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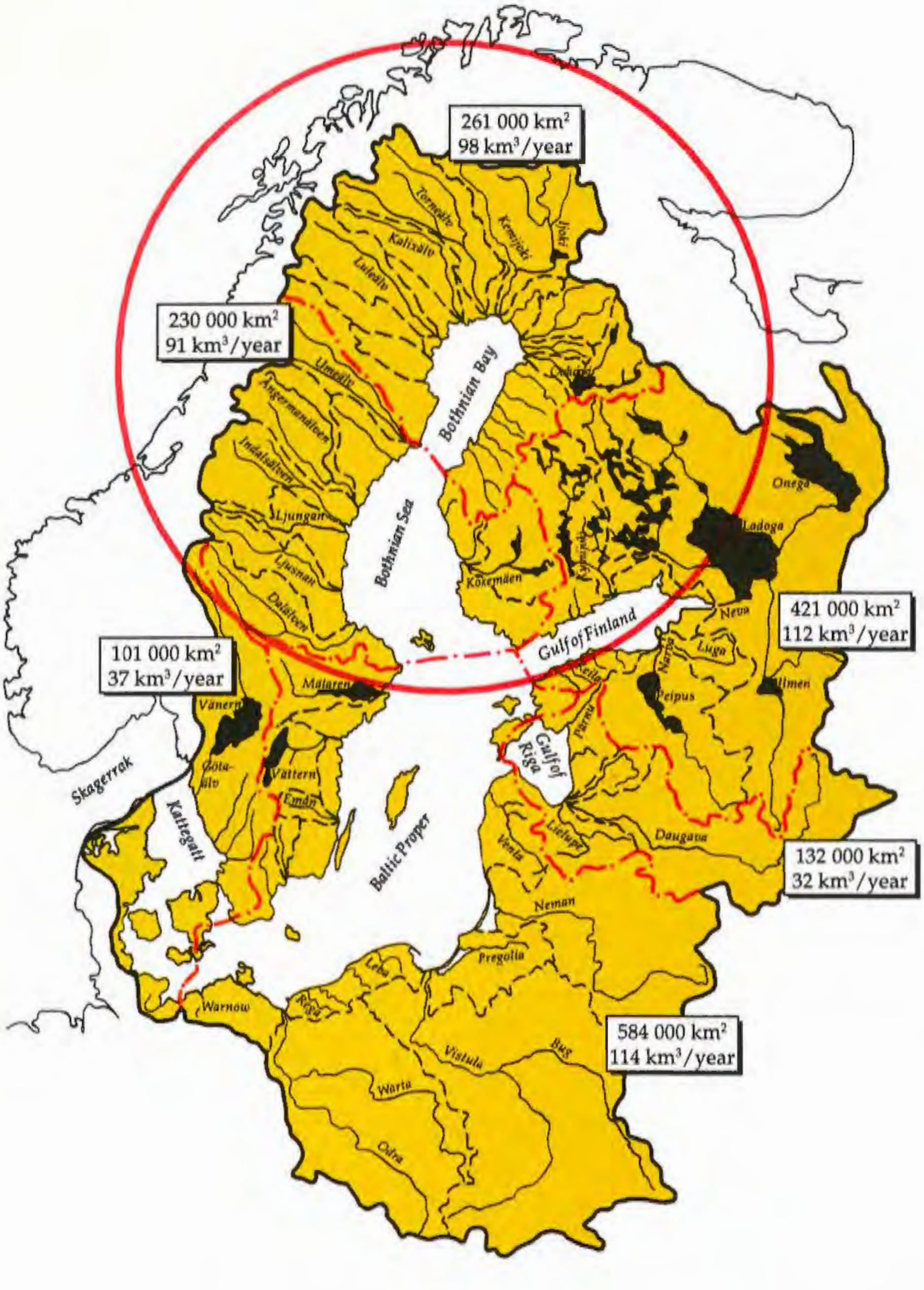

INFLUENCE OF RIVER REGULATION
ON RUNOFF TO THE GULF OF BOTHNIA

- The Gulf of Bothnia Year 1991 -

Bengt Carlsson and Håkan Sanner

SMHI REPORTS HYDROLOGY No 9, August 1994

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Key words

Gulf of Bothnia hydrology, hydropower, effects of regulation.

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Runoff from a land area of approximately 490 000 km^2 enters the Gulf of Bothnia. This runoff is of essential importance for the flushing of the Gulf. A change in the volume of runoff effects the residence time. There are many natural changes in the runoff, both long-term changes over many years and such within one year. There are also man-made changes. The most important of these is hydropower regulation. This report describes the effect of the development of the hydropower plants in Sweden and Finland by means of recorded regulated runoff and calculated natural runoff. The recent time period, 1980-91, and the time before regulation, 1925-36, are simulated. The monthly magnitudes of the redistributed flows were on the average 1 700 m^3/s, but the maximum redistributed monthly flow in May - June reached 5 000 - 6 000 m^3/s. The "Gulf of Bothnia Year 1991" is compared with the period 1981-91. The annual mean runoff in 1991 was c. 6 000 m^3/s, which is somewhat less than the examined period. This originated from a low spring and summer runoff, e.g. c. 9 000 m^3/s in May instead of 13 000 - 14 000 m^3/s. Also the effects of a hypothetical climate change of both a temperature increase and a decrease are simulated.

1. INTRODUCTION

The "Gulf of Bothnia Year 1991" was a multi-disciplinary programme aimed at achieving a better understanding of the ecological system of the northern part of the Baltic Sea and the Gulf of Bothnia. The program also included a study of water transport and water-carried substances to the Gulf of Bothnia as well as physical processes affecting the system.

The Gulf of Bothnia is the northern part of the largest brackish water body in the world, the Baltic Sea. The Gulf is divided in two major parts, the southern Bothnian Sea and the northern Bothnian Bay. Due to river inflow and water exchange through the Åland sea the northern part is less saline then the southern.

The total catchment area is of the size 490 000 km^2. The 12 largest rivers are denoted in Table 1. The annual mean runoff to the whole Gulf of Bothnia is just below 6 000 m^3/s. The runoff is of importance for the salinity stratification and thus for the renewal of the Gulf water through the Åland Sea.

There are many natural changes in the runoff, both long-term changes over many years and such within one year. There are also man-made changes. The most important of these is the hydropower regulation. The aim with the regulation is to store water from spring, summer and autumn until winter when more electricity is needed and the price is high. The subject of this report is to describe the effect of the development of hydropower by comparing registered runoff and calculated natural runoff. The recent time period, 1980-91, and the period before regulation, 1925-36, is simulated. The "Gulf of Bothnia Year 1991" is compared with the period 1981-91.

Table 1. The twelve largest rivers of the Gulf of Bothnia. Calculations for the period 1931-90 for Swedish rivers (Bergström, Sveriges Hydrologi, 1993) and 1961-90 for the Finnish rivers (Hydrological Yearbook, 1990).

River	m^3/s
Kemijoki	553
Ångermanälven	489
Luleälven	486
Indalsälven	445
Umeälven	431
Torneälven	387
Dalälven	344
Kalixälven	289
Oulujoki	259
Ljusnan	226
Kokemäenjoki	231
Skellefteälven	157

2. CLIMATE, HYDROLOGY AND RIVER REGULATION - AN OVERVIEW

Climatically Scandinavia is situated in a zone between a maritime climate to the west and a continental climate to the east. Dominant westerly winds deliver high precipitation to the Scandinavian mountains. A precipitation gradient occurs across the mountains towards the Gulf. The normal annual precipitation, corrected for measurement errors, in the area around the Gulf of Bothnia is 600 to 800 mm on the Swedish side (Eriksson, 1983) (except the mountain region) and 500 to 700 mm on the Finnish side (Atlas of Finland, 1987) and less in the north than in the south. The highest annual values are found in the Swedish mountain region, 1 000 - 2 000 mm, and the lowest precipitation is found in the northeast of Finland, 350 to 500 mm, about half or more of which is received as snow.

In the coastal and inland areas, the annual potential evapotranspiration is in the order of 400 - 500 mm. In the Swedish mountains (Eriksson, 1981) and in the north-west region of Finland (Atlas of Finland, 1987) it amounts to 300 - 400 mm.

The difference between precipitation and evapotranspiration gives the runoff to the rivers. A proper way to describe and compare runoff from different watersheds is to use the specific runoff, i.e. the runoff in $l/(s \cdot km^2)$. In Figure 2.1 the specific runoff from the whole Baltic Sea area can be seen (Bergström and Carlsson, 1993). The map illustrates that the contribution of runoff from Sweden is larger than that from Finland to the Gulf of Bothnia.

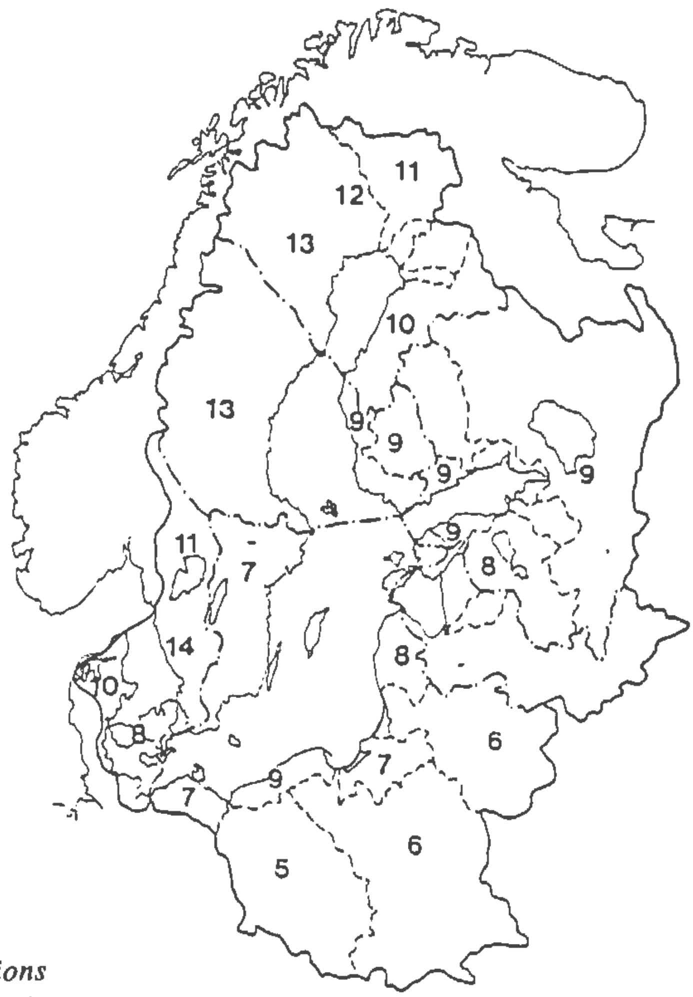


Figure 2.1.
Approximate specific runoff ($l/(s \cdot km^2)$) for different regions of the Baltic Sea drainage basin (Bergström and Carlsson, 1993).

From the hydropower point of view, the favored situation is high precipitation and low evapotranspiration. However, as the temperature during many months of the year is below 0 °C, a great amount of the precipitation over the watershed of the Gulf of Bothnia falls as snow and forms high spring floods. A large quantity of the spring floods can be stored in reservoirs and used for power production during the winter. This results in declined spring flood discharged to the Gulf. The regulation can be very drastic. Figure 2.2 shows examples from the Luleälven river, where one fifth of the hydropower in Sweden is produced, and the river Torneälven, which is a large unregulated river (Bergström and Carlsson, 1993). How the regulation influences the runoff from day to day during two years can be studied in Figure 2.3, also from the river Luleälven.

