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Stability of River Flow Regimes

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One of the most important consequences of future climate change may be an alteration of the surface hydrological balance, including changes in flow regimes, *i.e.* seasonal distribution of flow and especially the time of occurrence of high/low flow, which is of vital importance for environmental and economic policies. Classification of flow regimes still has an important role for the analyses of hydrological response to climate change as well as for validating climate models on present climatic and hydrologic data, however, with some modifications in the methodology. In this paper an approach for flow regime classification is developed in this context. Different ways of flow regime classification are discussed. The stability of flow regimes is studied in relation to changes in mean annual temperature and precipitation. The analyses have shown that even rather small changes in these variables can cause changes in river flow regimes. Different patterns of response have been traced for different regions of the Nordic countries.

Introduction

The development of hydrology has entered the era of global hydrology (Kundzewicz, Gottschalk and Webb 1987). Despite the significance of water, our knowledge of it as a part of the global system is meager (Barron, Hay and Thompson 1989). Traditionally, world waters have been inventorized and analyzed from a static point of view to produce maps over water balance elements (Korzun 1978, Baumgartner and Reichel 1975). Such maps usually show annual values, while seasonal variations are specified in terms of classifications of climate and river flow regimes. A variety of flow regime classifications exists, some covering the whole world, others locally adapted. The two most well-known and widely used are those by Lvovich (1938) and Pardé (1955). The study of flow regimes gives an insight in the character of hydrological processes, influenced by climate and physiography.

One of the most important consequences of future climate change may be an alteration of the surface hydrological balance, including changes in streamflow, soil moisture and groundwater recharge. Climate model experiments demonstrate the great sensitivity of the hydrologic cycle to climate change and to a set of specific forcing factors (Kutzbach 1981, Kutzbach and Street-Perrot 1985). These experiments, at present, establish first order relationships governing the hydrologic cycle. However, they imply large and complex variability of the hydrologic cycle as a part of the total global transfer and exchange of energy and matter. Much effort is now directed at better understanding these complex relations and in particular, the problem of parametrization of hydrological processes to a scale corresponding to the one used in climate models, as well as the problem of disaggregation (aggregation) of the results from such models to scales suitable for analyses of the implications for water resources. (Thomas (1990) provides a useful overview).

The traditional approach of producing maps and classifying flow regimes still has an important role in the process of validating climate models on present climatic and hydrologic data, however, with some alterations in the methodology. Maps of global or regional mean annual runoff, for instance, are contour maps, indicating variations across space. It is difficult to extract information comparable to the gridded simulations from these. There is, thus, a need for presenting hydrological information on grid networks at a variety of scales for both global and regional applications. This concerns both annual means and flow regime classes. Arnell (1992a) illustrates some methods of representing average annual runoff on a grid network, but little work has been done on flow regimes.

We can note the twofold role of flow regime classification. On one hand it can be used in the process of validation to check that the correct seasonal patterns are reproduced by climate models. On the other hand, flow regimes synthesize underlying processes involved in runoff formation and thereby also indicate the proper choice of hydrologic model formulation. That is why flow regimes are used for defining hydrological regions.

A methodology for flow regime classification which can answer these new demands, besides being automatic, should be stable, allow the unique definition of classes and be applicable to gridded data. This paper develops such a methodology, an has two objectives in particular. The first is to test a number of different ways of defining automatically flow regimes and the regions they cover; the second is to compare flow regime types in warm and cold, respectively wet and dry years. The paper builds on methodology for the flow regime classification developed for the Nordic countries by Gottschalk *et al.* (1979).

Regional studies of river flow regimes across national boundaries require access to regional data bases. The FRIEND (Flow Regimes from International Experimental and Network Data) data base (Gustard *et al.* 1989, Arnell 1992b), compiled recently within the frame of UNESCO International Hydrological Programme IV H-5-5, offers a possibility of such studies for northern and western Europe. Excerpts from this data base for the Nordic countries, complemented by temperature and precipitation data, form the basic data in this study.

Data Used

River flow data for a total of 81 gauging stations in Scandinavia have been used. Most of the stations come from the FRIEND data base. The length of the observation series varied between 22 and 181 years. Two common observation periods of different length have been used in the study. The longer common period is 66 years (1922-87), represented by 50 series; the shorter is 22 years (1965-1986), represented by 68 series.

The data for the longer common observation period of 66 years have been used as the basis in the study. For the regionalization of flow regimes it was, however, preferable to use all 81 series to get better spatial coverage. In this case the longest series were used for control purposes. Most of the basins have an area of less than 2,000 km^2.

Temperature and precipitation observation series were taken from climatic stations situated in the vicinity of flow gauging stations and having a common observation period. A total of 31 temperature and 50 precipitation series (66-year long) have been used.

Flow Regime Classification

A variety of river regime classifications exists, some covering the whole world, others locally adapted. The two most well-known are those by M. Lvovich (1938) and M. Pardé (1955).

The flow regime classification suggested by Lvovich is a development of an old (probably the first) genetic global flow regime classification, presented by A. I. Voeikov in 1884. Voeikov differentiated between nine types of flow regimes, based primarily on climatic features.

