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PETRI EKHOLM, BRIAN KRONVANG, MAXIMILIAN POSCH AND SEPPO REKOLAINEN

ACCURACY AND PRECISION OF ANNUAL NUTRIENT LOAD ESTIMATES IN NORDIC RIVERS

NATIONAL BOARD OF WATERS AND THE ENVIRONMENT
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Abstract

Efficient resource allocation in the practice of water protection calls for reliable estimates of the inputs of nutrients to surface waters. The estimation of riverine transport of nutrients is mostly based on daily flow values but relatively infrequent concentration data. The minimum number of samples which fulfills a preset level of precision (scatter) and accuracy (bias) in the load estimates can be evaluated by Monte Carlo techniques. In this study, we applied these techniques to obtain nutrient load estimates for 15 Nordic rivers. The minimum number of samples which produced annual load estimates with a scatter and bias ≤10% varied from 2 to 183 depending e.g. on flow regime and the variation in the concentration of water quality variables, both characteristic for a certain river type. The load of total nitrogen could usually be estimated with a lower number of observations than the load of total phosphorus and suspended solids. In general the most accurate results were obtained when the load was calculated on the basis of the annual flow-weighted the mean concentration. Almost as good results were obtained with a lower number of samples when the load was calculated as the sum of the load in the sampling intervals. The use of annual arithmetic mean concentration often led to highly inaccurate results. A sensitivity analysis showed that the results obtained by the Monte Carlo technique for load of TN are moderately reliable, but those concerning the load of TP may underestimate or on rare occasions overestimate the necessary number of samples.

Keywords
Rivers, nutrient flux, accuracy, precision, monitoring

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Tiivistelmä

Vesiensuojelutoimien oikea kohdentaminen edellyttää, että eri lähteistä tuleva ravinnekuormitus tunnetaan mahdollisimman tarkoin. Jokien ravinnevirtaamien arviointi perustuu yleensä päivittäisiin virtaamatietoihin ja suhteellisen harvoihin pitoisuushavaintoihin. Jokiainevirtaamien luotettavuuteen vaikuttavat pitoisuushavaintojen määrä ja ajoitus sekä ainevirtaaman laskentamenetelmä. Tässä tutkimuksessa määritettiin Monte Carlo -menetelmällä, miten nämä tekijät vaikuttavat ainevirtaama-arvioiden tarkkuuteen ja toistettavuuteen. Tavoitetasoksi asetettiin, että vuotuisten ainevirtaama-arvioiden keskimääräinen virhe ja hajonta olisivat ≤ 10 %. Aineistona oli 15 Pohjoismaista jokivesistöä.

Vuotuinen näytemäärä, joka tuotti luotettavia ainevirtaama-arvioita, vaihteli välillä 2-183. Määrään vaikuttivat mm. virtaamavaihteluiden suuruus, pitoisuushavaintojen jakauma sekä laskentamenetelmä. Kokonaistyppivirtaaman arviointiin tarvittiin yleensä vähemmän näytteitä kuin kokonaisfosfori- ja kiintoainevirtaaman arviointiin. Pienten maatalouden kuormittamien jokien kokonaisfosforivirtaama voitiin luotettavasti arvioida 12-26 näytteellä ja kokonaistyppivirtaama 4-12 näytteellä. Tässä ryhmässä virtaamapainotteinen näytteenotto paransi usein tasaväliseen näytteenottoon verrattuna ainevirtaama-arvioiden tarkkuutta. Keskikokoisista joista tarvittiin kokonaisfosforivirtaaman arvioimiseksi 6-26 ja kokonaistyppivirtaaman arvioimiseksi 2-12 näytettä. Virtaamapainotteinen näytteenotto ei juurikaan parantanut tässä ryhmässä tarkkuutta. Luotettavimmat tulokset saatiin joko virtaamapainotteista keskipitoisuutta käyttäen tai laskien vuotuinen ainevirtaama näytteenottojaksojen ainevirtaaman summana. Isojen säännösteltyjen jokien ainevirtaaman arvioimiseksi tarvittiin yleensä noin 12 tasavälisesti otettua näytettä. Luotettavimmat laskentamenetelmät olivat samat kuin edellisessä ryhmässä.

Pohjoismaissa käytössä olevat näytteenotto-ohjelmat tuottavat luotettavia ainevirtaama-arvioita vain eräiden isojen jokien osalta. Erityisesti pienistä joista pitäisi näytteitä ottaa useammin, jotta ainevirtaama-arvioiden tarkkuudessa ja toistettavuudessa saavutettaisiin tavoitetaso.

Tutkimuksessa arvioitiin Monte Carlo -menetelmän luotettavuutta. Herkkyysanalyysi osoitti, että tutkimuksessa esitetyt kokonaistyppeä koskevat tulokset ovat suhteellisen luotettavia, mutta kokonaisfosforia koskevat tulokset voivat aliarvioda tarvittavaa näytemäärää. Myös yliarviointi on tietyissä tilanteissa kokonaisfosforin osalta mahdollista.

Asiasanat (avainsanat)
Joet, ravinnevirtaama, tarkkuus, toistettavuus, seuranta

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En riktig inriktning av vattenskyddet förutsätter, att man möjligast exakt känner till storleken på den närsaltbelastning som kommer från olika källor. Uppskattningen av älvarnas närsaltflöden baserar sig vanligen på dagliga flödesuppgifter och relativt sällan gjorda haltbestämningar. Tillförlitligheten av uppskattningen av älvarnas ämnesflöden påverkas av haltbestämningarnas antal och tidpunkt samt metoden som används för ämnesflödeskalkylen. I denna undersökning bestämdes med Monte Carlo-metoden på vilket sätt dessa faktorer inverkar på precision och repeterbarhet för uppskattningarna av ämnesflödet. Som målnivå uppställdes, att de årliga ämnesflödesuppskattningarnas fel och spridning skulle vara ≤ 10 %. Föremål för undersökning var 15 älvar i de nordiska länderna.

Det antal prov, som på årsnivå ger tillförlitliga ämnestransportuppskattningar, varierade mellan 2 och 183. Antalet påverkades av bl a storleken i flödesvariationerna, fördelningen av haltbestämningarna och kalkylmetoden. För uppskattningen av det totala kväveflödet behövdes i allmänhet ett färre antal prov än för uppskattning av totalfosforflödet och flödet av suspenderad substans. Totalfosforflödet i mindre åar belastade av jordbruk kunde tillförlitligt uppskattas med hjälp av 12 - 26 prov och totalkväveflödet med endast 4 - 12 prov. I denna grupp förbättrade en flödesstyrd provtagning ofta precisionen i ämnestransportuppskattningarna jämfört med en tidsstyrd provtagning. För uppskattning av totalfosforflödet i de medelstora älvarna behövdes 6 - 26 och för totalkväveflödet 2 - 12 prov. Flödesstyrd provtagning förbättrade inte nämnvärt precisionen i denna grupp. De mest tillförlitliga resultaten erhölls antingen med en flödesvägd medelhalt eller genom att beräkna den årliga ämnestransporten som summan av ämnesflödet under de olika provtagningsperioderna. För en uppskattning av ämnestransporten i de stora reglerade älvarna behövdes i allmänhet ca 12 tidsstyrt tagna prov. De mest tillförlitliga kalkylmetoderna var de samma som i den föregående gruppen.

De provtagningsprogram som tillämpas i de nordiska länderna ger tillförlitliga ämnestransportuppskattningar endast för vissa stora älvar. I synnerhet i de mindre älvarna borde prov tas oftare för att uppnå den uppställda målnivån i frågan om precision och repeterbarhet för ämnestransportuppskattningarna.

I undersökningen utvärderades Monte Carlo-metodens tillförlitlighet. Känslighetsanalysen visade, att de resultat för totalkvävet, som presenteras i undersökningen, är relativt tillförlitliga, men på basis av totalfosforresultaten kan det erforderliga antalet prov underskattas. Också en överskattning är för totalfosforns del i vissa situationer möjlig.

Sakord (nyckelord)
Älvar, närsaltflöde, precision, repeterbarhet, monitoring

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CONTENTS

1 INTRODUCTION

Efficient resource allocation in the practice of water protection calls for reliable estimates of the inputs of nutrients to surface waters. The nutrient fluxes transported by rivers may vary appreciably in time. For example, in small rivers most of the annual flux of particulate nutrients may be transported during a storm period which lasts only few days (e.g. Walling and Webb, 1982; Meade and Parker, 1984). The probability that flow peaks are missed and river fluxes consequently underestimated increases with decreasing sampling frequency. Limited resources do not allow sufficient sampling frequency in most rivers. When sampling is infrequent, the reliability of the load estimates depends on the frequency and timing of sampling. In addition, the results are affected by the load calculation method, i.e. how concentrations during the unsampled days are estimated.

Monte Carlo simulation techniques have commonly been used to design optimal sampling schemes and load calculation methods (Walling and Webb, 1982; Richards and Holloway, 1987; Young et al., 1988; Rekolainen et al., 1991; deVries and Klavers, 1994). With these techniques it is possible to evaluate the accuracy, i.e. the lack of systematic bias, and the precision, i.e. the degree of scatter of the load estimates. The application of Monte Carlo techniques requires that frequent, e.g. daily observations are available, or at least that observations are frequent enough to allow the use of interpolation or extrapolation methods for estimating the values between sampling occasions.

Monitoring of riverine nutrient fluxes in Nordic countries is mainly based on daily flow measurements and on relatively infrequent sampling. Three different load calculation methods are in use (Holtan and Holtan, 1993). Although the accuracy and precision of nutrient flux in two small agricultural rivers in Denmark (Bruhn and Kronvang, 1990) and in two agricultural basins in Finland (Rekolainen et al., 1991) have been assessed, the reliability of Nordic river load estimates has not generally been evaluated.

The aim of this study was to estimate the accuracy and precision of nutrient load estimates of different types of Nordic rivers by the Monte Carlo technique. In addition, an optimal sampling scheme and load calculation method for Nordic rivers was assessed.

2 MATERIALS AND METHODS

2.1 Description of the rivers

A total of 15 Nordic rivers were chosen for the study (Table 1, Fig. 1). They included small unregulated and large regulated rivers, rivers loaded by industrial waste waters and rivers draining agricultural areas. Soil types in the drainage basin varied from clay to volcanic soils and land use from field cultivation to forested areas (Table 2).

Table 1. Rivers included in this study.

Country River, station	Coordinates	
	Latitude	Longitude
Denmark:		
Gelbæk, 210002	56°13'05"	9°49'06"
Gjern, 210009	56°12'59"	9°41'40"
Finland:		
Eurajoki, 12 Va6700	61°06'22"	22°10'34"
Kymijoki at Ahvenkoski	60°29'45"	26°27'48"
Paimionjoki, Va6301	60°27°42"	22°40'48"
Pyhäjoki, P1	61°01'50"	22°24'19"
Yläneenjoki, P2	60°52'18"	22°24'47"
Iceland:		
Fossá at Jaðar, VHM 127	64°16'06"	-20°11'46"
Þjórsá at Urriðafoss, VHM 30	63°55'59"	-20°38'07"
Norðurá at Stekk, VHM128	64°42'39"	-21°36'26"
Norway:		
Glomma at Sarpsfoss	59°16'40"	11°08'02"
Otra at Skråstad	58°11'15"	7°57'15"
Vefsna at Mosjøen	65°44'58"	13°14'21"
Sweden:		
Dalälven at Älvkarleby krv	60°33'89"	17°26'69"
Skivarpsån at Tånemölla	55°26'97"	13°35'74"

Daily flow observations were available for all the rivers. The number of annual water samples varied from 6-12 in the Icelandic rivers to more than 300 in the Danish rivers. The water quality data usually included total phosphorus (TP) and total nitrogen (TN). In addition, suspended solids (SS) and dissolved nutrients were studied in some rivers (Table 3).

The two **Danish** rivers included in this study (R. Gjern and Gelbæk) are both small and unregulated (Table 2). They belong to the Gudenå system in eastern Jutland. The Gelbæk is the smallest river in this study (drainage basin 8.5 km^2) and is a tributary of the R. Gjern. The drainage basins of both rivers are mostly cultivated and are composed of moraines and clay. The Gelbæk also receives loading from a sparse population.

The flow in the Gjern was moderately even in 1988; a flood occurred in January-March, but the peak flows were not high (Fig. 2). The coefficient of variation (CV) for the flow was low (Table 4). The concentrations of TP varied more than the flow (Table 4, Fig. 1). The concentrations were highest in summer and correlated inversely but weakly with the flow (Table 5). The concentrations of TN varied less than the concentrations of TP (Table 4, Fig. 2) and correlated strongly with the flow (Table 5).

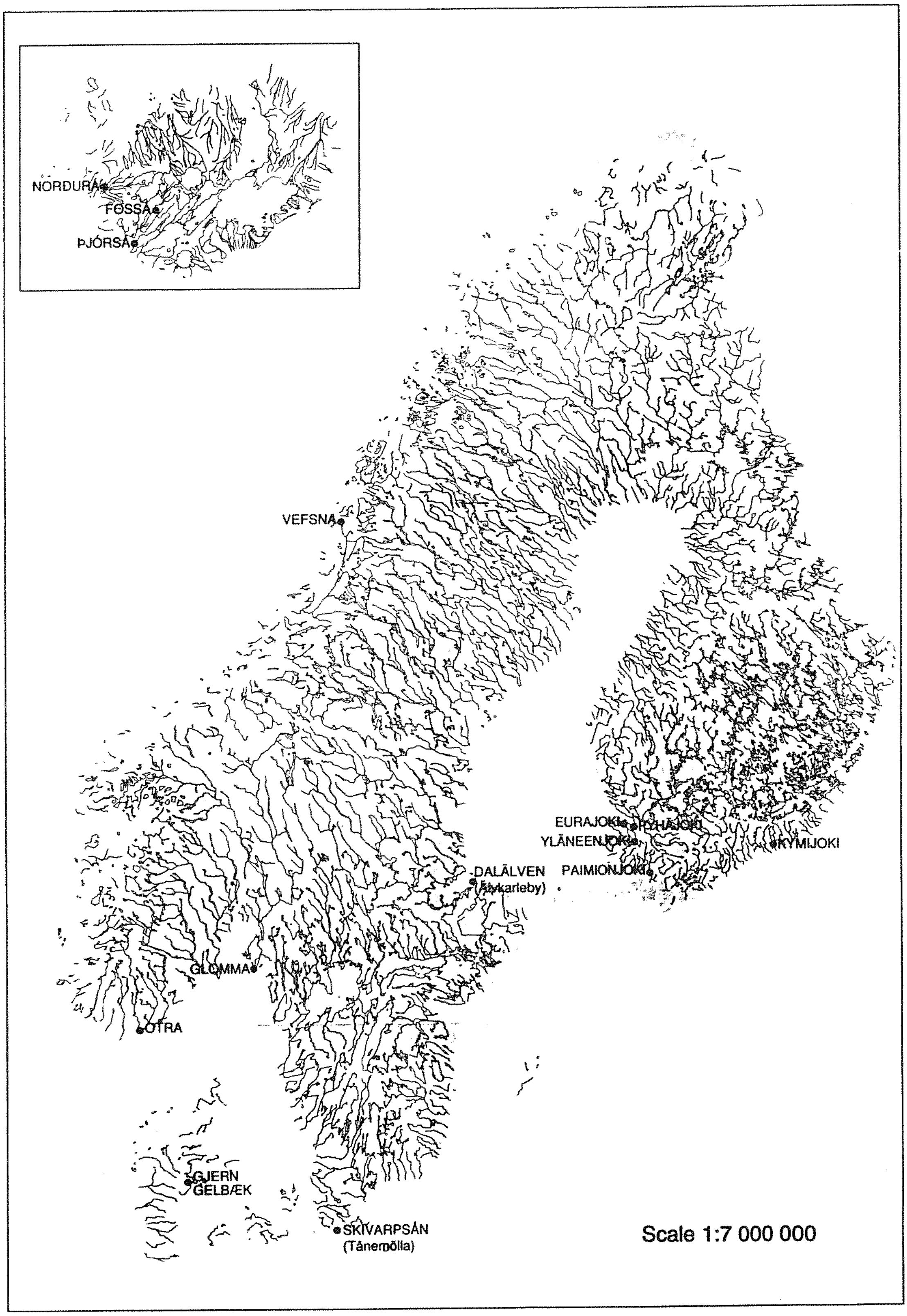


Fig. 1. Rivers included in this study.

