2011) evaluated the impact of climate change on river run-off at eight river basins in Latvia for 2071–2100. Based on the SRES A2 and B2 scenarios, results from the GCM–RCM combination HadAM3H-RCAO were used to force a conceptual rainfall-run-off model. While mean annual temperature, precipitation and evapotranspiration were projected to increase, the mean annual river run-off was projected to decrease by 2–24 %. However, strong seasonal changes were found especially in winter, spring and autumn. A shift in the timing of maximum run-off from spring to winter was projected, and winter run-off was shown to increase significantly. Summer run-off was not projected to change much. A higher frequency of days with heavy rainfall was also projected. It was concluded that the river run-off regime will become similar to that of present-day western European rivers with two principal periods, one with high flow during winter and one with low flow during summer.

12.2.7 Lithuania

Kriaučiūnienė et al. (2008) carried out an impact assessment of climate change on the river Nemunas located in eastern Lithuania and western Belarus. Based on projections from two GCMs (ECHAM5 and HadCM3), each forced by three emission scenarios (SRES A2, A1B, and B1), the delta change method was used to transfer the climate change signal to the conceptual rainfall-run-off model HBV. The changes in river run-off were forecast for five 10-year periods covering 2011–2100. The impact of climate change increased over time and generally showed the same tendency during the scenario period. River discharge decreased significantly, and the spring flood became earlier and decreased greatly. The largest changes in average river discharge were found for the SRES A1B scenario, with a decrease of up to 41 %, whereas the effects for A2 and B1 were comparable and less significant. The reason is that temperature increased the most for the A1B scenario, whereas precipitation was almost unchanged. Hence, locally, the good scaling between temperature increase and change in precipitation shown in Chap. 11, Fig. 11.2 may not be valid. Owing to the rise in temperature, the probability of snowfall decreased resulting in a reduced spring flood with the effect that the maximum flood discharge also decreased significantly.

The study by Kriaučiūnienė et al. (2008) was extended by Kriaučiūnienė et al. (2009) to include the impact of hydrological model uncertainty. Using a generalised likelihood uncertainty estimation (GLUE; Beven and Binley 1992) methodology, the impact of model parameter uncertainty was compared to the uncertainty from the choice of GCM and emission scenario. One thousand parameter sets were initially chosen using a Monte Carlo method and subsequently ranked according to a likelihood function that expresses the match to the observed data. A threshold value was defined in order to select the parameter sets resulting in the best match to the observed discharge. The choice of emission scenario was found to be responsible for 75 % of the uncertainty, while the choice of GCM was responsible for 18 %. Hence, the emission scenario has a greater influence on forecasting run-off than the choice of GCM. However, it should be noted that only two GCMs and three emission scenarios were analysed. The impact of parameter uncertainty was only 7 % of the total uncertainty. However, the significance of the parameter uncertainty depends to a high degree on the choice of threshold value used in the GLUE methodology, which is subjective. If all 1000 parameter sets are considered, the parameter uncertainty accounts for 23 % of the total uncertainty.

12.2.8 Norway

Beldring et al. (2008) presented projections of climate change impacts on four catchments in Norway using the rainfall-run-off model HBV based on scenarios from two GCMs (HadAM3H and ECHAM4/OPYC3), one RCM (HIRHAM), two SRES scenarios (A2 and B2) and two methods for bias correction of climate model results. The choice of bias correction method was found to have an especially important effect on the projections of river discharge. The delta change method was compared to an empirical adjustment procedure developed by Engen-Skaugen (2007) that not only adjusts the mean but also the variance of the RCM data. The delta change approach was found to overestimate temperatures around 0 °C because the same changes are applied to all temperature intervals resulting in an overestimation of snowmelt intensity. The empirical adjustment procedure of Engen-Skaugen (2007) was found to be more accurate than the delta change approach as changes in the frequency of temperature and precipitation events and trends in the climate scenarios are preserved. The most important impacts of climate change were found to be earlier snowmelt and reduced snow storage, with the result that snowmelt floods occur earlier and winter and autumn discharge decrease. The changes were found to be caused more by change in temperature than precipitation.

