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The influence of climate change on stream flow in Danish rivers

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Summary The influence of climate change on river discharges in five major Danish rivers divided into 29 sub-catchments is investigated for the future period of 2071–2100. Climate changes are modelled by the HIRHAM regional climate model on the basis of the IPCC A2 scenario. A hydrological model (NAM) is used to convert precipitation to river discharges. Difficulties are found in the direct use of climate model generated precipitation and potential evapotranspiration (reference evaporation) because of too many rainy days, deviations from mean annual values of precipitation and potential evapotranspiration from observed values, and poor agreement on seasonality. Therefore climate model generated data is corrected to match observed mean annual values and the mean monthly distribution. Mean annual precipitation is found to increase 7%, potential evapotranspiration to increase 3% and river discharges to increase 12% on average, between a control period (1961–1990) and the future period. Because of increased precipitation from October to March and reduced precipitation from July to September the monthly river discharges are found to increase from December to August and decrease in September and October. Extreme values of precipitation and river discharge are examined and the level of the highest precipitation and the highest river discharge events are estimated to increase. The precipitation amount exceeded 0.1% of all days increases by an average of 7%, the river discharge exceeded 0.1% of all days increases approximately 15%. The 100-year flood is modelled to increase 11% on average.
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Introduction

The effect of climate change is a major issue in the environmental discussion on both global and local scale (Houghton et al., 2001). The effect on river discharge by changes in precipitation (P), potential/actual evapotranspiration (E_p; E_a) and temperature (T), is an important factor in environmental (transport of nutrients, sediment and habitats of flora and fauna), agricultural (drainage and flooding) and economical applications (e.g. water supply, flooding, engineering, and agro economics). Therefore good estimates of future river discharges are an important input to the discussion of the effects of climate change.

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The effect of climate change on river discharges has been analysed in different ways, on different spatial scales and for time series of different lengths in various periods. Modelling of the effect of climate change on river discharge is usually achieved either by direct use of climate model data in hydrological models or by changing existing climate data series with expected changes (Singh and Bengtsson, 2004). Investigations have been made on catchments of different scales. Large-scale studies have been done on the Baltic Sea catchment by Graham (2004), Great Britain by Arnell and Reynard (1996) and Arnell (2004), five major rivers by Nijssen et al. (2001) the whole of Europe is examined by Arnell (1999) and the entire globe by e.g. Arnell (2003), and Manabe et al. (2004). A considerably smaller scale is used by Bergstrom et al. (2001) on six Swedish catchments and by Gellens and Roulin (1998) on Belgian rivers. Projections concerning North Western Europe generally predict wetter winters and dryer summers, and therefore increased winter river discharges and decreased summer river discharges.

In this study climate model data, corrected with regard to observation/calculations on the basis of observations, are applied to a hydrological model producing river discharge. Hydrological modelling is done with the NAM rainfall/runoff model (DHI, 2004a). Future river discharges have been modelled for five major Danish rivers divided into 29 sub-catchments (Fig. 1).

Data from four periods are used (1) Calibration/validation data from the period 1989 to 2001, (2) Observed data from the period 1961 to 1990. Observed data is used in the correction of raw control and scenario data. For E_p, values calculated from observations from the calibration/validation period are used in the correction because no data is available from the 1961 to 1990 periods. (3) Control data are regional climate model (RCM) generated data covering the 30 year period 1961–1990 these data are corrected to match monthly means of observed data. (4) Scenario data are RCM data generated on the basis of the IPCC A2 scenario (Houghton et al., 2001) covering the 30 year period 2071–2100 these data are corrected with the same factors as control data.

Calibration/validation input data have been used in the calibration of NAM. Control and scenario data are used in detecting climatic changes between the two periods. To be able to address the consequences of climate change on different scales both creeks and larger rivers are included, resulting in sub-catchment sizes from 23 to 814 km^2.

Study area

Five of the largest Danish rivers and catchments have been chosen for modelling river discharges (Fig. 1). Catchments are located in different parts of Denmark representing different types of geomorphology, climate and climate change. Geomorphologically, the eastern part of Denmark consists of clayey moraine landscapes from the Weischel glaciation (Smed, 1982). The clayey moraines result in relatively rapid responding hydrological regimes giving high peak flows and relatively low base flow discharges. River Gudenå, River Odense and River Suså are located in the geomorphologically and hydrologicaly eastern part of Denmark. The western part of the country consists mostly of sandy outwash plains from the Weischel glaciation and older sand and clay moraines from the Saale glaciation. The sandy soils result in slowly responding hydrological regimes giving small amounts of overland flow and high contributions from base flow.

The five river catchments also represent an east-west pattern in the amount of precipitation and evapotranspiration. Considering the spatial distribution of precipitation there is a maximum in the western- and central part of Jutland; a minimum in the Great Belt region and a small increase towards the central part of Zealand (Fig. 1). The spatial pattern of E_p is the opposite of the pattern for P. E_p is highest in the Great Belt region and lowest in the western part of Jutland, because of differences in sunshine hours (Fig. 1).

The rivers are lowland rivers and all points in any catchment are below 200 m.a.s.l. This means that snow is considered evenly distributed and melted, in the sub-catchments.

Method

The simulation by the HIRHAM RCM chosen for the present study follows the IPCC climate scenario A2 (Houghton et al., 2001).

For rainfall/runoff modelling the NAM model is used (DHI, 2004a). NAM is a lumped conceptual hydrological model, describing the hydrological system through 3–5 linear reservoirs in series (Chow et al., 1988; DHI, 2004a). In this work a minimum of four linear reservoirs are used. The linear reservoirs are placed in series, (1) snow storage, (2) surface storage, (3) root zone storage and (4) groundwater magazine. A second deep groundwater magazine is optional. The second deep ground water magazine is used if simulated river discharges have a tendency to fall below observed river discharges in dry periods. Routing of water to the watercourse occurs from the surface storage as overland flow, from the root zone storage as interflow and from the groundwater storage as base flow. Water from the snow storage can only be transported to the surface storage. Evapotranspiration occurs from the surface and the root zone magazine if water is available (DHI, 2004a).

