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Groundwater recharge – climatic and vegetation induced variations

Simulations in the Emån and Äspö areas in southern Sweden

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January 1999

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Abstract

Climate change and man-made interference will cause an impact on runoff and groundwater recharge in the future. With the aim to give a conception of seasonal variations and the magnitude of the differences, the HBV model has been used as a tool for simulating five climate alternatives in two areas of south-east Sweden. The climate alternatives include both increased and decreased temperature and precipitation. These are not predictions of a future climate change, and should only be regarded as examples. The purpose has been to exemplify a conceivable magnitude of change during temperate/boreal conditions. It has not been within the scope of this report to evaluate the most probable climate change scenarios.

The impacts of different climate scenarios on the total groundwater recharge and the deep groundwater recharge have been calculated as long-term mean values and are presented in comparison with model-simulated values with an actual (recorded) climate sequence. The results show great differences between the climate alternatives. An increase in temperature will decrease snow accumulation and increase the evapotranspiration and can totally extinguish the spring snowmelt peak in runoff and groundwater recharge. A decreased temperature, on the contrary, will imply decreased winter runoff and recharge values and an increase in spring and summer values.

Evapotranspiration and soil water content play a key role in the runoff and recharge processes. This report makes a review of some literature about work done within the areas of investigation and calculation of evapotranspiration. Research is in progress, not only on formulating future climate scenarios, but also on distinguishing evapotranspiration from different kinds of vegetation. These are complex questions, but vital ones, as a climate change will also affect the vegetation.

Until new research results are presented, well-known methods can be used for simulating the effects of logging on runoff and groundwater recharge. Model simulations have the advantage, once calibrated, of being able to distinguish between changes due to weather and changes due to alterations in the characteristics of a catchment.

The effects of forest growth are more difficult to quantify than the effects of logging. This is because forest growth is a slower process than logging, and the successive changes can be hidden by weather fluctuations.

Sammanfattning

Klimatförändringar och mänskliga ingrepp kommer att påverka avrinning och grundvattenbildning i framtiden. För att ge en uppfattning om säsongsvariationer och storleksordning på förändringar har HBV-modellen använts som verktyg för att simulera totalt fem olika klimatscenarier i två områden i sydöstra Sverige. Områdena är Blankaström i Emåns avrinningsområde och landområden runt Äspö norr om Figeholm. De klimatscenarier som använts berör såväl ökad som minskad temperatur och nederbörd. De är inga förutsägelser om ett framtida klimat utan ska endast ses som några olika exempel på möjliga klimatförändringar. Syftet har varit att ge en bild av de förändringar som kan tänkas förekomma under tempererade/boreala förhållanden. Det har inte legat inom ramen för denna rapport att bedöma vilka klimatscenarier som är mest troliga i framtiden.

De olika klimatförändringarnas påverkan på den totala och den djupa grundvattenbildningen har beräknats som långtidsmedelvärden och presenteras i jämförelse mot modellsimulerade värden med aktuell klimatserie. Resultaten visar på stora variationer i påverkan beroende på vilket klimatalternativ som applicerats. En höjning av temperaturen minskar snöackumulationen och ökar avdunstningen och kan helt ta bort snösmältningstoppen på våren. En temperatursänkning ger i stället minskad avrinning och grundvattenbildning under vintern och en ökning under våren och sommaren.

Avdunstning och markvattenhalt har en nyckelroll för hur mycket vatten som är tillgängligt för avrinning och grundvattenbildning. De flesta hydrologiska modeller har en förenklad beskrivning av evapotranspirationen, vilket försvårar möjligheterna att använda modellteknik för att simulera vilken påverkan förändringar i vegetationstäcket kan få för evapotranspirationen, och därmed också för avrinning och grundvattenbildning. Denna rapport gör en genomgång av en del litteratur i ämnet. Forskning pågår, såväl för att formulera framtida klimatscenerier som för att särskilja avdunstning från olika vegetationstäcken. Detta är en mycket komplex fråga, eftersom klimatförändringar också påverkar vegetationen. Man kommer alltid att tvingas till förenklingar, t ex varierar ett träds vattenförbrukning bl. a. beroende på trädets ålder.

Tills nya forskningsresultat finns att tillgå kan redan prövade metoder användas för att simulera effekterna av skogsavverkning på avrinning och grundvattenbildning. Detta ger en god uppfattning om effekterna av sådana drastiska ingrepp. Modellsimuleringar har fördelen att, efter att modellen en gång kalibrerats, kunna särskilja förändringar som beror på vädret och sådana som beror på ändrade karakteristika för området.

När det gäller plantering och skogstillväxt är effekterna svårare att kvantifiera, eftersom skogstillväxt är en långsammare process än avverkning. De successiva förändringarna i evapotranspirationen kan lättare döljas av väderfluktuationer. Modellberäkningar kan därför bli svårare att verifiera mot mätresultat. För att ge maximal effekt är det därför viktigt att hitta områden där största delen av avrinningsområdet är planterat.

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1 Introduction

For the purpose of storage of nuclear waste in rock, it is of interest to know how the infiltration of water in fissured rock is influenced by climate change. This includes natural variations as well as changes induced by man. This report describes the results of simulation of total groundwater recharge and deep groundwater recharge under different temperate/boreal climatic conditions and discusses the role of land use and the impact of changes in evapotranspiration due to vegetational cover.

Changes in climate since the latest glaciation are of the same magnitude as what could be expected in the future due to increased CO_2-emission. The maximum deviation of the mean temperature in Sweden has been about 2°C higher than today, and the precipitation about 20% lower. (Alexandersson, SMHI, pers. comm., Raab and Vedin, 1995, Olausson, 1998). Within the project "Climate change and energy production" a new climatic scenario for the Nordic countries has been formulated, based on existing information from international research (Aune, 1994, Saelthun et. al., 1998).

Climate change and man-made interference will also affect vegetation cover and consequently the evapotranspiration, which will influence groundwater recharge. Hydrological models often have an overly simple description of evapotranspiration, and research has been going on for some years in order to improve this. It is, however, important to find a way that does not increase the data demand too much, nor make the model structure too complicated for practical use.

The conceptual HBV model was developed at SMHI (Swedish Meteorological and Hydrological Institute) in the mid-seventies (Bergström, 1976). The model has got its name from the name of the department at SMHI where it was developed (Swe. Hydrologiska Byråns Vattenbalansavdelning, Eng. Water Balance Department). The original purpose was to forecast the inflow to hydropower stations, but through the years it has been developed and used for several applications (Bergström, 1992). For research purposes simulations of groundwater levels in different types of aquifers have been made (Bergström and Sandberg, 1983), and the effect of future climatic change on runoff has been studied in some Nordic projects (Lindström et. al., 1994, Saelthun et. al., 1998).

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2 Groundwater recharge simulations

2.1 General

The simulations presented in this study have been made using the HBV model. This model compiles daily values of runoff, and the total groundwater recharge is a component when calculating the runoff. Applications for groundwater simulation have shown that the model can be used with good results when compared with measurements for representation of total groundwater recharge (Bergström and Sandberg 1983, Bergström et. al., 1990).

The computations of deep groundwater recharge are based on the assumption that changes in deep groundwater recharge, which contributes to the base flow in the streams, are an indication of relative changes of infiltration in fissured rock. It is important to bear in mind that the model is not made for direct simulation of infiltration in fissured rock, and hence the terms of deep groundwater recharge may only be used as relative values for comparison purposes.

2.2 Method

Two areas in southern Sweden were chosen for this study: The river Emån catchment area (3,939 km^2) and the Äspö area, which is a coastal area of 10 x 10 km^2, centred around the island of Äspö. See figure 2-1. The model was calibrated against recorded discharge at the runoff station Blankaström in the Emån river. No recorded data of groundwater recharge are available, and the computed values are thus components of the discharge simulations. The Emån parameter set was then used for the simulations of the Äspö area, where no recorded discharge is available.

The total groundwater recharge is in this study defined as the sum of excess water from the soil plus the direct precipitation on saturated areas. It is described in the model by the excess water from soil, see figure 2-2 (the term R in the HBV model). The deep groundwater recharge is the portion of the total groundwater recharge that percolates to deep layers (the term PERC in the HBV model). The potential evapotranspiration is calculated with a temperature index method, similar to the one proposed by Thornthwaite (1948) (Lindström et. al., 1996). In this method an increase of temperature leads to higher evapotranspiration.

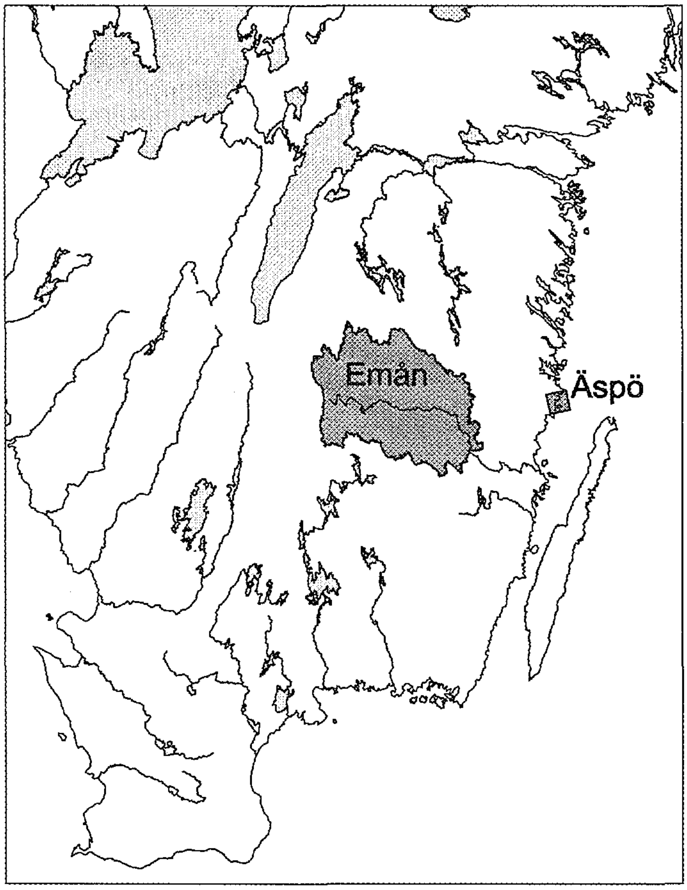

Figure 2-1. Location of areas used for simulation.