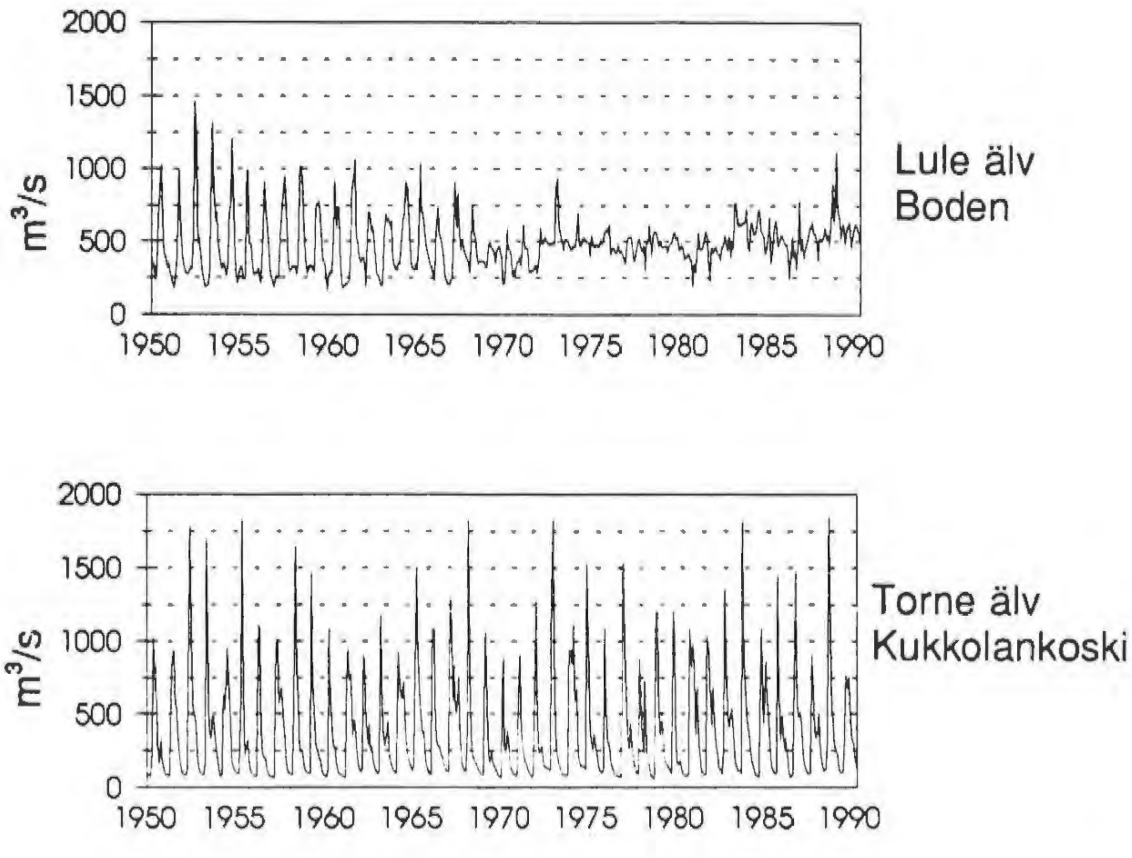


Figure 2.2. *Monthly runoff from one regulated and one unregulated river (Bergström and Carlsson, 1993).*

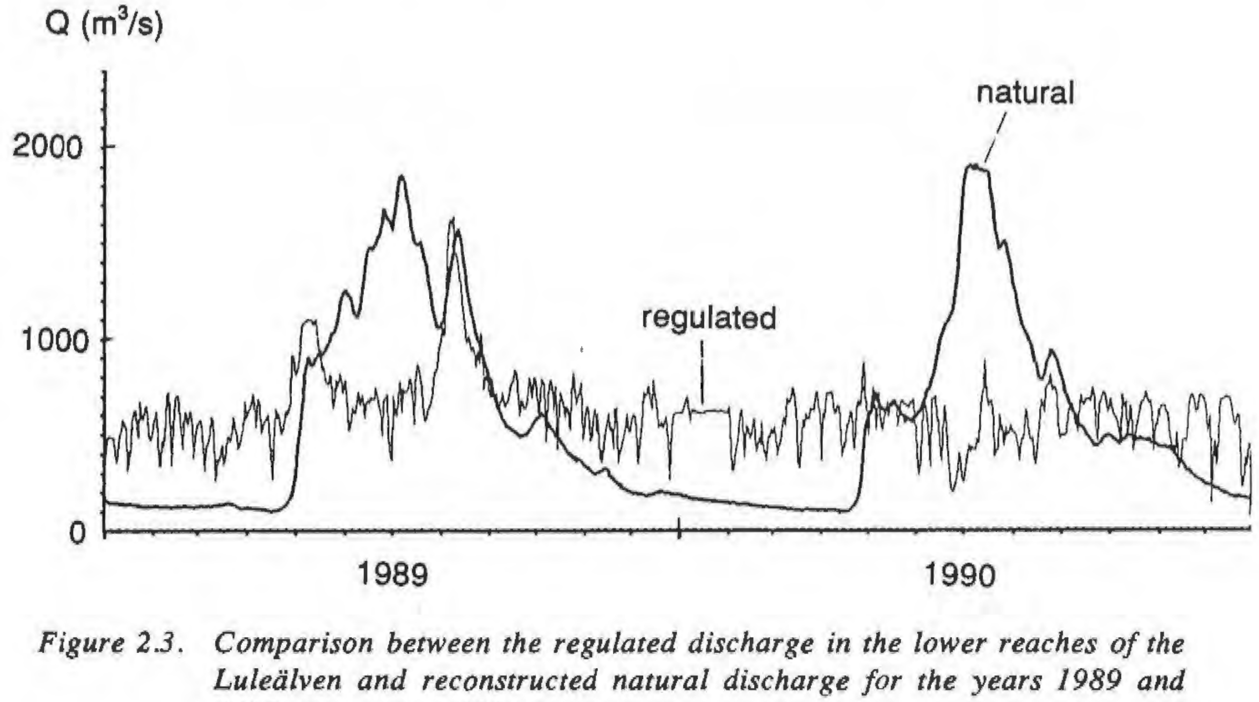


Figure 2.3. *Comparison between the regulated discharge in the lower reaches of the Luleälven and reconstructed natural discharge for the years 1989 and 1990 (Bergström, 1993).*

3. RIVER REGULATION AND HYDROPOWER DEVELOPMENT

Hydropower produces about 50 % of the electricity in Sweden. Almost 90 % of the total hydropower produced electricity in Sweden originates from rivers which discharge into the Gulf of Bothnia. With only four exceptions all the major rivers in Sweden are used for hydropower production. These four are Torneälven, Kalixälven, Piteälven and Vindelälven. Often the lakes in the system are used for storage, but there are also many artificial reservoirs. Some of the Swedish and Finnish rivers are developed to a very high degree. One of these is the Swedish river Ångermanälven. As an example, the hydropower system in this river and its tributaries is shown in Figure 3.1.

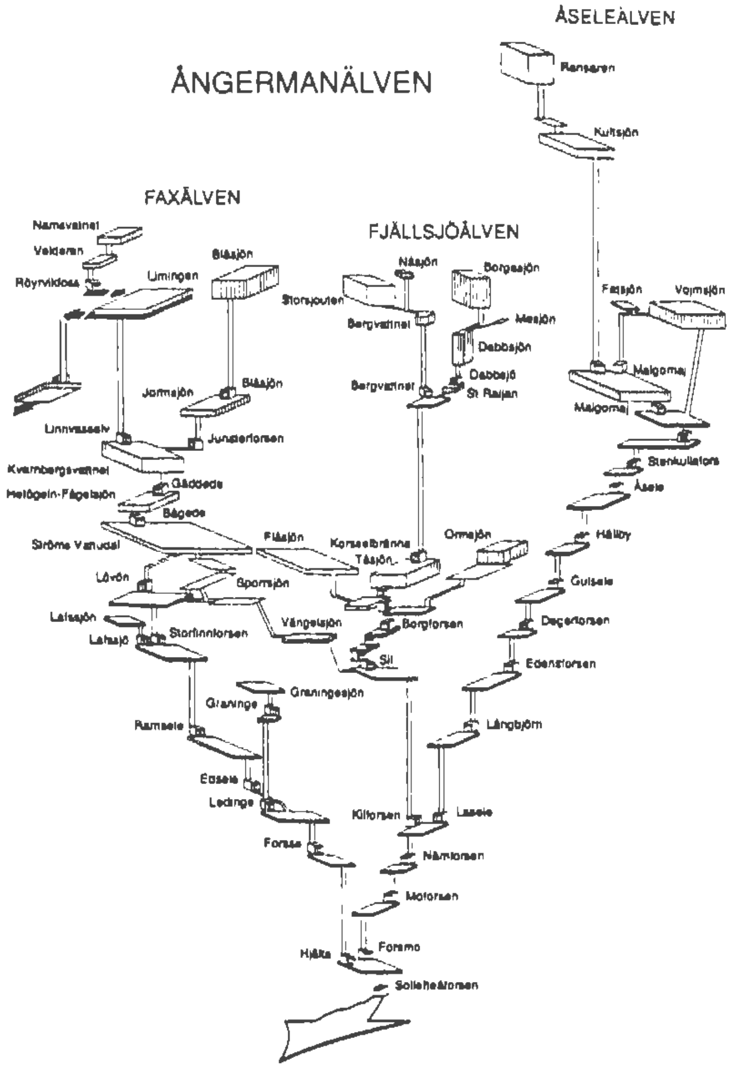


Figure 3.1. Schematic sketch of the hydropower system in the highly regulated river Ångermanälven and its tributaries.  *hydropower plant.*  *reservoir.*

(From Ångermanälven's Regulation Enterprises.)

Table 3.1.1. Large reservoirs in Finland included in this work.

Catchment area	Reservoir	Active storage Mm³	Reservoir area 1981-91	Lake area 1925-36
Finland to the Bothnian Bay				
47 Ähtävänjoki	Lappasjärvi	130	142	142[1)]
54 Pyhäjoki	Pyhäjärvi	137	126	126[1)]
57 Siikajoki	Uljua	151	30	30[1)]
59 Oulujoki	Oulujärvi	2 343	897	897[1)]
	Nuasjärvi	211	94	94[1)]
61 Iijoki	Kostojärvi	233	57	57[1)]
	Irnijärvi	216	62	62[1)]
65 Kemijoki	Kemijärvi	1 070	302	302[1)]
	Suolijärvi	250	111	111[1)]
	Lokka	1 140	417	0[2)]
	Porttipahta	1 097	215	0[2)]
Total		6 978[3)]	2 453	1 821
Finland to the Bothnian Sea				
35 Kokemäenjoki	Tammerkoski	385	257	257[1)]
	Lempäälä	309	172	172[1)]
	Kyräskoski	118	96	96[1)]
	Melo	195	125	125[1)]
	Hartolankoski	59	66	66[1)]
Total		1 066[3)]	716	716[1)]

[1)] Exact figures are missing, we have used the same areas for both periods, i.e. we assumed that the reservoirs have not lead to any large area changes.

[2)] Lokka and Porttipahta consist almost entirely of man made dams.

[3)] The totals cover at least some 80 % of active storage.

Table 3.1.2. Large reservoirs in Sweden included in this work.

Sweden to the Bothnian Bay				
Catchment area	Reservoir	Active storage Mm^3	Reservoir area 1981-91	Lake area 1925-36
9 Luleälven	Sourva	5 900	271	64
	Porjus	632	184	168
	Parki	460	96	83
	Seitevare	1 675	82	8
	Sitasjaure	640	79	68
	Satisjaure	1 260	86	58
	Remaining	386	182	80
9 total (16[1] res.)		**10 953**	**980**	**529**
20 Skellefteälven	Sädvajaure	605	44	29
	Hornavan	750	280	250
	Storavan	780	425	410
	Rebnis	740	70	44
	Remaining	136	124	31
20 total (15[1] res.)		**3 011**	**943**	764
Rest				
Total		**13 964**[2]	**1 923**	**1 293**

[1)] The figure gives the total number of reservoirs counted.
[2)] The totals cover at least some 90 % of the active storage.

Table 3.1.2 cont. Large reservoirs in Sweden included in this work.