Two aspects form the basis in Lvovich's classification: genetic source and seasonal distribution of flow. Four genetic sources are distinguished: snow, rain, glaciers and groundwater. 12 gradations for the four sources and the four seasons, respectively, which makes a total of 144 combinations of flow regimes, are distinguished.

In reality only 38 proved to be possible and have been generalized by Lvovich into 12 main types for the whole world.

Pardé's flow regime classification is global and is based on the genetic sources of flow formation and precipitation distribution within the year. This classification uses the well-known Köppen climate classification as a point of departure. Three main flow regimes are distinguished: megathermal, mesothermal and microthermal. These are subdivided into a number of subgroups in dependence of the distribution of high/low flow.

Both Lvovich's and Pardé's classifications are rather general and poorly suited for computer application. Percentages used in both of them are rather arbitrary. Besides, a correct application of Lvovich's classification implies hydrograph separation (based on daily data) to identify genetic sources of flow.

In Scandinavia snow and glacier melt water and rain are the main genetic sources of river flow. These are, as well, the sources which are most sensitive to changes in climatic conditions. Under such circumstances a suitable flow regime classification would be a quantitative one based on the time distribution of the role of the named genetic sources of flow within a year. A flow regime classification suggested for Scandinavia by a Scandinavian Working Group on Flow Regimes in 1979 (Gottschalk *et al.*) suits the demands formulated above. This classification, which is briefly presented below, is based on the time of occurrence of high and low flows.

High water:
H1: Dominant snowmelt high water. An area is classified as H1 if the three months with the highest average runoff belong to spring or early summer (typically May-July).
H2: Transition to secondary rain high water. An area is classified as H2 when the second highest or third highest monthly runoff takes place in autumn (typically October, November, on the Scandinavian peninsula – early in the west and late in the east and vice versa in Finland).
H3: Dominant rain high water. An area is classified as H3 when the highest monthly runoff takes place in autumn or early winter (typically November-December).

Low water:
L1: Dominant low flow in winter, caused by snow accumulation. An area is classified as L1 when the two months with the lowest runoff both belong to winter or early spring (typically: February-March).
L2: Transition zone, when the two months with the lowest runoff do not belong to the same time of the year (typically: February and July).
L3: Dominant summer low water caused by high evaporation and/or low precipitation when the two months with the lowest runoff belong to summer or early autumn (typically June-August).

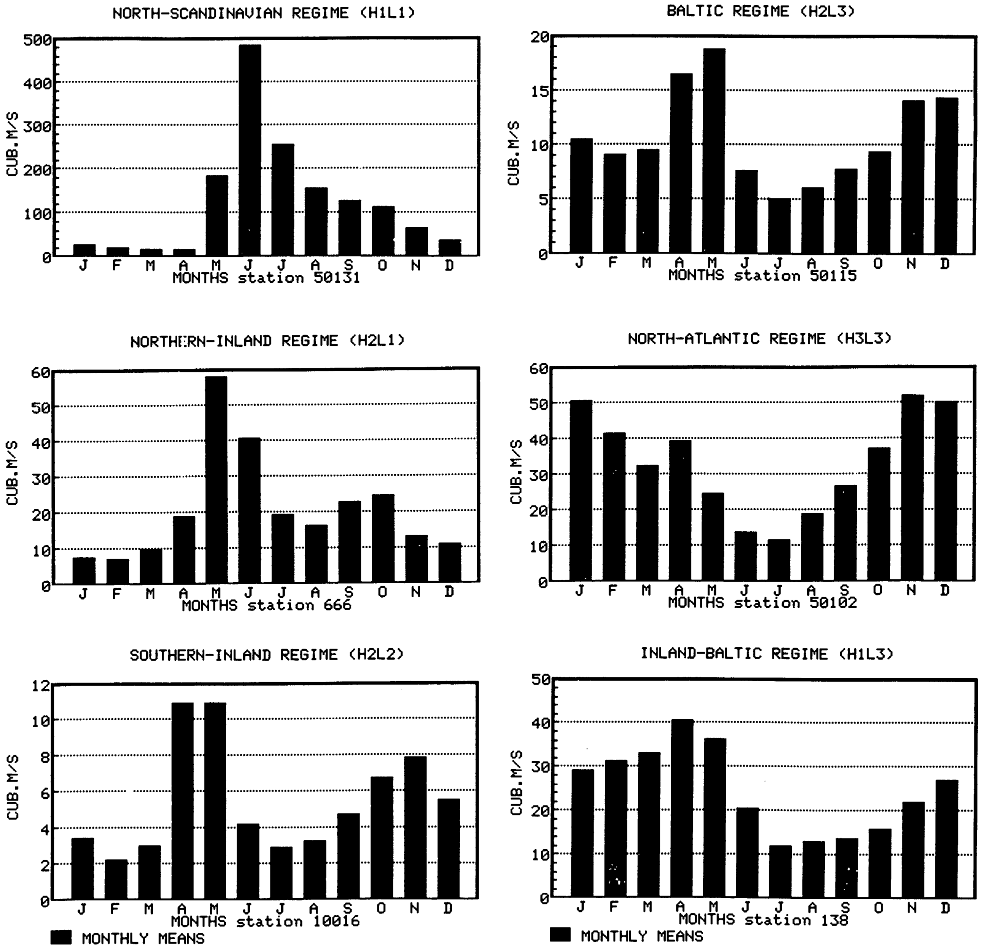


Fig. 1. Typical hydrographs for different flow regime classes.