2.2.1 Model description

The HBV model is a numerical hydrological model for continuous calculation of runoff, based on a conceptual approach. It was originally developed at the Water Balance Department (abbreviation HBV in Swedish) at the Swedish Meteorological and Hydrological Institute (Bergström, 1976), and is constantly being developed (Lindström et. al., 1996). Input to the model is usually daily values of rainfall and air temperature and monthly mean values of potential evapotranspiration. Shorter time-steps, down to one hour, can easily be introduced in the calculations. The model calculates snow accumulation and snowmelt, changes in soil moisture content and runoff generation. The catchment area can be divided into subbasins. Each basin is divided into zones according to altitude, lake area, glaciers and vegetation.

A schematic illustration of the model is given in figure 2-2. Further model description is presented in appendix A.

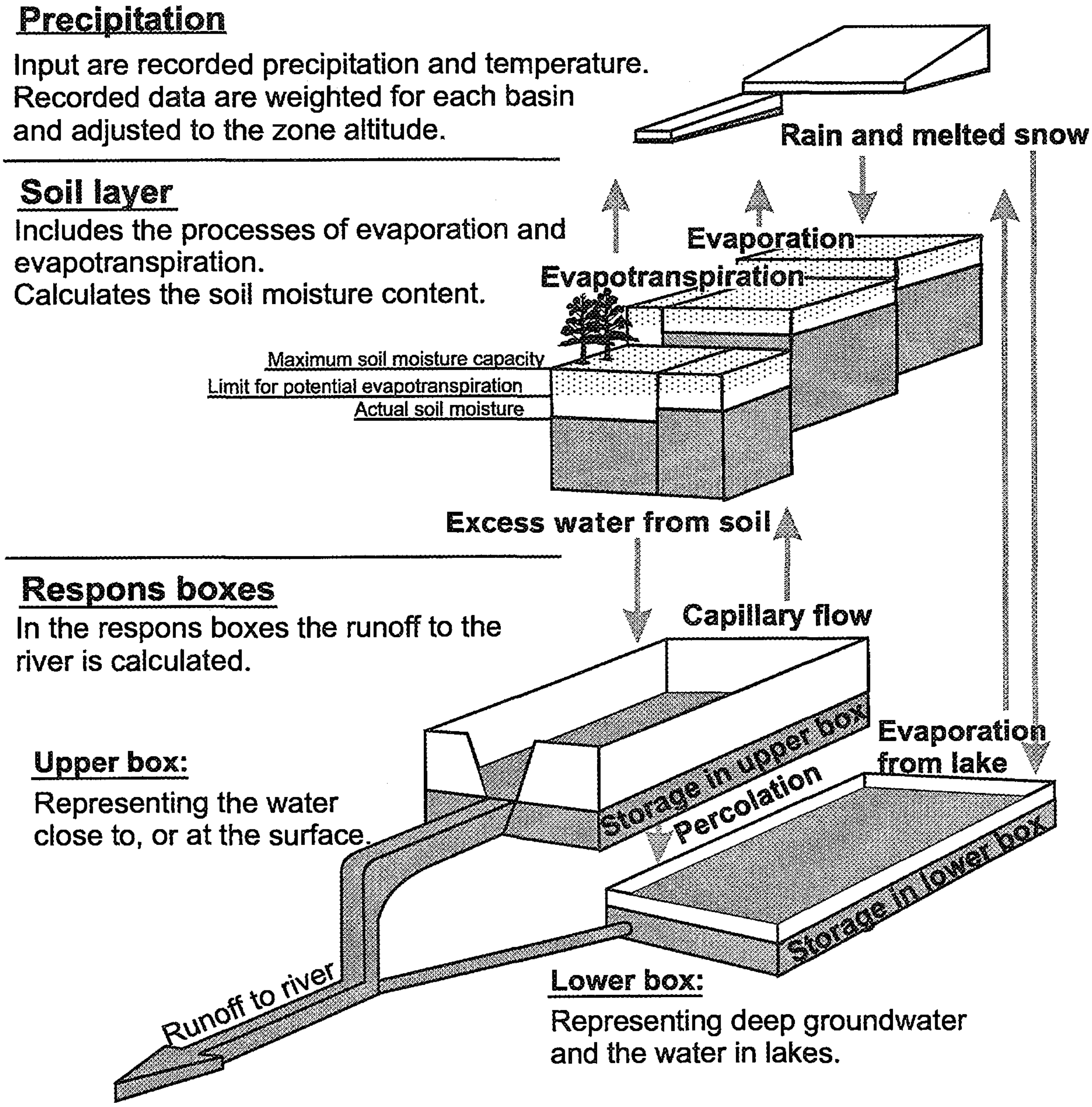

Figure 2-2. Schematic illustration of the HBV model. The arrows represent the movements of water. For a detailed description see appendix 1.

2.2.2 Precipitation

Input to the model is recorded values of precipitation and temperature. The temperature determines if the precipitation is rain or snow. The model calculates weighted mean values for the basin using chosen weights for the climate stations used. All precipitation values are multiplied by a general correction factor, but different factors can be used for rain and snow. A lapse rate for precipitation is applied to adjust to the actual altitude. Different lapse rates can be used for high or low altitudes.

Snowmelt is calculated separately for each elevation and vegetation zone according to the equation:

$$Q_m(t) = CFMAX \bullet (T(t) - TT) \tag{2-1}$$

where:

Q_m = snowmelt
CFMAX = snow melt factor (mm/°C and day)
T = temperature
TT = threshold temperature for snow/rain

The threshold temperature is normally used to decide whether precipitation is rainfall or snowfall. Different thresholds can be used for accumulation and melting. The threshold can also be extended to an interval within which precipitation is assumed to be a mix of rain and snow.

Because of the porosity of the snow, some rain and meltwater can be retained in the pores. In the model, a retention capacity of 10% of the snowpack water equivalent is assumed. Only after the retention capacity is filled, meltwater will be released from the snow. A snowfall correction factor, adjusting for systematic errors in calculated snowfall and winter evaporation, is also included.

2.2.3 Soil moisture and groundwater formation

The soil moisture content has a key role for controlling the runoff formation, and consequently also the total groundwater recharge (in this study equal to the term R in the HBV model, see figure 2-2). In the model, soil moisture dynamics are calculated separately for each elevation and vegetation zone. The relationship between precipitation and generated runoff depends upon the computed soil moisture storage (SM), the maximum soil moisture content (FC) and the empirical parameter BETA, as given in equation 2-2. Rain or snowmelt generates small contributions of runoff excess water from the soil when the soil is dry, and large contributions under wet conditions (figure 2-3).

$$R(t)=\left(\frac{SM\ (t)}{FC}\right)^{BETA} \bullet P(t) \tag{2-2}$$

where:

R = excess water from soil
SM = soil moisture storage
FC = maximum soil moisture content
P = zone precipitation
BETA = empirical coefficient

Different approaches can be used for determining the potential evapotranspiration. The specified potential evapotranspiration input value can be corrected by a general evaporation correction factor, and moreover by altitude, with an elevation correction factor. It can also be modified according to recorded temperature and related to normal temperature values. As an alternative to use long-term mean values as input data, potential evapotranspiration can be calculated, by using a simplified version of the Thornthwaite's (1948) formula, as was made in this study.

The actual evapotranspiration is computed as a function of the potential evapotranspiration and the available soil moisture (equation 2-3, figure 2-3):

$$EA(t) = \begin{cases} \dfrac{EP \bullet SM\,(t)}{LP} & if\ SM \leq LP \\ EP & if\ SM > LP \end{cases} \tag{2-3}$$

where:
EA = actual evapotranspiration
EP = zone potential evapotranspiration
LP = limit for potential evapotranspiration

SM = soil moisture content
IN = infiltration (from rainfall or snowmelt)
R = excess water from soil
FC = maximum soil moisture content
BETA = empirical coefficient
EP = potential evapotranspiration
EA = actual evapotranspiration
LP = limit for potential evapotranspiration

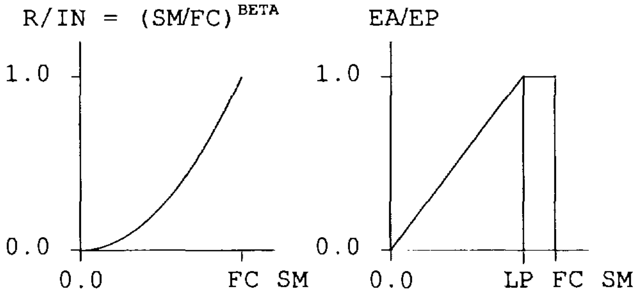

Figure 2-3. Schematic presentation of equations 2-2 and 2-3, illustrating the soil moisture routine of the HBV model.

