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# SPREAD OF THE WATERS FROM THE RIVER SIIKAJOKI IN THE BOTHNIAN BAY

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The River Siikajoki is rich in humus and has a high rate of substance discharge. To find out the effects of substance discharge, it is necessary to know about the mixing of river water and brackish water and the transformations due to that. The spreading of river water is investigated by means of electrolytic conductivity, the differences in which also express the proportion of the river water accumulated in the area from the total mass of water. Substance concentrations of water can be used for examining the changes in the river water fraction and for distinguishing the other river waters flowing into the area. It was found that the water from the Siikajoki mixes effectively with the brackish water in summer, while in winter the river water accumulates on the more saline water and spreads over a large area. This area may possibly suffer from detrimental effects due to the loading by rivers.

Index words: Fresh water, mixing, spreading, brackish water, Bothnian Bay, estuary, electrolytic conductivity.

## 1. INTRODUCTION

The loading carried by rivers can be seen in the sea area as an increasing substance concentration and as consequent changes in the biology and physiography of water. These effects are dependent on the amount of loading and the degree of mixing taking place in the coastal area. Moreover, the composition of river water is altered in a brackish water area (Ryhänen 1964).

The loading in the Siikajoki mainly consists of substances washed from the soil, waste waters from population and foodstuff industries, and substances released from three artificial lakes mostly in late winter. The population centres and industry account for 1–2 % of the $BOD_7$, phosphorus and nitrogen load of the river (Antila 1977). For instance the amount of phosphorus carried by the river is about half of that in the River Oulujoki, which has a nearly 7-fold discharge. The findings made on the current observation stations over 1962–1976 show that after the construction of the Uljua artificial lake (in 1969–1970) the oxygen content declined and the phosphorus, nitrogen and iron contents increased in the river water downstream of Uljua. This is due to the situation prevailing in the late winter, when the lake is nearly devoid of oxygen (Myllymaa 1976). It has been noted, however, that during the spring flood the artificial lake binds a considerable amount of nutrients along with the solids. This system of waterways also includes the artificial lakes of Kortteinen and Vähä-Lamu.

The disadvantages noted in the research area (Fig. 1) between the estuary of the River Siikajoki and the southern tip of Hailuoto include bad taste in fish, fouling of fishing equipment, etc., which have been attributed to the waste waters from the industry and population in Oulu on the one hand, and to the loading by the Siikajoki and the influence of the artificial lakes on the other. On the basis of previous observations, it has been assumed that Karinkannanmatala, a shallow northeast of the Siikajoki estuary, prevents the flow of water from the River Oulujoki as well as waste water to the area off the Siikajoki estuary during the ice-bound period, which here lasts from the beginning of December till mid-May.

It is mostly owing to the claim by the inhabitants on Hailuoto that the possibility of building an embanked road from Oulunsalo to Santonen is investigated. Such a procedure might also bring about changes in the hydrodynamics and quality of water off the Siikajoki, which is why the findings of the present investigation are useful.

The spread of river waters and their influence on the state of the sea area have been examined in the northeastern part of the Bothnian Bay since 1975 (Alasaarela 1977a). The area investigated includes more than half of all the river waters flowing into the Bothnian Bay. Some mixing of river waters takes place in this area. In the southern part of the research area, the spreading of the water from the Siikajoki river constitutes a separate whole, in which it is easier to investigate the behaviour of river waters in a sea area than in the other parts of the northeastern Bothnian Bay.

This study deals with the behaviour of the water masses discharged by the Siikajoki and their influence on the sea area. The work was motivated by local interests and a wish to apply the methods developed in investigating the northeastern part of the Bothnian Bay (Alasaarela 1976).

The drainage basin of the Siikajoki covers 4 440 km$^2$ and the lake percentage is 1.5 %. The mean discharge of the river, MQ (1961–1970), is 39 m$^3$/s. Despite regulating lakes, spring floods occur (MHQ = 430 m$^3$/s). For part of the year the problem is scarcity of water (MNQ = 2.6 m$^3$/s).

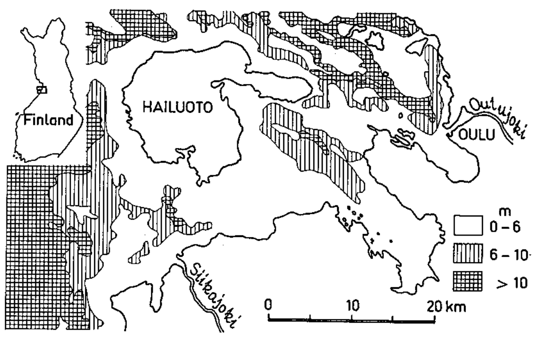


Fig. 1. Research area.

