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Modelling Influence of River Regulation on Runoff to the Gulf of Bothnia

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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 as well as man made changes in the runoff, both in the form of long-term changes over many years and those occurring within one year. The most significant man made changes come from hydropower regulation. This report describes the effect on runoff from the development of the hydropower plants in Sweden and Finland by means of comparing recorded regulated runoff and simulated natural runoff. A recent time period, 1980-91, and a time period before regulation, 1925-36, were simulated. The monthly magnitudes of the redistributed flows were found to be on average 1,700 m^3/s. The maximum redistributed monthly flow in May – June reached 5,000-6,000 m^3/s.

Introduction

The Gulf of Bothnia is the northernmost part of the largest brackish water body in the world, the Baltic Sea. The Gulf is divided into 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 about 490,000 km^2. The 12 largest rivers are denoted in Table 1. The annual mean runoff to the entire Gulf of Bothnia is just below 6,000 m^3/s. The runoff is of importance for the salinity stratification and thus for the exchange of the Gulf water through the Åland Sea.

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, 1993)

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

Besides natural changes in the runoff, occurring both as long-term changes over many years and as short-term changes within one year, there are also man made changes. The most important of these is the hydropower regulation. The aim with regulation is to store water from spring, summer and autumn for use in winter when more electricity is needed and the price is higher. This report describes the effect of the development of hydropower by comparing gauged regulated runoff to calculated natural runoff. A recent time period, 1980-91, and a period before regulation, 1925-36, were simulated. A more comprehensive report on this project is given in Carlsson and Sanner (1994).

River Regulation and Hydropower Development

Hydropower produces about 50% of the electricity in Sweden. Of this almost 90% 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 Torne, Kalix, Pite and Vindel Rivers. The natural lakes in the system are often used for storage, but there are also many artificial reservoirs. Some of the Swedish rivers are extensively regulated, with large numbers of hydropower stations in series along the river. Fig. 1 gives an example of how regulation in the highly developed Lule River affects the runoff (*i.e.* after about 1968).

The majority of both the Finnish and Swedish hydropower systems were in substance developed after the 1930s. Fig. 2 shows how the reservoir volume in the three Swedish areas considered in this study increased from 1930. Notice that the volume before 1936 was small and then rose until about 1980.

In Finland large lakes are commonly used as reservoirs, which implies that the lake surface area has not changed very much owing to the regulations. But there are also two very large man-made reservoirs in the northernmost part of Finland, Lokan tekojärvi and Porttipahdan tekojärvi. The active storage of these two reservoirs and

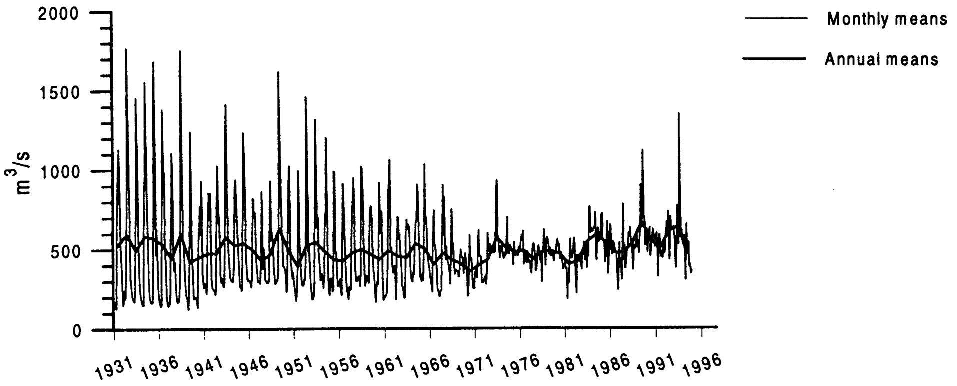


Fig. 1. Monthly and annual runoff from the regulated river Luleälven 1931-1994.