Sweden to the Bothnian Sea				
Catchment area	Reservoir	Active storage Mm³	Reservoir area 1981-91	Lake area 1925-36
28 Umeälven	Överuman	357	88	79
	Ajaure	209	51	39
	Gardiken	871	84	32
	Storuman	1 101	186	166
	Storjuktan	577	69	24
	Abelvattnet	398	34	21
	Remaining	178	114	3
28 total (14[1] res.)		**3 691**	**626**	**364**
38 Ångermanälven	Ransaren	414	29	23
	Kultsjön	246	59	53
	Malgomaj	554	105	80
	Blåsjön	490	43	41
	Kvarnbergsvattnet	625	68	67
	Ströms Vattudal	495	183	147
	Borgasjön	249	16	11
	Dabbsjön	337	18	6
	Tåsjön	262	49	45
	Flåsjön	330	114	112
	Storsjouten	290	31	20
	Vojmsjön	594	88	78
	Remaining	648	284	141
38 total (33[1] res.)		**5 534**	**1 087**	**824**
40 Indalsälven	Torrön	1 178	106	94
	Juveln	270	41	36
	Storsjön	1 254	456	456
	Håckren	700	43	14
	Anjan	210	28	26
	Remaining	1 330	430	358
40 total (35[1] res.)		**4 942**	**1 104**	**984**
42 Ljungan	Flåsjön	400	22	7
	Holmsjön	192	54	45
	Holmsjön-Leringen	360	65	58
	Remaining	219	95	77
42 total (7[1] res.)		**1 171**	**236**	**187**
48 Ljusnan	Lossen	500	35	10
	Svegssjön	237	60	0
	Grundsjöarna	240	20	8
	Remaining	567	302	234
48 total (36[1] res.)		**1 544**	**417**	**252**
53 Dalälven	Trängsletdammen	880	38	0
	Siljan	658	353	353
	Amungen	176	60	60
	Remaining	623	333	313
53 total (62[1] res.)		**2 337**	**784**	**726**
Total		**19 219[2]**	**4 254**	**3 337**

The majority of both the Finnish and Swedish hydropower systems were developed after the 1930s. Figure 3.2 shows how the reservoir volume in the three Swedish areas considered in this project increased from 1930. Notice that the volume before 1936 was very small and then rose until about 1980. A summary of data about dams and lakes included in this project is presented in Table 3.1.1 and 3.1.2.

From this table it can be seen that the total volumes of the reservoirs are not of comparable size at the Finnish and Swedish side of the Gulf. On the Swedish side of the Bothnian Bay the total reservoir volume is about 14 000 Mm^3 and that on the Finnish side is about 7 000 Mm^3. On the Finnish side of the Bothnian Sea the volume is only between 1 000 and 2 000 Mm^3 and distributed in several small reservoirs almost all in the Kokemäenjoki river system. On the Swedish side the reservoir volume is 10 - 20 times larger, or approximately 20 000 Mm^3.

In Finland usually large lakes are used as reservoirs, but there are also two very large man-made reservoirs, Lokan tekojärvi and Porttipahdan tekojärvi. The active storage of these two reservoirs is 1 140 and 1 097 Mm^3, respectively. Large lake reservoirs are the lakes Kemijärvi and Oulujärvi with an active storage of about 1 100 Mm^3 and 2 300 Mm^3 respectively. Together these four reservoir systems just mentioned represent some 5 600 Mm^3 or c. 70 % of the total regulated volume in Finland.

The Finnish reservoirs included in this work represent all together at least some 80 % of the total active storage within the Finnish Gulf of Bothnia watershed. For Sweden the corresponding figure is more than 90 %.

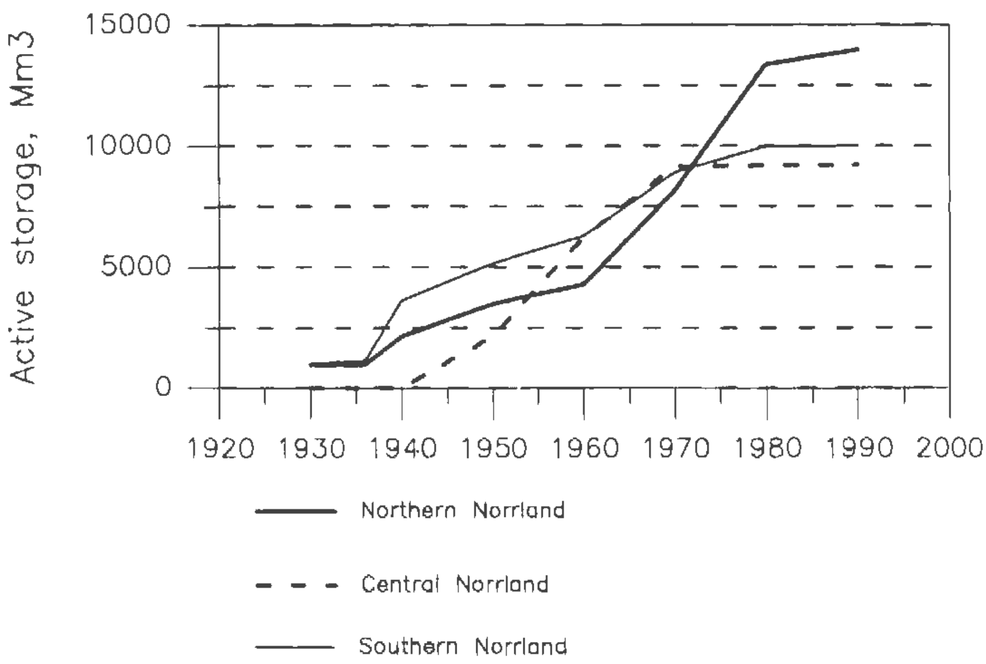
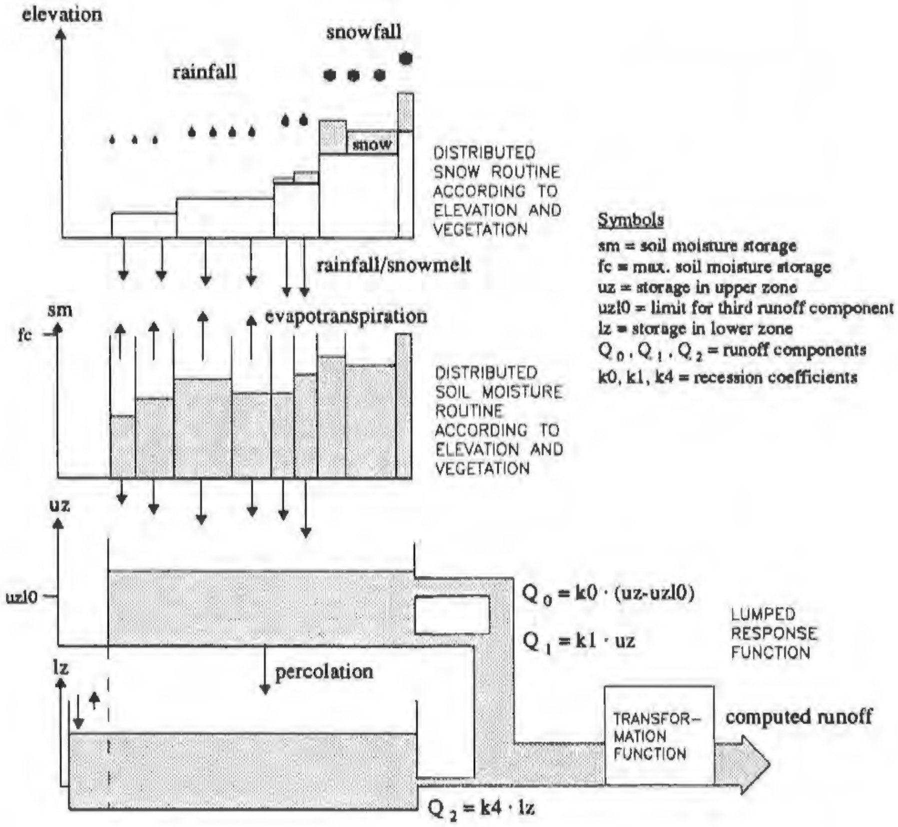


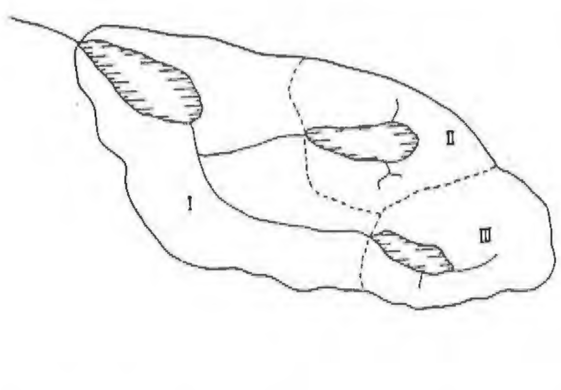
Figure 3.2. Reservoir development in northern Sweden. Volume of active storage.

4. THE MODEL

The model used in this project is a conceptual model essentially based on the earlier HBV and PULS models (Bergström, 1976; Bergström et al., 1985; Carlsson et al., 1987; Bergström, 1992 a; Bergström, 1992 b). It is included in a PC-based system called IHMS (Integrated Hydrological Model System).

Simulations are made for a main watershed, which can be split up into subbasins with lakes or reservoirs. For every basin the geographical data needed are: percentages of forest, field and lake, and elevation zones. The structure of the HBV model is shown in Figure 4.1.





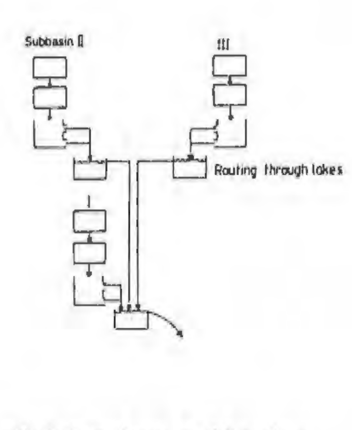


Figure 4.1. Model structure of the HBV model and the division into subbasins.

The model is run with daily values of rainfall and air temperature, and monthly values of potential evapotranspiration. There are routines for snow accumulation and melt, soil moisture accounting, runoff generation, regulation and routing. When the soil moisture is below a given soil moisture deficit, the actual evapotranspiration will be reduced.

In Chapter 7.4 of this report the effects of a hypothetical temperature change is simulated. For this reason a modification of the model with more realistic evapotranspiration routines than in the original model is introduced (Lindström et al., 1994). This routine accounts for temperature anomalies by a correction which is based on mean daily air temperatures and long term averages.

In the snow routine of the model it is decided whether the precipitation falls as snow or rain. The snowmelt occurs according to the day-degree method and the routine generates daily portions of water for the soil moisture routine.

The soil moisture routine treats the zone between the soil surface and the ground water surface. Some part of the water is returned to the atmosphere by evapotranspiration. The runoff generation, the response function, passes the water on to the lake and/or regulation routine. On its way there it passes the transformation routine. This is a triangular weighting function. There is also an option of using a Muskingum routing routine for modelling the damping of a generated flood pulse.

If there is a lake or reservoir at the end of the flow, its characteristics can be described either by a rating curve, or e.g. from a regulation routine.

The calibration of the model can be made by a manual trial and error technique, during which relevant parameter values are changed until acceptable agreement with observation is obtained. The judgement of the performance is also supported by a statistical criterion, usually called the R^2 value according to Nash and Sutcliffe (1970).

$$R^2 = \frac{\Sigma\left(Q_0 - \overline{Q_0}\right)^2 - \Sigma\left(Q - Q_0\right)^2}{\Sigma\left(Q_0 - \overline{Q_0}\right)^2}$$

where Q_0 = observed runoff,
$\overline{Q}_0$ = mean of observed runoff,
Q = computed runoff.

R^2 can vary between +1 and $-\infty$, where 1 is the perfect accordance. If the R^2 value lies around 0.80 and more, the agreement with observations is very good.

For the calibration of the model in this work we used both manual calibration and an automatic calibration procedure (Harlin, 1992).

The outputs from the model are daily values of runoff as well as areal means of temperature, precipitation, snow, evapotranspiration, soil moisture etc.

5. THE SIMULATION STRATEGIES

The main purpose of this work is to compare runoff at regulated and unregulated conditions from the watershed of the Gulf of Bothnia. All the simulations are made with daily data, but the results are mostly averaged into monthly and annual means. This procedure reduces the influence of the daily errors and gives a better overview. In this chapter the strategies and some results on daily basis are described. Results on monthly and annual basis are described in Chapter 7.

According to the model description above the whole catchment area of the Gulf of Bothnia was first divided into a number of subareas. Besides the separation of the runoff contributions to the Bothnian Bay and the Bothnian Sea, the boundaries between the areas have been selected so that regulated areas are separated from unregulated ones. Some areas will therefore contain reservoirs and others will not. In the areas with one or more reservoirs, the inflow to each of these is calculated on the basis of measured runoff and measured water level changes in the reservoirs. The model was calibrated against the discharge from the unregulated subcatchments and against the total inflow in the regulated ones.