## 2. METHOD

The investigation was carried out during 1975–1977 in cooperation between the Water Districts Office of Oulu and Pohjois-Suomen Vesitutkimustoimisto.

The river waters present in the sea area were charted with a portable meter of electrolytic conductivity. The vertical density of measurements was 0.25–1.00 m in winter and 1–2 m in summer. While making the measurements, samples of water were drawn at a 1-metre distance from both the surface and the bottom. The water samples were analyzed chemically according to the methods used by the National Board of Waters (Erkomaa and Mäkinen 1975).

The data were handled according to the methods described by Alasaarela (1976).

For the sake of clarity the brackish water of the Bothnian Bay is called sea water in this paper.

## 3. RESULTS

### 3.1 Spreading of river waters into the sea area

The streamflow into the sea area in winter is noticeably different from the open-water period streamflow. Owing to the low salinity of the water in the Bothnian Bay, no clear stratification is created off the river estuary during the open-water period (Alasaarela 1977a). Therefore, as the river water flows into the sea area, it is greatly diluted when still quite near to the river estuary. Moreover, the situation is highly variable in summer, depending on the wind conditions. Wind acts as a factor mixing and transporting water masses. The situation prevailing in winter is clearly more static. The movements of water masses in winter are due to the pressure affected by the discharge of the river and to the variations in the sea water level (Sarkkula and Forsius 1977). The river waters accumulate to form a layer under the ice, which spreads out as a fan-shaped formation (Ryhänen 1962). The mixing of river waters is markedly slower in winter than in summer. The quality of the surface water in the Bothnian Bay is therefore clearly different in winter and in summer.

The development and the shape of the fan of spreading river water is shown in Fig. 2. In February 1976, river water accounted for 0.14 $km^2$ of the sea area, which roughly corresponds to the amount of water discharged by the Siikajoki. This indicates that the river waters began to form a layer under the ice immediately after formation of the ice cover. In April the amount of river waters in the sea area was twofold compared with the quantity noted in February.

The iron concentrations observed in the sea area show that water from the River Oulujoki was conveyed to the area off the Siikajoki in the winter 1975 and that this water diluted the water from the Siikajoki. Water from the Oulujoki accumulates in the Luodonselkä area in winter (Alasaarela 1977a), and, contrary to the previous assumptions, spreads into the area influenced by the water from the Siikajoki through the narrow strait at Karinkanta. This observation receives support from the flow measurements made in this area (Sarkkula and Forsius 1977).

Figure 3 shows the proportion of the water from the Oulujoki off the Siikajoki estuary in 1975, as calculated by means of iron concentrations. Having flown through the strait, the water from the Oulujoki has been forced by the pressure due to the water flowing from the Siikajoki towards Hailuoto, and it has continued to drift northwest, simultaneously mixing with the masses of water from the Siikajoki and the sea water. The water from the Oulujoki divided to go round Hailuoto both ways, and the masses of water met west of Hailuoto. The proportion of the water from the Oulujoki in the area where the water from the Siikajoki spread was 10–20 % in 1975. The smaller data analyzed on the other years also give suggestions of the kind of spreading described above.

The proportion of river water in the surface water is indicative of the directions of surface currents. The Siikajoki waters flowed northwest. The data give no suggestions of any wintertime current towards Luodonselkä.

Table 1 shows the quantities of river water flowing into the research area and the quantities observed there as well as the sizes of the areas of river water influence.

The area into which river water spread was about the same in size in the winters of both 1975 and 1976. The discharge of the Siikajoki was greater by about 30 % in 1975 than in 1976. The quantity of river water observed in the sea area, however, was only greater by 10 %. When the amount of water discharged into the sea area by the Oulujoki is taken into account, it appears that the outflow of river water from the research area during the winter was 30–40 %. A comparison of this with the amount of river water observed in February shows that the outflow of river water from the research area took place towards the end of the winter, when the layer of river water covered the entire area.