Table 2. Flow data and the characteristics of the drainage basins of the rivers (Environment Data Base, National Board of Waters and the Environment, Finland; Forsberg and Löfgren, 1988; Hamarsland and Nagy, 1989; Hindar et al., 1993; Holtan, 1990; National Energy Authority, Hydrological Survey Iceland; Norwegian Water Information System; Norwegian Water Resources and Energy Administration; SMHI Hydrologi, 1993). CV=coefficient of variation, 1=During the study years, 2=Bifurcation, 3=Runoff from an area of 318.5 km^2 has been led to another watercourse.

Country River	Flow[1]			Drainage area				Regulation
	Mean		CV	Area	Agricultural areas	Forests	Lakes	
	m^3 s^{-1}	l s^{-1} km^{-2}		km^{-2}	%	%	%	
Denmark:								
Gelbæk	0.07	8.24	1.442	8.5	93	4	0	-
Gjern	1.27	11.6	0.503	110	80	13	<1	-
Finland:								
Eurajoki	5.7	9.3	0.614	615	15	58	25	-
Kymijoki[2]	182	9.6	0.201	37,159	6	75	17	+
Paimionjoki	10.9	9.8	1.486	1088	43	54	2	(+)
Pyhäjoki	0.78	9.7	1.158	77.5	23	77	0	-
Yläneenjoki	2.5	10.7	1.288	234	26	72	0	-
Iceland:								
Fossá	1.41	47.0	1.093	30	0	0	<1	-
Þjórsá	394	54.7	0.384	7200	<10	0	1	(+)
Norðurá	28.8	57.6	1.354	500	?	0	1	-
Norway:								
Glomma	645	16.0	0.442	41,218	6	43	3	+
Otra	164	44.0	0.473	3730	1	35	4	+
Vefsna[3]	185	48.8	0.868	4113	1	16	2	(+)
Sweden:								
Dalälven	329	11.4	0.376	28,959	4	74	6	+
Skivarpsån	0.717	7.0	1.113	102	≤96	3	1	-

Table 3. Number of water samples and the water quality variables included in the study. TP=total phosphorus, RP=reactive phosphorus (PO_4-P from unfiltered sample), DP=dissolved phosphorus (TP from filtered sample), DRP=dissolved reactive phosphorus (PO_4-P from filtered sample), TN=total nitrogen, NO_3-N=nitrate nitrogen, NH_4-N=ammonium nitrogen, SS=suspended solids.

Country River	Number of samples ($year^{-1}$)	Years	Variables
Denmark:			
Gelbæk	325	1988	TN, TP
Gjern	341	1988	TN, TP
Finland:			
Eurajoki	11-43	1991-1992	TP TN
Kymijoki	17-40	1985,1986, 1993	TP, TN
Paimionjoki	40-50	1985, 1988-1990	TP, DP, DRP, NO_3-N, SS
Pyhäjoki	20-52	1991-1992	TP, TN
Yläneenjoki	42-52	1991-1992	TP, TN
Iceland:			
Fossá	11-12	1972,1973	RP, NO_3-N, NO_2-N, NH_4-N
Þjórsá	11-12	1972,1973	RP, NO_3-N, NO_2-N, NH_4-N
Norðurá	6-11	1973,1974	RP, NO_3-N, NO_2-N, NH_4-N
Norway:			
Glomma	16-18	1990-1992	TP, TN, SS
Otra	12	1990,1991	TP, TN, SS
Vefsna	20	1990,1991	TP, TN, SS
Sweden:			
Dalälven	9	1990, 1992	TP, RP, NO_3-N, NO_2-N, NH_4-N
Skivarpsån	24	1990-1992	TP, RP, NO_3-N, NO_2-N, NH_4-N

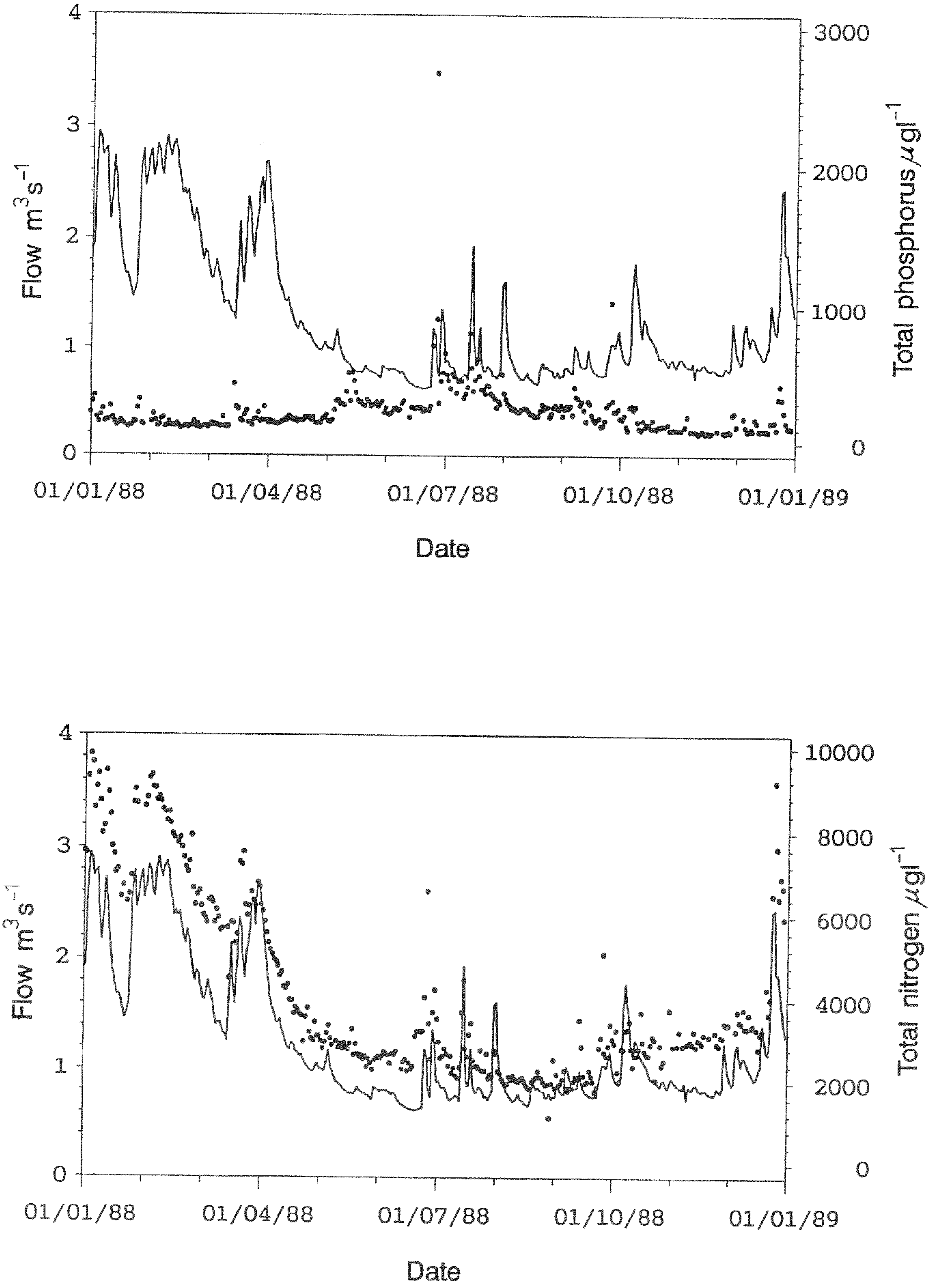


Fig. 2. Flow and the concentrations of total phosphorus and total nitrogen in the river Gjern in 1988.

The flow varied appreciably more in the Gelbæk than in the Gjern (Table 4); in the Gelbæk the peaks in winter were relatively higher, whereas the flow in summer was lower. The CV for the concentration of TP was, however, smaller in the Gelbæk than in the Gjern. TP did not correlate with the flow (Table 5). The correlation between TN and flow was lower than in the Gjern.

Table 4. Coefficient of variation for the flow and the concentration of total phosphorus (TP) and total nitrogen (TN) in the Danish rivers.

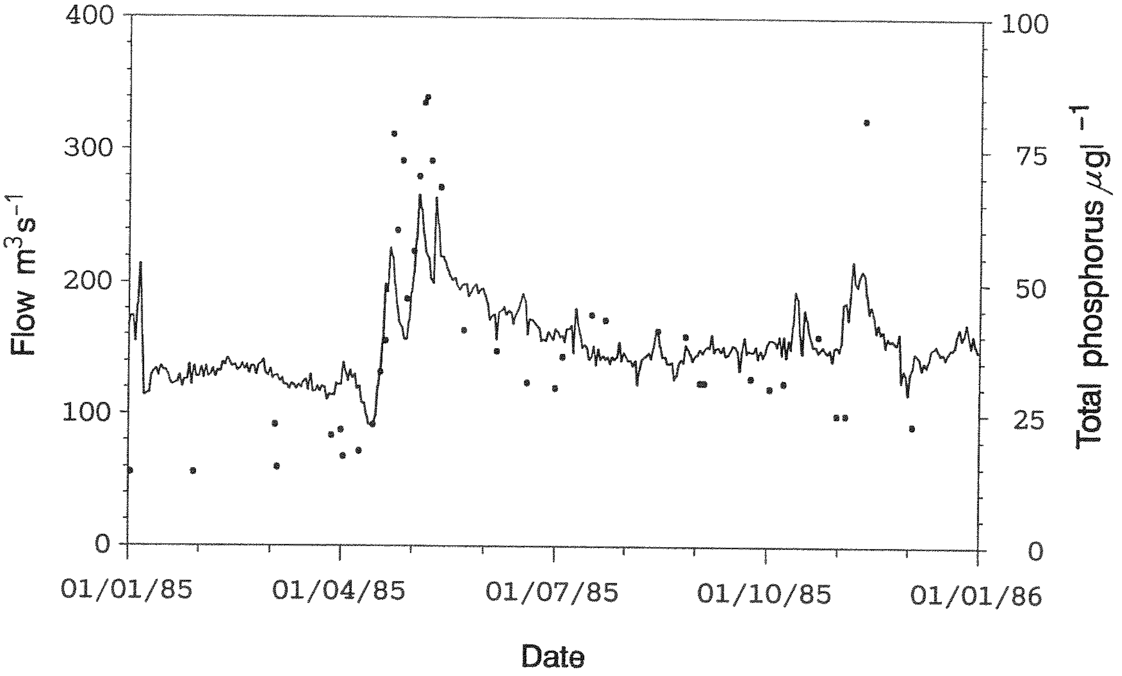
River	Q	TP	TN
Gjern	0.503	0.798	0.530
Gelbæk	1.442	0.641	0.648

Table 5. Correlation between the flow and the concentration of total phosphorus and total nitrogen in the Danish rivers. Statistical significance level: 1=P<0.001, 2=P<0.05, 3=P<0.01, ns=statistically not significant.

River	Q-TP	Q-TN
Gjern	-0.180^{1}	0.941^{1}
Gelbæk	0.000^{ns}	0.761^{1}

Five rivers from **Finland** were included in this study. The Kymijoki is one of the largest rivers in Finland. There are many lakes in the upper and middle reaches of the river. The lower reaches are regulated by hydroelectric power plants and have a high proportion (30 %) of cultivated fields. Pulp and paper mills and municipalities also discharge appreciable amounts of nutrients into the lower reaches. The Kymijoki discharges into the Gulf of Finland via two branches, of which the Ahvenkoski branch is included in this study. The rivers Eurajoki, Paimionjoki, Pyhäjoki and Yläneenjoki are small agriculturally loaded rivers in southwestern Finland (Table 2). The drainage basin of the river Paimionjoki is composed mainly of clay and fine sand, whereas the other rivers are situated on slightly coarser soils. From these small rivers only the R. Eurajoki is clearly regulated and has a large lake in its drainage basin (Table 2).

In the Kymijoki the flow was relatively even; the peak flows in spring and autumn were not appreciably higher than the flow during other seasons (Fig. 3). The CV for the flow was lower than in any other river in this study (Table 6). The CV for the concentrations of TP and TN were also rather low (Table 6, Fig. 3). TN correlated positively with the flow, whereas the level and sign of the correlation between TP and flow varied from year to year (Table 7).