The five river catchments are all divided into a number of sub-catchments. A NAM model represents each sub-catchment. Input climate data to the Rainfall/runoff model NAM is P, E_p and T. All E_p values are calculated using the modified Penman formula as described by Scharling (2001). The only direct use of temperature in NAM is to determine whether precipitation falls as rain or snow, 0 °C is chosen as the discriminating temperature. The degree-day snowmelt model included in NAM is used and a value of 2 mm/day/°C is chosen (DHI, 2004b). This value determines the rate of snow melt and thereby influences the magnitude of peak flows associated with snow melt. Observed data from the calibration/validation period (1989–2001) is provided on a grid basis. Grid size for observed P is 10×10 km and 20×20 km for T and E_p calculated from observations. Observed precipitation is not corrected for gauge under catch (Frich et al., 1997). RCM modelled climate data are available from a grid size of 0.22°

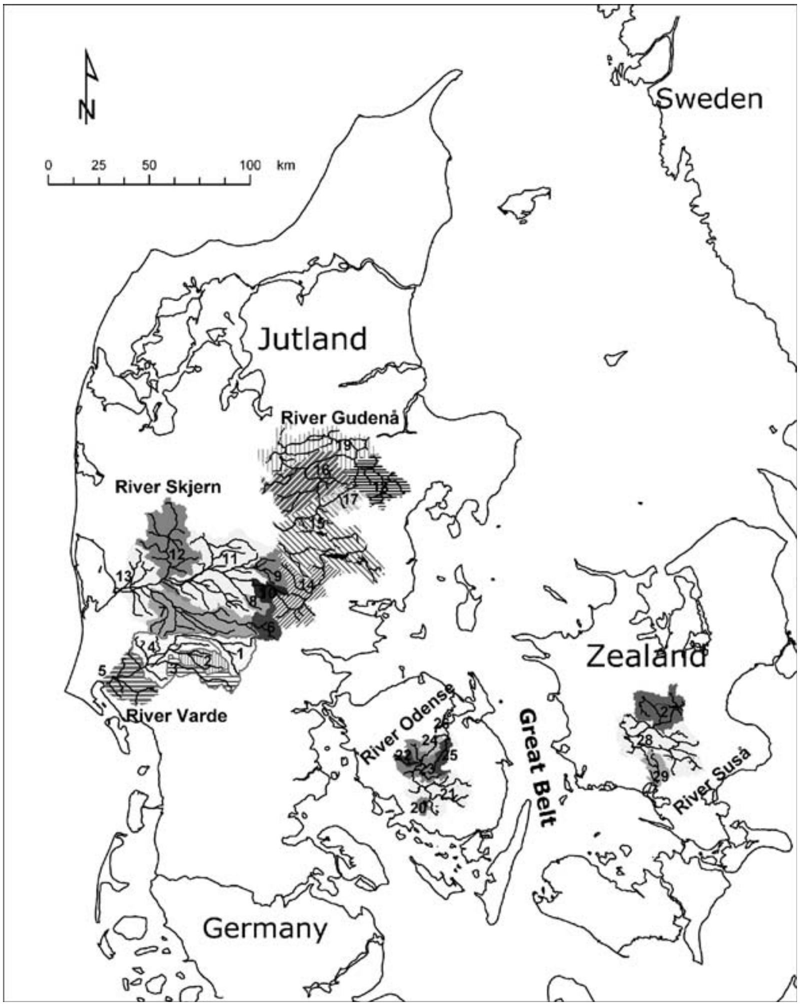

Figure 1 Locations of rivers, catchments and sub-catchments and sub-catchments size. Sub-catchments located on tributaries are named with the tributary name first e.g. River Grindsted at Egbro, all other sub catchments is located on the main river. Sub-catchments in River Varde catchment, (1) River Grindsted at Egbro (200 km^2), (2) River Ansager at Lavborg Bro (131 km^2), (3) River Holme at Hostrup (145 km^2), (4) Vagtborg (336 km^2), (5) Tarphage Bro (276 km^2). Sub-catchments at River Skjern catchment, 6 River Omme at Farre (112 km^2), (7) River Omme at Sønderskov (500 km^2), (8) River Brande at Hesselbjerg (47 km^2), (9) River Holtum at Hygild (117 km^2), (10) Tykskov (82 km^2), (11) Allergaarde (809 km^2), (12) Gjaldbæk (495 km^2), (13) River mouth (217 km^2). Sub-catchments in the River Gudenå catchment, (14) Voervads Bro (377 km^2), (15) Tvilum Bro (791 km^2), (16) Ulstrup Bro (508 km^2), (17) River Gjern at Smingevad Bro (114 km^2), (18) River Hadsten lilleå at Løjstrup fish farm (301 km^2), (19) Bridge at Highway A10 (814 km^2). Sub-catchments in River Odense catchment, 20 out flow Lake Arreskov sø (30 km^2), (21) Nørre Broby (272 km^2), (22) River Holmehave bæk (32 km^2), (23) Bellinge (153 km^2), (24) down stream Ejby Sluice (49 km^2), (25) River Lindved (65 km^2), (26) River Mouth (23 km^2). Sub catchments in the River Suså catchment, (27) River Ringsted at Vrangstrup (246 km^2), (28) Holløse Bro (517 km^2), (29) River Mouth (57 km^2).

(longitude and latitude ca. 25 km). All data are applied as mean daily values and is spatially converted into catchment values by area weighting grid cell values. Calibration of the most downstream sub catchment of each river catchment (except for River Gudenå) is not possible due to lack of available data from the river mouth. NAM model parameters are therefore estimated from representative parameter values in upstream sub-catchments.

NAM models are setup using observed P, T and E_p calculated from observations and is calibrated against observed river discharges from the downstream boundary of the sub catchment. A split-sample technique is used in the calibration/validation of the individual NAM models. The calibration is performed manually by adjusting model parameters so that the simulated river discharges correspond as well as possible to the observed river discharges. Water balances (volume) error on validation model runs are maximum 5%. Special calibrations regarding high and low flows have been made for the extreme value analysis. These calibrations have partly been made with the NAM auto calibration tool (DHI, 2004a).

Extreme values are analysed by calculating the 100-year flood using the Gumble EV1 method (Shaw, 1996). Both high and low flows are examined by calculating river discharge values exceeded between 0.1%, and 99.9% of the time.

Correction of input data

Estimating precipitation in a climate model is difficult and the values often need to be corrected, Giorgi and Mearns (2002) found ensemble average biases in excess of 200% for some parts of the world. Control (1961–1990) P and T data are corrected to match observed data (1961–1990) on a monthly mean values basis (Frich et al., 1997; Laursen et al., 1999). Data presented by Frich et al. (1997) and Laursen et al. (1999) are fixed station data, which are extrapolated to cover an area by the Thiesen polygon method. No E_p data calculated from observations covering the entire control period are available. Therefore E_p is corrected to match mean monthly values from the period 1989 to 2001.