Five main regime types were suggested by the Working Group based on these principles, of which two were transition types. This regime classification has, in the current study, been subjected to small modifications to define transition types more strictly and then computerized. Names were assigned to each regime class. Thus, the following flow regime classes have been obtained (Fig. 1):

H1L1 – North-Scandinavian
H2L1 – Northern-Inland
H2L2 – Southern-Inland
H2L3 – Baltic
H3L3 – North-Atlantic
H1L3 – Inland-Baltic

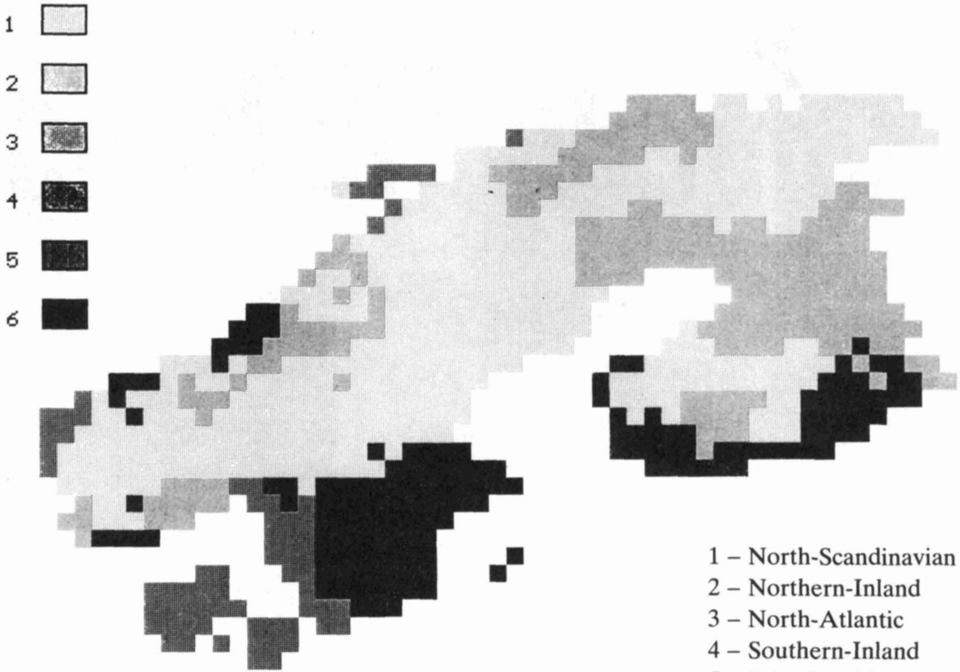
These are the most usual flow regime types in Scandinavia, but there exist, of course, other transition types though they are less common.

The regime classes listed above have been developed for Scandinavia, but it is not difficult to establish a connection between this classification and the "classical" ones, like Lvovich's and Pardé's at least for the largest classes. North-Scandinavian class, for example, corresponds to Yukon and DFc classes according to Lvovich's and Pardé's classifications, respectively; Northern-Inland class corresponds to Volga and DFb classes; Southern-Inland – to Oder and DFb/c classes, Baltic – to DFa/b class in Pardé's classification.

Flow Regime Classification Based on Longterm Mean Monthly Flow

The flow data have been classified automatically according to the suggested scheme and each station has been assigned a flow regime type. Two different approaches have been used. At first the longterm mean monthly flow values have been used as an input in a classification procedure. Representative areas have been outlined for each station utilizing information about physiographic regions, based on a synthesis of vegetation, geomorphology and climatic conditions (Anonymous 1976) and interpolation with the help of GIS (Eastman 1990). Overlaying the information about flow regimes for the stations on the representative areas for each station, flow regime regions, shown in Fig. 2, have been defined for the whole of Scandinavia.

The automatically produced map of flow regime regions coincides well with the



1 – North-Scandinavian
2 – Northern-Inland
3 – North-Atlantic
4 – Southern-Inland
5 – Inland-Baltic
6 – Baltic

Fig. 2. Flow regime regions.

manually made version of the Nordic Working Group. Some small differencies can be explained by the lack of observation data for automatical classification, specially on the Norwegian west coast, and the scale of the gridnet used. Besides, automatic classification procedure utilized one class more (Inland-Baltic) than the manual one.

Flow Regime Classification Based on Predominant Regime for Individual Years

An alternative approach was to use the mean monthly flow for each year of the period as input and assign the regime class represented by the majority of the years to the station. The results of these two classification approaches differed in almost 40 % of cases. A thorough analysis of the premises for assigning a regime class to the stations used in the second approach showed that in many cases it was practically impossible to trace a dominant regime type, as all the regimes were present at approximately the same proportions. In such cases the classification procedure becomes very uncertain. As a flow regime is a characteristic of longterm average behaviour of the flow, the classification based on the first approach, *i.e.* longterm mean monthly as an input, is preferable.