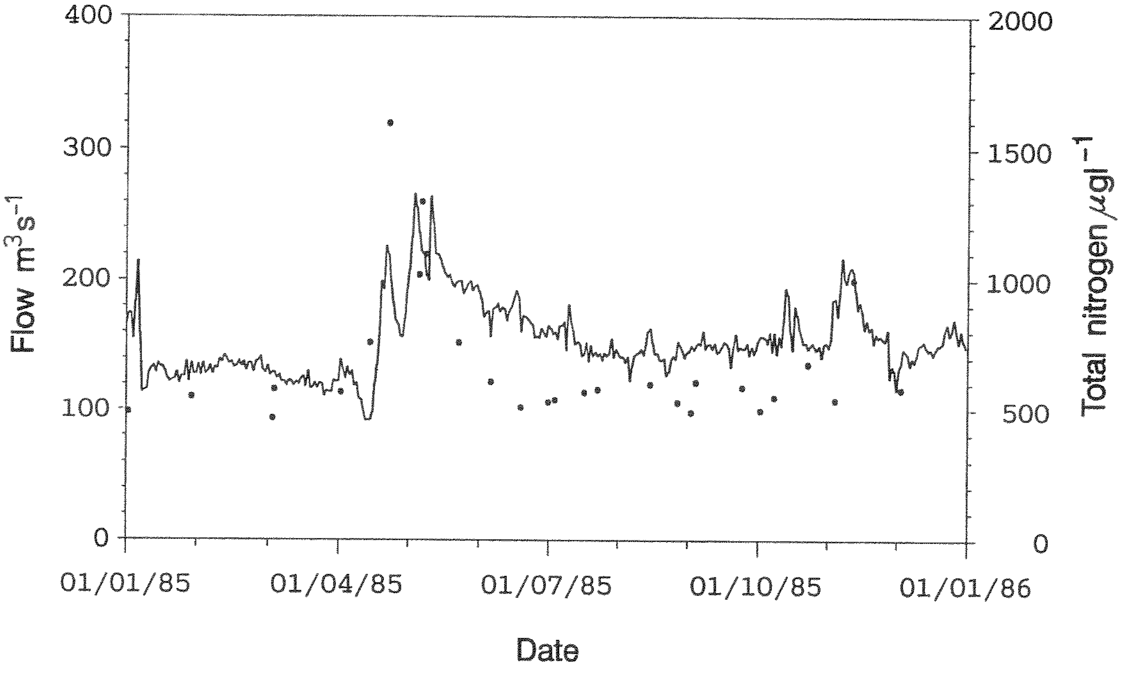
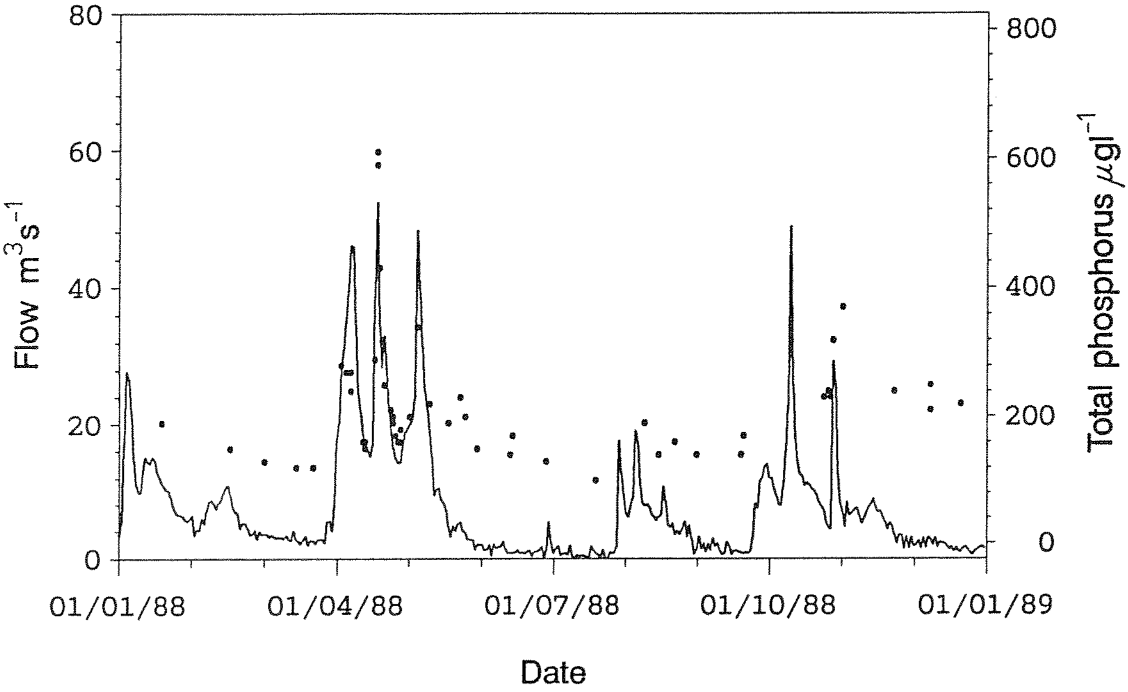


Fig. 3. Flow and the concentrations of total phosphorus and total nitrogen in the river Kymijoki in 1985.



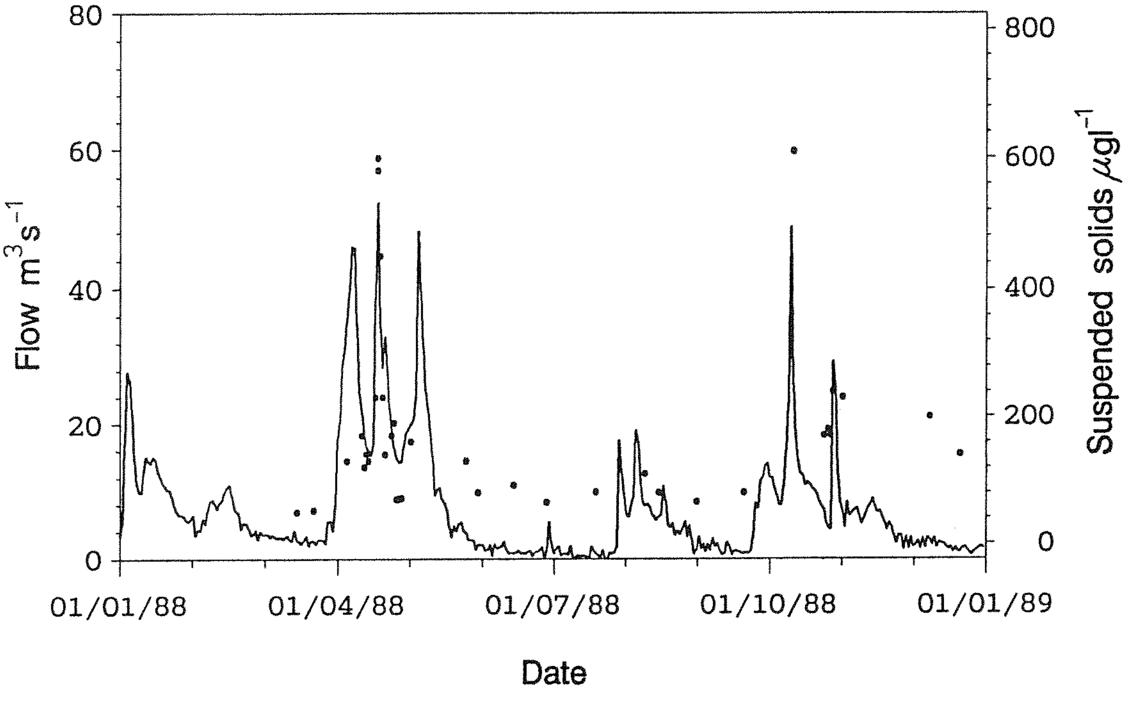


Fig. 4. Flow and the concentrations of total phosphorus and suspended solids in the river Paimionjoki in 1988.

The CV for the flow in the Paimionjoki was higher than in any other river in this study (Table 6). The flow was almost zero during dry periods, whereas it increased rapidly during snow-melt events and rains (Fig. 4). In addition to TP and TN, suspended solids (SS) and the dissolved nutrients were studied in the Paimionjoki. The concentrations of all water quality variables had a lower CV than the flow (Table 6, data on dissolved nutrients not presented). The concentrations of suspended solids (SS) varied most widely (see Fig. 4). All the water quality variables correlated positively with the flow (Table 7), the correlation being strongest for TP and SS.

In the Pyhäjoki and Yläneenjoki the CV for the flow was slightly lower than in the Paimionjoki (Table 6). The CVs for TP and TN in all three rivers were at the same level. As in the Paimionjoki, the correlation between the flow and TP and TN was positive in the Pyhäjoki and Yläneenjoki (Table 7). In the Eurajoki, the flow varied much less than in the Paimionjoki, Pyhäjoki and Yläneenjoki. The correlation between the flow and water quality variables was also lower and more obscure.

Table 6. Coefficient of variation for the flow and the concentrations of total phosphorus (TP), total nitrogen (TN) and suspended solids (SS) in the Finnish rivers.

River Year	Q	TP	TN	SS
Kymijoki:				
1985	0.184	0.519	0.398	..
1986	0.170	0.343	0.214	..
1993	0.250	0.511	0.176	..
Eurajoki:				
1991	0.536	0.470	0.475	..
1992	0.692	0.645	0.366	..
Paimionjoki:				
1985	1.776	0.398	0.317	0.749
1988	1.152	0.560	0.393	0.825
1989	1.528	0.367	0.561	0.559
1990	1.556	0.542	0.562	0.660
Pyhäjoki:				
1991	1.185	0.121	0.560	..
1992	1.130	0.267	0.376	..
Yläneenjoki:				
1991	1.298	0.666	0.475	..
1992	1.278	0.431	0.509	..

Table 7. Correlation between the flow and the concentrations of total phosphorus, total nitrogen and suspended solids in the Finnish rivers. Statistical significance levels as in Table 5.

River Year	Q-TP	Q-TN	Q-SS
Kymijoki:			
1985	0.791^1	0.700^1	..
1986	0.423^3	0.799^1	..
1993	-0.231	0.654	..
Eurajoki:			
1991	0.373^{ns}	-0.302^{ns}	..
1992	0.063^{ns}	0.190^{ns}	..
Paimionjoki:			
1985	0.787^3	0.289^3	0.857^1
1988	0.632^1	0.385^2	0.724^1
1989	0.697^1	0.209^{ns}	0.788^1
1990	0.777^1	0.328^3	0.782^1
Pyhäjoki:			
1991	0.816^1	0.846^1	..
1992	0.463^1	0.740^1	..
Yläneenjoki:			
1991	0.713^1	0.686^1	..
1992	0.479^1	0.584^1	..

The **Icelandic** rivers chosen for this study (the rivers Þjórsá, Fossá and Norðurá) are situated in the southwestern and western parts of the country. The rivers are loaded mainly by animal husbandry. A total of 14% of the drainage basin of the Þjórsá consists of glaciers and 10% of the drainage basin is regulated. The two other rivers are not regulated. The Fossá is a tributary of the Hvitá.

The flow varied appreciably in the Norðurá (Table 8), whereas in the Þjórsá it was relatively even. The concentration of reactive phosphorus (RP) varied markedly in all rivers. In the Norðurá, the concentration of NO_3-N also varied widely. The correlation between the concentrations and flow were relatively low and irregular in all the rivers (Table 9).

Table 8. Coefficient of variation for the flow and the water quality variables in the Icelandic rivers.

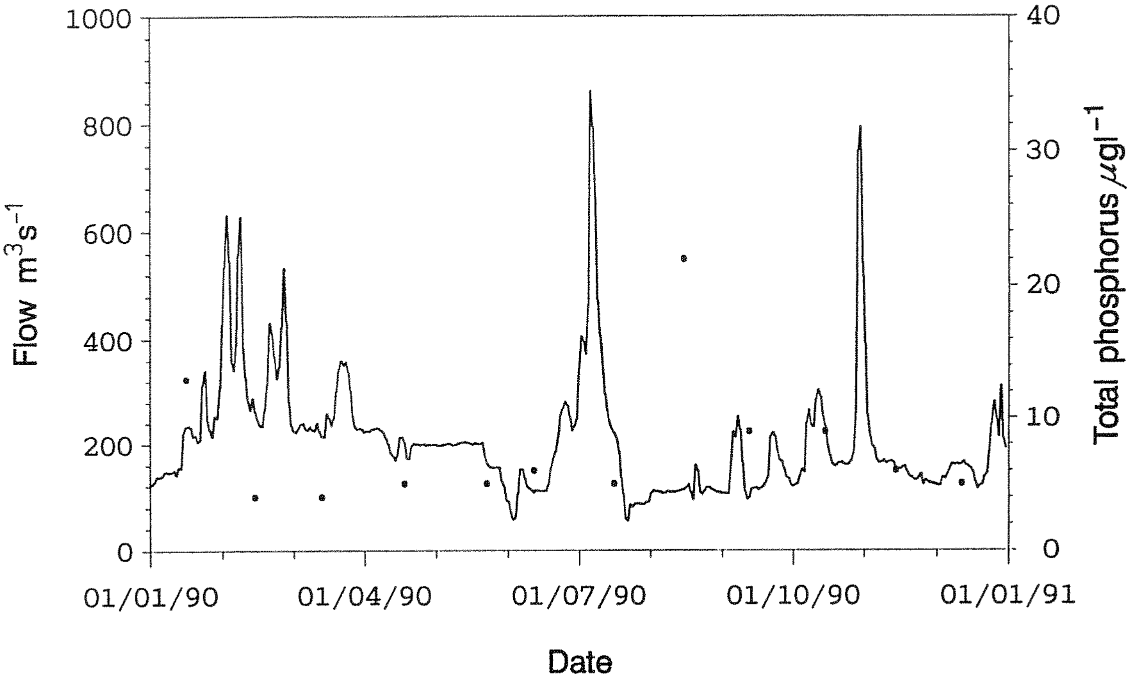
River Year	Q	RP	NO_3-N	NO_2-N	NH_3-N
Norðurá:					
1973	1.280	0.805	1.129	0.437	0.483
1974	1.427	0.335	1.079	0.256	0.485
Þjórsá:					
1972	0.459	0.815	0.381	0.574	0.489
1973	0.309	0.708	0.530	0.418	1.189
Fossá:					
1972	0.932	1.363	0.768	0.247	0.588
1973	1.253	2.099	0.840	0.367	0.358

Table 9. Correlation between the flow and the water quality variables in the Icelandic rivers. Statistical significance level as in Table 5.