Table 1 Percent of days with mean temperatures (T) below 0 °C and the mean annual maximum snow amount in five sub-catchments

River	Sub-catchment	Observed % frost days	Control % frost days	Scenario % frost days	Control snow (mm)	Scenario snow (mm)
River Varde	River Grindsted, Egbro	10.3	13.9	4.6	38	13
River Skjern	River Mouth	8.4	11.7	3.8	22	8
River Gudenå	River Gjern, Smingevad	10.6	14.5	4.7	36	14
River Odense	River Holmehave	8.1	12.1	3.2	23	7
River Suseå	River Ringsted, Vrangstrup	9.6	13.4	3.9	23	7

All observations are from the period 1989 to 2001.

Table 2 Precipitation data from control and scenario periods

River	Sub catchment/Gauging station	Raw control (mm/y)	Control (mm/y)	Scenario (mm/y)	Δ% control – scenario
River Varde	River Grindsted at Egbro	767	932	996	6.8
	River Ansager at Lavborg Bro	781	924	990	7.1
	River Holme at Hostrup	777	908	971	7.0
	Vagtborg	796	864	924	7.0
	Tarphage Bro	868	832	925	11.1
River Skjern	River Omme at Farre	762	855	906	6.0
	River Omme at Sønderskov	770	875	946	8.0
	River Brande at Hesselbjerge	753	878	933	6.2
	River Holtum at Hygild	774	842	891	5.7
	Tykskov	767	842	900	6.9
	Allergaarde	721	859	921	7.3
	Gjaldbæk	793	888	972	9.4
	River Mouth	793	843	933	10.7
River Gudenå	Voervads Bro	752	810	859	6.1
	Tvilum Bro	728	733	776	6.8
	Ulstrup Bro	707	687	727	5.9
	River Gjern at Smingevad Bro	703	700	749	7.0
	River Hadsten lilleå at Løjstrup fish farm	764	654	682	4.3
	Bridge highway A10	720	679	727	7.0
River Odense	Out flow lake Arreskov sø	688	716	773	8.0
	Nørre Broby	744	699	738	5.5
	River Holmehave bæk	701	687	735	7.0
	Bellinge	734	685	724	5.7
	Down stream Ejby Sluse	667	680	718	5.5
	River Lindved	756	639	667	4.2
	River Mouth	633	668	708	6.0
River Suså	River Ringsted at Vrangstrup	674	634	688	8.5
	Holløse Bro	719	642	672	4.7
	River Mouth	682	606	665	9.7
	Average	737	768	822	6.9

Control values have been corrected to match observed data and scenario data are corrected with the same factor.

Considering the small change (2—3%) found between the control and the scenario period E_p values the error introduced by this approach is considered to be small , Table 2(Table 3). Corrections are performed by multiplying a value ($P_{obs}/P_{control}$ or $E_{p,1989-2001}/E_{p,control}$) to all RCM values in the given catchment for a given month. Thus all January values, for a given catchment, are corrected with the same factor and the same correction factor is applied to both control and scenario data. Temperatures are corrected by adding the difference between mean monthly observations and mean monthly control ($T_{obs} + T_{control}$) to daily values in the respective control and scenario months.

Using P and E_p data corrected only on a mean annual basis is experienced to give an unsatisfying representation of the seasonal variation, similar problems are found by Arnell (2003). Annually corrected data is found to overestimated precipitations and underestimated E_p in summer months and vice verse for winter months causing underestimations of river discharges modelled for the control and scenario periods.

Results and discussion

Temperature

Mean annual observed T is 7.7 °C, mean annual raw HIRHAM control T is 8.4 °C. The observed values are between 0.5 °C and 1.0 °C below the raw HIRHAM in all sub-catchment. Therefore the control and the scenario values are corrected as described previously. Mean annual scenario temperature is 10.9 °C thus an increase of 3.2 °C is predicted. The temperature increases are between 3.2 and 3.3 °C in all catchments.

Snowfall and the percentage of days with temperatures below 0 °C has been calculated for a single sub-catchment in each of the five major catchments (Table 1).

The number of days with temperature below 0 °C is modelled to decrease to between a third and a fourth in the scenario data period compared to the control period. The mean annual maximum snow amount is found to be reduced by approximately 67% between the control and scenario periods, for the five sub-catchments in Table 1. This decrease in available snow will reduce the number and magnitude of peak flows associated with snowmelt.

Precipitation

Raw RCM precipitation data is found to be too inaccurate to be used as input to the NAM model. Differences of 4% on average and between −15% and +22% for individual sub-catchments were found for annual mean values between observed- and control data (Table 2). The largest errors are found for the western catchments. There is a tendency that HIRHAM overestimates mean annual precipitation values in the west and underestimates in the east. Control values have been corrected to match observed values on a monthly basis. Scenario values are corrected by the same factor.

It is seen in Table 2 that the annual mean precipitation is predicted to increase between 4.2% and 11.1%; the average increase is 6.9% from 768 mm/year to 822 mm/year. The highest increases are seen in the western part of the country and in sub-catchments close to the sea. The lowest increases are found in the upstream parts of River Skjern and River Gudenå and in the central and northern part of both River Odense and River Suså catchments. The temporal pattern of precipitation is examined by comparing duration curves for observed, control and scenario data (Fig. 2).

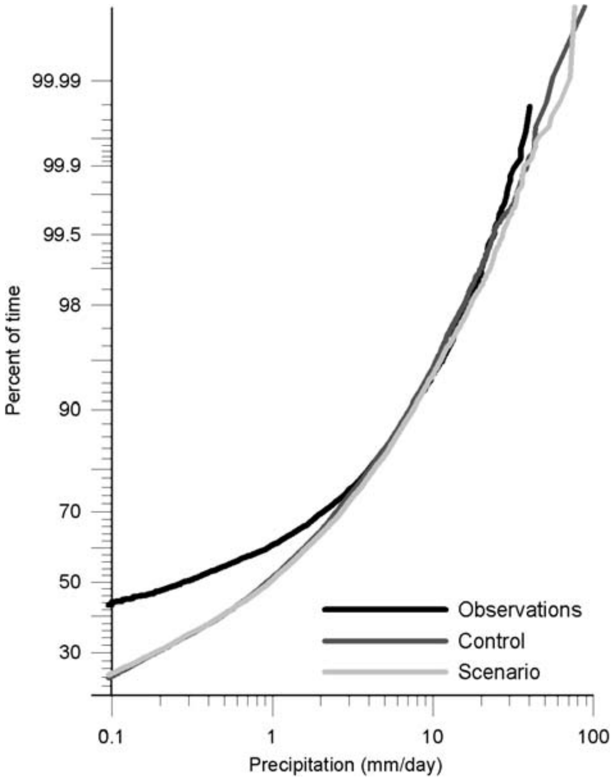

Figure 2 Duration curves for precipitation in the River Grindsted at Egbro (River Varde) catchment. Observed precipitation data for the period 1989—2001. Corrected RCM climate model data from 1961 to 1990 (control) and 2071—2100 (scenario).