2.2.4 Runoff response

Excess water from the soil and direct precipitation on open water bodies in the catchment area generates runoff from the response boxes according to equations 2-4 and 2-5.

$$Q_0(t) = K_0 \bullet UZ^{(1+ALFA)} \tag{2-4}$$

$$Q_1(t) = K_1 \bullet LZ \tag{2-5}$$

where:
Q_0 = runoff generation from upper response box
Q_1 = runoff generation from lower response box
K_0,K_1 = recession coefficients
UZ = storage in upper response box
LZ = storage in lower response box
ALFA = recession coefficient

The response boxes in the model represent the groundwater, and are a simple way of describing how the mobile water in the soil, i. e. the excess water from soil in equation 2-2, contributes to the runoff in the river.

In order to account for the moderation of the generated flood pulse ($Q = Q_0 + Q_1$) in the river, a simple routing transformation is made (see Appendix A). This is a filter with a triangular distribution of weights. It is also possible to use the Muskingum routing routine (Chow et. al., 1988), to account for river flow hydraulics.

Lakes in the subbasins are included in the lower response box, but can also be modelled explicitly by a water stage – discharge relationship. This is accomplished by subdivision into subbasins defined by the outlets of major lakes. The use of an explicit lake routing routine has also proved to simplify calibration of the recession parameters of the model, as the lakes account for most of the dampening effects.

2.3 Climate Scenarios

The period 1947–1996 was chosen for the calculations for the Emån river basin. The weighted values of precipitation or temperature from the following stations were used as input data: Ungsberg, Krokshult, Hjorted, Getterum, Bredshult, Tovehult, Gladhammar, Gunnebo, Sandbäckshult and Hinshult. Due to a shorter period of input data, the period 1961–1996 was used for the Äspö area, using data from the stations: Oskarshamn, Västervik, Tovehult, Kråkemåla, Gladhammar and Ölands Norra Udde.

As a reference, computations were initially made with actual (recorded) climate sequence for the used climatic stations. Based on the range of climatic variations since the last glaciation, four climate scenarios were formulated:

- recorded climate sequence +2°C
- recorded climate sequence +2°C, 20% less precipitation
- recorded climate sequence –1°C
- recorded climate sequence –1°C, 20% more precipitation

The alterations were made as corrections of temperature and precipitation on the recorded input data sequence and were applied on each daily value all through the year. This means that the inter-annual variations from the original sequence remain. The temperature and, where appropriate, precipitation curve has been displaced in parallel to the recorded data, using the corrections in the four scenarios above (see figures 2-5, 2-6, 2-7 and 2-8).

A climate change scenario assuming the climate 100 years from now was formulated by Aune (1994) and has been used as the 5th alternative climate sequence, see table 2-1. The scenario is, inter alia, based on analyses of GCM-simulations (General Circulation Models) at the Danish Meteorological Institute, and consists of different corrections of temperature and precipitation for each month.

Table 2-1. Climate change scenario used for the simulation of climate 100 years from now.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Prec (%)	+20	+20	+18	+15	+12	+10	+10	+10	+12	+15	+18	+21
Temp (°C)	+4.9	+4.9	+4.4	+3.7	+3.1	+2.7	+2.5	+2.6	+3.1	+3.7	+4.3	+4.7

2.4 Results

Mean values of discharge and groundwater recharge for the simulated period were computed for each of the two studied areas. Simulations were carried through for each of the five climate scenarios. The results for the Emån catchment are presented in section 2.4.1 in tables 2-2, 2-3 and 2-4 and in figures 2-4, 2-5 and 2-6. The Äspö results are presented in section 2.4.2 in tables 2-5 and 2-6 and figure 2-7.

We want to account for relative differences. The scenario results in tables 2-2, 2-3 and 2-5 are therefore expressed in percentages of the values obtained from the recorded data. Thus a simulated recharge of 110% means 10% higher recharge than the mean value computed with recorded climate data. Using percentages means that a high value for one month can represent a lower actual recharge than a low value for another, wetter month. This must be borne in mind when studying the results. The following example from table 2-3 and 2-4 illustrates this; in the climate change scenario 43% of the total groundwater recharge in March will remain while 48% will remain in May. 43% in March is 19 mm but 48% in May is only 8 mm.

The values of total groundwater recharge in mm, simulated with the actual (recorded) climate sequence, are shown in tables 2-4 for the Emån area and in table 2-6 for the Äspö area. Simulated monthly and yearly mean values of total groundwater recharge should be interpreted as areal mean values representing the total amount of water available for groundwater recharge in the modelled areas. In reality they are only relevant for the parts of the areas where infiltration occurs. For areas of the size of Äspö the values are useful, but for large areas, as the Emån catchment, these areal mean values are normally of little interest, as the precipitation varies a lot within the catchment. The assembled effect of the weighted precipitation is relevant for calculating the discharge at a specific site in a river basin, but the values of groundwater infiltration is usually of interest for specific aquifers within the catchment and needs to be calculated with site-specific precipitation.

In figures 2-5 to 2-7 the seasonal variations over the year are illustrated. The daily values are expressed in % of the yearly mean value obtained with the actual climate sequence. For the Emån river basin the simulated river discharge is presented together with the groundwater recharge in figure 2-5. The Äspö area is a 10x10-km square, which boundaries are no water divide, and thus simulation of discharge in m^3/s is not relevant.

2.4.1 Emån river basin

In the Emån river basin, simulations were made for the discharge station Blankaström. In figure 2-4 the simulated yearly mean values, using the recorded climate sequence 1947–1996, are shown. The discharge curve has a different scale than the groundwater recharge curves, but in spite of that it is obvious that the deep groundwater recharge is the most dampened curve. Normal inter-annual variations are however considerable for example between the years 1958–1959–1960 and 1988–1989.

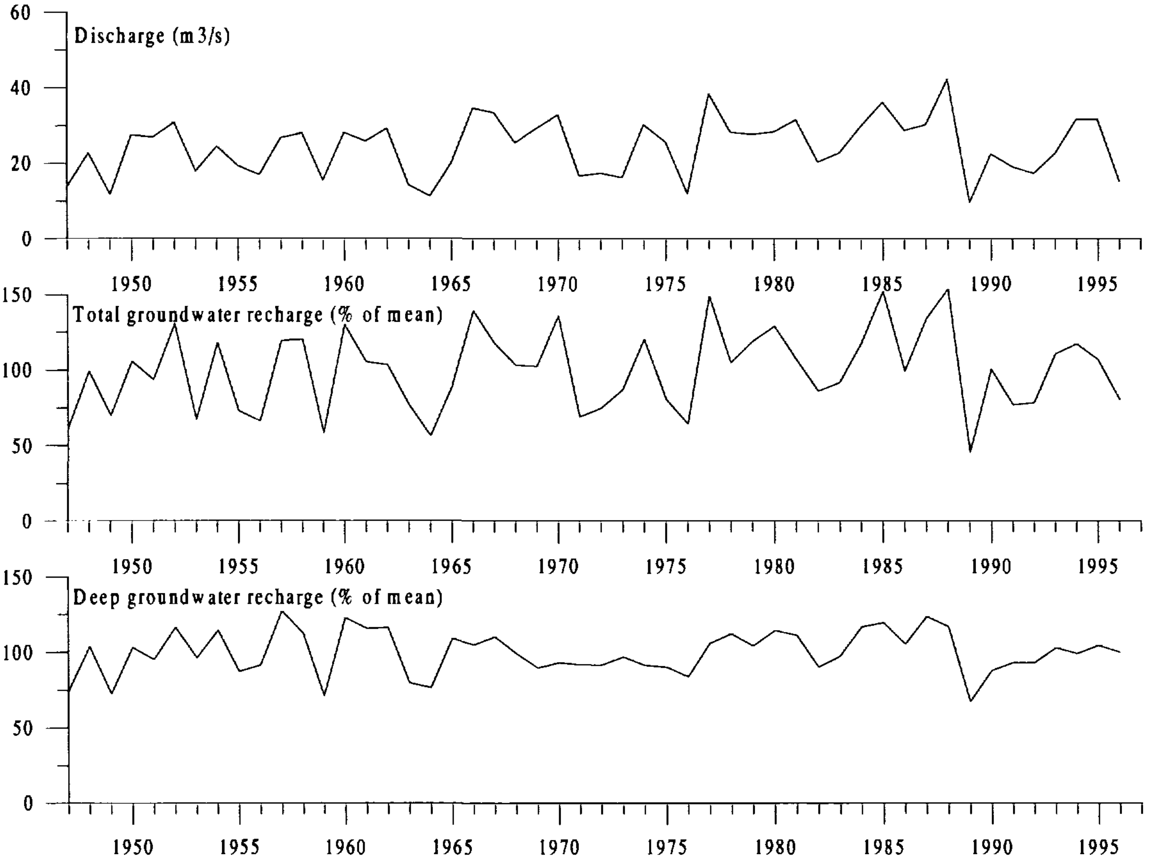

Figure 2-4. Simulated yearly mean values with actual climate sequence for the river Emån 1947–1996.

For the Emån simulations the period 1947–1996 was used. For the Äspö area data were only available for the period 1961–1996, and in order to avoid deviations due to different time periods in the study, simulations for Emån were made for the shorter period as well. The results from the two periods are shown in tables 2-2 and 2-3 and figures 2-5, 2-6 and 2-7. Table 2-3 and figure 2-7 show the results simulations using the shorter time period (1961–1996).

Thirty-six years (1961–1996) is quite a long period, and a quick glance at the computed results gives the impression that the differences between the simulated periods are negligible. For the computed yearly mean values of groundwater recharge the divergence is not more than 1 unit. But the differences in monthly and daily mean values are considerable, for example in February. The differences between the two sequences are larger for the mean precipitation than for the temperature. This example emphasises the importance of using the same time periods for comparison.