River Year	Q-RP	Q-NO_3-N	Q-NO_2-N	Q-NH_3-N
Norðurá:				
1973	0.436^{ns}	-0.655^{ns}	-0.544^{ns}	-0.798^{3}
1974	0.312^{ns}	-0.171^{ns}	-0.265^{ns}	0.846^{2}
Þjórsá:				
1972	-0.235^{ns}	-0.252^{ns}	-0.537^{ns}	0.335^{ns}
1973	-0.031^{ns}	-0.498^{ns}	-0.264^{ns}	-0.247^{ns}
Fossá:				
1972	-0.065^{ns}	0.596^{ns}	-0.224^{ns}	-0.567^{ns}
1973	-0.130^{ns}	0.218^{ns}	-0.220^{ns}	-0.105^{ns}

Of the three **Norwegian** rivers included in the study the Otra and the Vefsna are intermediate in size, whereas the Glomma is the largest river included in this study. The Otra, in southern Norway, is loaded by effluents from pulp and paper mill industry and by municipalities. Owing to regulation for energy production, the winter discharges have increased, whereas floods and summer discharges have decreased (Hindar, 1993). The CV for the flow and for the concentrations of TP, TN and SS was relatively low (Table 10). The concentrations of TP and SS correlated inversely with flow, although the correlation was not strong (Table 11, see also Fig. 5).

The Vefsna is situated in northern Norway. A total of 14% of its mountainous drainage basin belongs to Sweden. The river is loaded by municipalities, a sparse rural population, industry and agriculture. However, the load is relatively low taking into account the flow in the river (Hamarsland and Nagy, 1989). There are no hydroelectric power plants of any importance along the Vefsna. A flow peak occurs in June and one or more smaller ones in the first half of October. Winter flows are relatively even and small. The CV for the flow was larger than in the other Norwegian rivers (Table 10). The variation in the concentrations of SS and TN was greater than in the Otra (Table 8, Fig. 5).



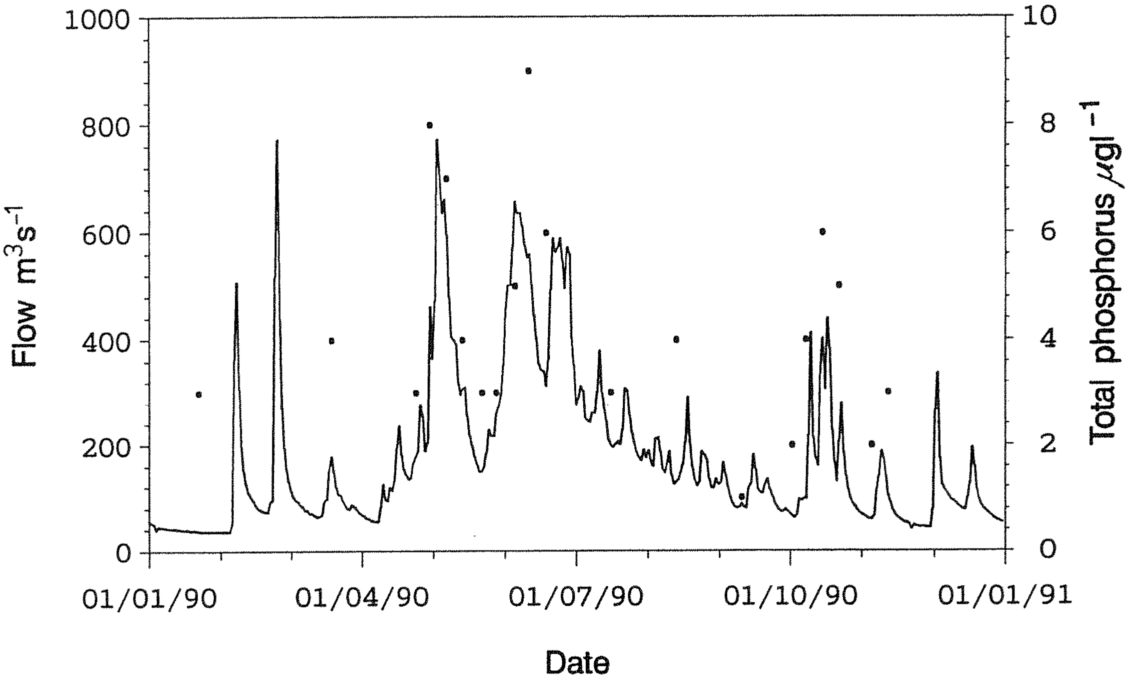


Fig. 5. Flow and the concentration of total phosphorus in the rivers Otra and Vefsna in 1990.

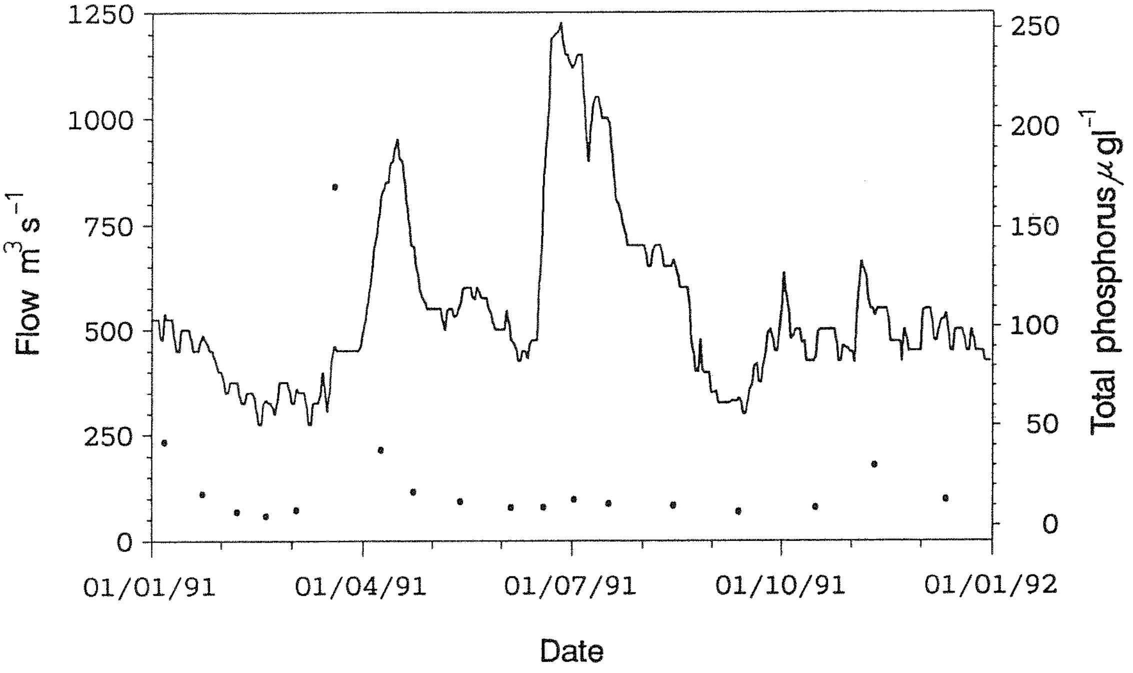
The Glomma is a large regulated river in southern Norway. The regulation has increased the winter flows (Holtan, 1990). The CV for the flow was low (Table 10). Soil erosion in the lower reaches increases the concentrations of SS and TP during floods (Holtan, 1990). Consequently, the variation in the concentration of SS and TP was very high (Table 10, Fig. 6). There were no correlations between the flow and the concentrations of TP, TN or SS (Table 11).

Table 10. Coefficient of variation for the flow and the concentrations of total phosphorus (TP), total nitrogen (TN) and suspended solids (SS) in the Norwegian rivers.

River Year	Q	TP	TN	SS
Otra:				
1990	0.555	0.672	0.169	0.407
1991	0.391	0.233	0.106	0.484
Vefsna:				
1990	0.887	0.430	0.577	0.829
1991	0.848	0.488	0.328	1.194
Glomma:				
1990	0.445	1.291	0.286	2.057
1991	0.374	1.613	0.423	1.021
1992	0.506	1.345	0.496	2.314

Table 11. Correlation between the flow and the concentrations of total phosphorus, total nitrogen and suspended solids in the Norwegian rivers. Statistical significance level as in Table 5.

River Year	Q-TP	Q-TN	Q-SS
Otra:			
1990	-0.331^{ns}	0.288^{ns}	-0.819^{2}
1991	-0.678^{3}	0.266^{ns}	-0.514^{3}
Vefsna:			
1990	0.648^{2}	-0.383^{ns}	0.537^{3}
1991	0.806^{1}	0.130^{ns}	0.638^{2}
Glomma:			
1990	-0.022^{ns}	-0.352^{ns}	-0.013^{ns}
1991	-0.079^{ns}	-0.147^{ns}	0.041^{ns}
1992	-0.133^{ns}	-0.323^{ns}	-0.088^{ns}



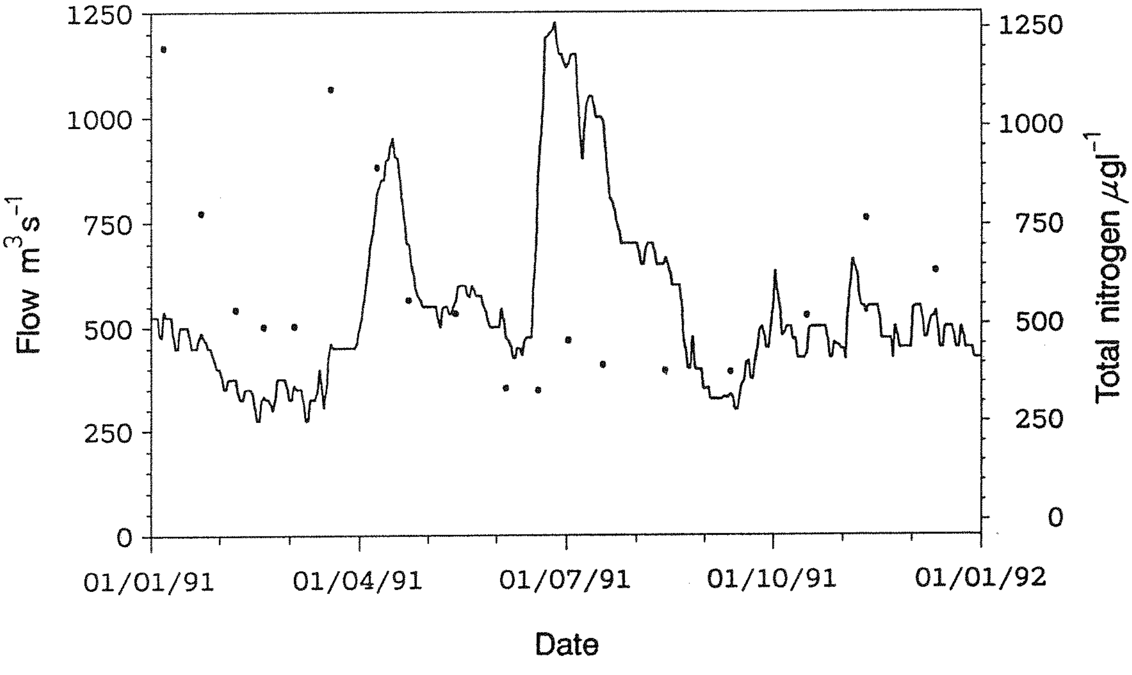


Fig. 6. Flow and the concentrations of total phosphorus and total nitrogen in the river Glomma in 1991.

Two **Swedish** rivers were included in this study. The Dalälven is a large regulated river in central Sweden. The Skivarpsån is a small, agriculturally loaded unregulated river in the southernmost part of the country. The large-scale variation in the flow of the Dalälven was not very high, but the short-term variation was appreciable (Fig. 7). The CVs for the flow and concentrations were rather small in the Dalälven (Table 12, Fig. 7). In the river the flow and the concentrations of TP, RP and nitrite nitrogen (NO_2-N) did not fluctuate much, but the concentrations of nitrate nitrogen (NO_3-N) and ammonium nitrogen (NH_4-N) varied substantially (Table 12). The correlation between the water quality variables and the flow was generally low (Table 13).

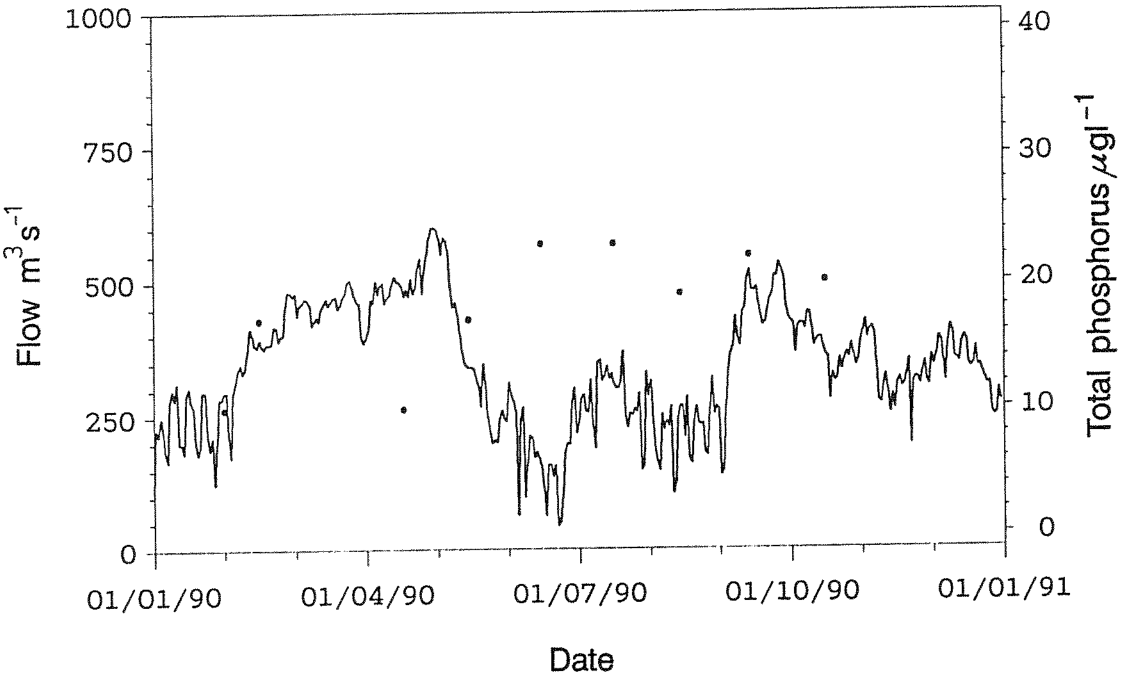
In the Skivarpsån the flow varied appreciably (Table 12, Fig. 8). The variation in the concentration was more obscure but at the same level as in the Dalälven. The concentration of NO_3-N correlated positively with the flow; the correlation between other water quality variables and flow was low (Table 13).

Table 12. Coefficient of variation for the flow and the water quality variables in the Swedish rivers.