The duration curve shows that the RCM generates too many precipitation events. Approximately 76% of all days have 0.1 mm or more precipitation in both the control and the scenario periods, but only around 57% of the observed days have more than 0.1 mm. The figure of 0.1 mm is the minimum observed precipitation value. The same temporal pattern of more days with precipitation in the control and scenario periods is found for all the sub-catchments. This will influence the NAM water balance and thereby the modelled river discharge. More water will be available for evaporation in dry periods, which will over-estimate the actual evapotranspiration (E_a) and thereby underestimate the simulated river discharge. The control and scenario periods appear to give relatively similar rating curves with precipitation in excess of 1 mm/day occurring slightly more frequently in the scenario period than in the control period, except the very highest value in this case.

Potential and actual evapotranspiration

Potential evapotranspiration is estimated to increase in all catchments (Table 3). The increase is 1.6—3.0% from

Table 3 Mean annual potential evapotranspiration, at the 29 sub-catchments

River	Sub catchment/Gauging station	E_p			E_a		
		Control (mm/y)	Scenario (mm/y)	Δ% control – scenario	Control (mm/y)	Scenario (mm/y)	Δ% control – scenario
River Varde	River Grindsted at Egbro	497	511	2.7	401	408	1.7
	River Ansager at Lavborg Bro	483	496	2.7	378	382	1.1
	River Holme at Hostrup	490	504	2.8	399	407	2.0
	Vagtborg	488	501	2.6	410	419	2.2
	Tarphage Bro	495	510	3.0	401	411	2.5
River Skjern	River Omme at Farre	493	507	2.9	410	419	2.2
	River Omme at Sønderskov	491	503	2.5	387	391	1.0
	River Brande at Hesselbjerge	492	506	2.7	407	414	1.7
	River Holtum at Hygild	491	504	2.6	400	406	1.5
	Tykskov	493	507	2.8	363	359	−1.1
	Allergaarde	486	497	2.2	400	387	−3.3
	Gjaldbæk	493	504	2.3	373	375	0.5
	River Mouth	502	514	2.3	385	388	0.8
River Gudenå	Voervads Bro	495	510	3.0	379	373	−1.6
	Tvilum Bro	498	513	3.0	357	348	−2.5
	Ulstrup Bro	489	501	2.5	367	363	−1.1
	River Gjern at Smingevad Bro	497	510	2.6	383	384	0.3
	River Hadsten lille at Løjstrup ff	500	514	2.8	364	355	−2.5
	Bridge highway A10	496	508	2.6	383	378	−1.3
River Odense	Out flow lake Arreskov	526	538	2.1	432	441	2.1
	Nørre Broby	524	535	2.1	397	397	0.0
	River Holmehave bæk	521	533	2.3	436	441	1.1
	Bellinge	515	526	2.2	426	424	−0.5
	Down stream Ejby Sluse	511	519	1.7	382	382	0.0
	River Lindved	510	521	2.1	399	400	0.3
	River Mouth	533	541	1.6	421	420	−0.3
River Suså	River Ringsted at Vrangstrup	543	556	2.4	426	429	0.7
	Holløse Bro	552	565	2.3	414	417	0.7
	River Mouth	558	573	2.3	420	421	0.2
	Average	506	518	2.5	396	398	0.3

Corrections of control data to match observations have been provided to all sub-catchments. Scenario data are corrected by the same factor.

506 mm/year to 518 mm/year on average and therefore it will not counter the increase in precipitation seen in Table 2. There is a clear trend of increasing E_p values on a west to east transect. A tendency of slightly higher increases of E_p values in the western part of the country than is the eastern part is seen.

The mean annual trend in E_a does not necessarily follow the trend in E_p between the control and the scenario period because water is only evapotranspirated from the surface if it is available. Parameters influencing the amount of water available for evapotranspiration are, for example, the size of the surface and root zone storages (in the NAM model), the length of droughts during summer where E_p is high. Sub-catchments with large surface and root zone storages supplies more water available for evapotranspiration therefore, they are more likely to experience increases in E_a. Longer drought periods will decrease the E_a because only little or no water is available during such a period which in summer is also a period with high E_p values. The regional difference in precipitation has influence on the values seen in Table 3. Sub-catchments with relatively high summer precipitation amounts are more likely to experience increased E_a values. The overall mean annual temporal pattern of E_a is illustrated in Fig. 3.

Differences in the temporal pattern are seen between the data calculated from observations (NAM observations) and the E_a data calculated from the HIRHAM control and scenario periods (NAM control and NAM scenario). Approximately 21% of all NAM observed days have an E_a value of <0.1 mm/day. Around 27% of the days in the NAM control data and 20% of the NAM scenario data have values below 0.1 mm/day. The increase in the number of days with more than 0.1 mm/day E_a from the control period to the scenario period is due to the increased temperature and consequently increased E_p during winter and spring months (see Table 5). More days with high E_a values are present in the control period than the scenario period; this is because

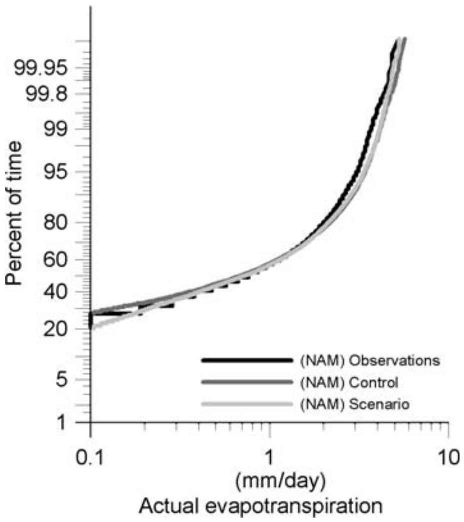

Figure 3 Duration curves of actual evapotranspiration (E_a) for the River Grindsted at Egbro (River Varde) catchment. E_a calculated from observations are from the period 1989 to 2001. RCM climate model data from 1961 to 1990 (control) and 2071–2100 (scenario).

more water is available for evapotranspiration during the wetter summers of the control period.