The division includes 5 major areas with coastline, and about 25 smaller areas which are merged to 15 as shown on the map and the principle sketch in Figures 5.1 and 5.2.

To be able to calculate the influence of regulation on the total water supply to the Gulf of Bothnia, one must make model calibrations for a period when no hydropower development was yet made. Both in Sweden and Finland the largest development took place after the middle of the 1930s. The selected unregulated calibration period was 1925-36.

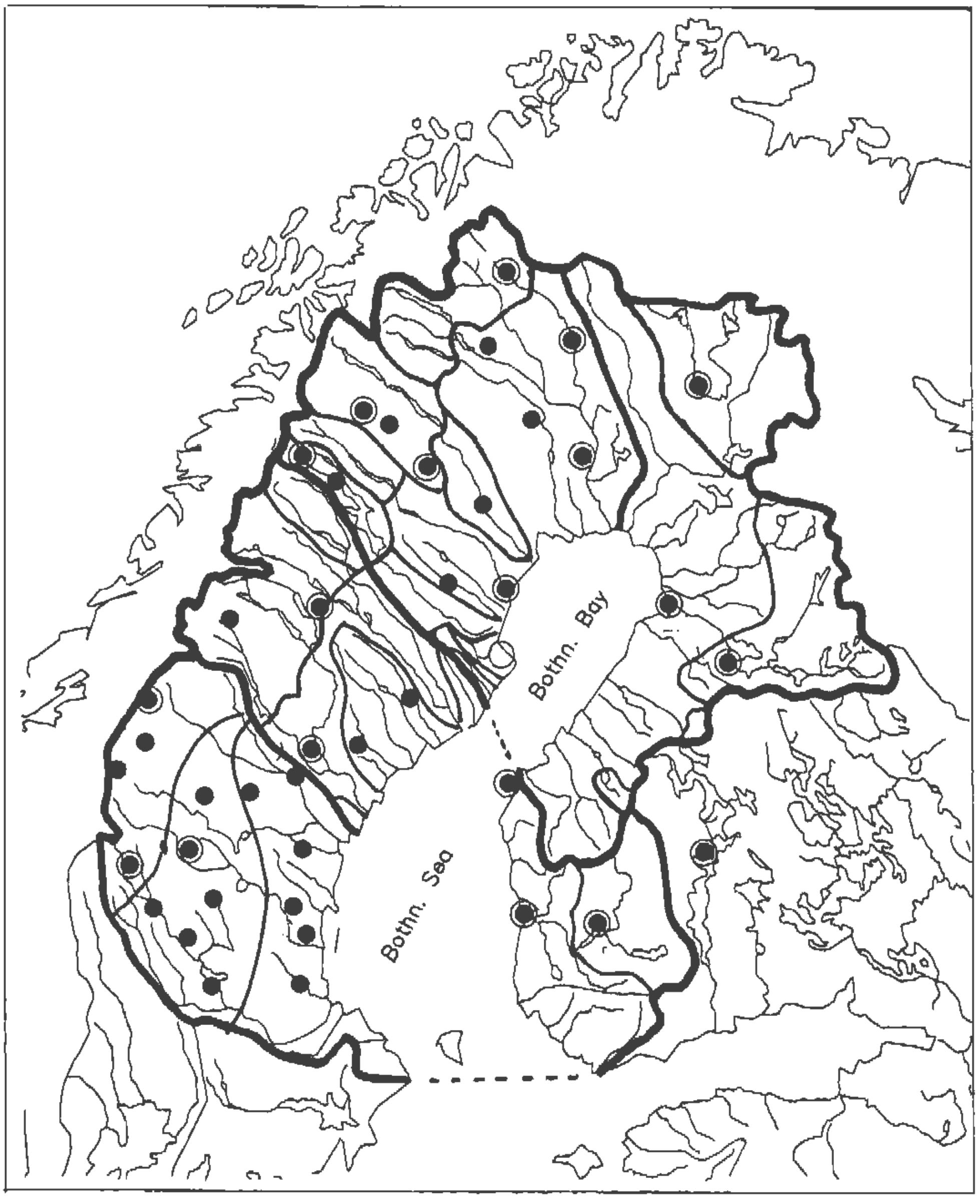
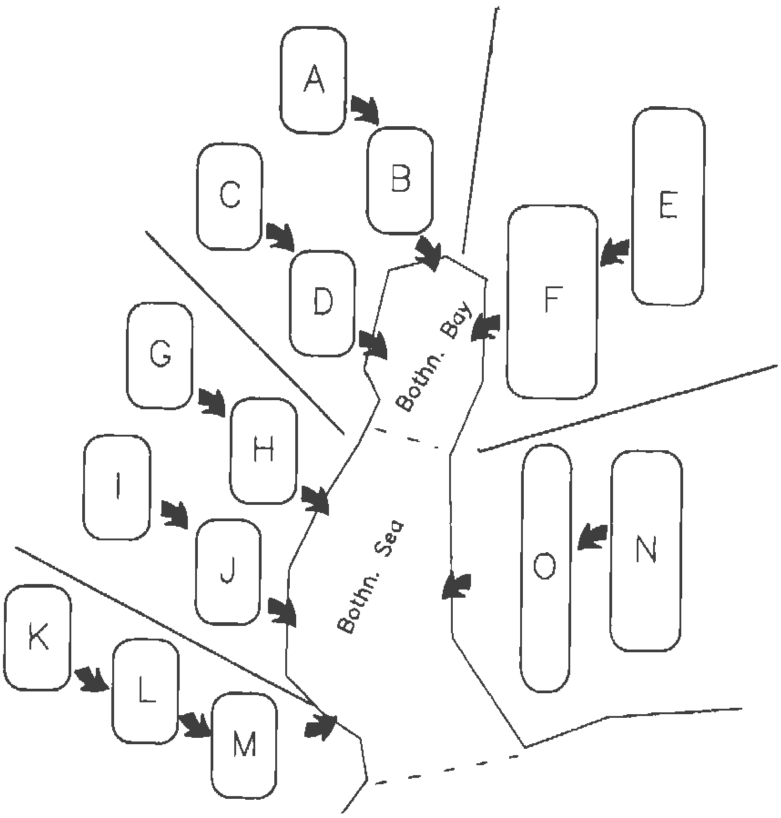


Figure 5.1. The drainage basin of the Gulf of Bothnia and the division into subbasins.
O = temperature station, ● = precipitation station.



Subbasin	Area (km²)	Reservoir (Mm³)
A Northern Norrland, unregulated mountain watersheds	24 491	
B Northern Norrland, unregulated forest watersheds	65 977	
C Northern Norrland, regulated mountain watersheds	23 115	13 539
D Northern Norrland, regulated forest watersheds	15 540	425
E Northern Finland, regulated forest watersheds	55 920	6 978
F Northern Finland, unregulated coast watersheds	76 260	
Sum A - F (The Bothnian Bay)	**261 303**	**20 942**
G Central Norrland, unregulated mountain watersheds	6 056	
H Central Norrland, unregulated forest watersheds	23 968	
I Central Norrland, regulated mountain watersheds	25 663	8 956
J Central Norrland, regulated forest watersheds	21 559	269
K Southern Norrland, regulated mountain watersheds	23 136	5 697
L Southern Norrland, regulated forest watersheds	25 813	2 076
M Southern Norrland, regulated coast watersheds	55 867	2 221
N Southern Finland, regulated forest	21 475	1 066
O Southern Finland, unregulated coast	29 200	
Total G - O (The Bothnian Sea)	**232 737**	**20 285**

Figure 5.2 The Gulf of Bothnia model structure and the approximate sizes of subbasins and reservoirs

The model was first calibrated for the period 1980-91 against the inflow to the power plant reservoirs and the unregulated runoff to the Bothnian Sea. As no reservoirs were included in this calibration, the model parameters also are valid for the period 1925-36. Figure 5.3 shows an extract from a calibration from southern Norrland in Sweden for the period 1980-91. A measure of the agreement of the simulated curve to the measured one is the above-mentioned R^2 value. In this simulation we found an R^2 value of 0.82.

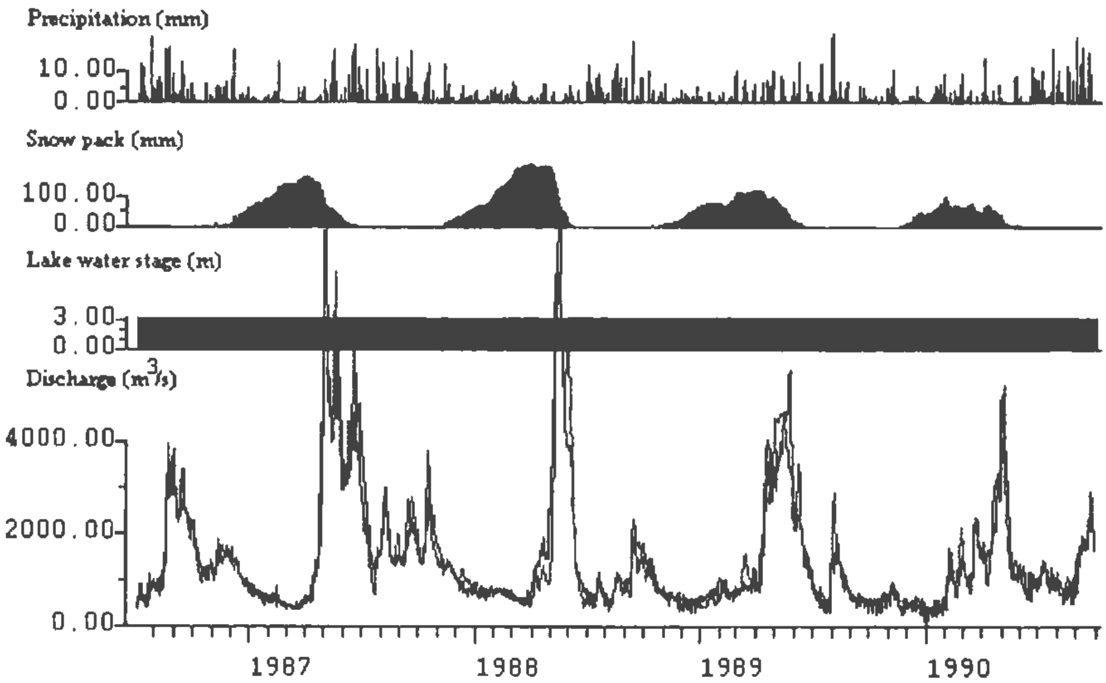


Figure 5.3 *Calibration of the model parameters against inflow to the reservoirs and unregulated runoff to the sea. Sweden, southern Norrland. Notice that the water stage is the same all the time as there are no lakes included in the simulation. Thin line is recorded discharge. Thick line is simulated discharge.*

The next step was to include the lake discharge parameters of the model in the calibrations. This can be done against data of an unregulated period. Therefore the model was run against the almost completely unregulated period 1925-36. As the reservoir areas nowadays and the areas of the original lake before the regulation are not the same, the areas of the original lakes were included and the lake discharge parameters of the model were calibrated. Figure 5.4 shows an extract from this calibration run. The R^2 value here is 0.83.