River Year	Q	TP	RP	NO_3-N	NO_2-N	NH_4-N
Dalälven:						
1990	0.334	0.280	0.354	0.951	0.300	0.750
1992	0.418	0.330	0.305	0.736	0.425	0.801
Skivarpsån:						
1990	0.968	0.834	0.744	0.538	0.555	0.795
1991	1.221	0.415	0.512	0.439	0.682	0.923
1992	1.151	0.341	0.434	0.715	0.989	0.738

Table 13. Correlations between the flow and the water quality variables in the Swedish rivers. Statistical significance level as in Table 5.

River Year	Q-TP	Q-RP	Q-NO_3-N	Q-NO_2-N	Q-NH_4-N
Dalälven:					
1990	-0.259^{ns}	-0.381^{ns}	0.499^{ns}	0.169^{ns}	-0 .087^{ns}
1992	-0.595^{3}	-0.479^{ns}	0.573^{ns}	0.580^{ns}	0.339^{ns}
Skivarpsån:					
1990	-0.232^{ns}	-0.424^{3}	0.892^{1}	0.167^{ns}	0.534^{3}
1991	-0.316^{ns}	-0.415^{3}	0.790^{1}	0.321^{ns}	0.278^{3}
1992	-0.113^{ns}	-0.463^{2}	0.904^{1}	0.010^{ns}	0.082^{ns}



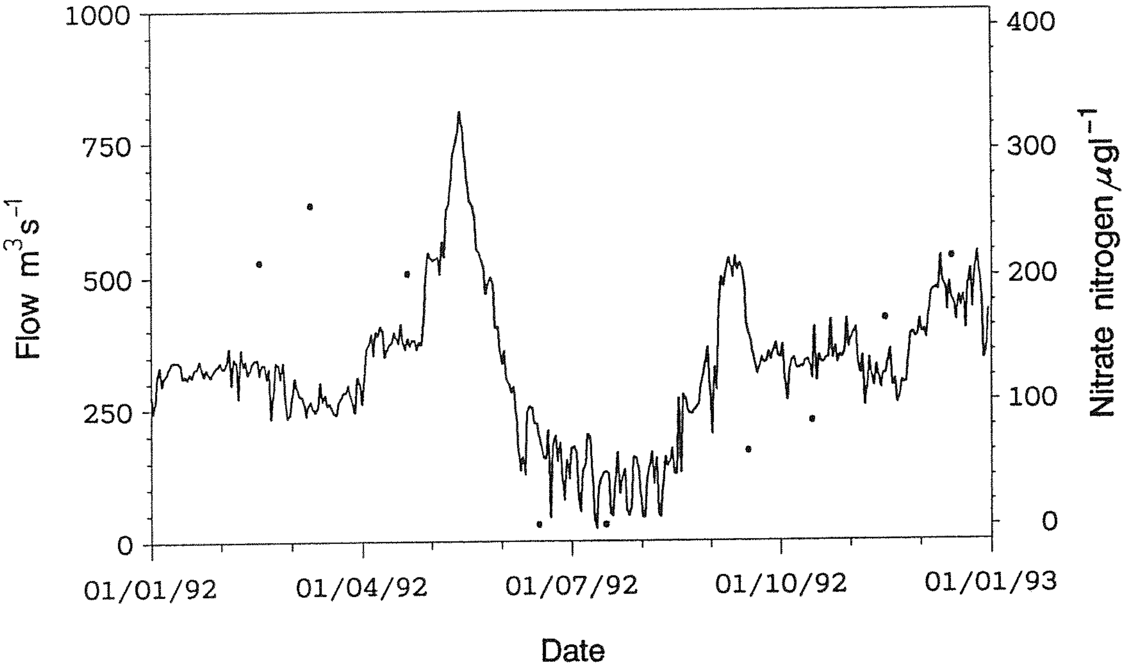


Fig. 7. Flow and the concentration of total phosphorus and nitrate nitrogen in the river Dalälven.

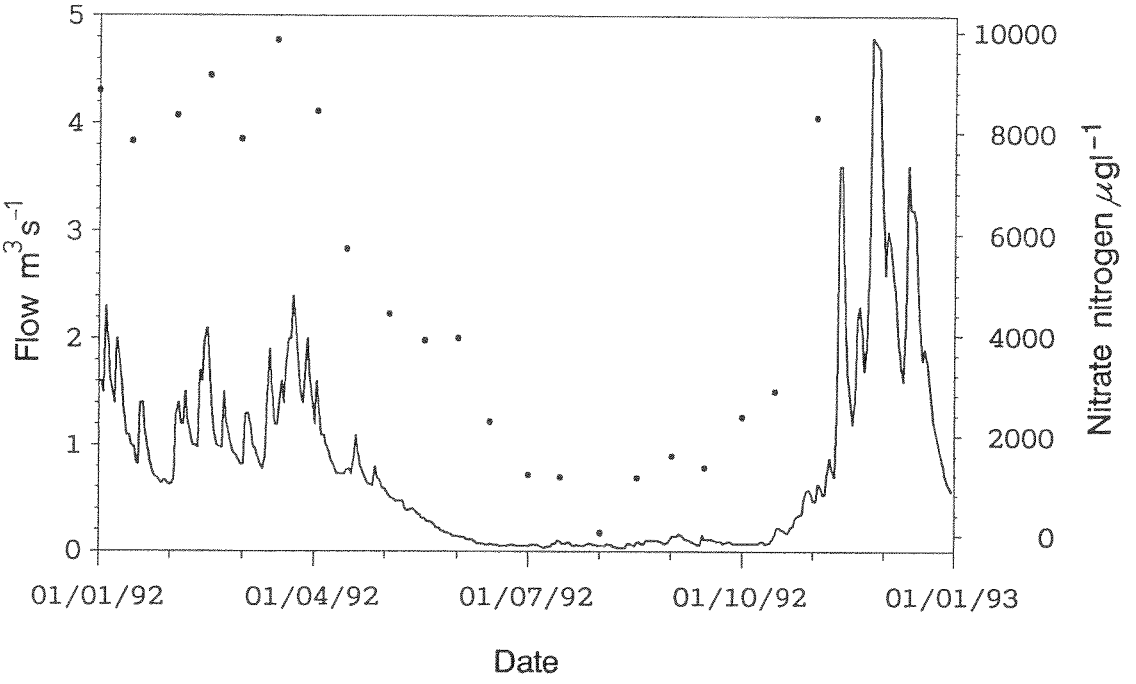


Fig. 8. Flow and the concentration of nitrate nitrogen in the river Skivarpsån in 1992.

2.2 The Monte Carlo method

In this study the Monte Carlo method of Rekolainen et al. (1991) was applied. With this technique, we compared three load calculation methods, using a regular time-dependent sampling strategy. In addition, two flow-weighted sampling strategies were tested for some rivers. To improve the reliability of results from the Monte Carlo runs, several years (up to four) were tested for all but the Danish rivers.

Daily data sets of concentrations were constructed from the observations by linear interpolation. The linearly interpolated data was used to produce replicate annual load estimates for different sampling schemes and frequencies. These estimates were compared with the reference load which was obtained by summing up the product of the interpolated daily concentration with the observed daily flow.

When a regular sampling strategy was used, the year under study was divided into a fixed number (N=1, 2, 4, 6, 12, 26, 52, 91 and 183) of sampling intervals (T_i) of regular length ((365+1)/N). The remainder (last days of the year) was added to the last interval. Within each sampling interval, a concentration at day t_i was selected randomly from the linearly interpolated data resulting in a set of concentrations. The selection was repeated 1000 times. Using these replicate data sets the annual load was calculated with the following methods:

In **Method 1** (mean discharge per interval) the annual load L was calculated by summing up the load in the sampling intervals:

$$L=\sum_{i=1}^{N} c(t_i)\,Q[T_i] \qquad (1)$$

where $c(t_i)$ is the concentration at day t_i obtained from the interpolated data set and $Q[T_i]$ is the discharge for the sampling interval T_i . N is the number of sampling intervals and thus the number of samples taken.

In **Method 2** (simple equation) the annual load was computed as the product of the annual discharge Q_a and the annual arithmetic mean of the concentrations at the sampling times t_i:

$$L=\frac{Q_a}{N}\sum_{i=1}^{N} c(t_i) \qquad (2)$$

In **Method 3** (weighted concentration) the annual load was calculated as the product of the annual discharge and the flow-weighted mean of the concentrations at the sampling times t_i :

$$L=\frac{Q_a\overline{L}}{\overline{Q}} \qquad (3)$$

where $\bar{L}$ and $\overline{Q}$ are the mean sampled load and flow, respectively:

$$\overline{L}=\frac{1}{N}\sum_{i=1}^{N} c(t_i)\,Q(t_i) \qquad (4)$$

$$\overline{Q}=\frac{1}{N}\sum_{i=1}^{N} Q(t_i) \qquad (5)$$

In the flow-weighted sampling **Strategy 1**, the year was divided into a fixed number of pre-set sampling periods and into outlying periods. The sampling periods were determined subjectively from the flow data and they included the high flow periods. The number of samples taken during each sampling period was proportional to the flow in the period. The load in the sampling periods was calculated with Method 1. The load in the outlying period was estimated by Method 3, replacing the annual discharge by the discharge outside the sampling periods. The annual load was obtained by adding the two resulting values. In **Strategy 2** there were no outlying periods; the year was divided into subperiods which were sampled proportionally to the flow.

The replicate load estimates were used to calculate the bias and scatter (accuracy and precision) of the load calculation method. The bias describes the deviation of a load estimate from the reference value:

$$bias = 100 \frac{L_{est} - L_{ref}}{L_{ref}} \% \qquad (6)$$

where L_{est} is the mean value of the load computed from the replicate runs and L_{ref} is the reference load:

$$L_{ref} = \sum_{k=1}^{365(+1)} Q_k c_k \qquad (7)$$

where Q_k is the daily flow and c_k the daily interpolated concentration value. A negative bias value indicates that the estimated load is lower than the reference load and *vice versa*.

The scatter around the mean value is computed as the coefficient of variation of the replicate runs:

$$scatter = 100 \frac{S_{est}}{L_{est}} \% \qquad (8)$$

where S_{est} is the standard deviation of the replicate load estimates.

3 RESULTS

3.1 Danish rivers

River Gjern:

Using regular sampling and Method 1 for load calculation, a total of 26 annual samples produced load estimates with ≤10% scatter and bias for TP (Table 14). If the load was calculated with Methods 2 or 3, the same level of accuracy and precision was obtained with 52 annual samples. Correspondingly, the load of TN could be estimated with ≤10 % scatter and bias with 6 annual samples when Method 1 was used and with 12 annual samples when Method 3 was used (Table 14).

With a given number of samples, Method 3 produced slightly more accurate but less precise results than Method 1. Method 2 gave the least accurate results. Owing to the positive correlation between the flow and TN concentrations, Method 2 underestimated the load of TN by about 25% regardless of the number of samples. The method overestimated slightly (7%) the load of TP.

The flow-weighted sampling strategy (Strategy 2) improved neither the accuracy nor the precision of the TP load estimates, evidently due to the weak correlation between the concentrations and flow. Compared with Method 1, the flow-weighted sampling strategy increased slightly the accuracy of the TN load. However, the frequency of sampling could not be reduced with flow-weighted sampling.

Gelbæk:

Using regular sampling, the load of TP could be estimated with ≤10% scatter and bias with 26 to 183 annual samples depending on the load calculation method (Table 14). On the other hand the load of TN could be estimated with only 4 to 6 samples. As observed for the R. Gjern, Method 3 was slightly more accurate and less precise than Method 1. Method 2 underestimated appreciably the load of TN. Although the correlation between the flow and TN was weaker in the Gelbæk than in the R. Gjern (Table 5), the underestimation of the TN load was greater (about 70 %) in the Gelbæk. This was probably due to the higher variation in the TN concentrations and especially in the flow in the Gelbæk.

The flow-weighted sampling strategy (Strategy 2) improved the precision of the load estimates. Using this strategy, a total of 52 and 4 annual samples gave precise and accurate load estimates for TP and TN, respectively (Table 14).

Table 14. Number of annual samples (N) resulting in a scatter and bias of ≤ 10% for the annual load of total phosphorus and total nitrogen in the Danish rivers. Bias of the corresponding load estimates is also given.

River Method	TP		TN	
	N	Bias (%)	N	Bias (%)
Gjern:				
Method 1	26	-2	6	-5
Method 2	52	7	-	-
Method 3	52	-1	12	-1
Strategy 2	26	-2	6	-4
Gelbæk:				
Method 1	183	-4	6	-5
Method 2	26	4	-	-
Method 3	183	0	6	-2
Strategy 2	52	-5	4	-5

Conclusions

In Denmark the monitoring of riverine nutrient fluxes includes sampling 12 to 32 times per year (Appendix 1). Table 15 presents the scatter and bias of the load estimates obtained with 26 annual samples. The scatter of the TN load varied between 3 and 4% in the R. Gjern and between 2 and 3% in the Gelbæk. The accuracy of load estimates was even better, except when Method 2 was used. The TP load estimates were more imprecise. For the R. Gjern Method 1 and Strategy 1 gave the smallest scatter (10%). Method 3 was most accurate (bias 1%) but relatively imprecise (scatter 12%). In the Gelbæk, the best precision (9%) was obtained with Method 2 and the best accuracy (-2%) with Method 3.

With a given number of samples, the most reliable estimates of TP and TN load for the R. Gjern are obtained either by flow-proportional sampling or by a regular sampling coupled with Method 1. To produce load estimates with ≤10% scatter and bias, a total of 26 annual TP and 6 TN samples must be taken. In the Gelbæk, the flow-weighted sampling gives probably the best results. For the reliable estimation of loads, a total of 52 annual TP and 4 TN samples must be taken. Although Method 2 gave the most precise and rather accurate results for the TP load in the Gelbæk in 1988, the method generally tends to give inaccurate results and is not recommended. The most accurate results for both rivers and both water quality variables were obtained by Method 3. However, this method presupposes more frequent sampling than Method 1.

Table 15. Scatter and bias of load estimates for total phosphorus and total nitrogen in the Danish rivers using 26 annual samples. In Strategy 2, samples were taken proportionally to the flow (In the Gjern: 11 samples in Jan-Mar, 2 in Apr and in Dec and 11 during the rest of the time; in the Gelbæk: 19 samples in Jan-Mar, 5 in Apr-Nov and 2 in Dec).