Table 2-2. River Emån basin 1947–1996. Modelled changes in mean discharge and groundwater recharge due to climate alterations.

Discharge (%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Recorded climate	100	100	100	100	100	100	100	100	100	100	100	100	100
T+2°C	97	104	86	54	50	54	49	52	60	69	76	84	74
T+2°C, P–20%	48	57	50	32	30	28	16	11	16	21	28	35	36
T–1°C	94	87	89	125	164	140	136	133	127	120	113	103	115
T–1°C, P+20%	132	114	114	166	228	196	209	235	234	214	189	158	167
Climate change scenario	135	125	78	39	35	37	38	57	77	94	105	118	82

Total groundwater recharge (%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Recorded climate	100	100	100	100	100	100	100	100	100	100	100	100	100
T+2°C	118	115	66	46	59	56	67	77	81	85	89	97	80
T+2°C, P–20%	79	80	43	29	31	23	27	35	37	44	48	59	47
T–1°C	80	80	100	162	140	129	122	115	112	108	104	90	111
T–1°C, P+20%	99	97	121	209	200	192	195	180	172	157	145	116	151
Climate change scenario	147	123	47	34	47	54	80	95	103	108	115	130	90

Deep groundwater recharge	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Recorded climate	100	100	100	100	100	100	100	100	100	100	100	100	100
T+2°C	101	104	99	84	64	46	65	78	83	85	92	97	86
T+2°C, P–20%	82	89	80	63	35	19	28	40	45	50	64	72	60
T–1°C	92	88	89	102	112	135	127	113	108	109	104	99	103
T–1°C, P+20%	101	96	95	106	118	162	173	151	137	132	115	108	118
Climate change scenario	109	110	91	64	43	38	73	91	97	98	101	105	87

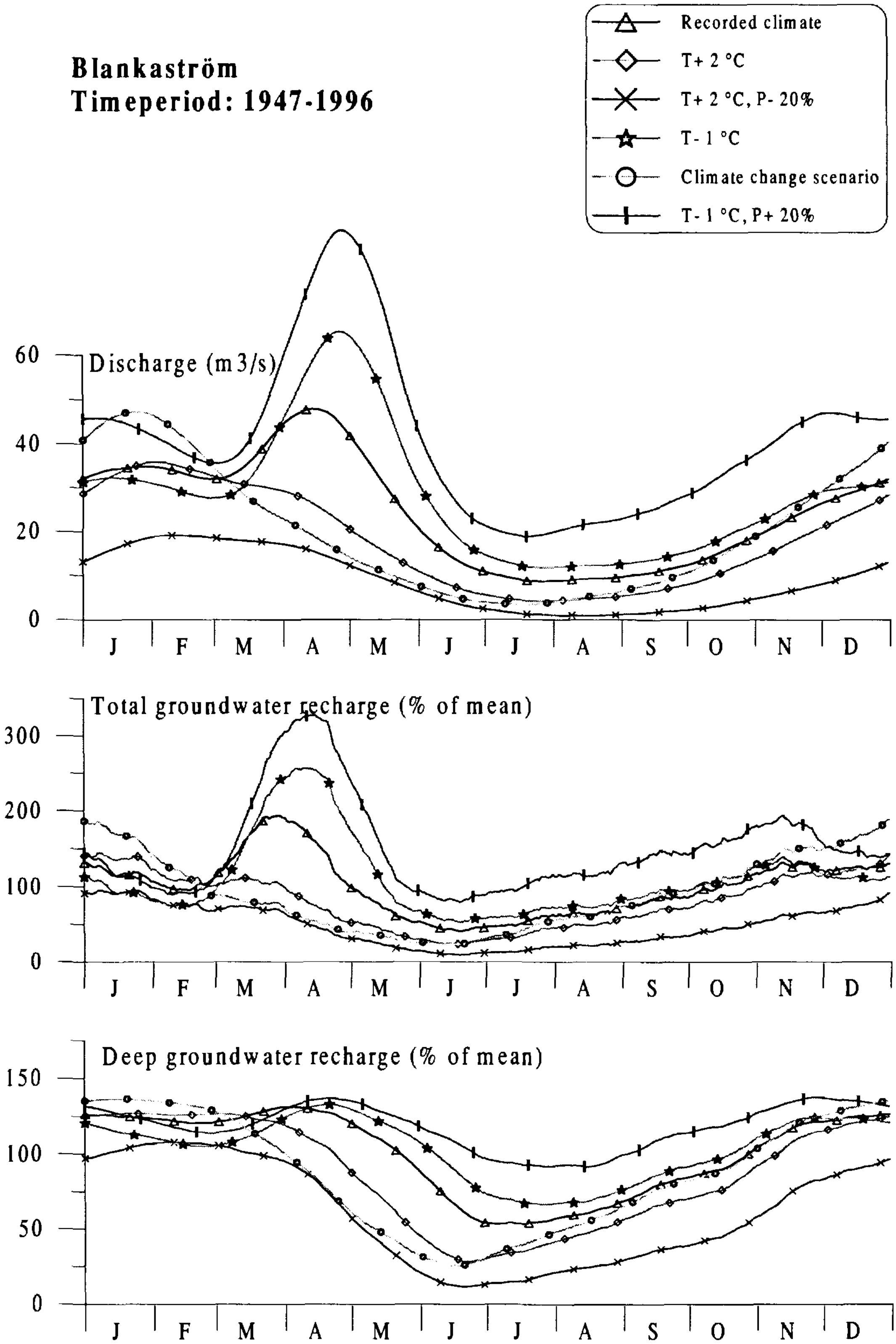

Figure 2-5. River Emån basin 1947–1996. Seasonal variations of discharge and groundwater recharge with different climate alternatives.

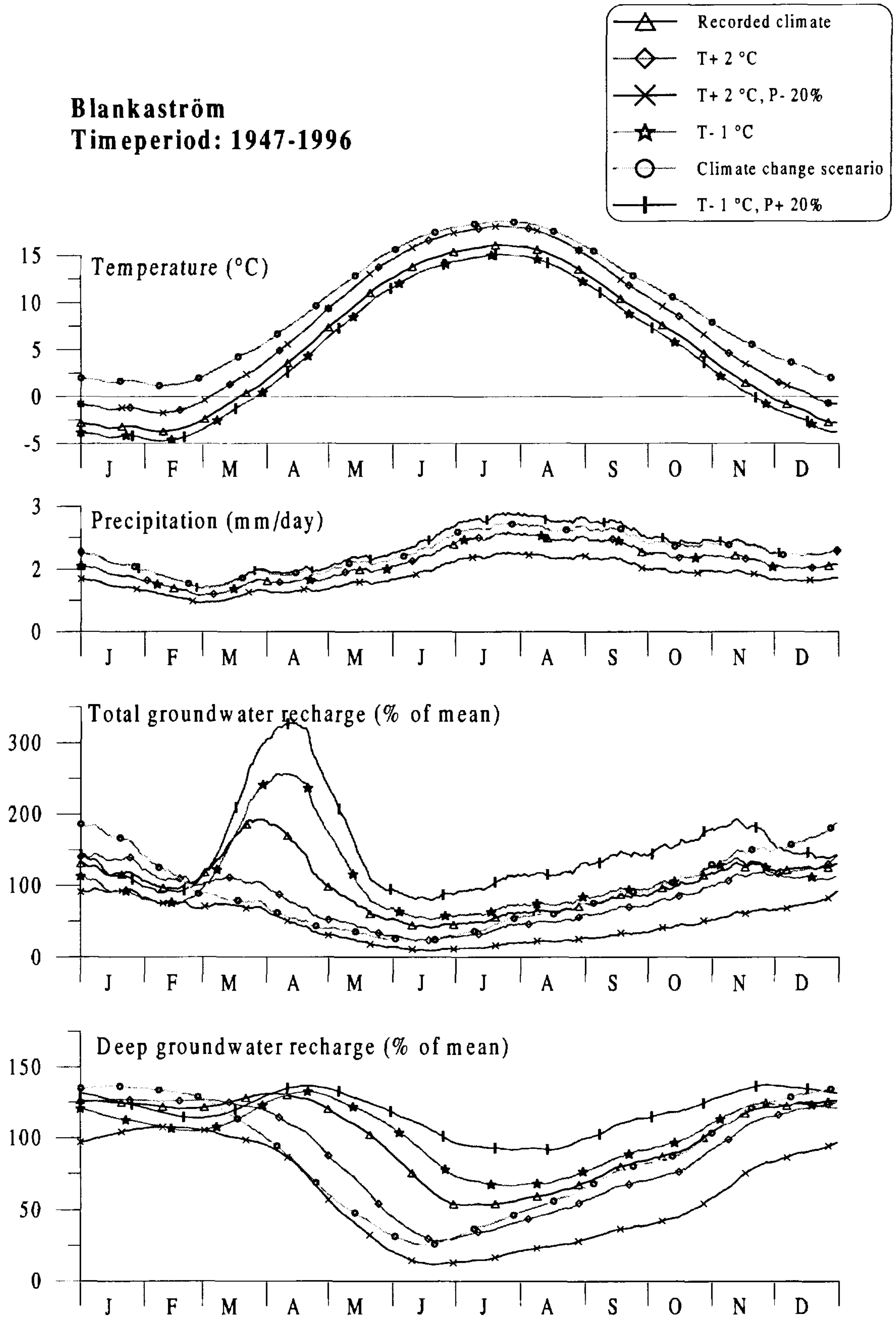

Figure 2-6. River Emån basin 1947–1996. The climate scenarios and their effects on modelled groundwater recharge.