River discharge

The modelled control river discharge corresponds relatively well with observations. The average percentage difference between observed and control river discharges are −1% (Table 4). There is a tendency that the control period gives larger river discharge values than observations in the eastern part of the country and vice versa for the western part. The increases modelled to take place between the control and the scenario periods are relatively consistent, the average increase being 12%. The five main catchments show comparable increases. The largest increases are found in the River Odense catchment and lowest increases in the upstream sub-catchments of the River Skjern catchment. The runoff values (mm/year) show a clear spatial pattern, with larger values in the western catchments than in the eastern River Odense and River Suså. The large differences found in the River Skjern catchment between the upstream sub-catchments, River Omme at Farre (279 mm/year), River Brande at Hesselbjerg (295 mm/year) and River Skjern at Tykskov (604 mm/year) are because the respective topographic and ground water catchment areas are not of the same size.

The temporal pattern of river discharges is shown for one river in Fig. 4. The largest changes are modelled to occur at the highest 50% of river discharges. But scenario river discharges are higher than control river discharges at all frequencies.

Monthly mean values

Examining the temporal pattern of monthly mean values gives an overview of the distribution of climate and climate change over an average year. Inter-annual patterns of *P* and E_a are the most important factors in estimating the risk of floods and the risk of very low river discharges. As an example of monthly changes between observed/control and scenario data the River Gudenå at Voervadsbro sub-catchment has been chosen (Table 5). The catchment is the most upstream in the River Gudenå system, and is located close to the upstream areas of both the River Skjern and River Varde system (Fig. 1).

E_p is seen to undergo only small alterations due to climate change, but most of the mean annual change happens in august, in this sub-catchment (Table 5). For E_a an increase occurs between December and April due to more available water. Between May and July E_a is nearly unchanged. From August to October there is a decrease in E_a because of the lower precipitation, despite an increase in E_p in the two first months. The changes in precipitation in average months are more pronounced. The period October–March becomes wetter, April–September with the exception of May, becomes drier, but as seen previously the mean annual precipitation will increase. The seasonality of *P* is becoming stronger as the difference between driest and wettest month increases, and the dry summer period is prolonged into August. Highest mean monthly river discharge is increased as a consequence of the higher winter precipitation, but the lowest mean monthly river discharge is the same because of the delay in base flow runoff from the increased annual mean precipitation, which in this case counterbalances the dryer summers.

Besides the climate conditions, river discharge is dependent on the physiographical parameters of the specific catchment, and therefore has a spatial variation. Differences in monthly river discharges caused by dissimilar flow regimes in four different sub-catchments, representing the different kinds of major landscapes types are seen in Fig. 5.

A stable signal with some regional differences is seen in the four sub-catchments in Fig. 5. The largest changes of river discharges are found at the Nørre Broby sub-catchment in the River Odense catchment and for the River Ringsted at Vrangstrup in the River Suså catchment. These two sub-catchments represent areas with clayey soils and consequently relatively high overland flow ratios, low base flow ratios and low time constants for base flow routing. The more sandy soils are reflected in the NAM base flow routing time constants for the sub-catchments of River Grindsted at Egbro and River Gudenå at Voervadsbro, which are between 2.5 and 5 times higher than at Nørre Broby at River Odense and Vrangstrup on the River Ringsted (DHI, 2004a).

Scenario river discharge trend

The trend of river discharge in the 30-year scenario period is used to check if the mean values used in this paper are representative for the entire scenario period; it can also be seen as a parameter for estimating the trends of river discharges in the first few years after the year 2100.

The same temporal pattern is seen for both Vrangstrup at River Ringsted (Fig. 6) and Egbro at River Grindsted (Fig. 7). The first half of the period is relatively stable and the middle of the period is simulated to have an increase in river discharges. The calculated river discharge peaks between 2086 and 2093 and the following period is simulated to have lower river discharges. This pattern is more pronounced at

Table 4 Mean annual discharges have been calculated for 29 sub-catchments of Danish rivers for the control period and the scenario and are compared with observations

River	Sub catchment/Gauging station	Observed m^3/s (mm/y)	Control (m^3/s) (mm/y)	Scenario (m^3/s) (mm/y)	Δ% obs − control	Δ% control − scenario
River Varde	River Grindsted at Egbro	2.84 (448)	3.36 (530)	3.70 (584)	18	10
	River Ansager at Lavborg Bro	2.03 (489)	2.26 (544)	2.50 (602)	11	11
	River Holme at Hostrup	2.26 (492)	2.36 (514)	2.61 (568)	4	11
	Vagtborg	12.02 (467)	12.79 (497)	14.14 (550)	6	11
	Tarphage Bro[a]	16.10 (467)	16.57 (481)	18.60 (539)	3	12
River Skjern	River Omme at Farre	0.92 (259)	1.16 (327)	1.25 (352)	26	8
	River Omme at Sønderskov	8.49 (438)	8.85 (456)	9.89 (510)	4	12
	River Brande at Hesselbjerge	0.42 (282)	0.48 (322)	0.52 (349)	14	7
	River Holtum at Hygild	1.19 (321)	1.30 (351)	1.40 (378)	9	7
	Tykskov	1.57 (604)	1.62 (623)	1.81 (697)	3	12
	Allergaarde[b]	15.80 (473)	15.11 (452)	17.25 (516)	−4	14
	Gjaldbæk	23.10 (470)	23.25 (473)	26.55 (541)	1	14
	River Mouth[a]	36.60 (486)	35.24 (467)	40.12 (532)	−4	14
River Gudenå	Voervads Bro	5.04 (422)	5.09 (426)	5.65 (473)	1	11
	Tvilum Bro[b]	16.47 (405)	15.72 (387)	17.65 (434)	−5	12
	Ulstrup Bro	22.24 (392)	20.83 (367)	23.37 (412)	−6	12
	River Gjern at Smingevad Bro	1.05 (291)	1.15 (318)	1.30 (360)	10	13
	River Hadsten Lilleå at Løjstrup ff	2.65 (278)	2.74 (287)	3.02 (317)	3	10
	Bridge highway A10	31.49 (342)	33.11 (360)	37.10 (403)	5	12
River Odense	Out flow Lake Arreskov	0.18 (189)	0.13 (137)	0.15 (158)	−28	15
	Nørre Broby[b]	2.96 (309)	2.69 (281)	3.05 (319)	−9	13
	River Holmehave bæk	0.26 (256)	0.25 (247)	0.29 (286)	−4	16
	Bellinge	4.47 (290)	4.07 (264)	4.65 (301)	−9	14
	Down stream Ejby Sluse	5.44 (320)	4.95 (291)	5.63 (331)	−9	14
	River Lindved	0.45 (218)	0.34 (165)	0.39 (189)	−24	15
	River Mouth[a]	6.50 (329)	5.47 (277)	6.23 (315)	−16	14
River Suså	River Ringsted at Vrangstrup	1.85 (237)	1.62 (208)	1.80 (231)	−12	11
	Holløse Bro[b]	5.90 (244)	5.32 (220)	5.89 (244)	−10	11
	River Mouth[a]	6.10 (235)	5.66 (218)	6.37 (245)	−7	13
	Average	(360)	(362)	(405)	−1	12

All nonmarked observed river discharges cover the period (1989–2001). For sub-catchments were the period of observed river discharge do not match the control period, gives additional errors to values in the Δ% obs − control column.