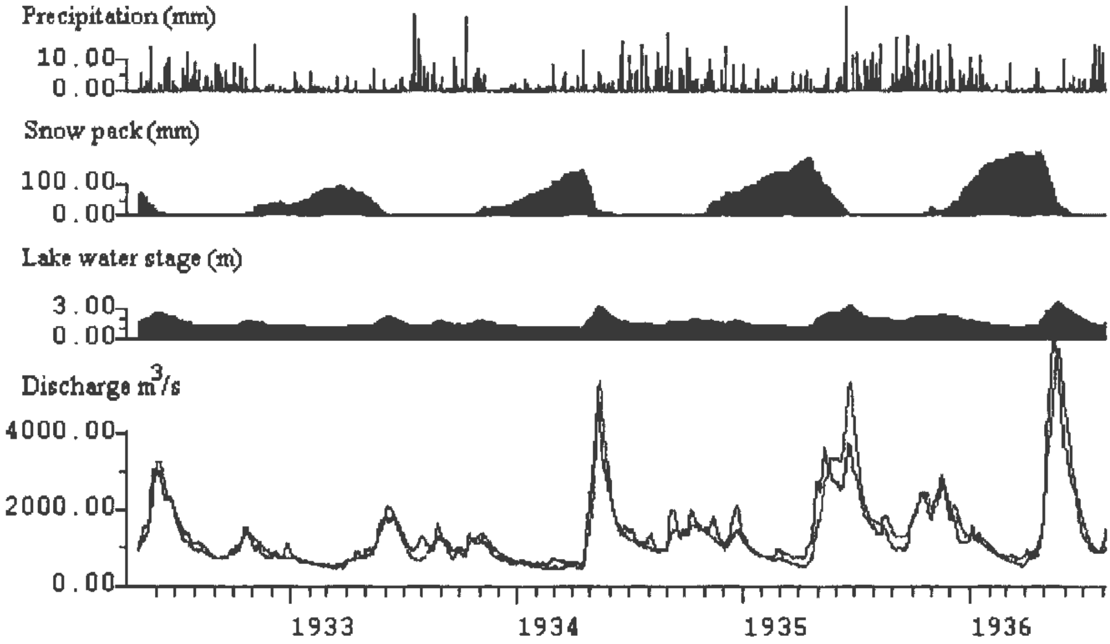


Figure 5.4. Calibration of the lake discharge parameters. Sweden, southern Norrland. Thin line is recorded discharge. Thick line is simulated discharge.

After these calibrations it is possible to simulate natural runoff in current time as if the regulations did not exist, and to compare with regulated conditions. Figure 5.5 gives an example from the same area as seen in Figures 5.3 - 4.

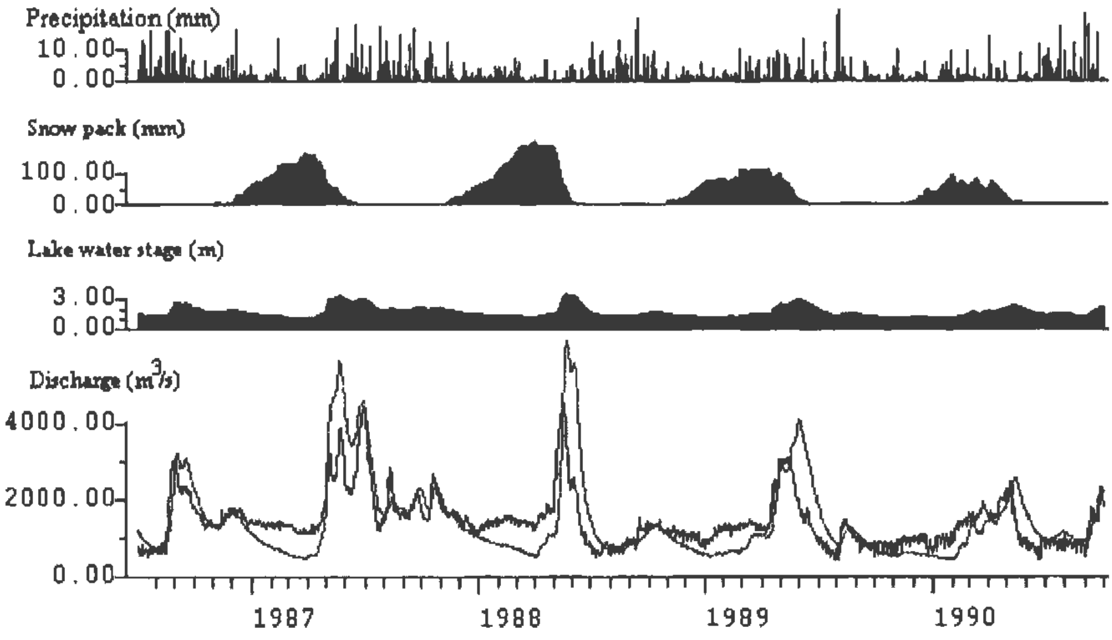


Figure 5.5. Simulated natural and recorded regulated runoff from southern Norrland in Sweden. Thin line is recorded discharge. Thick line is simulated discharge.

A measure of the model performance can be accomplished by means of a verification run, i.e. by simulating a period that was not used in the calibration. Figure 5.6 shows the results from a simulation for 1925-36 of the unregulated areas of the mountain region of central Norrland (G) with model parameters found for the period 1981-91. Some adjustment of the precipitation depth was made, as this obviously was incorrect for the period 1925-36. Visually, the curves show a good fit, and the R^2 value is high, 0.81. This result must be regarded as very good.

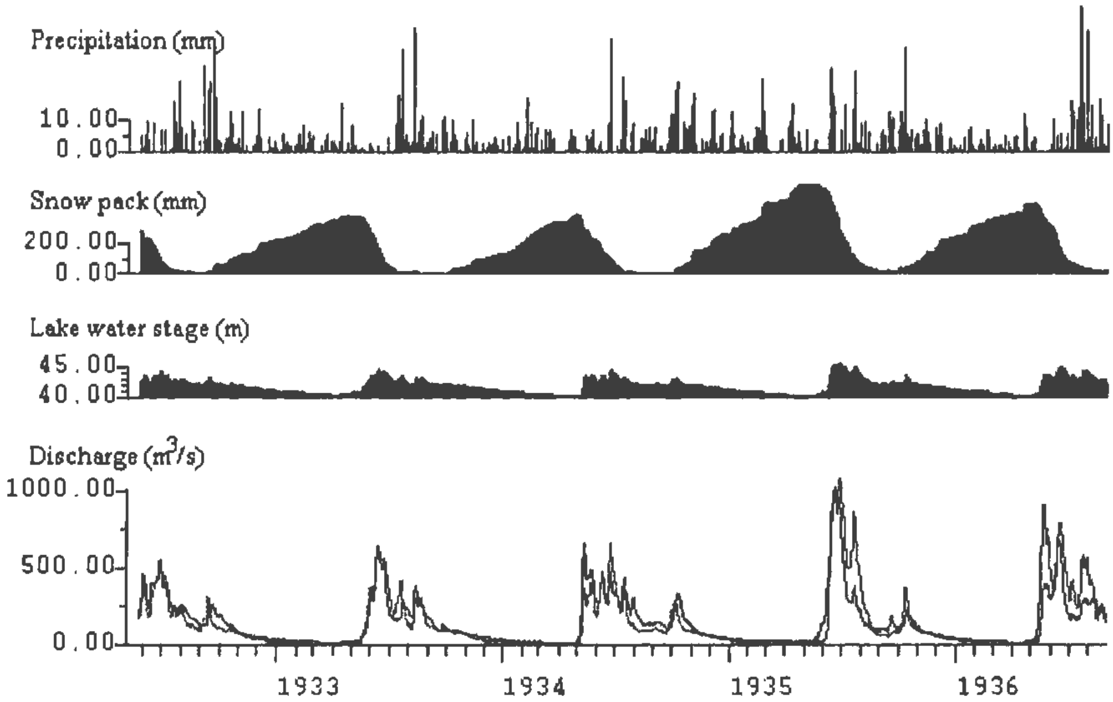


Figure 5.6. *Simulated natural and recorded unregulated runoff from the mountain region of central Norrland (G), 1925-36. Thin line is recorded discharge. Thick line is simulated discharge.*

6. DATA BASE

Sweden and Finland are covered by a large number of precipitation and temperature stations. There are synoptic stations, where registrations are made several times a day, i.e. with three hours' interval, as well as climate stations with registration once or twice a day. Both these kinds of stations were used in this work. For the simulations of the runoff from the Swedish side of the Gulf of Bothnia 33 precipitation and 12 temperature stations were used. Precipitation and temperature data from 11 stations were included in the runoff simulations for the Finnish side. In spite of the fact that it has limited the selection of stations, one criterion has been that all stations ought to have been in operation during both simulated periods 1925-36 and 1980-91. Potential evapotranspiration is also included in the model in the form of monthly mean values. For Sweden calculated values (Eriksson, 1981) and for Finland Class A pan measurements were used.

The precipitation and temperature stations used are marked in the map in Figure 5.1.

Present topographic data such as land areas, altitude zones, lake areas and drainage divides regarding Sweden were obtained from SMHI's data base SVAR (SMHI, 1993). Historic lake areas were taken from older SMHI data (De svenska vattendragens arealförhållanden 1910 - 1950). Finnish data were obtained from Finnish hydropower companies (Finnish Power Companies), Hydrological Yearbook 1990 or calculated from the topographic map.

The runoff to the Swedish coast was calculated by SMHI with data from all available gauging stations. Calculations are now available from 1925 and further.

The runoff to the Finnish coast from the period 1981-91 was calculated by means of 22 gauging stations situated near the coast in the same way as in Bergström and Carlsson, (1993). 12 of these were used for the calculation of runoff to the Bothnian Bay. During the period 1925-36 only eight of the 22 stations were in operation, of which six were at the Bay of Bothnia. Comparative calculations for the period 1981-91 show that the reduction from 12 to 6 stations gave quite acceptable runoff calculations from the Bothnian Bay, whereas the reduction from 10 to 2 stations were not sufficient to indicate the runoff to the Bothnian Sea. Lake discharge parameters from northern Finland were therefore used for the forest region of southern Finland. As the runoff from this southern region is comparatively small, this is of no practical consequence on the basin level.

The inflows to the power plant reservoirs were calculated on the basis of registered runoff and water levels in the reservoirs. Tables 3.1.1 - 2 show a compilation of the reservoirs included and their active storage volume. Such data as discharges, water levels, maximum pool elevations, discharge curves etc. were obtained from the different power companies in Sweden and Finland, from SMHI in Sweden and from the National Board of Waters and the Environment in Finland.

7. RESULTS

7.1 Monthly inflow to the Gulf of Bothnia 1981-91

In Figures 7.1 - 6 one can follow the monthly runoff to the Bothnian Bay, the Bothnian Sea, and to the total Gulf of Bothnia throughout the years 1981 to 1991. The scale is the same in the first four figures. Notice the low discharges from Finland to the Bothnian Sea where the annual mean discharge is in the order of 500 - 600 m^3/s. The discharge from Sweden to the Bothnian Sea is in the order of 2 600 - 2 700 m^3/s. From both Sweden and Finland to the Bothnian Bay it is in the order of 1 500 m^3/s to 2 000 m^3/s. The regulation of the flow from Finland to the Bothnian Sea must then be of little importance for the Gulf of Bothnia as a whole, but of course, the influence on the costal area outside the mouth of river Kokemäenjoki may be significant.