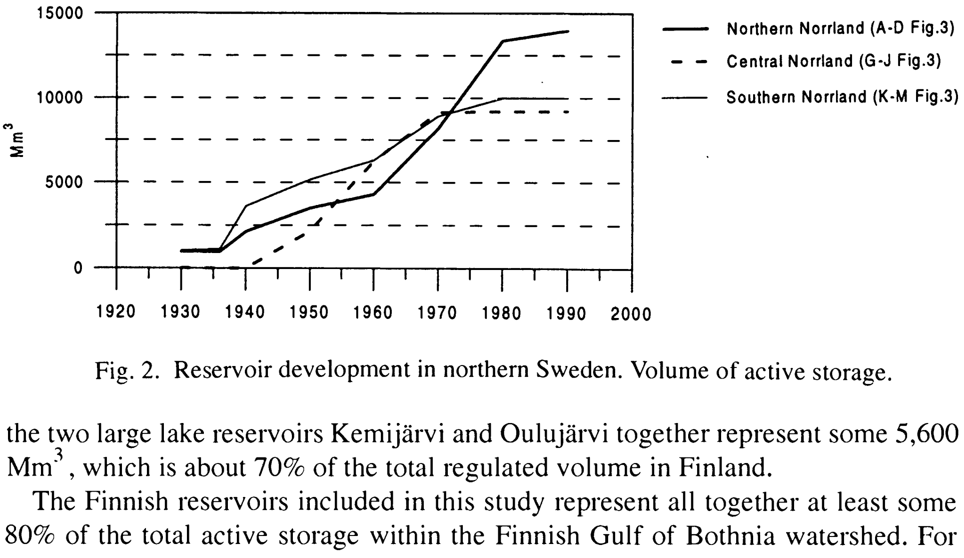


Fig. 2. Reservoir development in northern Sweden. Volume of active storage.

the two large lake reservoirs Kemijärvi and Oulujärvi together represent some 5,600 Mm^3, which is about 70% of the total regulated volume in Finland.

The Finnish reservoirs included in this study 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%. A summery is given in Table 2.

Table 2 – Summary of reservoirs data included in this study

	Number of reservoirs	Active storage Mm^3	Reservoir area 1925-36 km^2	Reservoir area 1980-91 km^2
Sweden/Bothnian Bay	31	13,964	1,293	1,923
Finland/Bothnian Bay	11	6,978	1,821	2,453
Sweden/Bothnian Sea	187	19,219	3,337	4,254
Finland/Bothnian Sea	5	1,066	716	716

The Model

The model used is the Swedish HBV model (Bergström 1976; Bergström *et al.* 1985; Bergström 1992). It can be classified as a semi-distributed conceptual model and uses subbasins as primary hydrological units. Within these an area-elevation distribution and a crude classification of land use – forest, open and lake – is made.

The model has a number of free parameters, values of which are found by calibration. There are also parameters describing the characteristics of the basin and its climate. The model is run with daily time steps. Input data are precipitation, temperature and potential evapotranspiration. Normally, monthly standard values of potential evapotranspiration are sufficient, but daily values can also be used as input or even calculated within the model from the air temperature (Lindström *et. al.* 1994).

Data Base

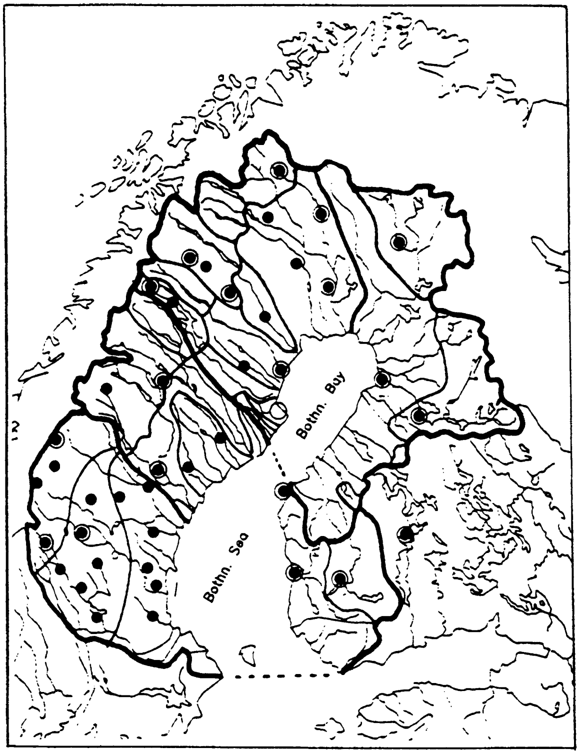
The precipitation and temperature stations used are shown in Fig. 3. In spite of the fact that it limited the number of useable stations, one criterion was that all stations ought to have been in operation during both simulated periods 1925-36 and 1980-91. A minor heterogeneity may be caused by the change in the mark of rain gauges in Finland from Wild to Tretjakov in 1981. Potential evapotranspiration was also included in the model in the form of monthly mean values. Swedish calculated values (Eriksson 1981) and Finland Class A pan measurements were used.