Application of Cluster Techniques

Clustering technique has been used in Scandinavia for hydrological regionalization of Sweden by Gottschalk (1985). Haines, Finlayson and McMahon (1988) applied cluster analysis for global classification of river flow regimes. Theoretical aspects of this method have been treated in many other works and will be ommitted here. Clustering has been used in this study as an alternative regime classification.

Mean monthly flow data have been subjected to a cluster analysis applying pairwise correlation, which has been shown to be the most suitable for flow regime identification by Gottschalk (1985). Six clusters were identified with this methodology. Each of the examined stations have been assigned the number of a corresponding cluster. A comparison of "cluster" numbers with a regime class assigned to the station before showed that in 80 % of cases on the average, stations with the same regime class belonged to the same "cluster". The discrepancies were at maximum 28 % (for Northern-Inland class). Cases with discrepancies were studied specially to see if there could be some common reasons for differencies. In the majority of cases, series representing the stations with discrepancies were short (<30 years) or/and the flow regime was unstable and changed from year to year.

In the same way as with the first approach, hydrological regions have been outlined around each station. A comparison of these to the flow regime regions obtained on the basis of regime classification showed a maximum deviation of 3 % in the areas in the Nordic countries.

The results of flow regime classification and regionalization with the help of clustering and GIS are quite encouraging. These methods give a possibility of computerized flow regionalization techniques.

Influence of Changes in Temperature and Precipitation Flow Regimes

The stability of flow regime classification have been tested by examining whether and how they differ if the mean annual temperature or precipitation changes.

Influence of Changes in Temperatures

The relationship between fluctuations in river flow and those of temperature showed to be rather weak. The average correlation between mean annual river flow and temperature for the available data was found to be equal to 0.14, for individual series the maximum was 0.51 and the minimum −0.20. Under such circumstances, a question is whether a minor mean annual temperature rise/fall can influence the flow regimes at all.

To answer this, first the available temperature series, having a longterm mean of 4.0°C (an average across all the stations), have been divided into two subsets: one for years with mean annual temperatures above the longterm mean and the other – for those with the mean annual temperature under or equal to it. These two data subsets will be called in this study "warm" and "cold" years, respectively. The longterm annual mean values have been calculated for the two data subsets. For the "warm" years this value equals 4.9°C and for the "cold years 3.2°C.

An examination of the distribution pattern of "warm" and "cold" years showed that there were 12 distinct "warm" periods in the 66-year long series, when the mean annual temperature was above the longterm mean for the whole period at almost all the stations: 1924-25, 1930, 1932-39, 1943-46, 1948-51, 1953-54, 1957, 1959-61, 1963-64, 1967, 1971-75, 1982-84. Table 1 illustrates the distribution of "warm" (marked by *w*) and "cold" years. In general, the average number of "warm" years was slightly less than that of "cold" years.

The river runoff series have been split into two subsets each: one for the "warm" and the other for the "cold" years. A annual temperature rise of 0.9°C during the "warm" years resulted in changes in the flow regime class for ≈21 % of stations (8 % shifted to a more "rain-dominated", 8 % to a similar and ≈4 % to a more "snow-dominated" regime type). Common for all those stations which moved to a more "rain-dominated" regime class was higher flow during winter (and even late autumn for some stations) compared to the flow behaviour during the whole period (see Fig. 3a). For the stations that moved to a more "snow-dominated" class, it was typical that the 2nd flow maximum occurred 1 to 2 months earlier (it moved from June to April-May) (see Fig. 3b).

An annual temperature fall of 0.8°C on the average during the "cold" years caused changes of the flow regime class for 27 % of the series (≈16 % – to a more "snow-dominated", 8 % – to a close and ≈3 % to a more "rain-dominated" regime class). Common for these stations was that flow became lower in spring and higher in summer, specially August.