[a] Observed river discharge values from Ovesen et al. (2000) do not cover the same period as the control data or the 1989–2001 period.

[b] Observed river discharges cover the control period (1961–1990).

Egbro at River Grindsted (Fig. 7) than at Vrangstrup at River Ringsted (Fig. 6). The overall trend in the 30-year period is a slight decrease in river discharges in both rivers. As the climate model is not an accurate weather forecast the timing of events happening over only a few years time scale e.g. the peak around 2087 seen in Fig. 7, should not be taken too literally, but should be considered as an indication of a high flow period in the middle part of the 30 year period, reflecting the climate variability simulated by HIRHAM.

Extreme events

Extreme events are an important aspect of the future climate and the future river discharge regime. The analysis is carried out for four sub-catchments representing different geomorphology with different flow regimes. Peak flows in Danish rivers are mainly coursed by rain events therefore both rain/precipitation and river discharge extreme events are addressed here. Not only peak flows but also low flows are of interest due to drying out events in especially smaller watercourses in the eastern part of the country.

The level of high daily precipitation events (exceeded respectively 0.1%, 1%, 5% and 10% of all days) are higher in scenario data than control data in four sub-catchments, except precipitation exceeded 0.1% of the time in the River Grindsted sub-catchment (Table 6). Increases in daily extreme precipitation amounts are also found for eight major European river catchments by Christensen and Christensen (2004). The exact values in Table 6 are not directly comparable between sub-catchments, because the catchments are of different size and therefore the precipitation amounts are not calculated from the same number of grid cells.

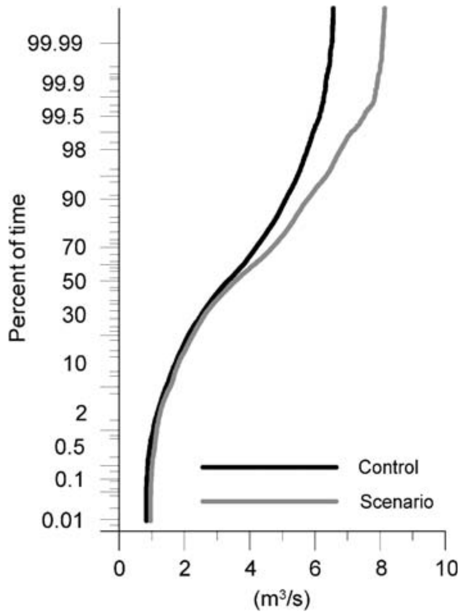

Figure 4 Duration curves of control and scenario discharges at River Grindsted at Egbro (River Varde).

Larger catchments overlapping more precipitation grid cells will have a smaller variation in precipitation values than small catchments perhaps gaining precipitation values from only one or two grid cells.

The modelled climate change is estimated to have different impacts on high and low flows depending on the characteristics of the catchments. The impact of climate change on different levels of high and low flows is simulated to be of different magnitudes and directions (Table 7). River discharges exceeded 0.1–10% of the time are all estimated to increase. The most distinct increases are seen in River Ringsted at Vrangstrup and the river Grindsted at Egbro. These two sub-catchments are very geomorphologically different. The River Ringsted sub-catchment have clayey soils which gives higher levels of surface runoff and therefore responds more quickly to larger precipitation events, and the increase in precipitation amount exceeded 0.1% of time is larger in this sub-catchment than in the other three. The River Grindsted sub-catchment is sandier therefore the largest river discharges are less likely to origin from single rainfall events. The River Grindsted sub-catchment sees the largest increase in the 1% highest precipitation events and the explanation of the high increase in the largest river discharges may well be found here. The two westerly sub-catchments are sandier than the other two and therefore soil infiltration rates are higher and water storage in the surface- and root-zone magazine is smaller. This combination gives higher ratios of base flow contributions to the river flow. The increased amounts of base flow in the two western sub-catchments are simulated to produce higher river discharges at all frequencies that exceed between 90% and 99.9% of the time (Table 7). In the two easterly sub-catchments this is not the case. The longer ''droughts'' in the scenario period are not counterbalanced by the increase in base flow at flood frequencies exceeded between 90% and 95% of the time. However, at frequencies exceeded 99% and 99.9% of the time, the increase in base flow is sufficiently high to giver larger river discharges. That river discharges between 90% and 95% are decreasing is because interflow decreases more between the control and the scenario period than the base flow increases at these river discharge frequencies. Base flow dominates at frequencies that exceed 99–99.9% and therefore increases.

The 100-year flood is another measure of peak river discharges and is often used in risk assessment (Table 8) (Shaw, 1996). All 100-year annual floods are calculated to be higher in the scenario period than in the control period, which corresponds with what is seen in Table 7.

Both the flow frequency analysis and the calculations of the 100-year flood points in the direction of higher peak flows in the future.

Table 5 Mean monthly observation, control and scenario values of river discharge (Q), precipitation (P), actual evapotranspiration (E_a) and potential evapotranspiration (E_p) at the Voervadsbro sub-catchment in the River Gudenå catchment

Observation		Control					Scenario			
	Q (m^3/s)	Q m^3/s (mm)	P (mm)	P_{raw} (mm)	E_p (mm)	E_a (mm)	Q m^3/s (mm)	P (mm)	E_p (mm)	E_a (mm)
January	21.6	21.9 (46)	61	73	4	2	26.6 (56)	92	4	3
February	22.5	21.7 (41)	42	56	8	4	27.9 (53)	52	8	6
March	21.3	21.5 (45)	48	62	24	14	26.4 (55)	53	22	20
April	19.7	18.7 (38)	41	60	48	41	20.7 (42)	34	49	45
May	14.6	14.9 (31)	49	67	85	72	17.3 (36)	58	85	71
June	12.0	12.4 (25)	56	66	90	70	14.2 (29)	51	91	67
July	11.0	10.7 (22)	67	66	98	67	11.7 (24)	59	102	66
August	11.1	9.6 (20)	66	66	80	57	9.7 (20)	40	90	49
September	11.7	9.7 (20)	73	62	39	32	8.5 (17)	47	42	27
October	14.1	12.1 (25)	77	60	16	14	10.6 (22)	98	14	13
November	17.3	16.4 (33)	83	70	4	4	16.2 (33)	96	4	4
December	21.2	19.3 (40)	70	77	2	1	22.5 (47)	102	2	2
Annual values	16.5	15.7 (386)	733	784	498	379	17.6 (433)	783	513	373

P_{raw} is raw HIRHAM control precipitation values.