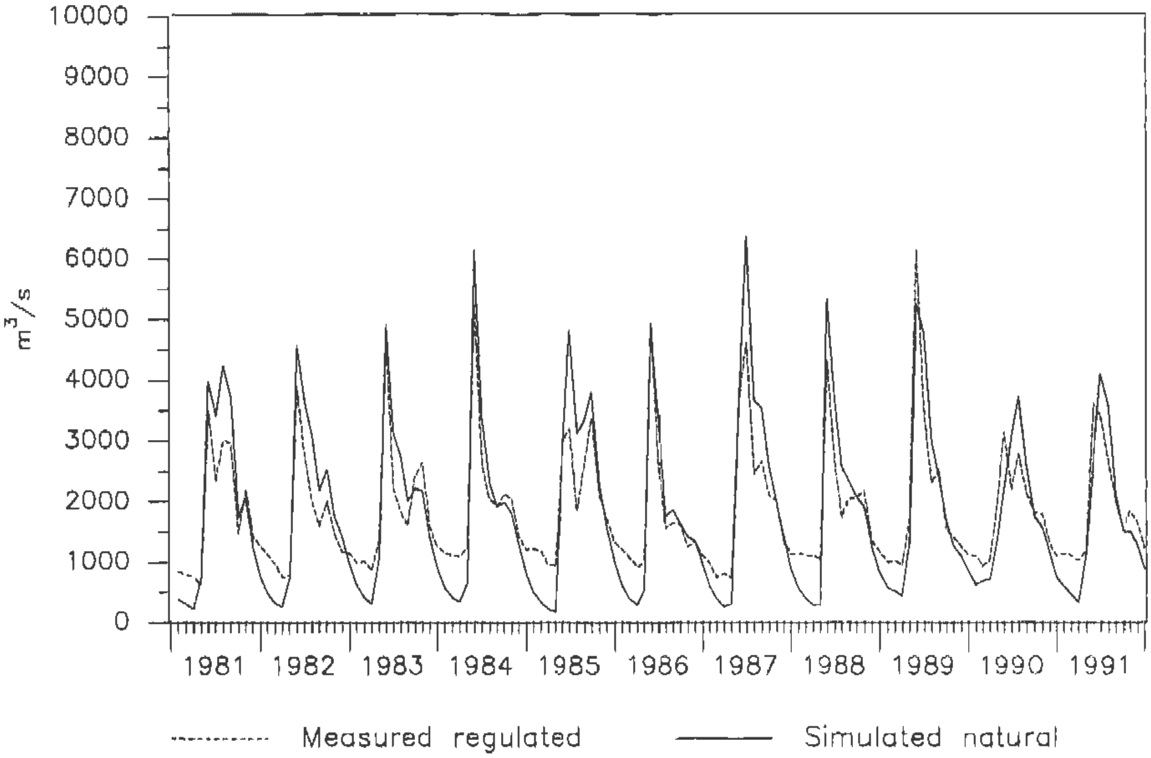


Figure 7.1. ***Simulated natural and measured regulated discharge from Sweden to the Bothnian Bay.***

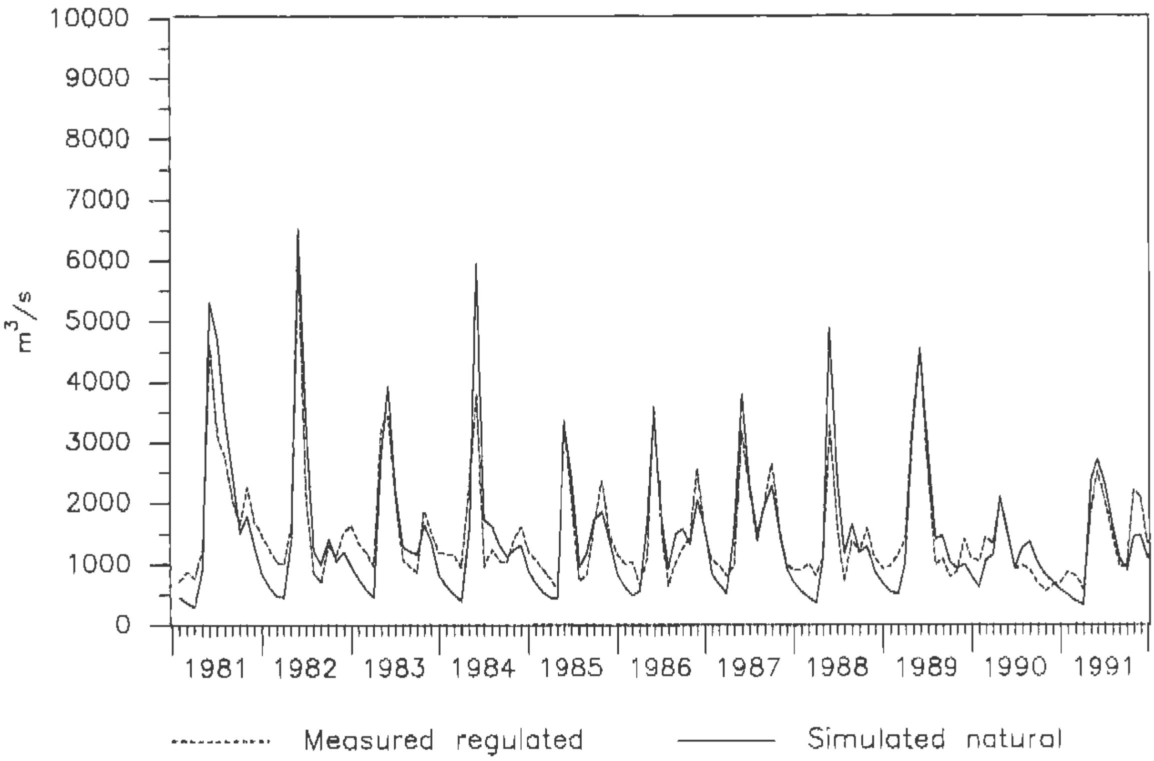


Figure 7.2. ***Simulated natural and measured regulated discharge from Finland to the Bothnian Bay.***

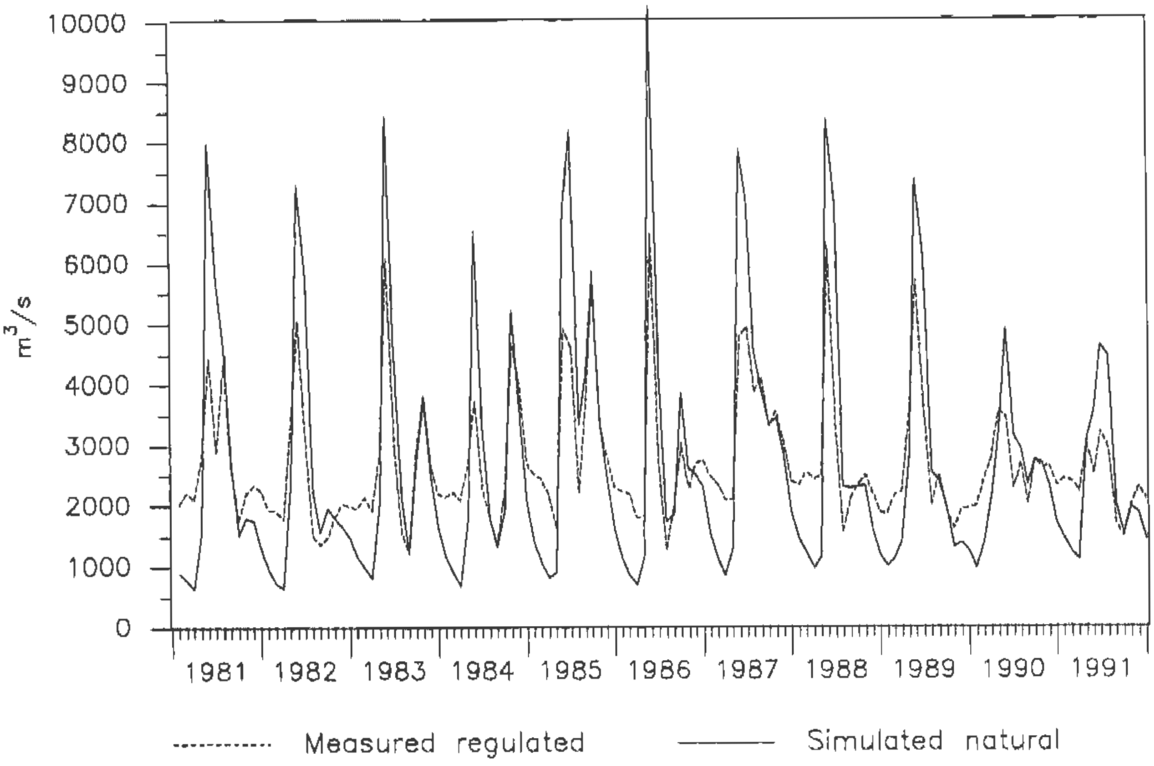


Figure 7.3. ***Simulated natural and measured regulated discharge from Sweden to the Bothnian Sea.***

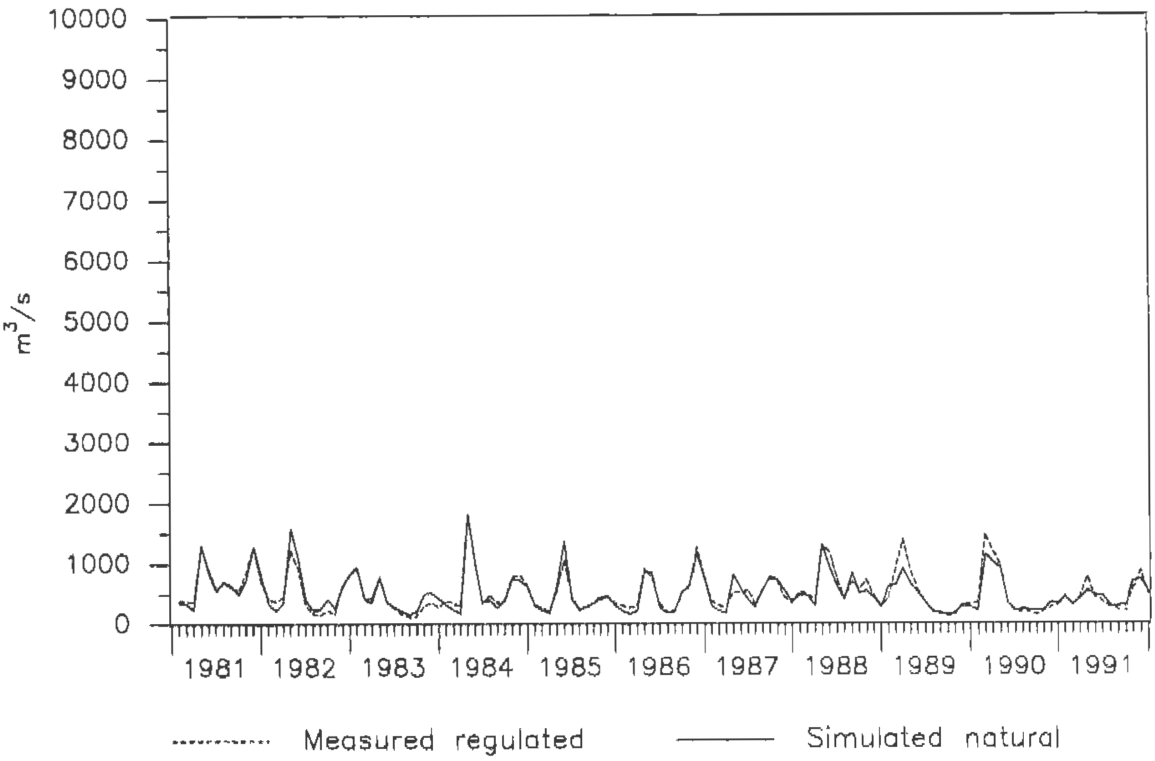


Figure 7.4. ***Simulated natural and measured discharge from Finland to the Bothnian Sea.***

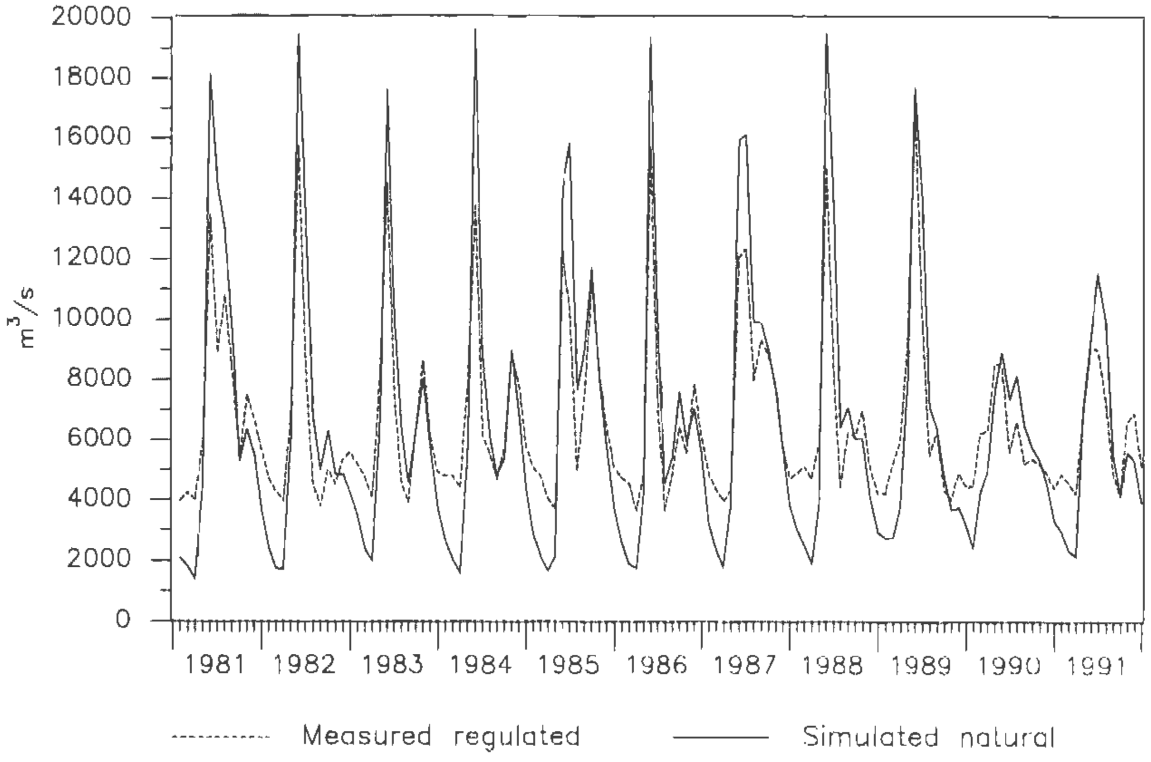


Figure 7.5. *Simulated natural and measured regulated discharge from Sweden and Finland to the Gulf of Bothnia.*