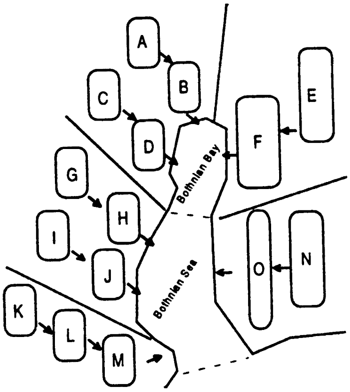
Swedish topographic data were obtained from SMHI data bases. Finnish data were obtained from Finnish hydropower companies and Hydrological Yearbook 1990 (1993) or calculated from topographic maps.

The runoff to the Swedish coast was calculated by SMHI with data from all available gauging stations. Calculations are now available from 1925 and onwards. The runoff to the Finnish coast from the period 1981-91 was taken from Bergström and Carlsson (1994). Especially in Finland some land use changes, *e.g.* bog drainage have been extensive in the river basins involved. Depending on climate and physical properties of the soil, changes in land use might have an impact on the water balance (Dunn and Mackay 1995). It has not been possible to include these effects in the current investigation.

The inflows to the power plant reservoirs were calculated on the basis of registered runoff and water levels in the reservoirs. Discharges, water levels, maximum pool elevations, discharge curves, *etc.* were obtained from power companies in Sweden and Finland, from SMHI in Sweden and from the National Board of Waters and the Environment in Finland.

Fig. 3. The drainage basin of the Gulf of Bothnia. The division into subbasins and a principle sketch of the modelstructure.
○ = temperature station, ● = precipitation station.





Subbasin		Area (km^2)	Reservoir (Mm^3)
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**

The Simulation Strategies

The main purpose of this study was to compare runoff under regulated and unregulated conditions from the watershed of the Gulf of Bothnia. All the simulations were made with daily data, but the results were mostly averaged into monthly and annual means. This procedure reduces the influence of the daily errors and gives a better overview.

As shown on the map and principle sketch in Fig. 3 the catchment area of the Gulf of Bothnia was divided into a number of subareas. Besides separation of the runoff into contributions to the Bothnian Bay and to the Bothnian Sea, boundaries between the areas were selected so that regulated areas were separated from unregulated ones. Thus some areas mainly contain reservoirs and others do not. In areas with reservoirs, the inflow to each of these was calculated on the basis of measured runoff and measured water-level changes in the reservoirs. The model was then calibrated against the discharge from the unregulated subcatchments and against the total inflow in the regulated ones.

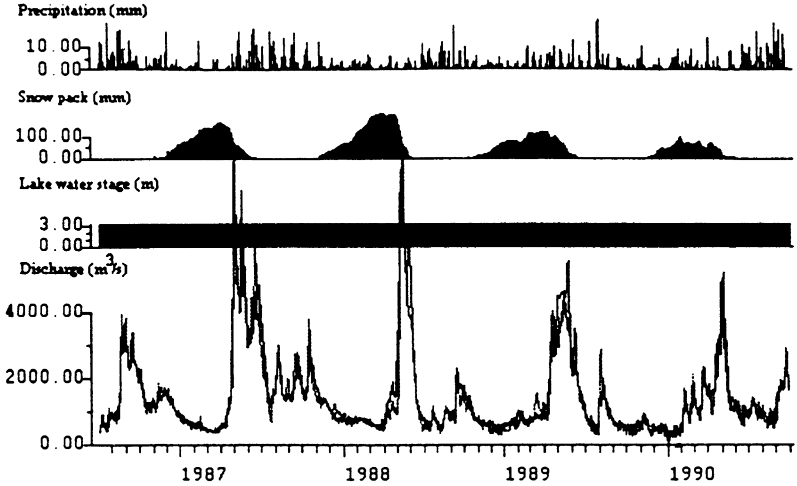
To calculate the influence of regulation on the total water supply inflow to the Gulf of Bothnia, one must make model calibrations for a period without hydropower development. As the largest development took place after the middle of the 1930s in both Sweden and Finland the selected unregulated calibration period was 1925-36.