In order to check that the shift in the flow regime was not caused only by the

Table 1 – Distribution of “warm” and “cold” years

Years Station	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87
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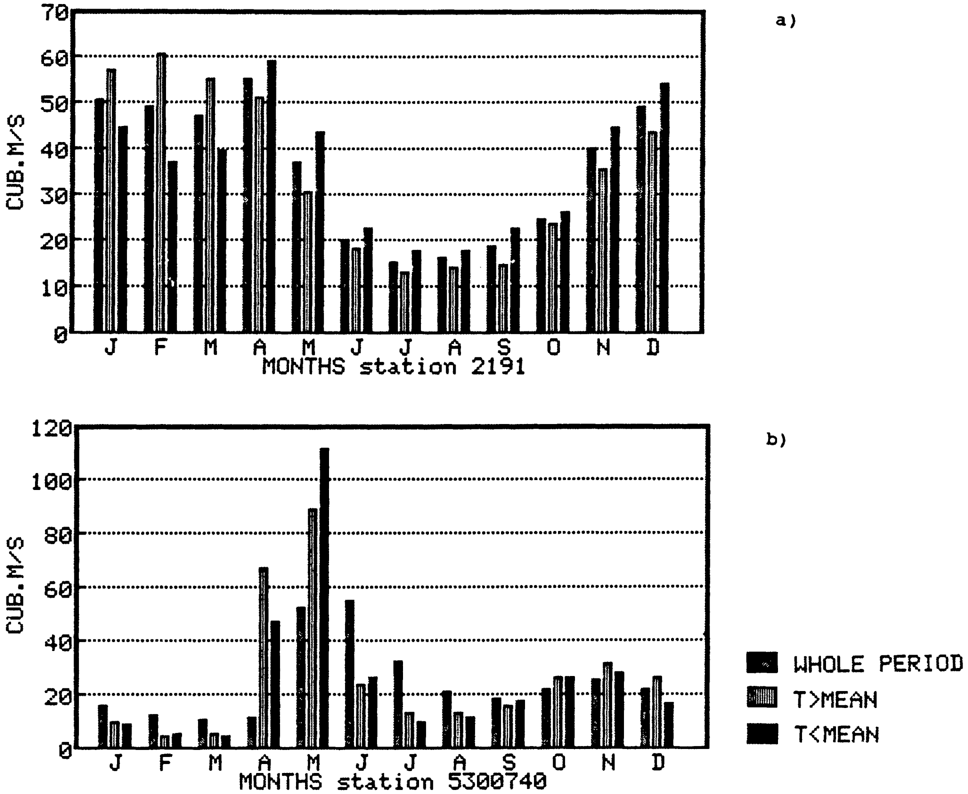

Fig. 3. Changes in the mean monthly flow during "warm" and "cold" years for stations in southern Sweden (a) and central Finland (b).

limitations in the used regime classification, mean monthly flow hydrographs (averages for 66 years) for "warm" respectively "cold" years have been compared to those for the whole period. This allowed to trace certain types of changes in flow regimes due to changes in temperatures. Table 2 shows the changes observed in each region of the Nordic countries and indicates that the changes are different in different geographical locations. In general, the "warm" years gave lower summer flow while the "cold" years increased it instead.

Series for stations in large basins (>2,000 km^2) and Western Lappland showed almost no change in the flow regimes for the "warm" or "cold" years (Fig. 4 a,b,c,).

Changes in the borders of the flow regime regions during "warm" and "cold" years can be seen in Fig. 5 a and b. The largest changes can be seen in southern Finland, western Norway and north-eastern Sweden. Table 3 offers some figures characterizing the changes in the areas of the six flow regime regions (in the percentage of the total territory) during the "warm" and the "cold" years compared to the whole period.