12.2.9 Poland

Szwed et al. (2010) analysed the impact of climate change on water resources in Poland with a focus on agricultural effects. Based on results from the GCM–RCM combination, ECHAM5-MPI-M-REMO a water balance given by precipitation minus evapotranspiration was calculated for 2061–2090. The water balance for the country as a whole is projected to become more negative, indicating increasing water deficit. A cumulative probability curve for water deficit shows a shift to lower values, with a decrease in the median value from −32 to −50 mm. In addition, the maximum number of consecutive dry days is projected to increase across most of Poland. The authors concluded that the water budget is likely to become increasingly stressed, meaning greater additional water supplies would be needed to exploit the agro-potential of the environment. However, the already limited water resources of Poland do not allow large-scale irrigation and so the situation is likely to become increasingly severe in the future.

12.2.10 Russia

No specific modelling studies on future catchment discharges to the Baltic Sea are available. However, part of Russia is included in the study by Veijalainen et al. (2010a) reported in Sect. 12.2.4 for Finland.

12.2.11 Sweden

Yang et al. (2010) used results from the GCM/RCM ECHAM5/RCA3 forced by the SRES A1B scenario as input to the rainfall-run-off model HBV (Bergström 1976) to quantify the effects of projected climate change on three catchments located in the northern, middle and southern part of Sweden. Two methods for adjusting the output from the RCMs were tested: the delta change method (Chap. 10, Sect. 10.3.1.2) and an approach referred to as distribution-based scaling (DBS; Chap. 10, Sect. 10.3.1.1). While the delta change method uses observed data as a baseline and only the mean is adjusted, the DBS method uses the RCM results as baseline and adjusts the entire frequency distribution. The DBS approach was found to better preserve the future variability of the RCM output. Based on comparison of future discharge from the HBV model, greater variability in discharge was found using the DBS-adjusted data resulting in, for example, larger extreme discharges than the delta change approach. DBS was found to be more sensitive to the projections used and preserved the annual variability from the corresponding climate model projection.

Olsson et al. (2011) used an ensemble of climate projections to investigate uncertainties in hydrological changes. Twelve climate model projections were used to simulate the inflow to Lake Vänern by the HBV rainfall-run-off model. Results from three GCMs were downscaled using four RCMs operated at different resolutions. In all cases, the climate signal from the RCM was adjusted using DBS, which was established for the reference period 1961–1990. The impact of emission scenario, GCM, initial conditions for the GCM, RCM, and resolution of the RCM were examined. All projections were found to accurately reproduce the observed discharge to the lake during the reference period. Subsequently, the changes calculated by the 12 models for the period 1991–2008 were evaluated against observed changes. The performance of the different projections varied widely with respect to simulating changes in monthly mean discharge. All projections underestimated the observed increase in January–February, and most overestimated the discharge in March. During the rest of the year, most scenarios were out of phase with the changes simulated using the observed precipitation and temperature. Projections for 2009–2030 suggested that winter discharge would increase and that summer and autumn discharge would decrease. However, the projections disagree on both the sign and magnitude of changes for all months of the year. The greatest sources of uncertainty were identified as the GCM used and its initialisation, which is in contrast to the study of Kriaučiūnienė et al. (2009) for Lithuania who concluded that the emission scenario was the most important source of uncertainty. The RCM and its resolution were found to have a smaller influence. It was found that the difference in hydrological change using the SRES A2 scenario compared to the A1B scenario is larger than the difference between scenarios B1 and A1B. This indicates that the effect of the emission scenario may depend on the specific scenario chosen. The effect of GCM initialisation shows the importance of natural variability within the models on the resulting climate change projections. The authors indicated the importance of further development of climate models that are in phase with the historical climate and thus potentially able to generate decadal forecasts rather than projections. However, several uncertainty sources were not covered in the study, including the choice of bias correction method and the choice of hydrological model.

Wetterhall et al. (2011) used a response surface approach to handle the uncertainties in impact scenario modelling.