Table 2-3 and figure 2-7 show the results simulations using the shorter time period (1961–1996). These were made to enable comparisons with the simulations made for the Äspö area.

Table 2-3. River Emån basin 1961–1996. Modelled changes in mean discharge and groundwater recharge due to climate alterations.

Discharge %	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Recorded climate	100	100	100	100	100	100	100	100	100	100	100	100	100
T+2°C	96	107	87	53	51	55	51	53	62	69	75	84	74
T+2°C, P–20%	47	59	51	31	30	29	17	11	17	21	26	35	36
T–1°C	96	91	87	123	162	139	134	132	126	120	114	102	115
T–1°C, P+20%	134	119	111	162	224	194	209	232	234	220	193	158	166
Climate change scenario	134	132	77	37	35	39	40	58	80	95	106	119	82

Total groundwater recharge (%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Recorded climate	100	100	100	100	100	100	100	100	100	100	100	100	100
T+2°C	120	125	63	46	59	57	68	77	81	85	90	99	81
T+2°C, P–20%	82	87	41	29	31	24	28	35	38	43	48	60	47
T–1°C	84	81	96	161	142	128	121	114	111	108	104	89	110
T–1°C, P+20%	104	99	115	207	204	191	192	182	172	159	144	114	150
Climate change scenario	151	132	43	35	48	56	81	96	104	109	117	134	90

Deep groundwater recharge (%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Recorded climate	100	100	100	100	100	100	100	100	100	100	100	100	100
T+2°C	103	106	101	85	66	48	65	77	85	85	92	99	87
T+2°C, P–20%	82	94	83	66	37	20	28	39	47	49	63	73	61
T–1°C	89	86	88	103	111	132	126	113	108	108	104	98	103
T–1°C, P+20%	101	93	93	106	118	157	172	157	135	130	114	106	117
Climate change scenario	112	113	93	67	45	39	73	90	97	98	101	105	88

Table 2-4. River Emån basin 1961–1996. Values of total groundwater recharge.

Total groundwater recharge (mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Recorded climate	27	19	44	36	16	10	11	13	20	22	30	28	276

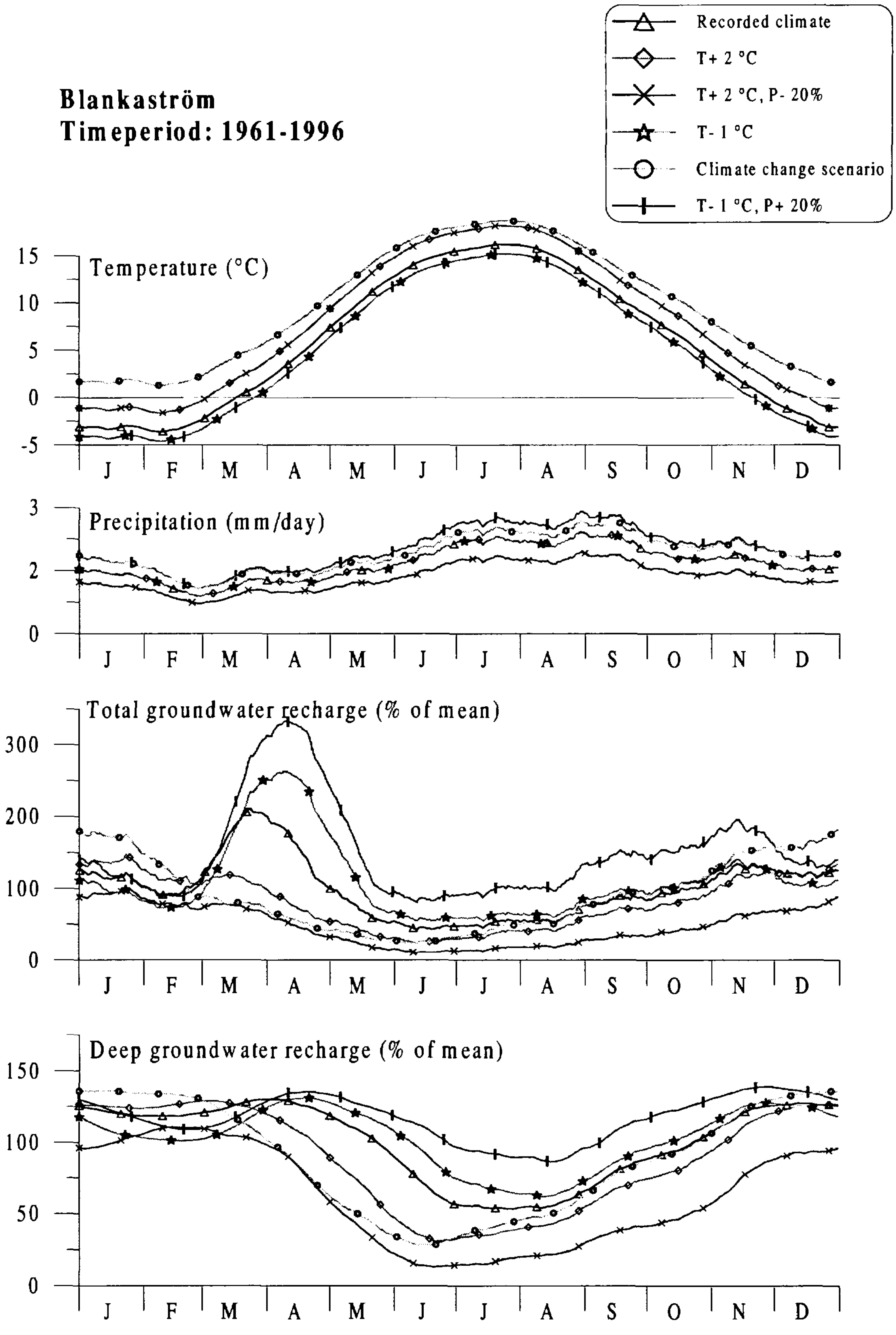

Figure 2-7. River Emån catchment 1961–1996. The climate scenarios and their effects on modelled groundwater recharge.

The results show that alterations in temperature and precipitation of the magnitudes specified in the scenarios imply considerable changes in groundwater recharge and in discharge. Primarily the distribution over the year is influenced, due to alterations in snow conditions during the winter and in evapotranspiration during the summer. Changes in evapotranspiration and precipitation also imply changes in the yearly runoff and recharge values.

For example a temperature increase of 2°C results in a halving of the simulated deep groundwater recharge in June, a slight increase in January-February and for the total year a decrease by almost 15% (see table 2-2 and figures 2-5 and 2-6). For deep groundwater recharge, a decrease in temperature by 1°C is hardly noticeable for the total year, but the recharge increases during the summer and decreases during the winter.

The greatest effects for the total year occur when the precipitation is altered. The differences in discharge and total groundwater recharge are more pronounced when temperature is increased by 2°C than in the scenario with a decrease of 1°C.When there is a simultaneous change of precipitation (T+2°C, P–20% and T–1°C, P+20%), the effects are of the same magnitude.

The climate change scenario has the greatest temperature changes, but lesser change of precipitation than the other scenarios. This results in smaller effects on modelled yearly mean values of discharge and groundwater recharge. The climate change scenario however has the greatest influences on the seasonal variations. The recharge and discharge increase in the winter and the spring flood peak is totally extinguished. Note that the increased precipitation in the summer months will not cause increased discharge and recharge, as long as there is a contemporaneous increase in temperature. In the alternative with 2°C increase of the temperature and 20% decrease of the precipitation, the seasonal variations are damped. In this scenario both the total and the deep groundwater recharge decreases by 60–80% in the summer months (See figure 2-5.)

2.4.2 The Äspö Area

The Äspö area is a 10x10-km square in south-east Sweden. It consists of islands as well as mainland, with the island of Äspö in the centre, see figure 2-1. The area covered by the Baltic Sea has been excluded from the computations, implying that the area used for simulations is 70.3 km^2.

Site specific parameters were used in the modelling work, for example altitude and land use, and appropriate climate stations were chosen for input data. For the rest, the parameters from Emån (Blankaström) were applied in the simulations. The same model and climate scenarios as for the Emån river were used, and the results are shown in table 2-5 and figure 2-8. As the area is not a river catchment, the modelled discharge should be interpreted as areal runoff. This discharge is expressed as percentage deviations from the recorded climate sequence,see table 2-5. In table 2-6 the total groundwater recharge is shown in mm, like in table 2-4 for the Emån river catchment.

Table 2-5. The Äspö area 1961–1996. Modelled changes in mean runoff and groundwater recharge due to climate alterations.

Runoff (%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Actual climate	100	100	100	100	100	100	100	100	100	100	100	100	100
T+2°C	79	83	73	47	46	38	27	33	35	36	58	67	61
T+2°C, P–20%	16	21	22	15	15	8	3	2	2	1	12	11	15
T–1°C	103	89	102	142	152	145	154	161	150	148	128	114	122
T–1°C, P+20%	165	130	139	201	215	208	267	345	375	367	264	210	193
Climate change scenario	114	110	56	27	26	18	16	35	52	61	88	105	66

Total groundwater recharge (%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Actual climate	100	100	100	100	100	100	100	100	100	100	100	100	100
T+2°C	105	105	62	51	56	51	65	72	79	82	85	98	78
T+2°C, P–20%	64	68	37	30	28	18	24	25	31	35	40	52	41
T–1°C	81	77	116	161	131	135	127	121	114	112	107	100	113
T–1°C, P+20%	105	96	143	213	182	209	212	220	192	184	159	138	160
Climate change scenario	139	112	39	37	43	50	79	94	105	111	114	132	88

Deep groundwater recharge (%)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Actual climate	100	100	100	100	100	100	100	100	100	100	100	100	100
T+2°C	97	96	87	73	52	44	61	70	76	79	89	94	81
T+2°C, P–20%	66	76	62	47	27	15	23	23	33	32	46	62	49
T–1°C	101	93	99	107	123	146	137	119	117	112	107	101	109
T–1°C, P+20%	112	104	104	111	133	200	202	185	174	178	139	112	131
Climate change scenario	105	101	76	50	33	37	69	90	97	101	103	103	81

Table 2-6. The Äspö area 1961–1996. Values of total groundwater recharge.