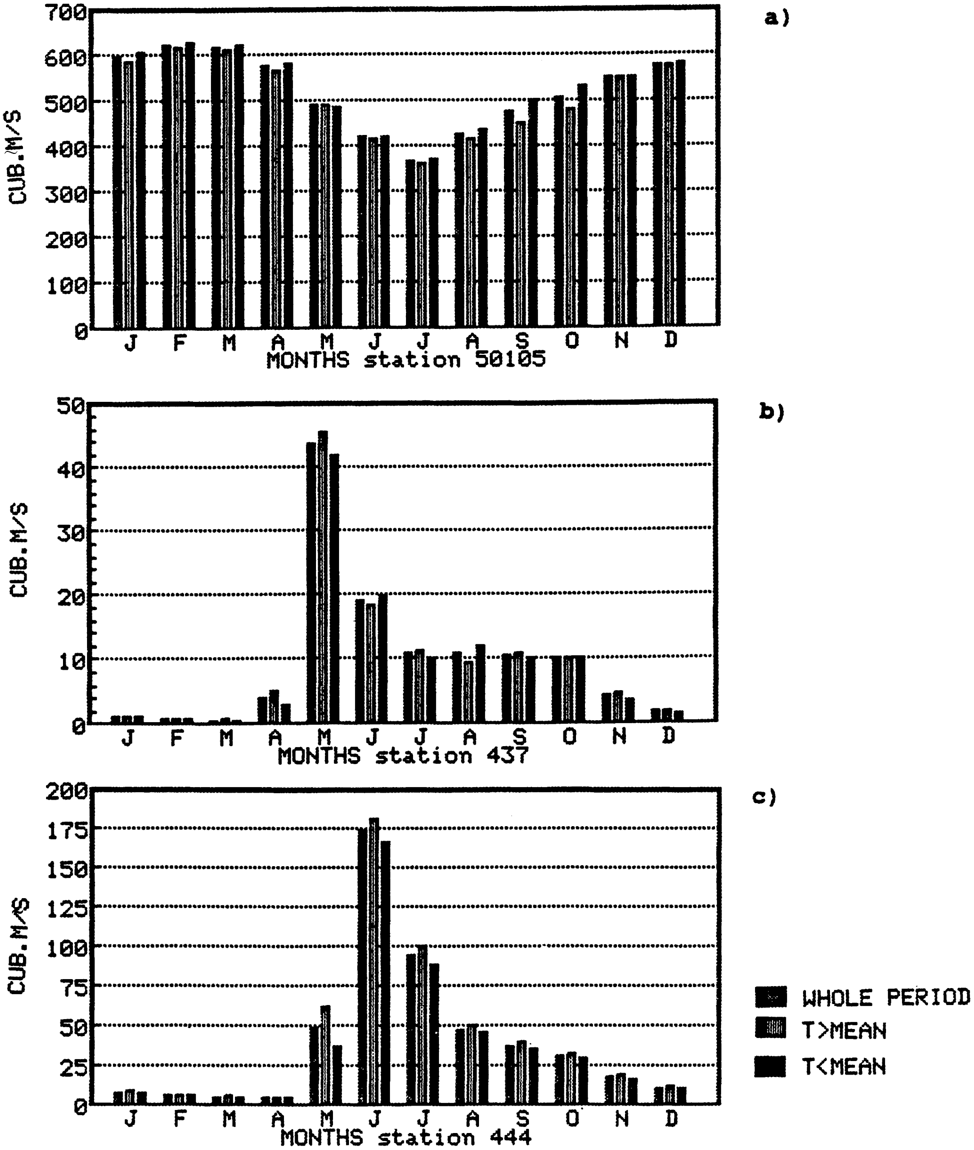

Fig. 4. Comparison of flow regimes during "warm" and "cold" years for large basins (a,b) and basins in Western Lappland (c).

A conclusion that can be made on the basis of the results presented above is that a relatively small rise or fall of average annual temperature of about 1°C can cause significant changes in flow volumes and their distribution within the year for almost all series except those for large basins. Amplitude of changes seems to be larger in the southern part of the territory studied.

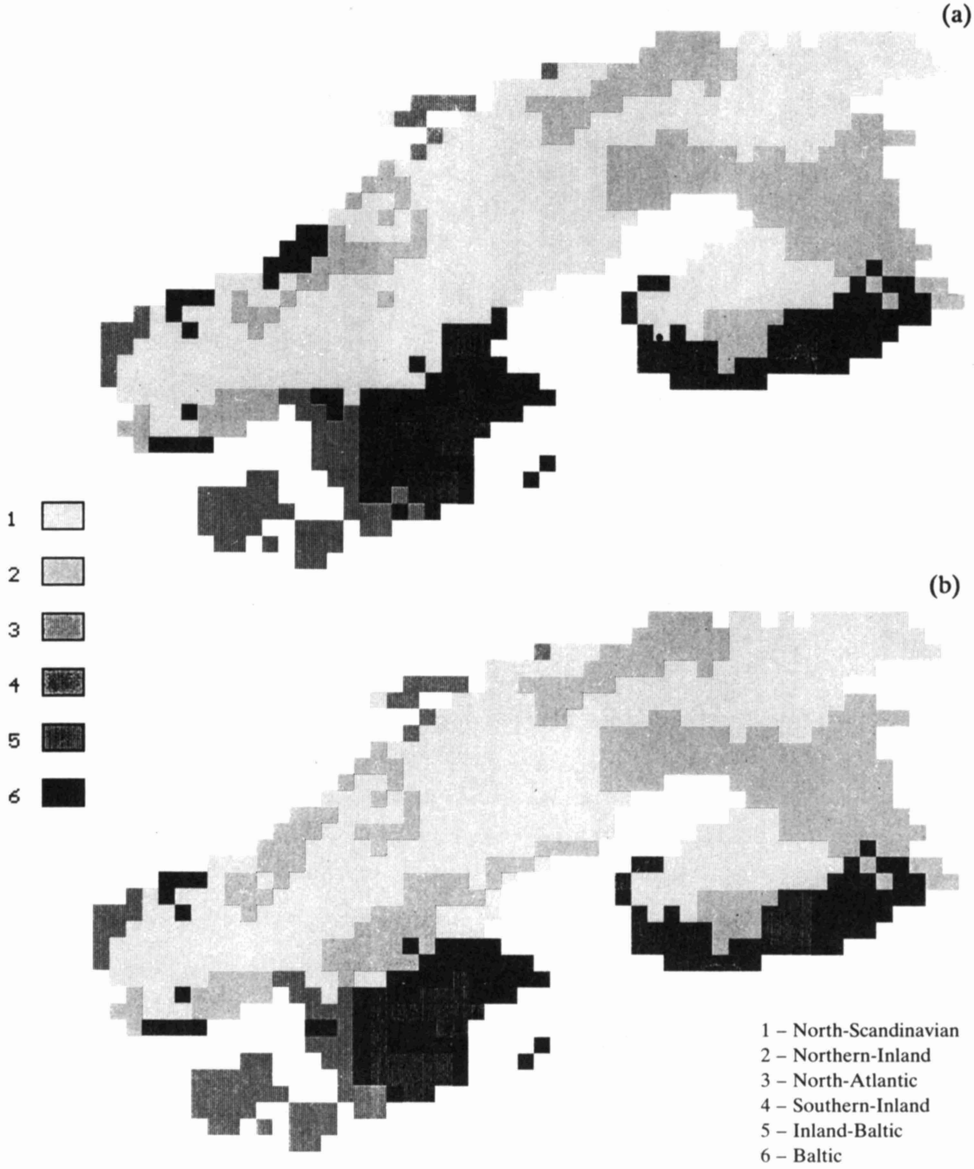

Fig. 5. Flow regime regions during "warm" (a) and "cold" (b) years.

Influence of Changes in Precipitation

Mean annual precipitation and mean annual runoff showed to be rather highly correlated. The correlation coefficient was on the average 0.51, varying from 0.93 at maximum and 0.16 at minimum.