During the open-water period in October 1976 the ostensible area of river water influence was small (10 $km^2$). The estimated total amount

Table 1. Quantities of river water and the size of the areas of river water influence in April.

| | | 1975 | 1976 |
|---|---|---|---|
| Water discharged by the Siikajoki | $km^3$ | 0.49 | 0.35 |
| River water observed in the sea area | $km^3$ | 0.32 | 0.29 |
| Area with river water | $km^2$ | 330 | 330 |

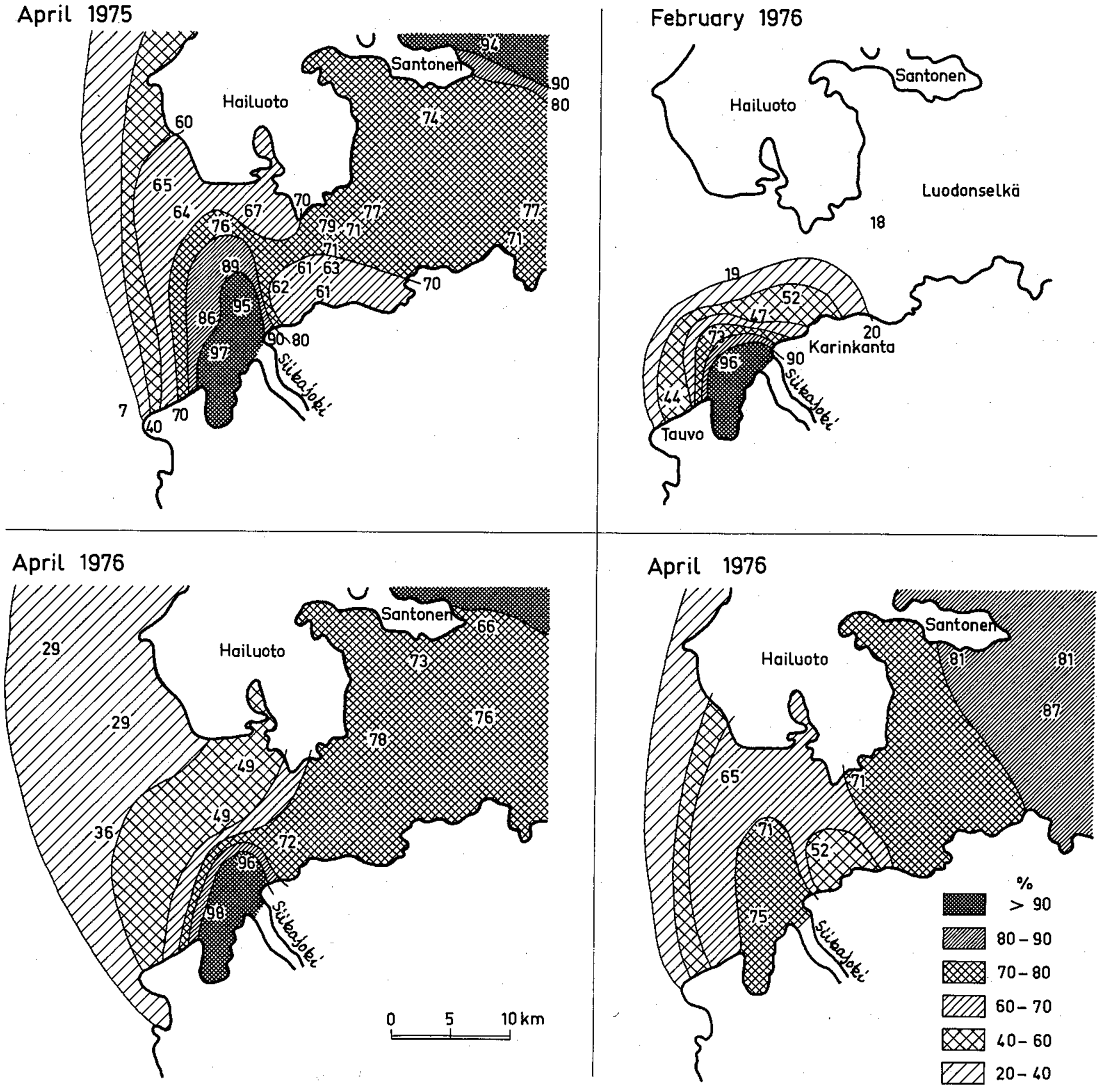


Fig. 2. Percentage of river water from the surface water (0—1 m) according to measurements of electric conductivity.

of river water in the sea area was 0.02 $km^3$, which corresponds to the river discharge of half a month. It hence appears that the river water was diluted quite rapidly during the research period.