The strategy for the simulations is described below with an example from the southern Norrland region in Sweden (K,L,M in Fig. 3). This region was divided into three subregions – coast, forest and mountain –, which are all regulated. The subregions together have an area of 105,000 km^2.

The model was first calibrated for the period 1980-91 against the inflow to the power plant reservoirs plus the unregulated runoff to the Bothnian Sea. As no reservoirs were included in this calibration, the model parameters are also valid for the period 1925-36. The top of Fig. 4, shows a period, 1987-90, of the calibration from southern Norrland in Sweden for the period 1980-91.

To calibrate the lake discharge parameters, the model was then run against the almost completely unregulated period 1925-36. As the current reservoir areas are not the same as the original lake surface areas before regulation, the areas of the original lakes were included and the lake discharge parameters of the model were calibrated. The middle of Fig. 4 shows an excerpt from this calibration run.

Fig. 4. Top: 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.
Middle: Calibration of the lake discharge parameters. Sweden, southern Norrland.
Bottom: Simulated natural and recorded regulated runoff from southern Norrland in Sweden.
Thin line is recorded discharge. Thick line is simulated discharge.


Precipitation (mm)
10.00
0.00
Snow pack (mm)
100.00
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Lake water stage (m)
3.00
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Discharge (m^3/s)
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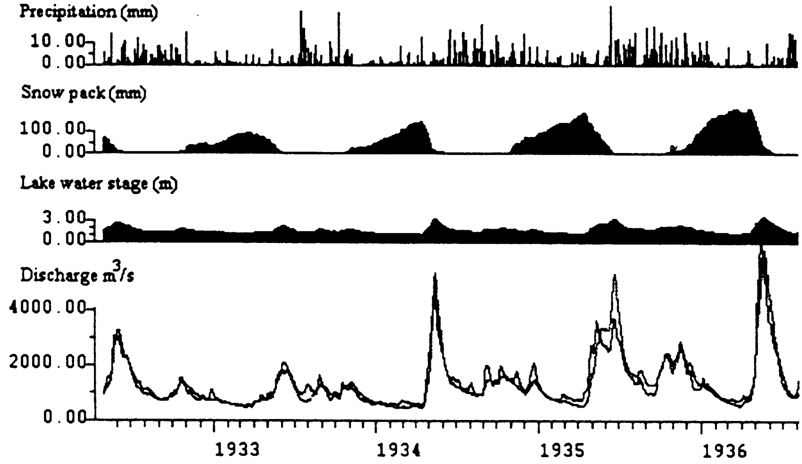
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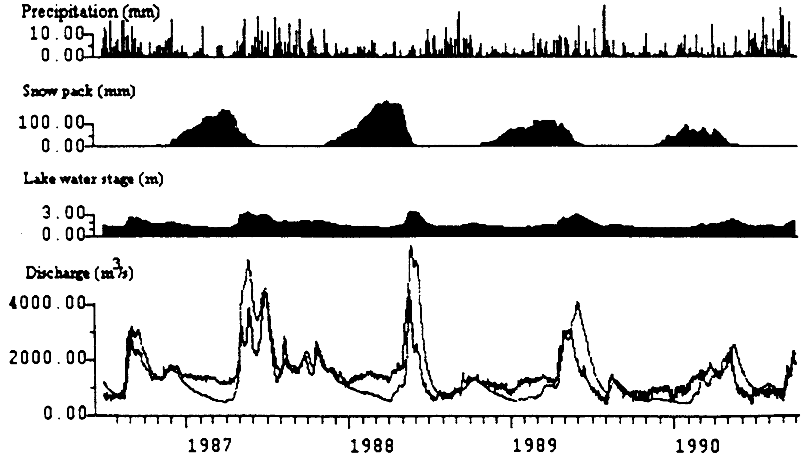
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A measure of the model performance can be accomplished by means of a verification run, that is by simulating a period that was not used in the calibration. This could be done for the unregulated area of central Norrland (G in Fig. 3) from where there were discharge measurements for both periods. No changes of model parameters were needed here as no regulations were made within the subbasin. After some adjustments of the precipitation depth, as this obviously was incorrect for the period 1925-36, the verification period showed the same fitness performance as the calibration period 1981-91. For the periods 1925-36 and 1981-91 the mean discharge was the same, but the mean precipitation from all the used stations was less for the period 1925-36.