In the same manner as for the temperature series the precipitation series have

Table 2 – Types of changes in river flow regimes caused by temperature rise/fall

Locality	Type of changes in flow regime T>MEAN	T<MEAN
Southern Finland	Moderately higher volumes during autumn, winter, spring.	Moderately higher volumes in summer, specially the beginning.
Southern Sweden	Much higher flow volumes in winter and somewhat lower in summer.	Much higher volumes in late spring-summer, specially May.
West coast	Much higher volumes in spring and winter and somewhat lower or unchanged in summer.	Much higher volumes in summer.
Northern inland	Somewhat higher or unchanged volumes in winter, higher in spring and lower in summer.	Very small changes or somewhat lower volumes in autumn-winter and volume rise in summer, specially June-July.
Southern inland	Same as the northern, but larger amplitudes.	
Western Lappland	Almost unchanged, very small rise in summer.	Somewhat lower volumes in summer, almost unchanged the rest of the year.
Eastern Lappland	Higher volumes in spring and summer.	Higher volumes in winter.

Table 3 – Changes in the areas of flow regime regions during "warm" and "cold" years compared to the whole period

Region	Whole period	Temperature T<mean	T>mean
		% of the total area	
North-Scandinavian	49.0	46.0	48.3
Northern-Inland	25.3	29.0	24.0
North-Atlantic	7.9	7.5	8.2
Southern-Inland	5.3	3.5	5.3
Inland-Baltic	3.8	5.0	5.6
Baltic	8.7	9.0	8.6

been divided into two subsets: one for the years with the mean annual precipitation above the longterm mean (878.4 mm, an average across all the stations) and the other – for those with the mean annual precipitation below or equal to the longterm mean. The first subset will be called "wet" and the second "dry" years in this study.

The average mean annual precipitation for the "dry" years equals 775.2 mm and for the "wet" years – 1,000.8 mm. No sign of grouping or regularity in the distribution pattern of the "wet" and "dry" years have been noticed. The number of "wet" years was larger than the number of "dry" years. There was no correlation between the pattern of precipitation and temperature. The highest correlation coefficient between the precipitation and temperature series (mean annual values) equaled only 0.40, being 0.09 on the average. To study the effect of longterm changes in annual precipitation amounts on the flow regimes, the runoff series have been subdivided into two subsets: one for the "dry" and the other for the "wet" years, similar to the case for temperatures.

The decrease in the mean annual precipitation by ≈103.2 mm on the average during the "dry" years resulted in changes of the flow regime class for 32 % of the series, of which nearly a half has shifted to a similar regime type and the rest – to both more "rain-dominated" and more "snow-dominated" regime classes. The character of influence was much less obvious than in the case of temperatures. Although lower flow in autumn was common.

The increase of the mean annual precipitation by ≈122.4 mm on the average during the "wet" years caused changes in flow regime classes for 20 % of the series, half of which shifted to a similar regime type and the rest to both more "rain-dominated" and more "snow-dominated" regime classes, similar to the case for precipitation decrease. Thus, no general tendency in the regime shifts could be outlined.

When the hydrographs for the subsets for mean monthly flow for "dry" and "wet" years are studied, it is possible to trace some main types of changes in flows due to the changes in precipitation amounts. Common for all the series was naturally the increase of flow during the "wet" years and decrease during the "dry" ones (see Fig. 6), which was quite expected due to relatively high correlation between flow and precipitation. However, the timing of increase/decrease in flow volumes seems to be different in different geographical locations. Table 4 gives a summary of the observed changes in flows.

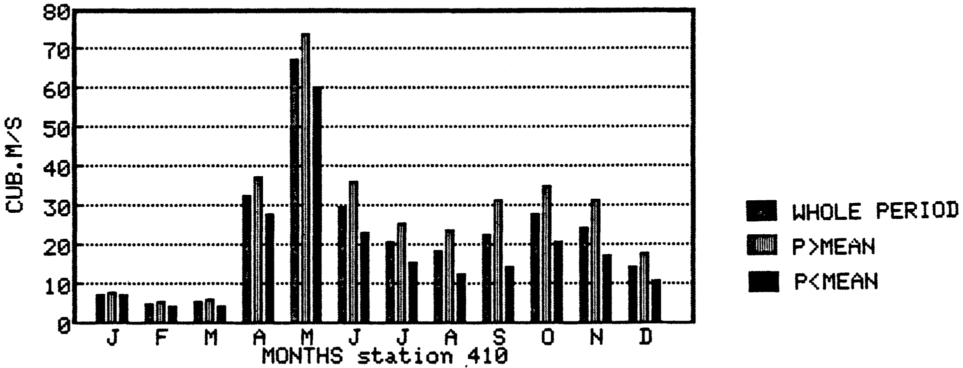

Fig. 6. Illustration of changes in the flow regime for "wet" and "dry" years for a station in south-eastern Norway.