## 3.2 Structure of the river water layer

The investigation carried out during the open-water period showed that the river water was diluted almost uniformly into the whole water column at the river estuary already. A distinct layer of river water was only formed in winter (Fig. 3).

Figure 4 shows that the river water layer does not consist of mere river water even in winter. Sea water mixed with the layer not far from the estuary. The layer of surface water, with more than half consisting of river water, reached over 10 km from the estuary in April. The phase junction surface between river water and sea water was most distinct near the estuary. The stratifying tendency of river water is shown by

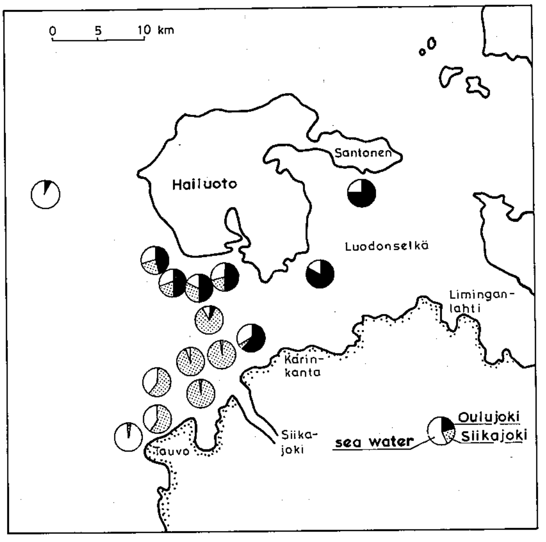


Fig. 3. Proportions of Oulujoki water, Siikajoki water and sea water in the surface water in April 1975.

the fact that hardly any river water was found to be present in the water masses deeper than 5 metres.

Table 2 shows the values of three winters for some properties of the water of the Siikajoki which are significant indicators of the state of the sea area and the spreading of river water. The value of each period was obtained by calculating the mean of the concentrations weighted according to the discharge rates of the days of observation.

Table 3 shows the corresponding concentrations recorded at the permanent observation station F-2 of northern Bothnian Bay (Jaatinen and Paulsson 1976).

The total nutrient concentrations were several times greater in river water than in sea water. The iron content was nearly 100-fold in the water of the Siikajoki as compared with sea water.

The chemical composition of the river water layer was examined by taking samples from the topmost part of the layer. Reference samples were drawn from near the sea bottom. The chemical analyses show the river water layer to consist of a mixture of river and sea water, in which the dilution noted in the different chemical qualitative parameters is parallel to that in salinity. The layer is characterized by high nutrient contents compared with sea water and

Table 2. Concentrations of the water of the Siikajoki recorded off Revonlahti in January-March 1975–1977.

| Year | $O_2$ % sat. | Colour Pt mg/l | Tot.N N µg/l | Tot.P P µg/l | Fe µg/l |
|---|---|---|---|---|---|
| 1975 | 71 | 227 | 711 | 51 | 3 310 |
| 1976 | 65 | 200 | 550 | 74 | 3 476 |
| 1977 | 68 | 177 | 573 | 75 | 3 096 |

Table 3. Concentrations in the surface water of the Bothnian Bay (1 m) in February 1976–1977.

| Year | $O_2$ % sat. | Colour Pt mg/l | Tot.N N µg/l | Tot.P P µg/l | Fe µg/l |
|---|---|---|---|---|---|
| 1976 | 95 | 10 | 274 | 5 | 37 |
| 1977 | 94 | 20 | 272 | 7 | 43 |