River Method	TP		TN	
	Scatter (%)	Bias (%)	Scatter (%)	Bias (%)
Gjern:				
Method 1	10	-2	3	-2
Method 2	13	7	3	-25
Method 3	12	-1	4	0
Strategy 2	10	-2	3	-1
Gelbæk:				
Method 1	23	-11	3	-1
Method 2	9	4	3	-71
Method 3	26	-2	3	0
Strategy 2	15	-5	2	-2

3.2 Finnish rivers

Kymijoki:

Using regular sampling, load estimates with ≤10% scatter and bias were obtained for TP with 4 to 12 annual samples and for TN with 2 to 12 samples, depending on the year (Table 16). The annual variation in the number of samples producing reliable load estimates seemed to depend on the coefficient of variation in the concentrations and on the correlation between the concentrations and the flow. For example, the highest number of samples for the estimation of TP load was needed in 1985, when both the variation in the TP concentrations and the correlation between TP and flow were highest (Table 6 and 7). In 1993 the variation in the TP concentration was at the same level as in 1985 but the correlation between the concentrations and flow was negligible. Consequently, only 4 samples were needed to produce reliable load estimates in 1993.

The precision obtained with 12 annual samples did not depend on the load calculation method (Table 17). However, Method 2 had the poorest accuracy (Tables 16 and 17).

It underestimated the loads when the correlation between the concentrations and flow was positive and overestimated the loads when the correlation was negative.

Two flow-weighted sampling strategies were tested. In Strategy 1, samples were taken during the spring flood (8 samples) and autumn flood (4 samples). This strategy gave more precise results than the regular sampling, but it overestimated the loads (Table 17). In Strategy 1 the estimation of the load during the low-flow period was based on the mean concentration during the sampled periods. Owing to the positive correlation between the flow and concentrations, the mean concentration during the sampled periods overestimated the mean concentration in the unsampled periods.

In Strategy 2a, six samples were taken during the spring flood, three samples during the autumn flood and three samples during the rest of the year. This strategy gave more imprecise results than the regular sampling (Table 17). The accuracy was at the same level as with regular sampling and the load calculation method 1 or 3.

Strategy 2b is used in Finland in the monitoring of riverine nutrient loads. It includes sampling during the spring (6 samples) and autumn floods (4 samples). The load during the low flow period is estimated on the basis of the samples taken in March and August. Compared with Strategy 1, Strategy 3 had slightly poorer precision but higher accuracy (Table 17).

Table 16. Number of samples (N) resulting in annual load estimates of total phosphorus and total nitrogen with ≤10% scatter and bias in the river Kymijoki. Bias of the corresponding load estimates is also given.

Year Method	TP		TN	
	N	Bias (%)	N	Bias (%)
Kymijoki 1985:				
Method 1	12	-1	12	-1
Method 2	12	-6	12	-3
Method 3	12	1	12	0
Kymijoki 1986:				
Method 1	4	-1	4	-1
Method 2	4	-1	4	-2
Method 3	6	-1	4	0
Kymijoki 1993:				
Method 1	4	1	2	0
Method 2	4	2	2	-3
Method 3	4	1	2	0

Table 17. Scatter and bias of the load estimates obtained with 12 annual samples for total phosphorus and total nitrogen in the river Kymijoki. In the table the lowest values observed in the study years are presented.

Method	TP		TN	
	Scatter (%)	Bias (%)	Scatter (%)	Bias (%)
Method 1	8	-1	6	-1
Method 2	8	-6	6	-3
Method 3	9	-1	7	0
Strategy 1	6	17	3	21
Strategy 2a	16	-1	6	-1
Strategy 2b	7	13	3	17

Paimionjoki:

Using regular sampling, the number of annual samples which produced load estimates with a scatter and bias ≤10% ranged from 4 to 182 depending on the variable, the year and the load calculation method (Table 18). As observed earlier, Method 2 gave the most precise and most inaccurate results. Owing to the high inaccuracy of the results obtained by Method 2, the following discussion is limited to Methods 1 and 3.

As in the Kymijoki, Method 3 gave slightly more accurate but more imprecise results than Method 1. Using Method 1, the load of TP could be estimated with ≤10% scatter and bias with 26 to 52 samples, depending on the year. For the estimation of the SS load with the same level of reliability, a total of 26 to 91 samples had to be taken. The load of TN, NO_3-N, DRP and DP could be estimated with ≤ 26 samples (Table 18). The annual variation in the number of samples which produced precise load estimates seemed to depend mainly on the correlation between the concentrations and flow; the higher the correlation, the higher the number of samples. In contrast to Kymijoki, the coefficient of variation of the concentrations seemed not to correlate with the frequency of sampling. This may be caused by the high variation in flow in the Paimionjoki.

A flow-weighted sampling was tested for TP, TN and SS. Using Strategy 2 the number of samples producing load estimates with ≤10% scatter and bias could clearly be reduced (Table 18). Compared with Method 1 the number of samples for TP and SS load estimation could be reduced by about 50% in three out of the four years studied when Strategy 2 was used. In one year the number of samples needed for reliable TN load estimation could also be reduced by this strategy (Table 18).

Table 19 presents the scatter and bias of the TP, TN and SS loads obtained by 26 annual samples using Methods 1 and 3 and Strategy 2. The most accurate results were obtained with Method 3. However, this method gave poorer precision than Method 1 or Strategy 2. Using Strategy 2 and 26 annual samples the load of TP and TN could be estimated with ≤10% scatter and bias and the load of SS with ≤ 17% scatter and ≤ 11% bias. The bias using all methods and the Strategy 2 was negative for all water quality variables, i.e. the loads were underestimated.

Eurajoki, Pyhäjoki and Yläneenjoki:

Using a regular sampling strategy, a total of 6 to 52 samples had to be taken for the estimation of TP load with $\leq$10 % scatter and bias in these rivers. For TN load, a total of 6 to 26 samples were sufficient (Table 20). The annual variation in the required number of samples seemed to depend on the coefficient of variation of the concentrations. Method 3 gave more accurate results than Method 1, but sometimes the results were more imprecise. Method 2 was not tested at all.

Using the flow-weighted sampling scheme (Strategy 2) the number of samples for TP load estimation could often also be reduced in these rivers (Table 20). However, in the case of TN load, Strategy 2 decreased the frequency of sampling only in the Pyhäjoki and Yläneenjoki in 1991.

Conclusions

In Finland the monitoring of the riverine nutrient fluxes includes sampling about 12 times per year; in large rivers the samples are taken regularly, whereas in smaller rivers they are taken proportionally to the flow (Appendix 1). In the large and regulated Kymijoki a regular sampling actually gave better results than a flow-weighted sampling. In this river, there are distinct flood periods but no real low flow periods; most of the water is discharged outside the flow peaks.

In the Paimionjoki, the regular sampling strategy gave rather imprecise results. A total of 12 regular-interval samples gave reliable load estimates only for NO_3-N. Using a flow-weighted sampling strategy a total of 12 annual samples was needed for reliable estimation of the TN load, 26 for TP load and 52 for SS load. Similarly, in Eurajoki, Yläneenjoki and Pyhäjoki, a total of 12 flow-weighted samples had to be taken for reliable estimation of TN load and 26 samples for TP load. However, the flow-weighted sampling did not improve the reliability of the results in these rivers as clearly as in the Paimionjoki.

The most accurate results are obtained by using regular sampling and the load calculation method 3. However, this usually requires a considerably higher number of samples than the use of Method 1 or flow-weighted sampling strategy.

Table 18. Number of samples (N) resulting in a scatter and bias ≤10% for the annual load of total phosphorus, dissolved phosphorus (DP), dissolved reactive phosphorus (DRP), total nitrogen, nitrate nitrogen (NO_3-N) and suspended solids (SS) in the river Paimionjoki. The corresponding bias is also given.

Year	Method	TP		DP		DRP		TN		NO_3-N		SS	
		N	Bias (%)	N	Bias (%)	N	Bias (%)	N	Bias (%)	N	Bias (%)	N	Bias (%)
1985:													
	Method 1	52	-3	26	-2	26	-2	12	-8	..	..	91	-2
	Method 2	-	-	-	-	-	-	-	-	..	..	-	-
	Method 3	52	-10	52	0	52	0	26	-1	..	..	182	0
	Strategy 2	26	-5	..	..	..	..	12	-7	..	..	52	-4
1988:													
	Method 1	26	-6	26	-3	6	-14	12	-9	4	-4	52	-3
	Method 2	-	-	-	-	-	-	-	-	4	-7	-	-
	Method 3	52	-8	26	0	12	0	26	-1	6	-2	91	0
	Strategy 2	26	-8	..	..	..	..	12	-5	..	..	52	-4
1989:													
	Method 1	26	-3	12	-7	6	-5	26	-4	6	0	26	-3
	Method 2	-	-	-	-	-	-	-	-	-	-	-	-
	Method 3	26	-1	12	0	12	-1	26	-1	12	-2	52	0
	Strategy 2	12	-6	..	..	..	..	12	-5	..	..	12	-3
1990:													
	Method 1	52	-3	12	-10	6	0	12	-2	12	-4	52	-4
	Method 2	-	-	-	-	-	-	-	-	-	-	-	-
	Method 3	52	0	12	-1	6	-1	26	-5	26	0	52	0
	Strategy 2	26	-4	..	..	..	..	12	-2	..	..	26	-2

Table 19. Scatter and bias of load estimates of total phosphorus, total nitrogen and suspended solids in the river Paimionjoki using 26 annual samples taken regularly coupled with Method 1 and Method 2 or flow-weighted. The lowest values observed in the study years are presented. In strategy 2, samples were taken as follows: 2 in Jan; 9 in Feb - Mar; 5 in Apr 1 - May 14; 4 in May 15 - Oct 6; 4 in Oct 7 - Nov 18; 2 in Nov 19 - Dec 31.

Method	TP		TN		SS	
	Scatter (%)	Bias (%)	Scatter (%)	Bias (%)	Scatter(%)	Bias (%)
Method 1	12	-10	5	-4	22	-17
Method 3	17	-3	8	-1	30	-4
Strategy 2	10	-8	5	-3	17	-11

Table 20. Number of samples producing load estimates for total phosphorus and total nitrogen with bias and scatter ≤10%. The corresponding bias of the load estimate is also given.

River/year	TP		TN	
Method	N	Bias (%)	N	Bias (%)
Eurajoki 1991:				
Method 1	6	-3	6	2
Method 3	12	1	6	2
Strategy 2	12	1	6	1
Eurajoki 1992:				
Method 1	52	0	6	-1
Method 3	52	0	12	0
Strategy 2	26	2	12	1
Pyhäjoki 1991:				
Method 1	26	-4	26	-5
Method 3	52	0	26	-1
Strategy 2	12	4	12	5
Pyhäjoki 1992:				
Method 1	12	-2	12	-7
Method 3	12	-1	12	-1
Strategy 2	12	4	12	10
Yläneenjoki 1991:				
Method 1	52	-5	26	-4
Method 3	52	-1	26	0
Strategy 2	26	8	12	5
Yläneenjoki 1992:				
Method 1	26	-4	12	-7
Method 2	26	0	26	0
Strategy 2	12	5	12	9

3.3 Icelandic rivers

Using regular sampling, load estimates with ≤10% scatter and bias were obtained generally with 2 to 26 samples depending on the river, water quality variable, year and load calculation method (Table 21). Method 2 gave the poorest accuracy and was omitted from the following discussion.

The number of samples producing reliable load estimates seemed to depend on the variation in the concentrations. For example, in the Norðurá the concentrations of NO_3-N had the highest coefficient of variation and consequently the highest number of samples (12 to 26 using Method 1) in that river was needed to estimate the load of NO_3-N. Similarly, in the Þjórsá the highest number of samples (6 to 26) was needed for the estimation of NH_3-N load in 1973. During this year the variation in the concentrations of NH_3-N was high. Accordingly, in the Fossá the highest number of samples was needed to obtain a precise load estimate for RP.

In general, 26 annual regularly spaced samples coupled with load calculation method 1 gave precise and accurate load estimates for the Icelandic rivers. Method 3 gave slightly more accurate results than Method 1. However, it sometimes required a markedly higher number of samples.

Table 21. Number of samples producing load estimates with ≤10% scatter and bias for the Icelandic rivers. The corresponding bias of the load estimate is also given.

River/year Method	RP		NO_3-N		NO_2-N		NH_3-N	
	N	Bias (%)	N	Bias (%)	N	Bias (%)	N	Bias (%)
Norðurá 1973								
Method 1	4	-4	12	7	4	-5	6	6
Method 2	4	-9	-	-	6	1	-	-
Method 3	26	1	182	0	6	1	6	1
Norðurá 1974								
Method 1	6	-4	26	3	6	-1	6	-4
Method 2	6	-1	-	-	4	7	-	-
Method 3	6	-1	12	-1	6	0	26	1
Þjòrsá 1972								
Method 1	6	-1	4	2	4	1	6	0
Method 2	6	5	4	5	4	1	6	-8
Method 3	12	1	6	0	4	0	6	1
Þjòrsá 1973								
Method 1	12	1	6	1	4	2	26	0
Method 2	12	3	6	5	4	1	26	4
Method 3	12	0	12	0	4	-1	26	0
Fossá 1972								
Method 1	6	-2	4	-1	2	-1	6	1
Method 2	6	-9	6	-10	2	-1	12	5
Method 3	91	0	26	-1	2	-1	12	1
Fossá 1973								
Method 1	26	0	12	4	4	-2	6	-2
Method 2	-	-	-	-	4	6	4	-4
Method 3	52	1	26	-1	26	0	12	-4

3.4 Norwegian rivers

Otra:

The flux of TN in the Otra could be estimated with ≤10% scatter and bias with only 1 to 2 annual samples. A higher number of regularly spaced samples (4-12) was needed for the estimation of the TP and SS flux. The highest number of samples (12) was needed for the estimation of TP in 1990. The frequency of sampling which produced reliable load estimates seemed to depend on the coefficient of variation in the concentration and on flow; the higher the coefficient of variation the higher had to be the number of samples (Tables 10 and 22).

All load calculation methods gave similar levels of scatter. An exception was the SS load in 1991; Method 3 gave lower precision than Methods 1 and 2. As observed earlier, Method 2 was least accurate: it overestimated the loads of TP and SS. The most accurate results were obtained with Method 3, although the difference between Methods 1 and 3 was small. Flow-weighted sampling was not tested, since the correlation between the concentrations and flow was not strong.

Vefsna:

Using regular sampling, a substantially higher number of samples (6 to 52) had to be taken for reliable load estimates in the Vefsna than in the Otra. The highest number of samples was needed to estimate the flux of SS. SS concentrations had a higher coefficient of variation than the concentrations of TP and TN. As observed earlier, Method 2 gave the most precise load estimates but underestimated the TP and SS loads and overestimated the TN load. Flow-weighted sampling (Strategy 2) did not markedly increase the accuracy or precision of load estimates (Table 22).