The explanation is likely the modification in equipment that occurred between the two periods, but it could also be other reasons such as a raise in the evapotranspiration due to increased forest growth as discussed by Dunn and Mackay (1995).

After the calibrations it was possible to simulate natural runoff in current time as if the regulations did not exist, and to compare with regulated conditions, which is shown at bottom of Fig. 4.

Results

In Figs. 5-10 one can observe the monthly runoff to the Bothnian Bay, the Bothnian Sea, and to the total Gulf of Bothnia throughout the years 1981 to 1991. Notice the low discharges from Finland to the Bothnian Sea (Fig. 8) where the annual mean runoff is in the order of 500-600 m^3/s, as compared to the runoff from Sweden to the Bothnian Sea (Fig. 7) which is in the order of 2,600-2,700 m^3/s. From both Sweden and Finland to the Bothnian Bay (Figs. 5 and 6) 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 appears to be of little importance for the Gulf of Bothnia as a whole, however the influence on the coastal area outside the mouth of big rivers like the Finnish river Kokemäenjoki may be significant.

All figures show the characteristic differences between natural and regulated flow, that is a higher flow in wintertime and a decreased flow in springtime. The regulated discharge in the winter is at least about twice as large as that of the natural discharge. The greatest differences between natural and regulated spring floods occur in the runoff from Sweden to the Bothnian Sea. The differences are in the order of 2,000 to 3,000 m^3/s.

Due to the unregulated rivers Torne and Kalix Rivers and large unregulated areas in northern Finland 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 recorded regulated spring flood was even higher than the simulated natural flow, from the Swedish side of the bay (Fig. 5). In 1989 there was a volume error in the calibration during the spring flood, which made the simulated natural discharge too

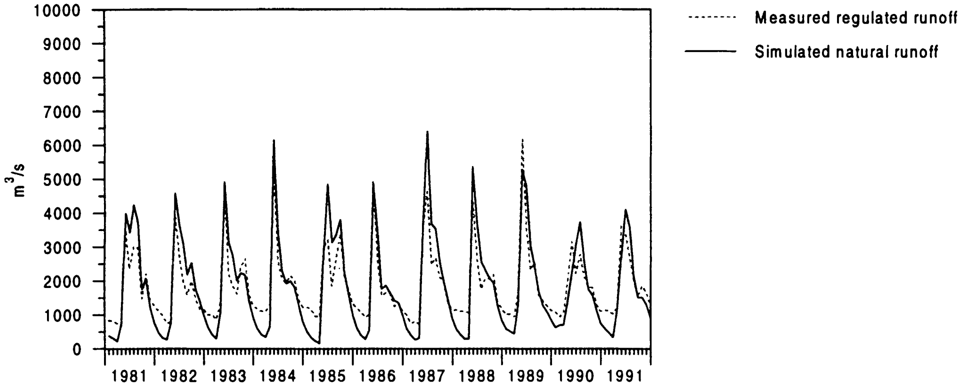

Fig. 5. Simulated natural and measured regulated discharge from Sweden to the Bothnian Bay.