Total groundwater recharge (mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Actual climate	21	21	31	26	13	7	8	7	12	12	24	24	206

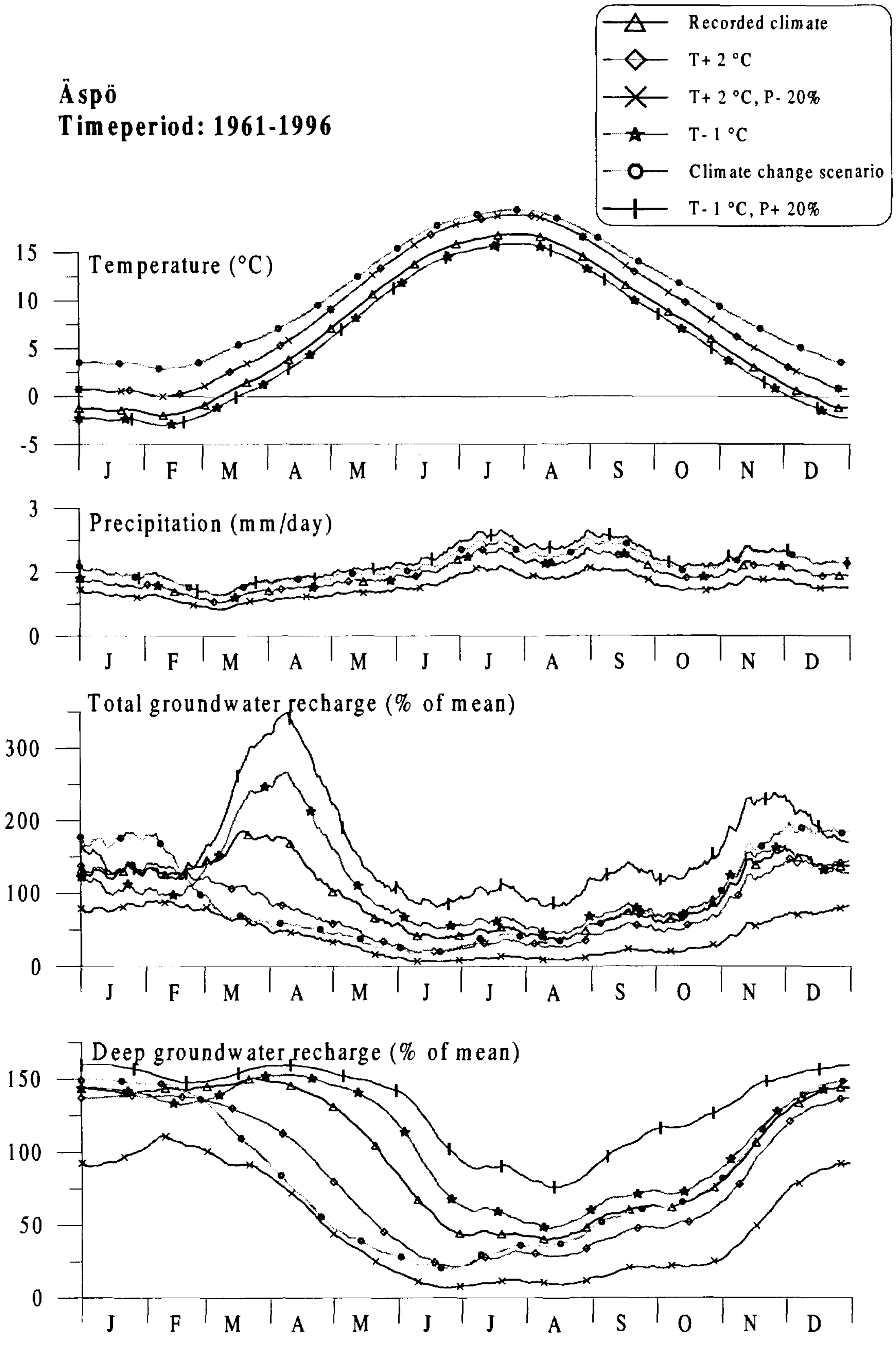

Figure 2-8. The Äspö area 1961–1996. The climate scenarios and their effects on modelled groundwater recharge.

Figure 2-8 illustrates that the recorded temperature at Äspö is higher and the precipitation is lower than in the Emån river catchment. In the coastal region of Äspö the seasonal variations are differing from the Emån area which has a more continental climate. Äspö has less snow and hence lower spring flood peak and a higher peak in November. The precipitation sequence shows more daily variations for Äspö, reflecting the fact that this area is smaller and simulated with fewer climatic stations than Blankaström, where many precipitation values are weighted together and the areal mean values form a smoother curve.

Table 2-5 shows that the effects of the different climate scenarios, expressed as percentage of actual monthly and yearly mean values, are greater in Äspö than in Emån river basin (table 2-3). It is, however, important to bear in mind that the total amount of precipitation, and consequently runoff and recharge, is lower in Äspö. 100% in Äspö is consequently less water than 100% in Emån river catchment. Therefore the curves can not be used for comparison of changes in actual amounts of water between the two areas.

The results of the climate alternatives are similar for the two areas studied, except for differences in magnitude. For example, the runoff at Äspö would almost vanish in July-October with the second climate alternative (+2°C and –20% precipitation).

2.5 Discussion

It is hard to predict which influence a future climate change would have on the groundwater in hard rock. The question is simply put too soon. The two most important difficulties are the quantification of future regional climate and its variability and the modelling of the infiltration process. Research concerning these issues is in progress. The method in this report does not claim to quantify the infiltration process, but should be regarded as a qualitative model-based sensitivity analysis of the impact of climate on the availability of water for infiltration.

It is important to bear in mind that the climate change scenarios presented in this report are not predictions of future climate. They are simply a presentation of possible range of climate change during temperate/boreal conditions. Several climate scenarios have been defined for the Nordic countries and are shortly presented in Saelthun et. al. (1998). The report describes simulations similar to the ones presented in this report, and the results shown on a yearly basis are of the same magnitude. Saelthun et. al. (1998) points out that changes in precipitation scenario is more problematic than temperature changes and that the sensitivity of the climate models to an increase in greenhouse gases is an uncertain factor.

3 The role of land use for evapotranspiration

3.1 General

The role of land use for runoff has been discussed for several years. (Inter alia: Bosch et. al., 1982, Brandt et. al., 1988, Johansson, 1994.) Evapotranspiration and soil water deficit have a key role for runoff and groundwater recharge.

An increased amount of trees in the forests in a catchment leads to higher interception of snow and rainfall, which implies less water available for runoff when the intercepted water evaporates. The runoff process will correspondingly be influenced by tree plantation on former farmland or bogs.

During the first years after a clear-cutting, there will be a larger amount of water available for runoff and groundwater recharge, which is the result of mainly smaller transpiration and interception.

The scenery is complex, however. For example, trees have different transpiration rates depending on the ages of the trees, and clear-cut areas and bogs are often drained before plantation in order to improve survival of the plants. Plantation of energy forest often includes irrigation of the plants, which supplies more water for transpiration as well as for runoff and groundwater recharge at that specific site. This will interfere if measurements are made to compare the water balance between planted and unplanted areas. Linder (1998) emphasises the need for further research and modelling to be able to quantify the effects on forest ecosystems of climate change.

3.2 Evapotranspiration

Evapotranspiration is a main element of the water budget and affects the water available for groundwater recharge to a great extent. The hydrological models in practical use today often have a very simple description of evapotranspiration.

Evapotranspiration (E) from the earth surface is the sum of two parts:

- Evaporation from ice, snow, water surfaces and bare soil.
- Transpiration from vegetation via dry parts of leaves or needles – has passed through the roots.

These two parts often occur at the same time. Instead of evaporation, there can be condensation on the earth's surface. Evapotranspiration is a part of the water balance of the earth surface (E in mass units: kg m^{-2} s^{-1}). It is also a part of the energy balance (L*E in energy units, W m^{-2}, where L is the latent heat of vaporisation):

$$R_n - G = H + L^*E \qquad 3\text{-}1$$

where:

R_n = net radiation flux
(= received minus emitted heat radiation by the earth's surface)
G = energy flux to heat storage in soil, water and vegetation
H = sensible heat flux
(= heat transportation to the atmosphere via air)
L*E = latent heat flux
(= heat transportation to the atmosphere via vapour)

It is important to distinguish between actual and potential evapotranspiration. The potential evapotranspiration is a theoretical term referring to the rate at which evapotranspiration would occur from a large area covered with vegetation, under given values of temperature, wind and humidity, and with access to an unlimited supply of water in the root zone. However factors as the characteristics of the vegetative surface and the presence or absence of intercepted water, also have a strong influence on the evapotranspiration rate, even when there is no limit to available water. In spite of these ambiguities, the term 'potential evapotranspiration' is frequently used, but in practice there are different methods by which to calculate it, and often it is not specified which method is referred to. Potential evapotranspiration has often been calculated from climate data by the method of Penman (1948). The Penman-Monteith equation (Monteith, 1965) has also been used for calculation of potential evapotranspiration (e.g. Lindroth, 1993). These are combination methods, i. e. they include both an energy term, describing radiation conditions, and a ventilation term, describing how fast water vapour is transported away. Other methods can be classified as temperature-based, radiation-based, or pan methods, on the basis of their data requirements (Dingman, 1994).