Glomma:

Using regular sampling, the flux of TP could be estimated with ≤10% scatter and bias with 12 to 26 annual samples. For the estimation of the TN load only 4 to 12 samples had to be taken, but 26 samples were necessary for estimation of the load of SS. Method 2 was most inaccurate (Table 22). Unlike most other rivers included in the study, in the Glomma the accuracies of Methods 1 and 3 were at the same level.

Table 22. Number of annual samples (N) producing a scatter and bias of ≤10% for annual load of total phosphorus (TP), total nitrogen (TN) and suspended solids (SS) in the Norwegian rivers. The bias of the load estimate is also given.

River/year Method	TP		TN		SS	
	N	Bias (%)	N	Bias (%)	N	Bias (%)
Otra 1990						
Method 1	12	2	2	0	6	1
Method 2	12	10	2	-1	6	6
Method 3	12	1	2	0	6	0
Otra 1991						
Method 1	4	2	1	-1	4	1
Method 2	4	6	1	-1	4	11
Method 3	4	1	1	-1	12	1
Vefsna 1990						
Method 1	26	-2	12	0	52	0
Method 2	-	-	6	1	-	-
Method 3	26	0	12	-1	52	0
Strategy 2	26	-5	12	1	52	0
Vefsna 1991						
Method 1	12	-3	12	3	26	-5
Method 2	-	-	-	-	-	-
Method 3	12	-1	12	0	26	0
Strategy 2	12	-2	26	1	12	-3
Glomma 1990						
Method 1	12	-1	4	1	26	-2
Method 2	4	4	4	4	26	5
Method 3	26	0	4	0	26	0
Glomma 1991						
Method 1	26	1	6	-1	26	0
Method 2	6	6	6	2	26	0
Method 3	26	0	6	-1	26	0
Glomma 1992						
Method 1	12	0	12	1	26	0
Method 2	12	6	6	5	26	5
Method 3	26	-2	12	-2	26	-2

Conclusions

In Norway 12 to 20 samples (from some rivers only 4 to 5) are taken when monitoring nutrient fluxes. The load is calculated by Method 3 (Appendix 1). With 12 regularly spaced samples, the loads of TP, TN and SS in the Otra could be estimated with ≤2% bias and ≤6% scatter using Methods 1 and 3 (Table 23). The most accurate and precise estimates were obtained for TN.

In the Vefsna and Glomma, a total of 12 regularly spaced samples produced load estimates with ≤10% bias and scatter only for TN (Table 23). To estimate the load of TP and SS, a total of 26 and 52 samples had to be taken from the Vefsna and 26 from the Glomma. The load could be calculated with Method 1 or 3. The latter gave slightly better accuracy but poorer precision.

Table 23. Scatter and bias of the load estimates based on 12 annual samples for total phosphorus (TP), total nitrogen (TN) and suspended solids (SS) in the Norwegian rivers.

River Method	TP		TN		SS	
	Scatter(%)	Bias(%)	Scatter(%)	Bias(%)	Scatter(%)	Bias(%)
Otra						
Method 1	6	2	1	0	3	1
Method 2	5	10	1	-1	3	11
Method 3	6	1	2	0	4	0
Vefsna						
Method 1	11	-6	9	3	28	-15
Method 2	7	-22	9	11	21	-36
Method 3	13	-1	8	-1	36	-2
Strategy 2	10	-7	11	3	32	-15
Glomma						
Method 1	18	-1	2	4	16	6
Method 2	20	7	5	2	14	-2
Method 3	19	6	5	5	16	-9

3.5 Swedish rivers

Dalälven:

Using regular sampling, the loads of TP and RP could be estimated with ≤10 % scatter and bias with 4 annual samples and the load of other variables with up to 12 samples (Table 24). As observed earlier, Method 2 generally gave the least accurate and Method 3 the most accurate results.

Skivarpsån:

Using regular sampling, a total of 6-12 samples produced a load estimate with ≤10% scatter and bias for NO_3-N, 6-26 samples for TP and 6-52 samples for RP (Table 24). The highest number of samples was needed in years when the concentrations varied most. For example, in 1990 a total of 52 samples was needed for reliable estimation of the RP load. In 1990 the coefficient of variation for RP was higher than during the other study years. The most accurate results were obtained with Method 3, but its precision was lower than that of Method 1. Flow-weighted sampling strategy (Strategy 2) did not improve the accuracy or precision of the load estimates (results not presented).

Conclusions

In Sweden, the monitoring of nutrient load includes sampling 12 times per year (Appendix 1). This frequency of sampling seems to lead to accurate and precise

Table 24. Number of samples (N) resulting in load estimates with ≤10% scatter and bias in the Swedish rivers. The corresponding bias of load estimates is also given.

River/year Method	TP		RP		NO_3-N		NO_2-N		NH_4-N	
	N	Bias (%)	N	Bias (%)	N	Bias (%)	N	Bias (%)	N	Bias (%)
Dalälven 1990										
Method 1	4	2	4	1	6	-2	4	-2	12	0
Method 2	4	2	4	3	-	-	4	-9	12	2
Method 3	4	0	4	0	6	0	4	-1	12	1
Dalälven 1992										
Method 1	4	2	4	4	12	-1	6	-4	12	-1
Method 2	4	-2	4	5	-	-	6	-8	12	-7
Method 3	4	0	4	0	6	-1	6	-1	12	-2
Skivarpsån 1990										
Method 1	12	-3	52	0	6	-3	12	-1	12	-2
Method 2	-	-	-	-	-	-	12	-6	-	-
Method 3	26	0	52	1	12	-1	12	2	12	-4
Skivarpsån 1991										
Method 1	12	1	12	3	6	-6	12	-1	12	-5
Method 2	-	-	-	-	-	-	-	-	-	-
Method 3	12	0	12	0	12	1	26	-1	52	-1
Skivarpsån 1992										
Method 1	6	-2	12	-1	6	-5	26	3	6	1
Method 2	6	5	-	-	-	-	26	-7	12	-9
Method 3	12	0	12	0	12	-1	26	-1	4	-1

estimates for the Dalälven, but is not sufficient for all water quality variables in the Skivarpsån. In the Skivarpsån, the loads of NO_2-N and RP, based on 12 annual regularly spaced samples and on Method 1, could include a scatter of 14% and 13%, respectively.

4 DISCUSSION

4.1 Reliability of the Monte Carlo method

The accuracy of a load estimate can be determined only when the true river flux is known. The literal true load will never be known, but it can be realistically estimated by frequent, e.g. daily monitoring of the flow and concentrations. In this study, daily observations were not available from any of the rivers. For the Monte Carlo procedure, daily data sets were generated from the observations by linear interpolation. Accuracy was estimated by comparing the mean of replicate load estimates produced on the basis of randomly selected concentrations with the load calculated from the entire interpolated daily data set. Precision was calculated from the coefficient of variation in the replicate load estimates. Thus, the reliability of the results obtained by the Monte Carlo method strongly depends on how realistic the linearly interpolated data really is.

The sensitivity of the results to the number of observations available for generation of the daily data set was tested with the data from the rivers Gjern and Gelbæk. The original data sets of more than 300 annual TP and TN observations were divided into subsets which contained every second observation. From these subsets, observations were deleted systematically in order to obtain files with every fourth, eighth, sixteenth and thirty-second observation. The results obtained using these data sets were compared with those obtained using the complete set of observations. In the comparison, load was calculated using method 1.

The sensitivity analysis revealed that the number of samples available for generation of the daily data set affects the results. When the daily values were interpolated from about 10 observations, the Monte Carlo method indicated that in the Gelbæk four annual samples would produce load estimates of TN with $\leq$10% scatter (Fig. 9). When a higher number of observations (40 to 80) was used in the interpolation, the required frequency of sampling increased to six per year. The accuracy of load estimates seemed to be better the less observations were used in the interpolation. However, the differences in accuracy were small.

The results concerning TP were more sensitive to the construction of the daily data set than those of TN. In the Gelbæk, the number of samples producing load estimates of TP with $\leq$10% scatter was higher the more observations were used in the interpolation (Fig. 10). The same holds true for the subset 2 of the R. Gjern, but in the subset 1 the necessary number of samples was highest when the interpolation was based on 86 and 170 observations. The accuracy of the load estimates of TP varied only slightly, although more irregularly than that of the TN load.

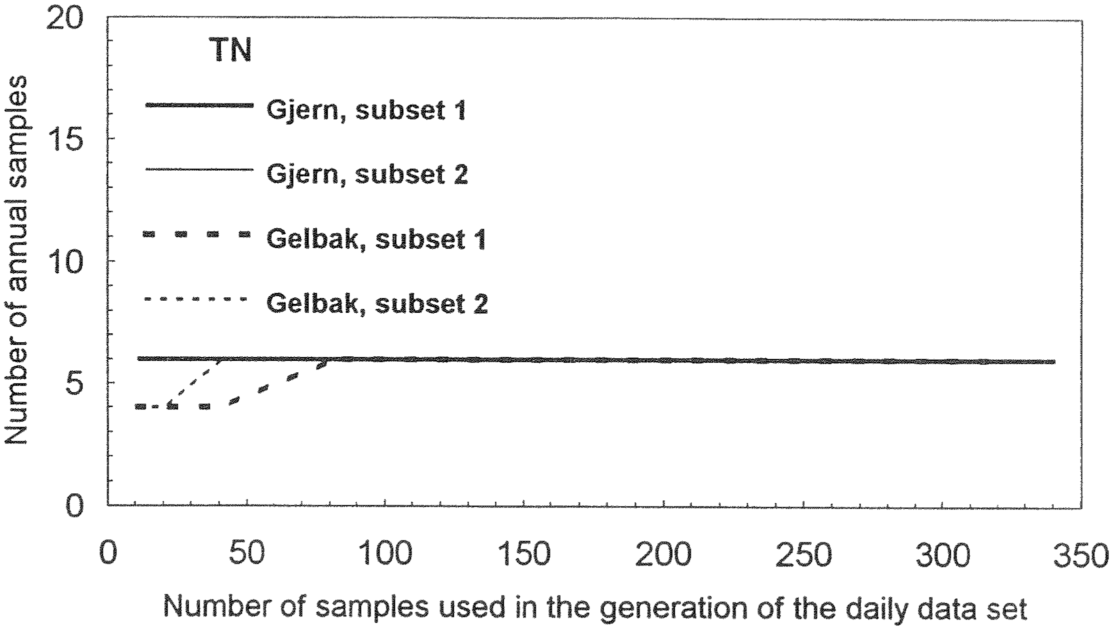


Fig. 9. Dependence of the number of samples producing load estimates of total nitrogen with ≤10% scatter and bias on the number of observations used in the generation of the daily data set in the rivers Gjern and Gelbæk. Load calculation method 1 used.

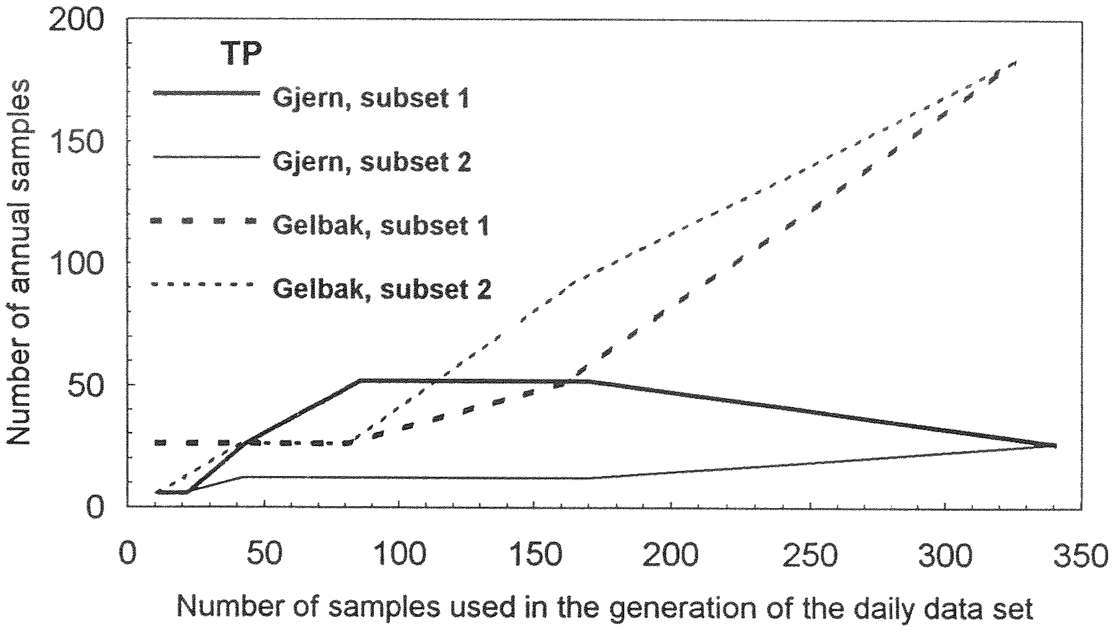
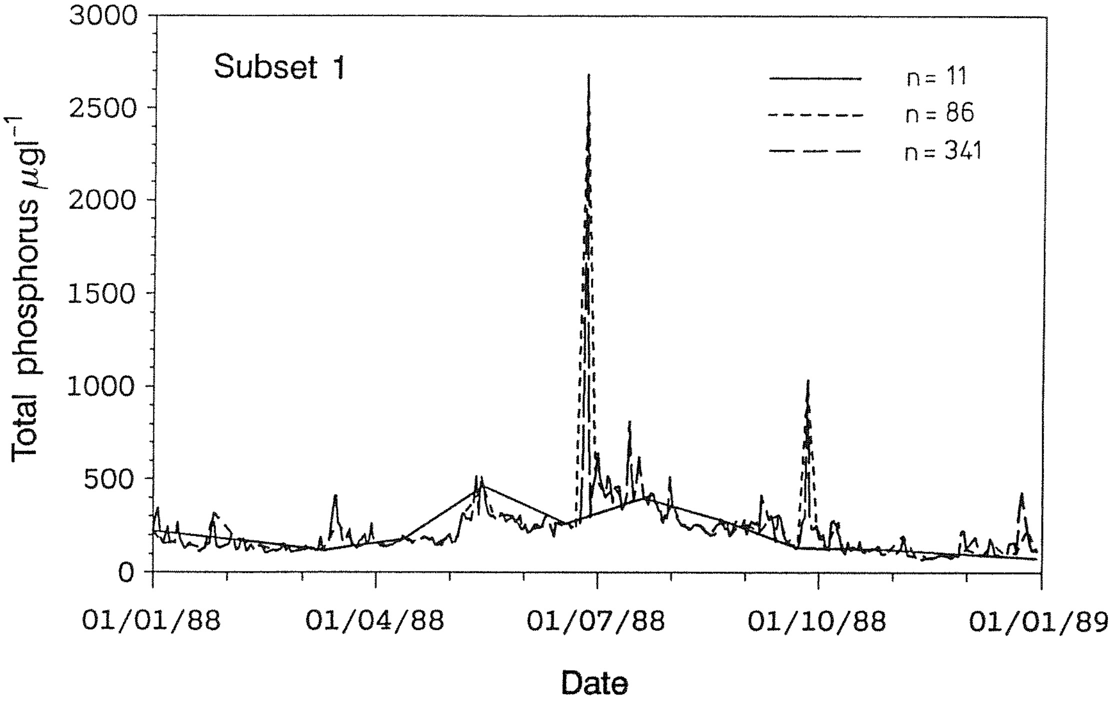


Fig. 10. Dependence of the number of samples producing load estimates of total phosphorus with ≤10% scatter and bias on the number of observations used in the generation of the daily data set in the rivers Gjern and Gelbæk. Load calculation method 1 used.