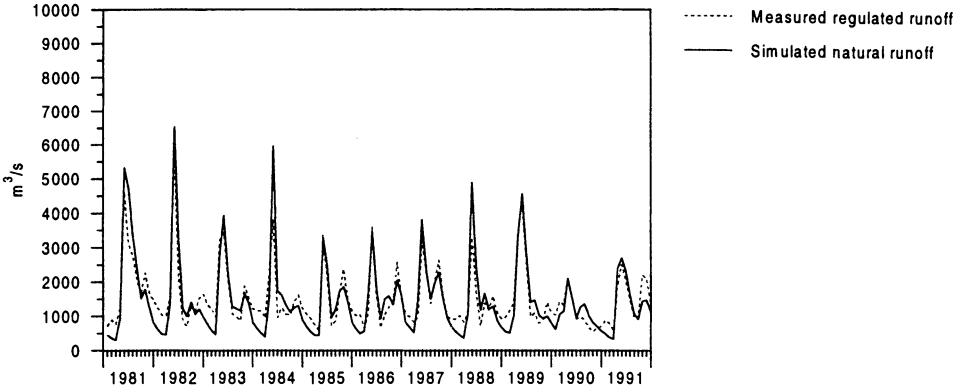

Fig. 6. Simulated natural and measured regulated discharge from Finland to the Bothnian Bay.

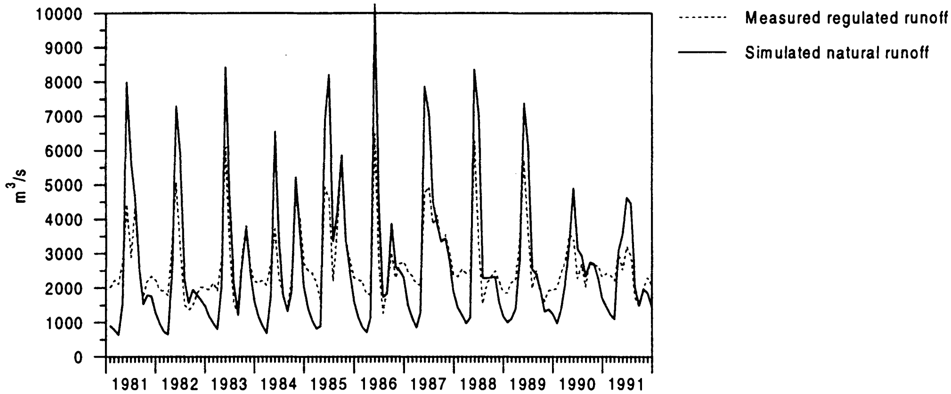

Fig. 7. Simulated natural and measured regulated discharge from Sweden to the Bothnian Sea.

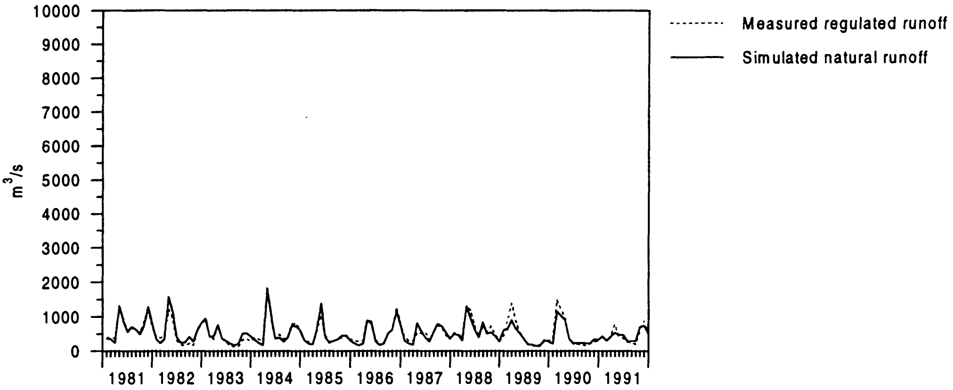

Fig. 8. Simulated natural and measured discharge from Finland to the Bothnian Sea.

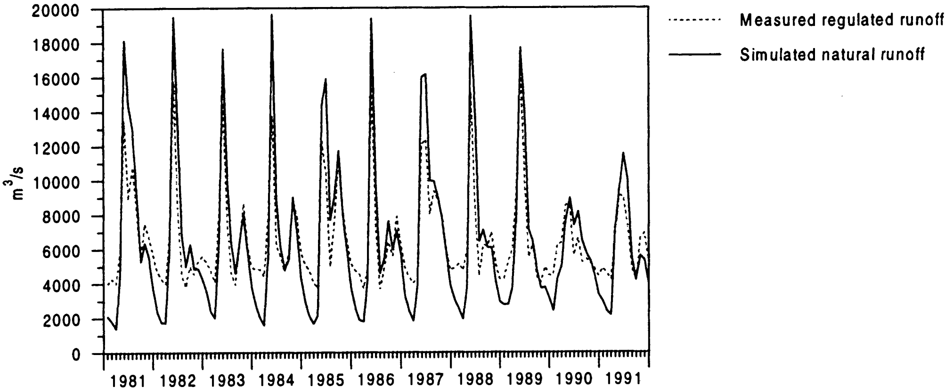

Fig. 9. Simulated natural and measured regulated discharge from Sweden and Finland to the Gulf of Bothnia.