Actual evapotranspiration is normally smaller, impeded by the soil moisture deficit, because transpiration is reduced when the soil is dry. In calculations there are methods to reduce potential evapotranspiration to actual evaportranspiration, using soil moisture deficit. The words evapotranspiration, evaporation and potential evapotranspiration are often used without defining which term or method is intended, which can easily confuse the reader.

Evapotranspiration data can also be obtained from meteorological models (climate models and weather forecast models). Models should be validated against measured evapotranspiration values. Today such data is continuously recorded at a number of measuring sites, using micrometeorological methods.

The eddy correlation method is currently the most commonly used method by which to measure evapotranspiration. The air humidity and the vertical wind speed component are recorded from a meteorological mast several times per second at a few metres above the surface or vegetation top. The deviations of the fluctuations of these two variables from their respective time averages (over a period of 20–60 minutes) can be used to calculate the evapotranspiration flux. If, for example, the upward wind fluctuations are more humid than the downward ones, a net upward water vapour flux takes place.

3.3 Further literature

There are several methods used to quantify actual evapotranspiration, for example:

- by using potential evapotranspiration plus reduction (Penman, 1948, Thornthwaite 1948), the Priestley-Taylor method (Priestley and Taylor, 1972), and
- by direct calculation: the Penman-Monteith equation (Monteith, 1965).

All these methods have been used in several research projects with the aim of quantifying the actual evapotranspiration from different vegetation types at different sites and to improve the calculation of evapotranspiration in hydrological models. It has shown to be a very complex matter. Within Swedish Regional Climate Modelling Programme (SWECLIM), research projects are proceeding on this issue, but results are not available at this stage.

Runoff is easier to measure, and several investigations have been made of the effects of changed land use on runoff, which, inter alia, is caused by changed evapotranspiration.

Burton (1997) found a 52% increase of runoff from a river basin after clearcutting 25% of the area. 10 years of pre-harvest and 20 years of post-harvest conditions were monitored in the harvested basin and a control basin.

Brandt has made several simulations with the HBV model in order to distinguish the effects of clearcutting and forest growth on river runoff. She found that forest management practices have a strong local influence on flooding risks, especially in small streams in areas where the percentage of deforestation is high. The model helps to quantify the integral effects of different sizes and geographical location of the clearcut areas within a catchment. Three small basins (0.16–1.5 km^2) were monitored before and after clearcutting and the effects with increased values of runoff were clearly seen in the model simulations. Simulations of hypothetical partial cutting in a larger basin were made, using model parameters from the clearcut period in the small basins. The model results showed that clearcutting, which is a very drastic way of changing the conditions in a catchment, had a major effect in small catchments. The effect of logging 10% of a catchment area was however of minor importance compared to the effects of extreme weather conditions and other factors (Brandt et. al., 1988).

The same modelling method as above can be used for simulating the effects on evapotranspiration and groundwater recharge, which has been the main objective of this study.

Regarding forest growth, the picture is more complicated. Brandt (1992) made an investigation of the effects of forest growth in Sweden on river runoff and evapotranspiration. A growing forest will need more water for evapotranspiration, which would result in a decrease in runoff from the area. She compared available statistics of forest growth with climatological and hydrological sequences, with recorded data as well as with the HBV model, for about 15 runoff stations in different parts of Sweden. The areas were between 263 and 12,000 km^2. The effects of forest growth were hard to distinguish. The weather fluctuations will often hide the effects on river runoff caused by changed evapotranspiration, as forest growth is a slow process by contrast to clear-cutting.

Several international investigations have shown that runoff increases after logging and decreases at forest plantation (Bosch and Hewlett, 1982, Brandt et. al., 1988, Brandt, 1992, Burton, 1997). This indicates high evapotranspiration values for forests, compared with open land. Preliminary results from the Northern Hemisphere Land Surface

Climate Processes Experiment (NOPEX) area indicate contradictory results from simultaneous measurements of evapotranspiration from different types of vegetation, but no results have yet been published. Hence it is hard to draw specific conclusions about the effects of increased Swedish forest growth on the water balance.

Johansson (1994) found a significant correlation between the increase of open land and the decrease in evapotranspiration, using the HBV model in 11 catchments ranging from 1.6 km^2 to 350 km^2 in the southernmost part of Sweden. Evapotranspiration was calculated as the difference between precipitation and observed runoff. The decrease, however, was small: For each increase of open land by 1%, the evaporation decreased by 0.8 mm/year. This shows once again the fact, that to be able to see the effects, there should be changes of land use in a considerably greater part of the catchment.

Pettersson (1995) made an investigation to find changes in recorded runoff that may be related to changed evapotranspiration. Changed evapotranspiration could be possible to relate to changes in landuse. The water balance was calculated using recorded precipitation and runoff for 19 small catchments in Sweden for the years 1986–1994 and the results were compared to the reference figures for the standard period 1961–90. All divergences were within the range of standard deviation, although one station was very close to the limit. This means that no significant changes were found, neither in precipitation nor runoff. It implies that the evapotranspiration, which was calculated as the difference between precipitation and runoff, was similar for the two periods. Hence no significant increased or decreased evapotranspiration, possible to relate to changes in land use, was found.

Evapotranspiration models have been developed for several years. Tallaksen (1996) compared three models for rainfall interception loss from a coniferous forest during two summer seasons. All models had the most difficulties in periods of high interception losses, but the physically most advanced model showed the highest potential for improvement.

Persson (1995) found the evapotranspiration in May to October to be largest for spruce, slightly lower for willow and much lower for agricultural crops. The higher values for spruce were due to the contribution from evaporated rainfall interception. A soil model and the Penman-Monteith equation were used. The willow data was collected at four sites in south and middle Sweden.

Lundberg (1996) presents measurements and model results on rainfall interception and snow interception. It was found that the aerodynamic resistance to evaporation of snow intercepted on forest was 10 times larger than for intercepted rainwater.

Lindström et. al. (1994) tested different modifications of the evapotranspiration routine in the HBV model in order to improve the possibilities to use the model for simulations of climate change effects on water resources. They found that the uncertainty in climate change predictions probably is more important than the problem of weaknesses in the hydrological model.

Gardelin and Lindström (1997) estimated evapotranspiration, using the Priestley-Taylor method, as input to the HBV model. This gave minor improvement of the runoff simulation for three drainage basins during a 20-year period.

Work is in progress within the SWECLIM project to improve the evapotranspiration routine in the HBV model. An evapotranspiration model using three-hourly weather observations in the Penman-Monteith equation has been used for calculations of actual evapotranspiration values, which then will be used as indata to the HBV model (Bringfelt, 1998).

Grelle (1997) treats measurements of evapotranspiration from the main forest site (Norunda) in the NOPEX area north of Uppsala in Sweden. Measurements have been made continuously since 1994 of sensible heat flux and latent heat flux by the eddy correlation method at three levels above the forest. In the NOPEX area the eddy correlation method and other micrometeorological methods have been used to record evapotranspiration simultaneously at forest, agricultural field and lake sites.

3.4 Discussion

In spite of many calculations and investigations there is still no clear answer to the question on how evapotranspiration is affected by changes in land use. This is due to the fact that the process is complex and depending on site-specific factors.

As evapotranspiration from an area is the result of interaction between vegetation and climate factors, the components forming evapotranspiration are not easy to verify. Many theories about evapotranspiration for different kinds of vegetation are treated in literature. When it comes to quantifying the actual evapotranspiration and generalizing the different vegetation types, research has yet no clear results. Another very complex issue, which has not been considered in this study, is the feedback between increased carbon dioxide in the atmosphere and plant use of water (Bosemark, 1998).

Climatic factors affect surface resistance, which is caused by the action of the stomata of transpiring vegetation. In some areas and climates evapotranspiration can be smaller for forest than for grass, due mainly to the higher surface resistance for trees, while other conditions may give higher evapotranspiration for forest, mostly due to high interception of rainfall. The importance of interception needs to be emphasized if a total picture of the circumstances is to be gained.

The primary difference between coniferous and deciduous forest is the seasonal variation of leaf area. In the modelling work this can be achieved by a monthly variation of the leaf area index and, in consequence, a variation in surface resistance and rainfall water storage capacity.

Natural climate fluctuations might overlap the differences due to vegetation characteristics, making it difficult to verify the theories against field measurements. For example, if there are summers with plentiful rain showers spread out in time, the interception and subsequent evaporation will be larger than if the same amount of rain falls in large quantities on few occasions.

An investigation of runoff stations, with catchment areas smaller than 6 km^2, and run by SMHI in the national Swedish network, was made within the work of this report. The aim was to find sites where the land use has been changed significantly during the last few years. Using data from these kinds of stations would facilitate future investigations of changes in evapotranspiration and runoff. However, only one station with great differences in land use was found. Here the forest was clear-cut in 1983, and the runoff has increased during the period after clearcutting. Results in Pettersson (1995) show, however, that the changes are not significant. Regarding areas with forest plantation, no stations with a sufficient amount of planted area were found. Therefore it does not seem possible to use this method for monitoring the effects of land use change on the water balance of a catchment. It might still be possible that there are other stations, for example in research projects that could be used. It could also be useful to make this investigation again within some years.