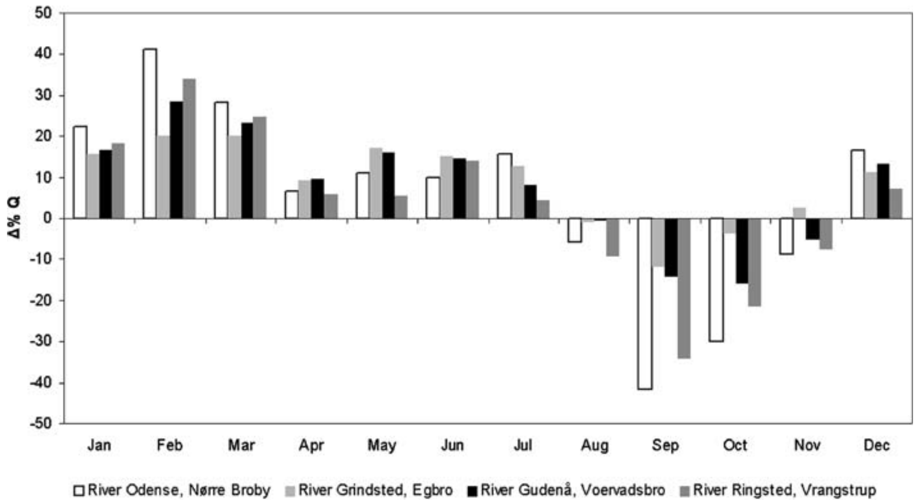

Figure 5 Percentage changes of mean monthly river discharges between control (1961—1990) and scenario (2071—2100) periods in four sub-catchments. The River Ringsted is a part of the River Suså catchment and the River Grindsted of the River Varde catchment.

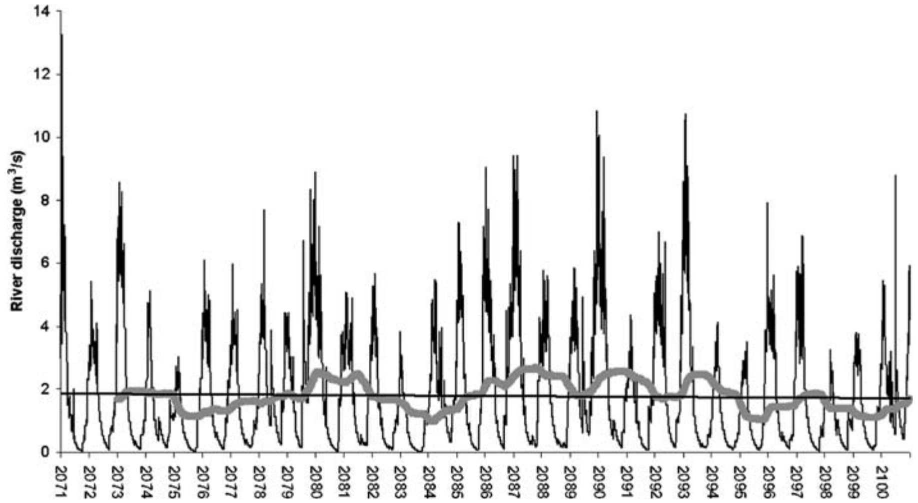

Figure 6 River discharges at Vrangstrup River Ringsted (River Suså) for the scenario period (2071—2100). Straight line is the 30 year trend showing a slightly decreasing tendency, grey line is a 2 year moving average.

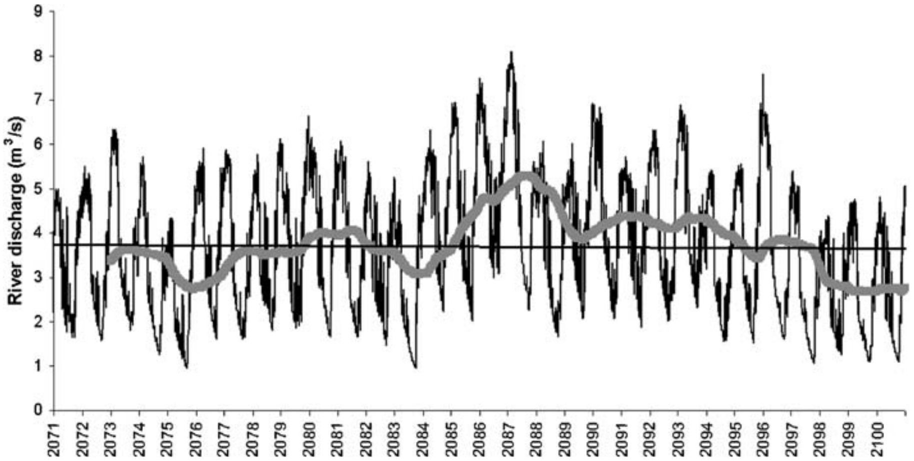

Figure 7 River discharges at Egbro River Grindsted (River Varde) for the scenario period (2071—2100). Straight line is the 30 year trend showing a slightly decreasing tendency, grey line is a 2 year moving average.

Table 6 Changes in precipitation extreme values between control data and scenario data in four sub-catchments

Precipitation exceeded percent of time	River Grindsted at Egbro (mm/day)		River Odense at Nørre Broby (mm/day)		River Ringsted at Vrangstrup (mm/day)		River Gudenå at Voervadsbro (mm/day)		Average change %
	Control	Scenario	Control	Scenario	Control	Scenario	Control	Scenario	Con–Sce
0.1	38.5	36.8	26.1	28.9	25.6	29.4	31.8	33.4	7
1	19.9	22.7	14.7	15.9	13.6	14.2	16.3	18.4	10
5	10.5	11.2	8.0	8.5	7.3	7.6	8.9	9.6	6
10	7.2	7.5	5.3	5.6	4.9	5.1	6.1	6.4	5

The River Ringsted is a part of the River Susă catchment and the River Grindsted of the River Varde catchment.