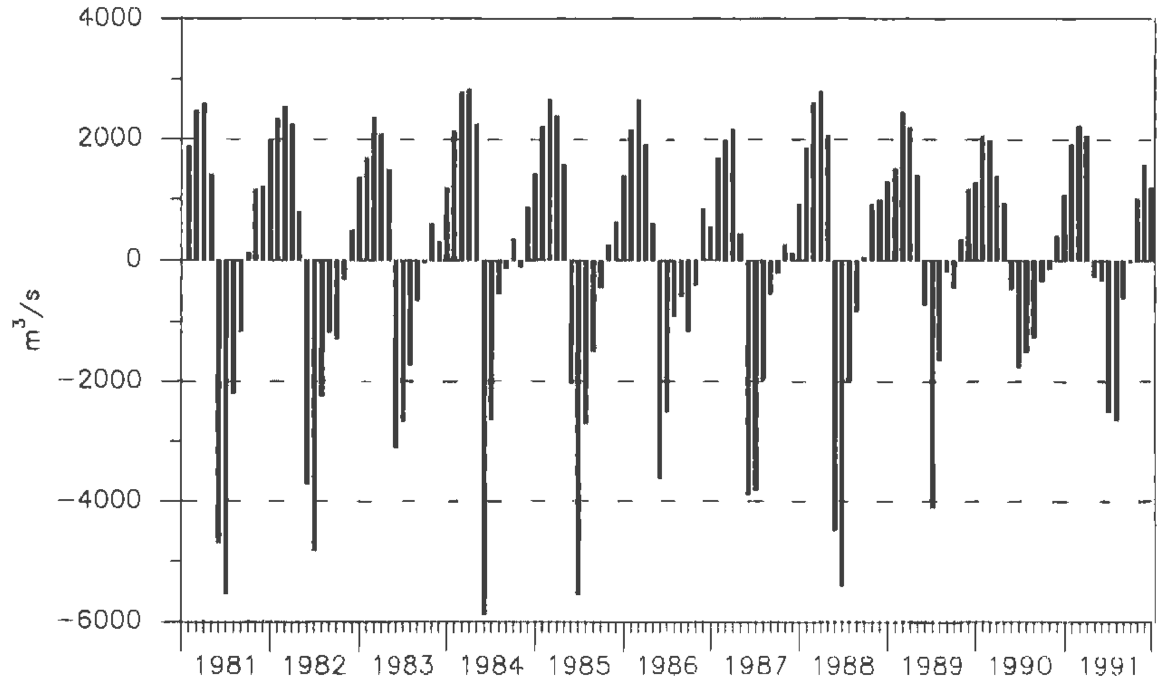


Figure 7.6. *Monthly means of measured regulated discharge minus simulated natural discharge to total Gulf of Bothnia from Sweden and Finland 1981-91.*

Figures 7.1 - 3 and 7.5 show the characteristic differences between natural and regulated flow, i.e. a higher flow in wintertime and a decreased flow in springtime. The regulated discharge in the winter is about twice as large as that of the natural discharge. The greatest difference between natural and regulated spring floods occurs in the runoff from Sweden to the Bothnian Sea. The differences are in the order of 2 000 to 3 000 m^3/s. From the Finnish side of the Bothnian Sea (Figure 7.4) the influence of regulation as a whole is very small.

The retention of the spring flood by stream regulation is not as pronounced in the Bothnian Bay as in the Bothnian Sea. During one year, 1989, the regulated spring flood was even higher than the simulated natural flow, both from the Finnish and the Swedish sides of the bay.

Figures 7.5 and 7.6 present the total regulated and simulated natural runoff to the Gulf. Notice that the scale on the x axis is doubled in Figure 7.5 compared to Figures 7.1 - 4. For all years we can see that the spring peak flood has decreased by stream regulation and that there is an increased flow during wintertime.

The monthly magnitudes of the redistributed flows are shown in Figure 7.6. The size of the redistribution was on the average 1 700 m^3/s, but the maximum redistributed monthly flow reached 5 000 - 6 000 m^3/s in May or June for many years. This is the same value as the total mean runoff to the whole of the Gulf of Bothnia.

7.2 Highly regulated areas

Some of the areas within the watershed of the Gulf of Bothnia are regulated to a very high degree. To show the effect of this regulation, two of these areas were examined. The areas chosen are denoted as C and E on the map in Figure 5.2. The degree of regulation, i.e. how much of an annual inflow to a reservoir can be stored, is very high in the Swedish area C, where one of the largest Swedish reservoirs, Suorva, is situated. The area C represents all regulated areas in northern Norrland. The degree of regulation here is almost 90 %. In the Finnish area E it is just below 40 %.

The monthly bars in Figure 7.7, representing C, show that during springtime, when there normally is a spring flood, there is instead a decline in the runoff. At snowmelt in June the runoff is reduced from approximately 1 400 m^3/s to approximately 400 m^3/s, and during wintertime, runoff has risen to approximately 600 m^3/s from natural levels of 100 - 200 m^3/s. The tendency is the same in the Finnish area E (Figure 7.8) but not as pronounced as in C, as the regulation effect here is smoothed by unregulated areas upstream lake Kemijärvi.

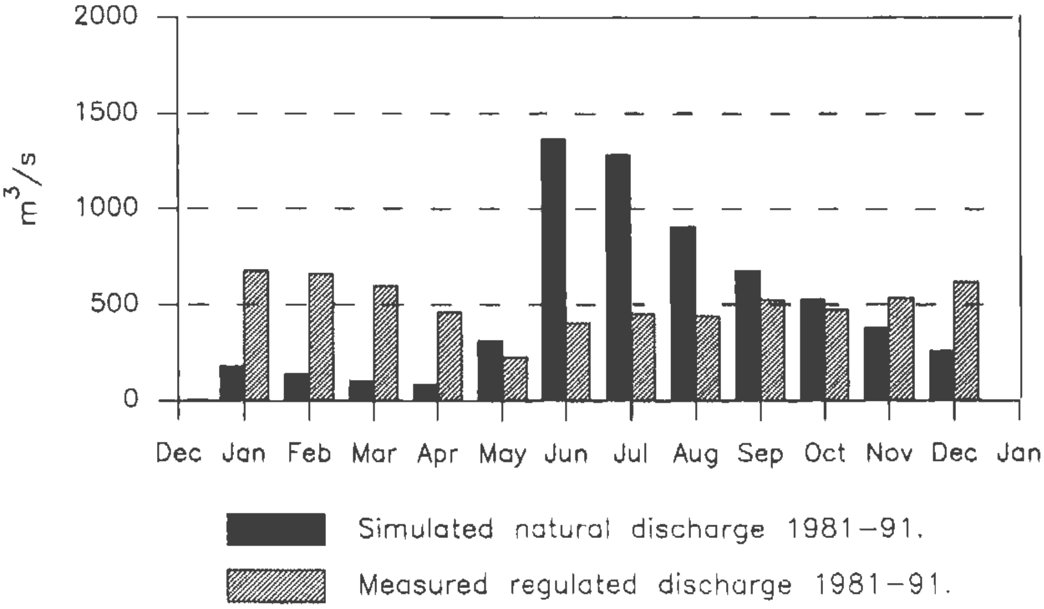


Figure 7.7. ***Simulated natural and measured regulated discharges from northern Sweden 1981-91, regulated area C.***

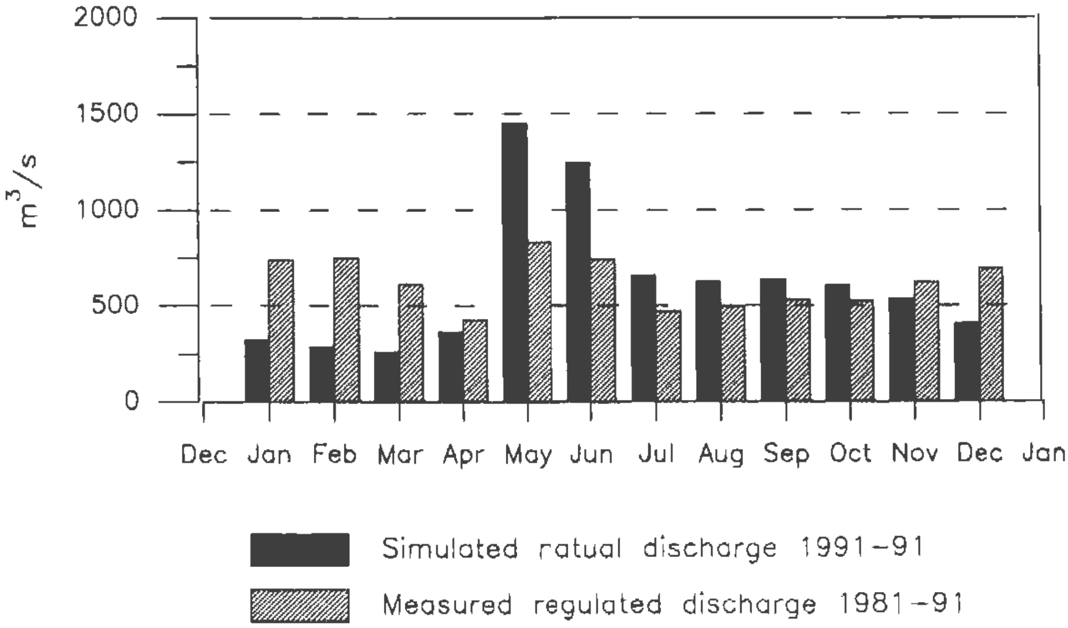


Figure 7.8. ***Simulated and measured regulated discharges from northern Finland, 1981-91, regulated area [illegible].***

7.3. The Gulf of Bothnia year 1991 compared with the period 1981-91

The annual mean runoff in 1991 was c. 6 000 m^3/s (Figure 7.9). This is somewhat less than the average for the examined period. But the examined period was on the contrary somewhat wetter than the average 1920-90 (Bergström and Carlsson, 1993). One reason why the registered and simulated values for individual years are not the same is that the reservoirs were not filled up to the same level on January 1st every year.

From Figure 7.10 we can see that during winter, when the need for electricity determines the reservoir discharges, the flow was at quite the same level in 1991 as the average. The annual average discharge, somewhat lower as noticed above, originated from low spring and summer runoff. In May 1991 the runoff was about 9 000 m^3/s, which is 4 000 - 5 000 m^3/s below the regulated average of 13 000 - 14 000 m^3/s. The difference between 1991 and the average of 1981-91 in simulated natural runoff in May was in the order of 7 000 m^3/s.