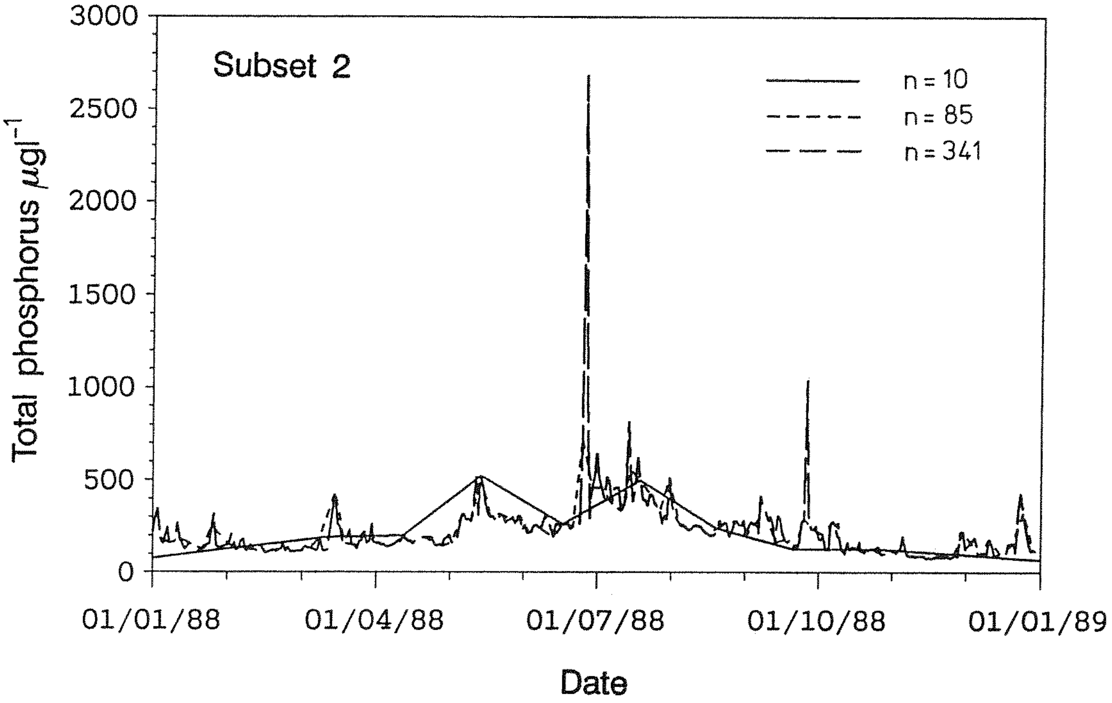


Fig. 11. Linearly interpolated daily data sets for the river Gjern. The interpolation is based on 341, 85/86 and 10/11 samples.

The strong dependence of the precision of the TP load obtained by the Monte Carlo method on the number of observations used in the interpolation is mainly caused by the irregular variations in the TP concentration. For example, there was one exceptionally high TP concentration in the R. Gjern in 1988. Whether this observation was included in the data set (subset 1 with 86 and 170 samples) or not (subset 2) strongly affected the results. When the peak value was included in an infrequent data set, the Monte Carlo method overestimated the number of samples producing precise load estimates. On the other hand, the method may more likely underestimate the necessary number of samples as was observed in the Gelbæk and in subset 2 for the Gjern. Figure 11 presents the generated daily data for the Gjern interpolated with various numbers of observations.

The results from the sensitivity analysis can be summarized as follows. The Monte Carlo method tends to underestimate the necessary number of samples which must be taken to produce precise load estimates for TP. An overestimation is also possible but it is less probable than an underestimation. In contrast to TP, it seems that the results concerning the estimation of TN load are relatively reliable even when they are based on a low number of observations.

The systematic error caused by the use of a small number of observations in the interpolation was counteracted (but not eliminated) in this study by the analysis of several years of data for most of the rivers. In the summarizing Table 25 the results of years with the poorest precision and accuracy have been presented in order to reduce the risk of underestimating the necessary sampling frequency. As a general conclusion for both TP and TN it may be stated that the accuracy of the load estimate can be estimated with a lower number of observations than the precision.

4.2 Evaluation of the load calculation methods and sampling strategies

In this study only three different load calculation methods were used. The methods used in Finland and Norway were included in the study, but the linear interpolation method used in Denmark and Sweden was not tested. Furthermore, the regression method and the Beale's stratified ratio estimator, which have both been found to give reliable results (Young et al., 1989; Bruhn and Kronvang, 1990, Rekolainen et al., 1991), were omitted from this study.

Generally, the most accurate results were obtained when the load was calculated as the product of the annual mean flow and flow-weighted mean concentration (Method 3). This result is in agreement with those of Rekolainen et al. (1991) and deVries and Klavers (1994). Using the same sampling frequency, more precise results are obtained when the load is calculated for each interval and then summed to an annual load (Method 1). Independently of the number of samples, the accuracy of these two methods is usually better than their precision. The simplest method; multiplying the mean annual flow by the mean annual concentration (Method 2), often leads to appreciable bias. The method misses the peaks and thus either underestimates or overestimates the loads, depending on the relationship between concentration and flow (cf. Rekolainen et al., 1991; deVries and Klavers, 1994). It also decreases the variation and thus increases the precision.

In this study, the regular sampling strategy was generally used. For some rivers, a flow-weighted strategy was also tested. In small agricultural rivers, the necessary sampling frequency can be reduced by flow-weighted sampling. This is especially true for variables that show a high correlation with flow. The use of flow-weighted sampling requires that the flow periods can be assessed. If high flow events occur ouside the pre-set sampling periods, the resulting load estimates can be rather biased, even with frequent sampling within these periods. In this study the high flow periods were determined from the flow data of the study years. It should be pointed out that many different flow-weighted strategies exist, e.g. sampling above a threshold limit of flow, by which the reliability of river loads may be improved. However, most of these strategies call for automatic sampling equipment.

4.3 Factors which affect the necessary sampling frequency

The number of annual samples producing reliable load estimates varied widely between years, water quality variables and rivers. In some rivers the annual variation in the necessary sampling frequency seemed to depend on the variation in the CV for water quality variables and in the correlation between the variables and the flow; the higher the CV or correlation the higher the number of samples which produced reliable load estimates. However, these statistical analyses did not explain the differences between the rivers and water quality variables. For example, although CVs for TP and TN were often at the same level, the load of TN could usually be estimated with a lower number of samples than the load of TP (Table 25).

A more careful examination of the water quality data revealed that, even if the CVs for TP and TN were at the same level, the TP data had a higher skewness and kurtosis than the TN data. A good example is the river Gjern, with one exceptionally high TP value in 1988. The skewness and kurtosis of TP were 7.52 and 90.7, respectively, whereas the corresponding values for TN were 1.03 and -0.24, respectively. Thus, TN tends to be normally distributed, whereas TP may be strongly skewed to the right, i.e. the TP data includes some exceptionally high values. Successful capturing of these peak values of TP calls for a high frequency of sampling.

As was reported earlier (Walling and Webb, 1982; Richards and Holloway, 1987) the highest frequency of sampling was usually needed for SS. This is probably due to the very incidental nature of the erosion process.

Total and dissolved nutrients were tested only for the river Paimionjoki and the Swedish rivers. In Paimionjoki, the load of dissolved nutrients could usually be estimated with a lower number of samples than the total nutrients. However, in the Swedish rivers there were no clear differences between the number of samples needed for TP or RP load estimation. This may be partly due to the fact that RP, which is analyzed from unfiltered samples, also includes part of the P bound onto suspended solids. In Paimionjoki the dissolved P fractions were analyzed from filtered samples.

The differences between the rivers could be explained to some degree by the variation in the CV for flow. Generally, the smaller the area of a drainage basin, the higher was the variation in the flow. In the following discussion, the rivers are divided into three categories; small agricultural rivers, intermediate sized rivers and large regulated rivers.

Small agriculturally loaded rivers

In this category the temporal variation in the flow was often high. A total of 12 to 26 annual samples taken using a flow-weighted strategy produced load estimates for TP with ≤ 10% scatter and bias (Table 25). The corresponding number of samples for TN load was 4 to 12.

The results obtained for two Finnish small agriculturally loaded drainage basins has shown that relatively infrequent (e.g. monthly) sampling seldom produces accurate or precise load estimates for TP or TN (Rekolainen et al., 1991). For these variables, which show high variation according to flow, the flow-proportional sampling strategy has given better results than regular-interval sampling. In this study, in five out of seven small agriculturally loaded rivers the flow-weighted sampling strategy improved the reliability of load estimates of TP or TN or both (Table 25). If a regular-interval sampling scheme had been used in these rivers, the necessary number of samples would have been about twice as high as when using the flow-weighted sampling strategy.

In the Skivarpsån, the necessary number of samples for producing precise load estimates of TP was lowest in this category. In addition, the flow-weighted sampling strategy decreased the precision. However, the results concerning the Skivarpsån probably underestimate the necessary frequency of sampling. This is due to the fact that only 26 annual observations were available for the Skivarpsån. If this number of observations had been available from e.g. the Gelbæk, the Monte Carlo technique would also have indicated a much lower frequency of sampling for this river.

Intermediate sized rivers

This category includes the intermediate sized rivers in Iceland and Norway with mountainous drainage basins: the Otra, Vefsna, Fossá and Norðurá (size of the drainage basin 500 - 7200 km^2). The number of samples which produced load estimates for TP and TN with ≤10% bias and scatter varied from 2 to 26. In this category the lowest frequency of sampling was needed for the regulated river Otra. The flow-weighted sampling strategy improved the results only for the Vefsna. The load calculation methods 1 and 3 generally gave the best results.

Large regulated rivers

In the case of large regulated rivers (drainage basin > 25 000 km^2), a regular monthly sampling usually gave load estimates with ≤10% bias and scatter for TP and TN. The Glomma formed an exception; in this river 26 annual samples had to be taken for the reliable estimation of TP load. The higher frequency of sampling necessary in the Glomma may have been due to the erosion of soil in the lower reaches of the drainage basin (Holtan, 1990).

In this group, flow-weighted sampling did not improve the reliability of results. The sensitivity of the results to the load calculation method was rather small. Load calculation methods 1 and 3 generally gave the best results.

Table 25. Optimal frequency and strategy of sampling coupled with the best load calculation method in the rivers studied. The combinations presented in the table produce load estimates for total phosphorus and total nitrogen with a scatter and bias of $\leq$10%. 1=TP not measured, RP used. 2=TN not measured, NO_3-N used.

Category river	TP		TN	
	N	Method	N	Method
Small agricultural rivers:				
Eurajoki	26	S2	6	M1
Gelbæk	26	M2	4	S2
Gjern	26	M1,S2	6	M1,S2
Paimionjoki	26	S2	12	S2
Pyhäjoki	12	S2	12	S2
Skivarpsån[2]	12	M1	6	M1
Yläneenjoki	26	S2	12	S2
Intermediate rivers:				
Fosså[1,2]	26	M1	12	M1
Þjórsá[1,2]	12	M1,M2,M3	6	M1,M2
Norðurá[1,2]	6	M1,M2,M3	12	M1
Otra	12	M1,M2,M3	2	M1,M2,M3
Vefsna	26	M1,M3,S2	12	M1,M3
Large regulated rivers:				
Dalälven[2]	4	M1,M2,M3	6	M3
Glomma	26	M1,M3	12	M1,M3
Kymijoki	12	M1,M2,M3	12	M1,M2,M3,S2

5 CONCLUSIONS

The number of samples producing reliable load estimates for Nordic rivers varies appreciably between different types of rivers and between water quality variables. In small agricultural rivers 12-26 samples taken in proportion to flow seem to produce load estimates for TP with $\leq$ 10% scatter and bias. A lower number of samples is sufficient for the estimation of the load of TN, whereas a higher frequency is necessary for SS. In the intermediate sized rivers of Iceland and Norway the necessary number of samples is slightly lower than in small agricultural rivers. The frequency of sampling cannot be reduced by flow-weighted sampling. In two out of three large regulated rivers studied, a total of 12 regularly spaced samples will produce reliable annual load estimates. In the Glomma the erosion of soil in the lower reaches increases the irregular variation in the TP concentrations and also the necessary frequency of sampling.

The results of this study are highly dependent on the water quality data which was available for the Monte Carlo technique. The number of observations was usually the highest for the small agriculturally loaded rivers. Thus the higher frequency of sampling indicated by the Monte Carlo method for these rivers may partly reflect the fact that the variation in the concentrations was known in more detail than e.g. for large regulated rivers.

It seems that in the Nordic river monitoring programmes the frequency of sampling is generally too low, at least for small rivers. The results of this study can be used to determine approximately the frequency and strategy of sampling in a river. However, when designing a monitoring programme all aspects which affect nutrient loads (e.g. load from point sources) in an individual river must be taken into account.

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APPENDIX 1. FREQUENCY OF SAMPLING AND THE LOAD CALCULATION METHODS USED IN THE MONITORING OF RIVERINE NUTRIENT FLUXES IN THE NORDIC COUNTRIES.

Based mainly on Holtan and Holtan (1993). 1=Before 1990. Presently, 12-26 annual samples combined with a continuous sampling strategy at some stations.

Country	Sampling frequency per year	Load calculation method
Denmark	12-32[1]	Linearly interpolated daily concentration times daily flow
Finland	at least 12-13	Summing up of monthly loads (mean monthly concentration times mean monthly flow)
Iceland	12	No permanent monitoring of river loads
Norway	12-20 (4-5)	Flow weighted annual mean concentration times annual mean flow
Sweden	12	Linearly interpolated daily concentration times daily flow

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