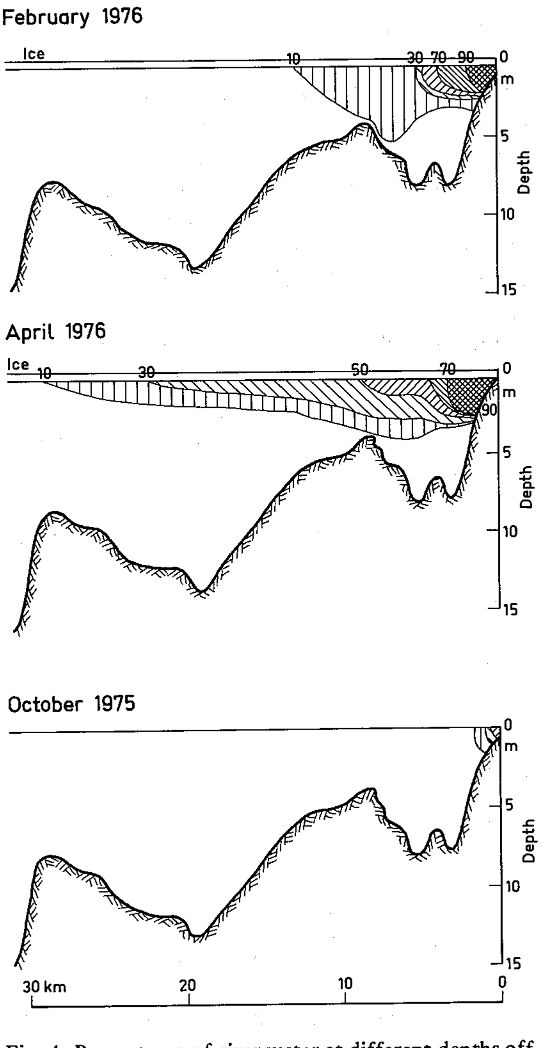


Fig. 4. Percentages of river water at different depths off the Siikajoki estuary.

high values of the parameters indicative of humus concentration of the river water. When the latter qualitative parameters are compared with the dilution ratio, which can be calculated from the salinity values, it appears that their concentrations in river water are lower on an average than could be expected on the basis of the dilution ratio. This suggests that river water undergoes structural transformation in the sea area, which transformation is due to the slowing down of the motion of river water and the effect of saline sea water (Ryhänen 1964). It is owing to these factors that sedimentation of the river water humus takes place in the sea area.

Figure 5 shows the decline of substance concentrations in the sea area as a function of the distance from the river estuary. The calculations were based on the concentration values of the Siikajoki and the sea water as well as the electrolytic conductivity of water. The results are remarkably scattered, the reasons for it being the diluting effect of the Oulujoki water in the area where the water from the Siikajoki spreads, sensitivity of analysis, and the temporal fluctuations in the quality of the Siikajoki water. These render the interpretation difficult. It can be seen from the results that the degree of phosphorus reduction is the lowest of the components examined.

The increasing effect of river waters on the nutrient level of the sea area is noticeable in the winter (Fig. 6). In April 1975, the surface water of a 80 $km^2$ area had a fourfold phosphorus content and a more than twofold nitrogen content compared with the sea water values.

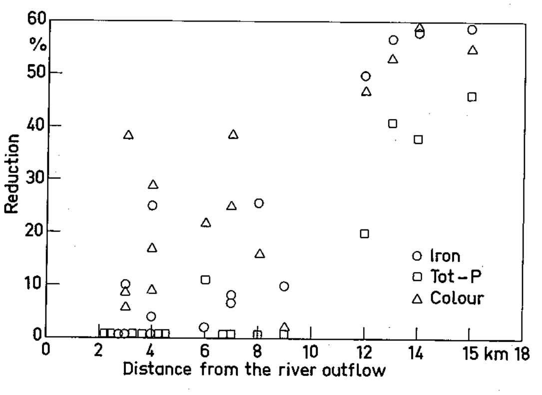


Fig. 5. Iron, colour and total phosphorus reduction in the river water present in the sea area in the winters 1975–1977.

The oxygen situation in the river water layer is relatively good. In a 150 $km^2$ area off the river estuary the oxygen saturation deficit was 20–30 % in April 1975. Underneath the river water layer the oxygen content was nearly equal to the oxygen content of sea water.

Observation of the changes in oxygen content in the river water of the sea area is made difficult by the fact that oxygen content declines in the water of the Siikajoki during the winter. Assuming that the river water which has reached the extreme margins of the spreading area by April has flown into the sea in the early winter, we can conclude that the degree of oxygen saturation in the river water fraction has declined by 10 % in the sea area during the winter.

# 4. DISCUSSION

## 4.1 Spreading and mixing of river waters

The spreading of river waters into the northeastern part of the Bothnian Bay between the Rivers Siikajoki and Tornionjoki has been investigated since 1975. Reports have been published in 1975–1976 (Alasaarela 1977a). These works have shown that the river waters only accumulate in winter to form a distinct surface water layer, and that even this layer does not consist of absolute river water. The amount of sea water included in the layer increases as a function of depth and distance from the river estuary. The summertime stratification is transient and clearly less extensive than that in winter.