low. An explanation of the result lies also in the hydrological situation as the winter 1988/89 was rich in snow. During the first half of the year the inflow to the reservoirs was 40% more than normal, which resulted in a reservoir storage about 20% over the normal during spring (Kraftsam 1990). This situation made it necessary to spill from some of the reservoirs during the spring. On the Finnish side of the Bay, where the model performance was good, the situation was similar with a simulated natural runoff of the same size as the recorded regulated (Fig. 6).

The monthly magnitudes of the redistributed flows (*i.e.* the difference between natural and regulated flows) are shown in Fig. 10. 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, which is the same value as the total mean runoff to the entire Gulf of Bothnia. Monthly and annual averages from the period 1981-91 can be seen in Figs. 11 and 12.

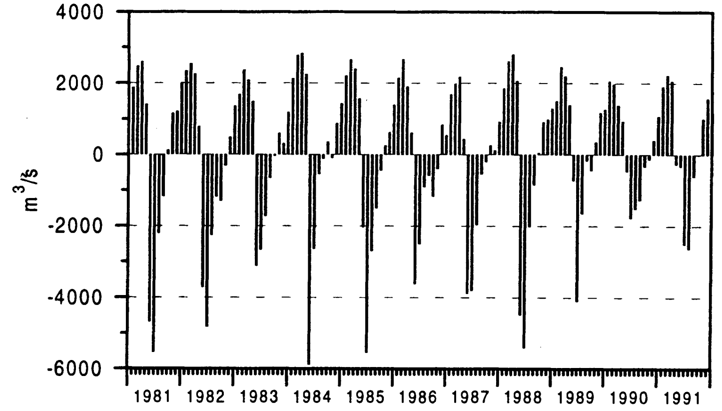

Fig. 10. Monthly means of measured regulated discharge minus simulated natural discharge to total Gulf of Bothnia from Sweden and Finland 1981-91.

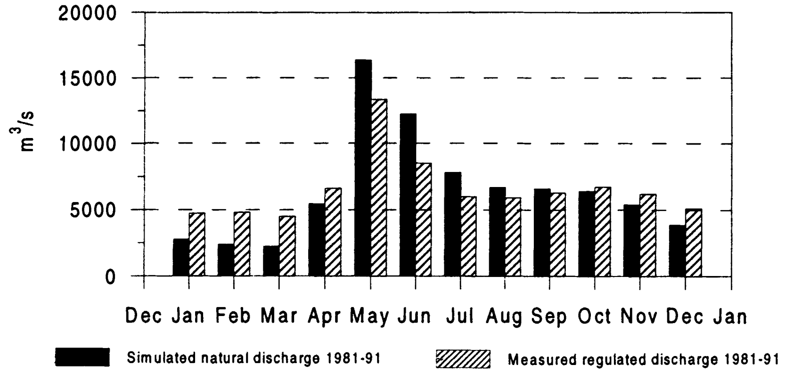

Fig. 11. Monthly simulated natural and measured regulated total discharge to the Gulf of Bothnia.

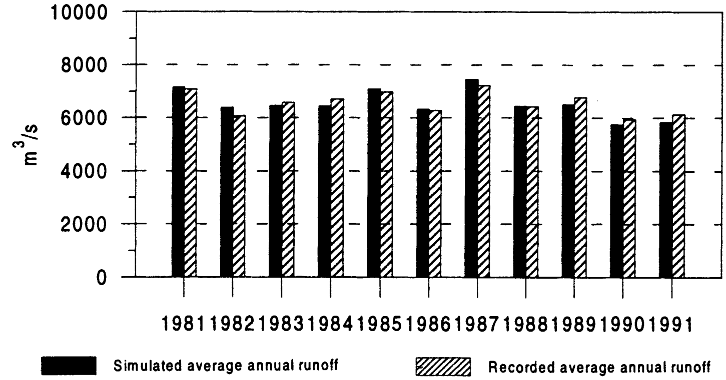

Fig. 12. Annual simulated natural and measured regulated total discharge to the Gulf of Bothnia.