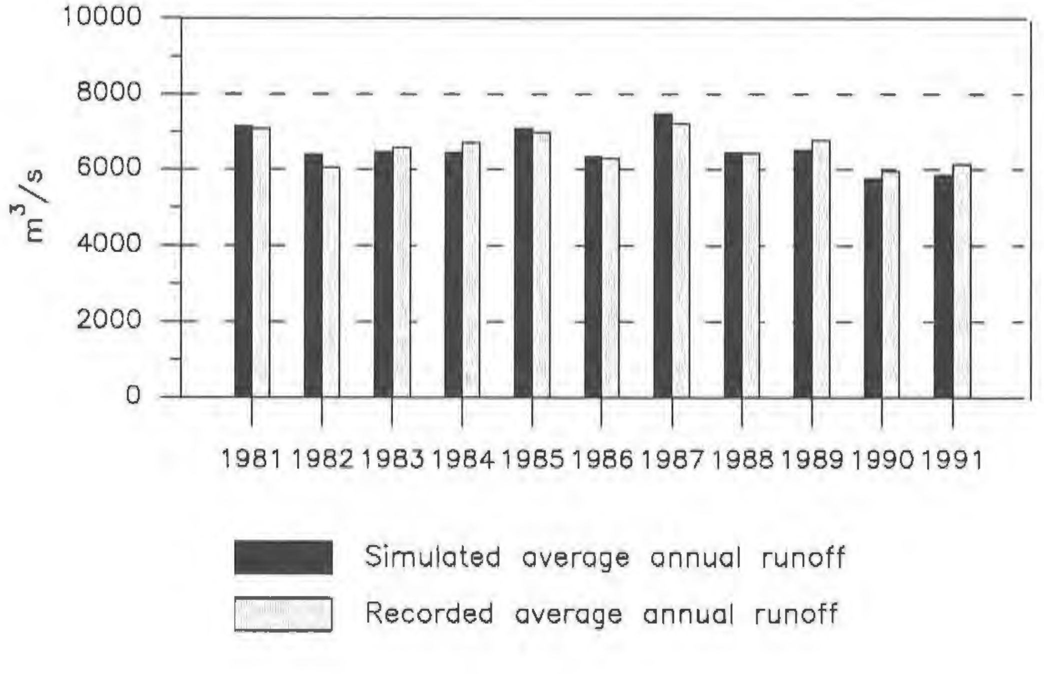


Figure 7.9. Annual simulated natural and measured regulated total discharge to the Gulf of Bothnia.

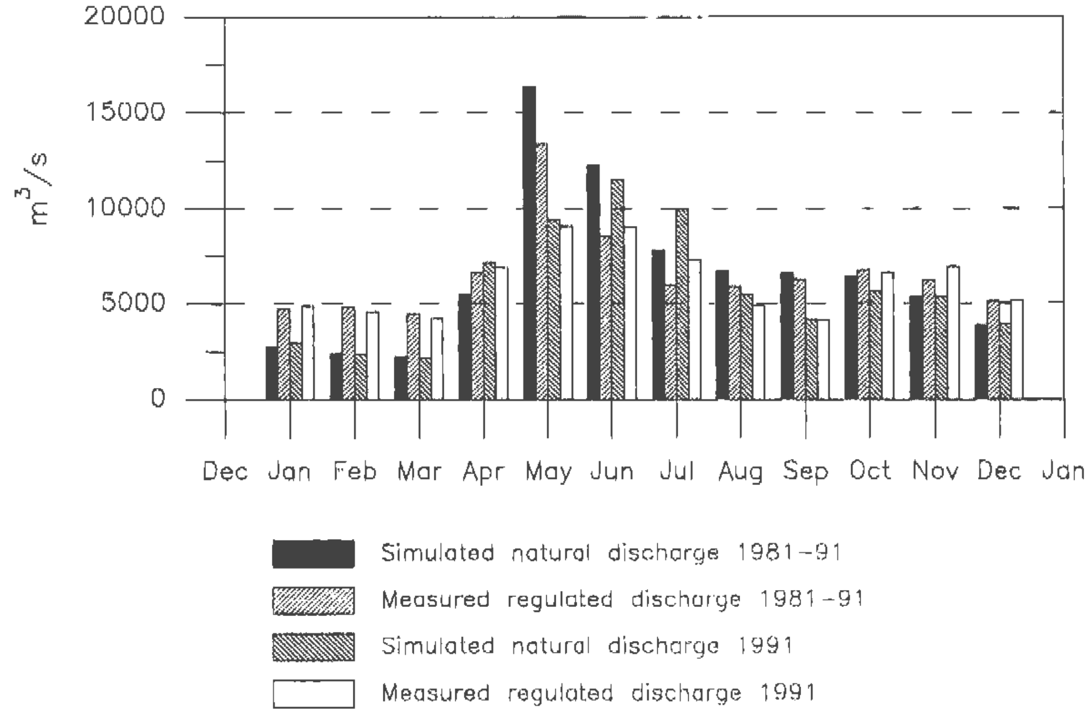


Figure 7.10. Monthly simulated natural and measured regulated total discharge to the Gulf of Bothnia.

7.4 Simulation of the effect of a hypothetical climate change

River regulation has the greatest man-made influence on runoff so far in the area. Now, there is a discussion going on about a possible climate change and its consequences. With the modelling technique it is possible to give a rough estimate of what would happen if the temperature decreased or increased (Lindström et al., 1994). In these simulations we assume that the precipitation pattern and volume are unchanged. We also assume that the vegetation is similar to that of the present situation.

At an international workshop in Finland in 1993 (Academy of Finland, 1993), it was recommended to test a temperature rise of 3 °C in Scandinavia. Figures 7.11 shows simulations of unregulated conditions with the following temperatures: *actual temperature minus 3 °C*, *actual measured temperature* and *actual temperature plus 3 °C*. The simulations are made for the total runoff to the Gulf of Bothnia.

The results suggest that a decrease in temperature would result in both more snow instead of rain and for a longer period of the year, and in a spring flood that will occur later in the season. During the summer, the total discharge becomes higher than normal because of less evapotranspiration than normal. The total annual runoff would increase.

A temperature rise would result in lower runoff during summer because of higher evapotranspiration. During wintertime, the higher temperature would result in less snow, and thus more runoff. The total annual runoff will decrease.

The overall annual mean discharge to the Gulf of Bothnia for the three simulated cases were 8 000 m^3/s, 6 500 m^3/s and 5 400 m^3/s respectively. Note that the simulated temperature changes resulted in runoff volumes that were roughly plus or minus 1.2 times the normal average case.

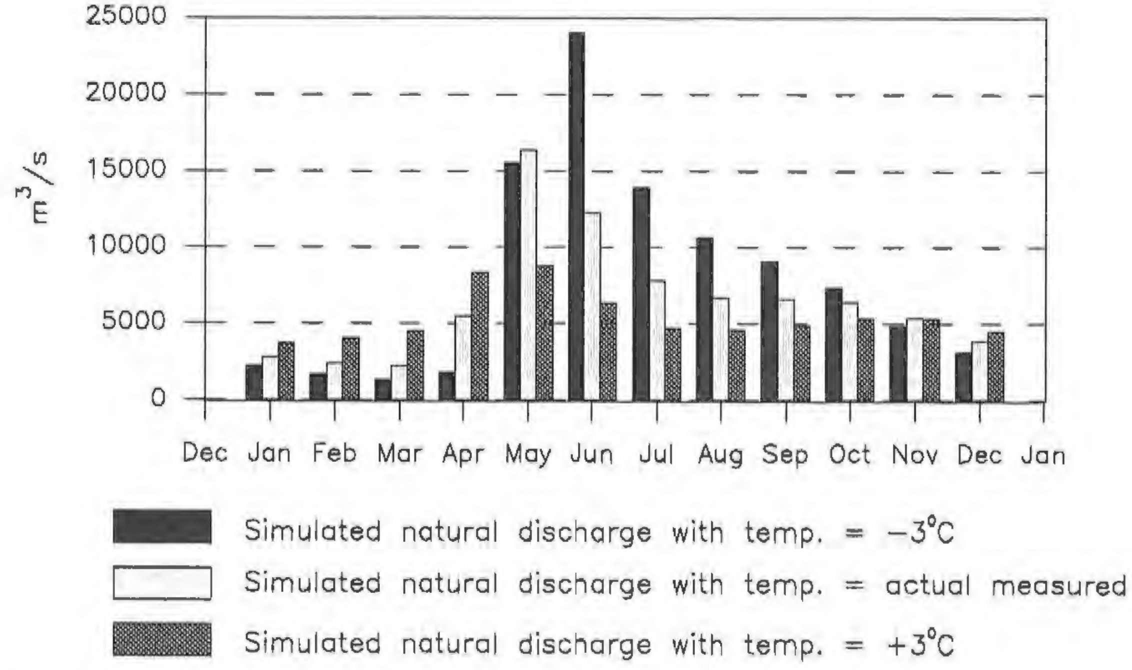


Figure 7.11. Simulated natural discharge at three different temperatures from Sweden and Finland to the Gulf of Bothnia. Monthly means 1981-91.

8. DISCUSSION AND CONCLUSIONS

In this work the size of the redistribution of water runoff caused by the river regulation is described and quantified. During the autumn the redistribution of water is small, but during the rest of the year it varies between 35 and 70 %. It is shown that the decrease in runoff in May - June can reach 5 000 - 6 000 m^3/s (- 35 %) which is in the same order as the total mean runoff to the Gulf of Bothnia as a whole. In wintertime there is normally a monthly increase in runoff of 2 000 - 3 000 m^3/s (+ 70 %). There is no doubt that this must imply changed river transport of suspended materials, elements, nutrients and so on and thus have effects on the sea water. Work on these subjects have been done e.g. by Brydsten et al. (1990) and Grimvall et al. (1994). Brydsten compared regulated and unregulated rivers and analyzed statistically 20 different chemical compounds. He found that regulation decreased the transport by 10 - 50 % depending on compound. This work opens the possibilities to simulate the influence of the changed runoff in one and the same river. An attempt to simulate regulation influence on nitrogen is made by Johansson (1994), who has combined the model used in this work with a nitrogen model. It is not only the amount of nutrients that matters. The time when it reaches the Sea is also of interest, especially for the costal area outside the mouth of the regulated rivers.

The sea level variations in the Gulf of Bothnia are due mainly to meteorological forces but also to some extent to river runoff. The meteorological forces create inflows and outflows to the Gulf of Bothnia which cause variations in the water level. The runoff simulations make it possible to examine a hypothetic effect on the sea level of the regulated runoff. The theoretical monthly differences in water stage and corresponding water transport caused by the regulations are illustrated in Figure 8.1. The calculations do not mean that the water level has changed this much but maybe the regulation has resulted in an increased outflow through the Åland Sea and Archipelago with c. 6 km^3 during each winter month and a decreased outflow with up to c. 10 km^3 in May and June (right scale). These figures should be compared with an annual mean fresh water outflow through these straits of just below 200 km^3 and a meteorological forced in- and outflow of 1 200 km^3. Even if 5 - 10 km^3 seems small it is anyhow large enough to have influence on fresh water content in the upper layers. The increased inflows of fresh water due to regulation during wintertime may decrease the surface salinity and thus increase the stability.

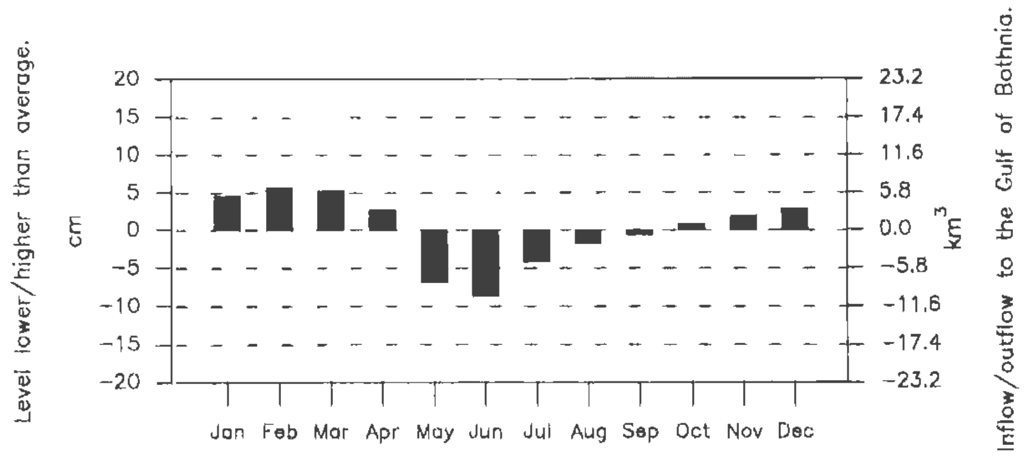


Figure 8.1. Changes in water level and flow to the Gulf of Bothnia due to the difference between simulated natural and recorded regulated fresh water runoff.

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