Table 7 Changes in discharge extreme values between control data and scenario data at four sub-catchments

Discharge exceeded in % of time	River Grindsted at Egbro Δ%	River Odense at Nørre Broby Δ%	River Ringsted at Vrangstrup Δ%	River Gudenå at Voervadsbro Δ%	Average change %
0.1	25	12	20	4	15
1	20	11	20	11	16
5	16	17	19	14	17
10	13	21	17	12	16
90	5	−20	−13	9	−5
95	9	−31	−6	0	−7
99	10	21	10	4	11
99.9	16	81	38	16	38

The River Ringsted is a part of the River Susă catchment and the River Grindsted of the River Varde catchment.

Table 8 Magnitude of the 100 year flood (Gumble EV1) based on control and scenario data and the modelled changes in percent

	Control (m^3/s)	Scenario (m^3/s)	Change %
River Grindsted at Egbro	10.0	10.5	5
River Odense at Nørre Broby	22.9	26.0	14
River Gudenå at Voervadsbro	38.8	47.0	21
River Susă at Vrangstrup	16.9	17.5	4
Average			11

Historical river discharge trends

An increase of 12% in mean annual river discharges simulated to happen between the control- and the scenario period are considered to be modest. As a perspective of this consideration the simulated increase is compared with observed changes in river discharge at 18 gauging stations in Danish water courses during an approximately 80 year period (Larsen et al., 2005). Of these, four are considered in this article (Table 9).

In some parts of the country the increase during the last 80 years have been larger than the simulated increases for the coming nearly 100 years (Tables 4 and 9). The river discharge is estimated to increase about the same between the control and scenario periods at River Gudenå at Tvilum bro and River Odense at Nørre Broby. Future increases are estimated to be only half the size of historical ones at River Skjern at Allergaarde and River Susă at Holløse bro (Tables 4 and 9). The historical increase in river discharge is related to an increase in precipitation. The development in the monthly pattern of river discharges over the last 80 years reported by Larsen et al. (2005) is more or less the same as in the simulations. River discharges have been increasing in all

Table 9 Changes in discharges during a historical period. Percentage changes are calculated as changes in relation to mean annual values

	Mean annual Q (m^3/s)	ΔQ (m^3/s)	ΔQ (%)	Period
River Guden Å at Tvilum bro	16.10	1.63	10.1	1917–2001
River Skjern Å at Allergaarde	14.69	4.18	28.5	1920–2001
River Odense Å at Nørre Broby	2.84	0.36	12.8	1917–2001
River Susă at Holløse bro	5.66	1.89	33.3	1934–2001

All changes are significant on the 95% level (Larsen et al., 2005).

months at most catchments and most significantly in winter and spring months and less in summer and autumn months. Both high and low flows have generally also been increased over the last 80 years (Larsen et al., 2005). It can be seen as surprising that the effect of the global warming/climate change are modelled to be smaller than changes occurring over the past 80 years, because human impact in this period is much smaller than what is expected in the future. It is important to be aware that this study uses the results of a single climate model the HIRHAM and a single emission scenario. The use of other climate models or other emission scenario would produce different results (Arnell and Reynard, 1996; Arnell, 2003).

Discussion of effects

The projected effects of climate change seen on the 29 sub catchments of Danish rivers are larger amounts of precipitation and higher mean annual river discharges, relatively unchanged mean monthly low flows and higher mean monthly high flows. This corresponds well with results reported for other Northern European catchments (Arnell, 1999). The higher peak flows simulated for the scenario period than for the control period would potentially cause more floods, which would have some effect on agriculture (flooded fields and crops and lower accessibility of fields), wetlands, and floodplains and near river urban areas would experience a higher flooding frequency. However, floods are normally not considered a serious problem in most Danish rivers, as they rarely impact on infrastructure or buildings.

It is important to realise that the modelling of climate change with RCM's and GCM's (general circulation models) is associated with relatively large uncertainties and that using a different RCM than the HIRHAM would have given different results than the ones shown in this paper (Gellens and Roulin, 1998; Houghton et al., 2001). The hydrological modelling using the NAM is considered to be less uncertain, as the water balance error on the validation periods are <5%. The differences in the number of precipitation and evapotranspiration days in the control period compared to the observations enlarge the uncertainties. The water balance error is up to 10% between observed and control river discharges in sub-catchments with observations from the period 1961 to 1990.

The increase of mean annual river discharges will increase the width and depth of natural watercourses by increasing erosion according to regime theory (Blench, 1966; Leopold and Maddock, 1953). This effect is limited by the fact that about 98% of all Danish water courses have been manipulated e.g. straightened, deepened and widened (Brooks, 1983).

The occurrence of both extreme high and low flows and the stability of flow are known to have effects on stream ecology (Milner et al., 2003). The indication that the lowest river discharges will become higher is positive seen in the perspective of the smallest streams being less prone to drying out, which has a positive influence on the aquatic ecosystem e.g. the fish species diversity (Baattrup-Pedersen et al., 2004; Clausen and Biggs, 2000).

Besides the effects of climate change on river discharges in the scenario period will be influenced by changes in land cover and anthropogenic use of water affecting the hydrological system (Arnell, 2002). For example the Danish parliament in 1989 decided to double the forested area to 20–25% within a tree generation (80–100 years) (Danish Forest and Nature Agency, 2005). This will probably increase E_a and reduce river discharges from the affected areas (Bosch and Hewlett, 1982; Nosetto et al., 2005). Expansion of urban and paved areas will most likely respond in higher mean annual river discharges and flashier river regimes, because of the quick delivery of rain water to the river (Arnell, 2002). Efforts to account for such changes were not undertaken in this analysis.

Conclusions

It can be concluded that the river discharge in Danish rivers would increase as a consequence of the wetter climate from a projected future modeled by the HIRHAM RCM, on the basis of the IPCC A2 emission scenario. Increases in precipitation between 4% and 11% are modelled to increase mean annual river discharges 7–16%. The monthly mean river discharges are seen to increase from December to August, and decrease in September and October, mixed signals are found for November. The largest monthly variations and changes are modelled for the easterly sub-catchments with clayey soils. There are no clear trends of increasing or decreasing river discharges during the 30-year scenario period.

The climate model data needs correction on a monthly scale to reproduce the seasonal variation and mean annual values comparable to observed data.

Extreme river discharges are modelled to increase. This is the case for both extreme high flows and extreme low flows. The increases in extreme high flows are considered to be modest.

The number of days with frost in the scenario period will decrease up to a fourth of the days in the observed and control data. This will reduce the amount of snow in the catchments and consequently floods associated with melt water.

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