Table 4 – Types of changes in river flow regimes caused by precipitation rise/fall

Locality	Type of changes in flow P>MEAN	P<MEAN
Southern Scandinavia	Volume increase in October-December, sometimes even in April-May and in summer.	Lower volumes during summer and autumn.
Southern Finland	Significant increase of volumes in summer and autumn especially.	Lower volumes in summer and autumn.
Northern coastal regions	Moderate rise of volumes, especially in autumn.	Moderate decrease in volumes during all seasons.
Northern inland regions	Almost no change in winter and late autumn, moderate increase in summer.	Moderate decrease in volumes, especially in summer-autumn.

Table 5 – Changes in the areas of hydrological regions during "dry" and "wet" years compared to the whole period

Region	Whole period	Temperature P<mean	 P>mean
		% of the total area	
North-Scandinavian	49.0	46.3	42.3
Northern-Inland	25.3	25.0	31.6
North-Atlantic	7.9	8.0	8.4
Southern-Inland	5.3	6.7	4.7
Inland-Baltic	3.8	5.5	4.5
Baltic	8.7	8.5	8.5

Unlike the case with the temperatures, series representative of large basins showed the same pattern as the small ones. The largest changes could be noted in north-eastern Sweden, south-western Sweden and south-eastern Norway. Table 5 shows the changes in the areas of the flow regime regions (in the percentage of the whole territory) during "dry" and "wet" years compared to the whole period.

On the basis of the results it is possible to conclude that it is in southern Scandinavia that the flow changes due to changes in temperature and precipitation are most pronounced in general. The flow in Scandinavia is to a great part fed by snow and glacier melt water. This can explain much higher winter-spring and lower summer flow volumes during "warm" years, when the snowmelt begins earlier than usual. The opposite situation with higher summer flows is characteristic of "cold" years. Precipitation rise in summer-autumn during "wet" years can be be a reason for a general tendency to a higher autumn flow (rain floods) but even to a higher spring flow due to larger snow accumulation.

Conclusions and Discussion

Plenty of flow regime classifications at global and regional scales exist. A common feature for all of them is that they perform well for the flow regimes of a distinct type (like snow-fed or rain-fed, for example), but are rather vague when coping with less clearly pronounced regime types. This has been clearly demonstrated when a regime type, characteristic for the majority of years, was used to determine a flow regime type – no dominating single flow regime could be outlined in many cases. To avoid this a classification has been performed on the mean monthly data for the whole observation period, characterizing some average conditions.

The flow regime has also been used in this study to get an indication of possible response patterns of river flow to changes of two climatic variables influencing it: temperature and precipitation. River flow regime describes a flow behaviour on the average in time and is a characteristic important from both the economic and environmental point of view. Changes in flow regime cause environmental change and necessitate adaptation of those economic activities dependent on river flow.

The analysis of temperature data has shown that during the "warm" years the mean temperature was 0.9°C (an average across all the stations) higher than the longterm mean for the whole period of 66 years, while during the "cold" years it was 0.8°C lower, *i.e.* a total amplitude of nearly 2°C. For the "wet" years the precipitation amount was ≈122.4 mm (an average across all the stations) higher compared to the longterm mean, while during the "dry" years it was ≈103.2 mm lower.

The flow regime's response to a temperature change of about ±1°C and precipitation change of about ±100 mm was specially pronounced in southern Scandinavia. Higher winter-spring (evidently due to earlier snowmelt) and lower summer flow volumes can be expected during "warm" years, while for "cold" years the situation is the opposite, *i.e.* higher summer flows. Precipitation rise in summer-autumn during "wet" years can be a reason for a general tendency to higher autumn flow (rain floods) but even to higher spring flow due to larger snow accumulation. In order to see if the observed tendencies in the response of the river flow regimes to changes in temperature are persistent, the study is continued with the analysis of the response of the extremes in the river flow to climate change on the example of Norway.

Changes in the flow regimes and volumes due to changes in temperature and precipitation have also been studied for the Nordic countries by Saelthun *et al.* (1990) and Vehviläinen and Lohvansuu (1991). They have used a different approach to the problem starting from assumed changes in temperature and precipitation and simulating the resulting discharges applying conceptual models.

It is difficult to direct compare the conclusions of these two studies to those given here for several reasons. The results of the studies rely heavily on the accuracy and relevance of the used models (Vehviläinen and Lohvansuu 1991). The effects of simultaneous increase in temperature and precipitation have been investigated in these studies with much higher amplitudes than those observed in the actual data series used here. We have not found any significant correlation between variations in temperature and precipitation in the observation series studied. The lengths of the series as well as the number of basins used are quite different, which certainly influence the results and make them difficult to compare. The investigation of the flow regime classification has demonstrated that a few decades of flow observations are not sufficient to make conclusions about the timing of the high/low flow, *i.e.* flow regime. The conclusion about the stability (or shift) of the flow regime for a whole region can differ from the one of an individual station.

Impact of climatic variability and change on river flow regimes have also been studied for the UK by Arnell *el al.* (1990). The weak relationship found, in general, between annual river flow and temperature agrees well with this latter study. Arnell *et al.*, however, analysed the river flow regimes for the UK, where rain is the predominant genetic source in the flow formation. Most of the basins included in this study has a predominant snowmelt component. That is why even a moderate change in annual temperature causes significant changes in the seasonal distribution of flow, *i.e.* the flow regime.

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