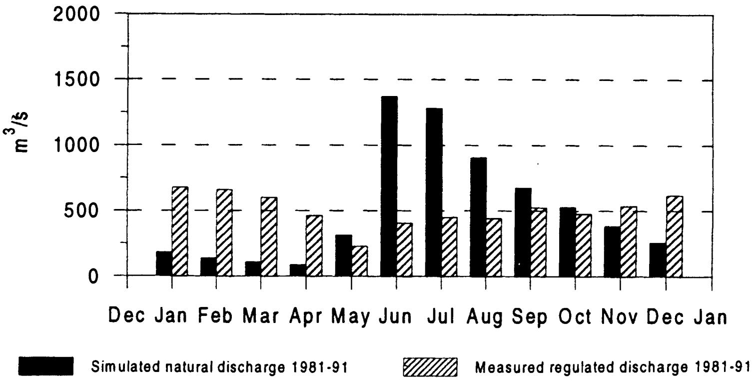

Fig. 13. Simulated natural and measured regulated discharges from a highly regulated area in northern Sweden, 1981-91.

Some of the areas within the watershed of the Gulf of Bothnia are regulated to a very high degree. Fig. 13 shows an example of how the regulation has changed the runoff regime from the mountain region in northern Sweden (region C in Fig. 3) where one of the largest Swedish reservoirs, Suorva, is situated. The degree of regulation here is almost 90%, that is 90% of the annual mean discharge can be stored. The monthly bars in the figure show that during springtime, when there should normally be 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 it rises to approximately 600 m^3/s from natural levels of 100-200 m^3/s.

Discussion and Conclusions

In this study the size of the redistribution of runoff to the Gulf of Bothnia caused by 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 implies changed river transport of suspended materials, elements, nutrients and others, and thus has effects on the sea water (Grimvall *et al.* 1994). Brydsten *et al.* (1990) found that regulation decreased transport by 10-50% depending on the compound. An attempt to simulate regulation influence on nitrogen was made by Johansson (1994), who combined the model used in this work with a nitrogen model. It is not only the amount of respective nutrients that is important, but the time when they reach the Sea is also of interest, especially for the coastal area outside the mouth of regulated rivers.

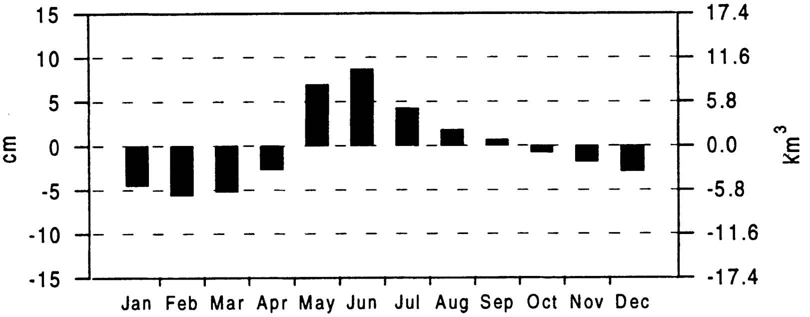

Fig. 14. Changes of water level and volume of the Gulf of Bothnia due to the difference between simulated natural and recorded regulated fresh water runoff.

Sea level variations in the Gulf of Bothnia are due mainly to meteorological forces, but also to some extent to river runoff. 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 hypothetical 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 Fig. 14. The calculations should not be taken to imply that the water level changed this much but that perhaps the regulation has resulted in an increased outflow through the Åland Sea and Archipelago with about 6 km^3 during each winter month and a decreased outflow with up to about 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 inflow and outflow of 1,200 km^3. Even if 5-10 km^3 seems small it is anyhow large enough to have influence on the fresh water content in the upper layers of the sea. The increased inflows of fresh water due to regulation during wintertime may decrease the surface salinity and thus increase the stratification stability.

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