A framework consisting of four steps was proposed, including the definition of scenarios of changes in key climatic variables (e.g. precipitation or temperature), performing a sensitivity analysis of the climate change using the impact model, identifying critical thresholds (e.g. extreme flows) and evaluating the probability exceedance of the thresholds. The response surfaces are generated by perturbing the observed time series incrementally and using the resulting data as input to the impact model, in this case the rainfall-run-off model HBV. The probability of exceeding the defined threshold is plotted on diagrams as a function of the key climatic variables. This information can subsequently be used as an easy way to estimate the risk of reaching a predetermined threshold given information on projected changes in the key climatic variables from one or more climate models. Based on three test cases, the Lule River, Lake Vänern and Lake Mälaren, the method was found to provide a visualisation tool for expressing probabilistic hydrological change that is able to assess the uncertainties caused by climate models. Results suggested that low water levels in Lake Mälaren are likely to become more common in future, while the run-off at Lule River is very likely to increase in winter and spring and decrease in summer. Wetterhall et al. concluded that the thresholds should be selected carefully based on a good understanding of local conditions. The method also requires that the climate change can be expressed by a few variables, for example change in mean temperature or precipitation.

12.3 Conclusion

The studies cited in this chapter generally confirm the conclusions of the first assessment of climate change in the Baltic Sea basin (BACC Author Team 2008). For areas presently characterised by spring floods due to snow melt, the floods are likely to occur earlier in the year and their magnitude is likely to decrease owing to less snowfall and a shorter snow accumulation period. As a consequence, sediment transport and the risk of inundation are likely to decrease. In the southern part of the Baltic Sea area, increasing winter precipitation is projected to result in increased river discharge during winter. In addition, groundwater recharge is projected to increase in areas where the infiltration capacity is not currently exceeded, resulting in higher groundwater levels. Decreasing precipitation combined with rising temperature and evapotranspiration during summer is projected to result in a drying of the root zone which would drive increasing irrigation demands in the southern part of the Baltic Sea area.

The issue of uncertainty in the model projections has received increasing attention. Many studies have been carried out using a range of emission scenarios, GCMs and RCMs. The results indicate that the choice of GCM is especially important for the projected changes in climate (see also Chap. 11). A single study, by Olsson et al. (2011), suggested that the initialisation of the GCM is also important, at least for near-future projections. This indicates that natural variability in the GCM has a large effect on the projected changes, especially if short time spans are considered, or if the time spans investigated are periods for which the effect of increasing greenhouse gas (GHG) emissions is low, such as the near-future or emission scenarios with low GHG emissions. Olsson et al. (2011) proposed that climate models that are able to reproduce historical variability and so provide forecasts (as opposed to projections) of the future climate should be developed. A few studies have evaluated the impact of how climate model results are transferred to the hydrological model, also referred to as bias correction. It is indicated (Beldring et al. 2008; Yang et al. 2010) that the commonly used delta change approach may not produce satisfactory results, for example when dealing with snowmelt or extreme discharges. However, the quantity of work undertaken on this topic is low and more research is needed to quantify the accuracy and uncertainty associated with other bias correction methods.

The effect of impact model uncertainty has only been investigated in one study (Kriaučiūnienė et al. 2009). Several uncertainties are associated with impact modelling, including parameter uncertainty and model structure uncertainty. The values of the parameters of a hydrological model are normally found through calibration against historical data and are always associated with uncertainty. This uncertainty will translate into uncertainty in the projected changes. Model structure may also affect the response to climate change. In most of the studies cited in this chapter, conceptual rainfall-run-off models have been used to quantify the impact of climate change on river discharge. However, different types of hydrological model including physically based and/or distributed models may respond differently. Hence, studies are needed that not only consider the impact of climate projection uncertainty but also consider the hydrological model uncertainty.

The many uncertainties involved in projections of climate change impacts pose a challenge in presenting the results to stakeholders and decision-makers. The approach of Wetterhall et al. (2011) where response surfaces for exceeding a predetermined threshold are generated as a result of changes in climate variables (e.g. temperature and precipitation) is interesting as it effectively visualises the impact of climate change. Although associated with limitations on the ability to capture all changes in magnitude and especially the dynamics of future climate, the method provides a useful screening tool for assessing the impact of climate change on key impact variables and thresholds.

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