4 Conclusions

The future changes in the earth's climate are complex and challenging scientific issues. Several international research projects are working on developing reliable scenarios of future climate and the consequences for vegetation and water balance. In Sweden, for instance, this is being studied in the Swedish Regional Climate Modelling Programme, SWECLIM. Within the next few years results will be available from these projects. However, it is important to bear in mind that a climate change scenario is only a presentation of possible climate development and not a prediction of future climate conditions.

While research is proceeding, it is still possible to estimate the effects of climate change on groundwater recharge, using schematic scenarios and model simulations, bearing in mind the limitations of the methods used. For instance, the HBV model can easily be used for simulating the effects of changes in temperature and precipitation in a specific catchment, as has been shown in this report.

The aim of the present work has been to give a picture of the possible changes in hydrological conditions with different climate scenarios, within temperate/boreal conditions in Sweden. The results of the model simulations in this report show considerable effects on discharge and groundwater recharge when temperature is altered 1–2°C, and even greater if precipitation also is changed.

The role of vegetational cover for runoff is another complex question, where available literature does not give a clear picture, but where research is being carried out within, for example, the NOPEX project.

The effects of clearcutting are however possible to estimate, and the results indicate that the clearcut area has to cover a large percentage of a basin, to give significant effects on river runoff. Simulation of the effects of clearcutting on groundwater recharge can be made with the HBV model in the same way as has been made for runoff, using the method described in Brandt et. al. (1988). This would give a good conception of the impact on groundwater recharge and a clue to what the long-term mean values could be in a catchment under new conditions.

Regarding other changes in vegetational cover, it is advisable to await results from ongoing research projects. There are still too many ambiguous factors and connections between the components in the processes involved.

The land use in the catchments of runoff stations draining small areas should be controlled in the future, so that investigations can be made of the effects of major changes in land use on the water balance, if and when these occur. This could enable a possibility to improve model simulations.

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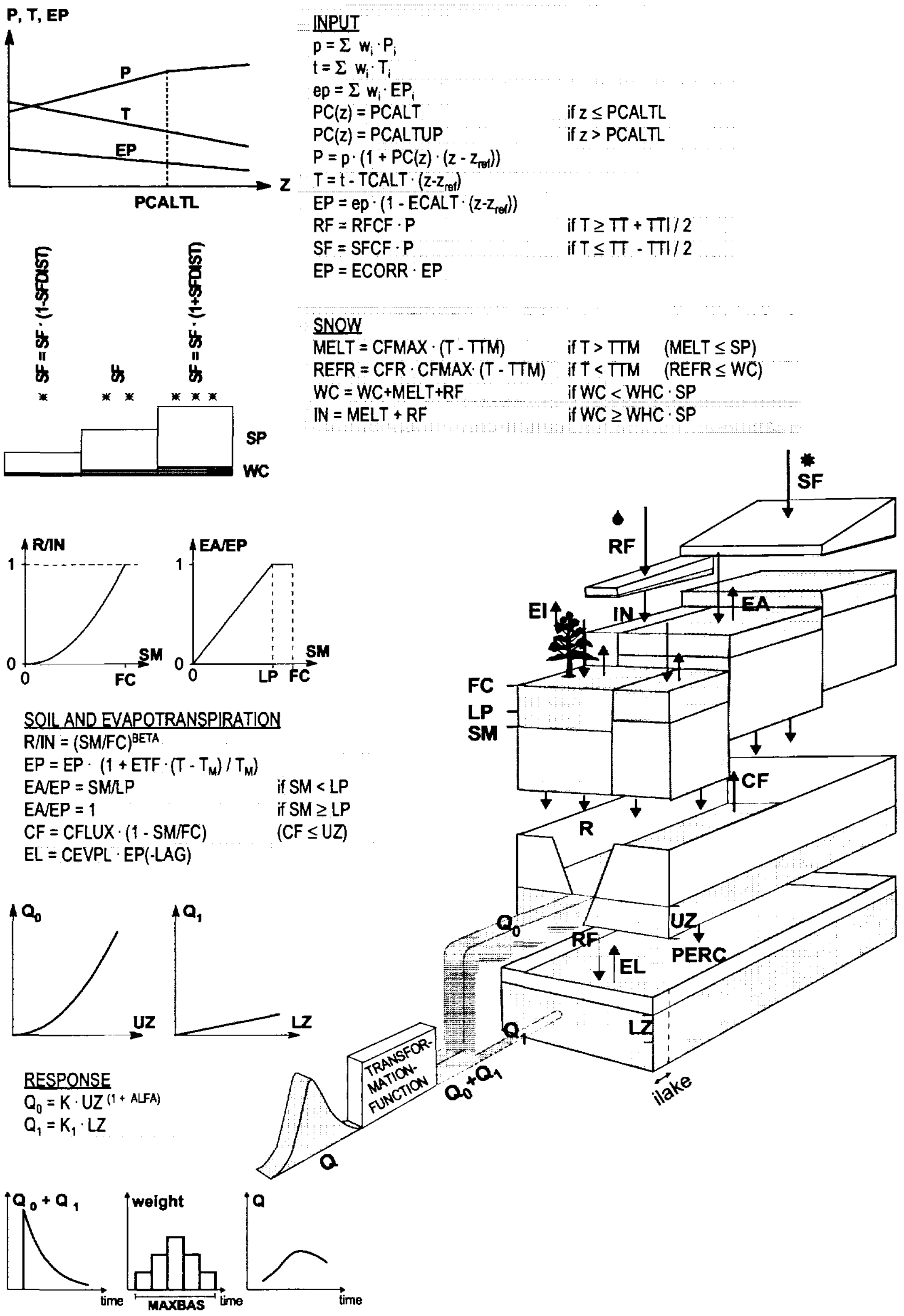
Appendix A

Structure of the HBV model



INPUT

$p = \Sigma\ w_i \cdot P_i$

$t = \Sigma\ w_i \cdot T_i$

$ep = \Sigma\ w_i \cdot EP_i$

$PC(z) = PCALT$ if $z \le PCALTL$

$PC(z) = PCALTUP$ if $z > PCALTL$

$P = p \cdot (1 + PC(z) \cdot (z - z_{ref}))$

$T = t - TCALT \cdot (z - z_{ref})$

$EP = ep \cdot (1 - ECALT \cdot (z - z_{ref}))$

$RF = RFCF \cdot P$ if $T \ge TT + TTI / 2$

$SF = SFCF \cdot P$ if $T \le TT - TTI / 2$

$EP = ECORR \cdot EP$

SNOW

$MELT = CFMAX \cdot (T - TTM)$ if $T > TTM$ $(MELT \le SP)$

$REFR = CFR \cdot CFMAX \cdot (T - TTM)$ if $T < TTM$ $(REFR \le WC)$

$WC = WC + MELT + RF$ if $WC < WHC \cdot SP$

$IN = MELT + RF$ if $WC \ge WHC \cdot SP$

SOIL AND EVAPOTRANSPIRATION

$R/IN = (SM/FC)^{BETA}$

$EP = EP \cdot (1 + ETF \cdot (T - T_M) / T_M)$

$EA/EP = SM/LP$ if $SM < LP$

$EA/EP = 1$ if $SM \ge LP$

$CF = CFLUX \cdot (1 - SM/FC)$ $(CF \le UZ)$

$EL = CEVPL \cdot EP(-LAG)$

RESPONSE

$Q_0 = K \cdot UZ^{(1 + ALFA)}$

$Q_1 = K_1 \cdot LZ$

Figure A-1. Schematic structure of one subbasin in the HBV model, with routines for snow (top), soil (middle) and response (bottom).

Input

Variables:

p = Weighted mean precipitation
t = Weighted mean temperature
ep = Weighted mean evaporation
P_i = Precipitation at station i
T_i = Temperature at station i
EP_i = Potential evaporation at station i (long-term mean values)
P = Zone precipitation
T = Zone temperature
EP = Zone potential evapotranspiration
RF = Zone rainfall
SF = Zone snowfall

Parameters and constants:

PC(z) = Elevation correction factor
TCALT = Elevation correction factor
ECALT = Elevation correction factor
z = Zone elevation
z_{ref} = Reference level
TT = Temperature limit for snow/rain
TTI = Temperature interval with a mixture of snow and rain
RFCF = Rainfall correction factor
SFCF = Snowfall correction factor
ECORR = Evaporation correction factor

Snow

Variables:

SP = Frozen part of snowpack
WC = Liquid water in snow
MELT = Snowmelt
REFR = Refreezing of liquid water
IN = Infiltration to soil

Parameters and constants:

SFDIST = Distribution factor for snowfall
WHC = Water holding capacity
CFMAX = Snow melt factor
TTM = Temperature limit for melting
CFR = Refreezing factor

Soil and evapotranspiration

Variables:

SM = Soil moisture
R = Excess water from soil
EA = Actual evapotranspiration
EI = Interception evaporation
CF = Capillary flow
EL = Lake evaporation
T_M = Subbasin mean temperature (long-term daily mean)

Parameters and constants:

FC = Maximum soil moisture content
LP = Limit for potential evapotranspiration
BETA = Parameter in soil routine
CFLUX = Maximum value of CF
CEVPL = Lake evaporation correction factor
LAG = Time lag for lake evaporation
ETF = Temperature correction factor

Response

Variables:

UZ = Storage in upper response box
Q_0 = Outflow from upper response box
LZ = Storage in lower response box
Q_1 = Outflow from lower response box
Q = Outflow from transformation function

Parameters and constants:

K = Recession coefficient
ALFA = Response box parameter
PERC = Percolation from upper to lower response box
K_1 = Recession coefficient
MAXBAS= Transformation function parameter
ilake = Internal lake zone

Figure A-1. Continuation.