Ryhänen (1962) surveyed the spreading of the water from the Kokemäenjoki into the Gulf of Bothnia by measuring electrolytic conductivity. According to his findings, the river water spreads as a very thin layer. The thickness of the river water layer was 1–2 m in winter and 1 m in summer. The phase junction surface between river water and sea water was very distinct in both summer and winter.

According to the present findings, the water from the River Siikajoki spreads into the sea area in accordance with the same hydrodynamic laws as do the water masses discharged into the north-

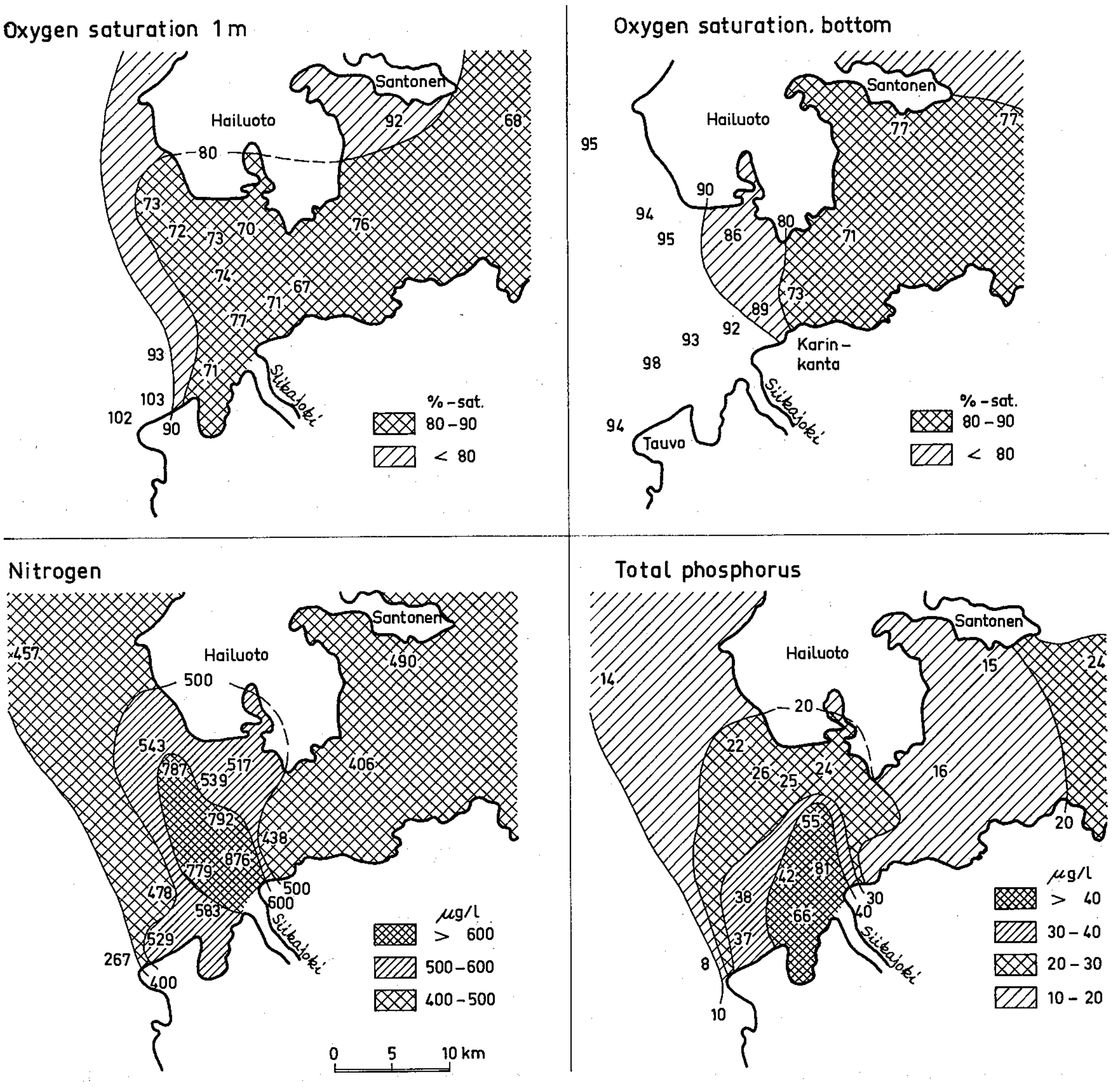


Fig. 6. Total nutrients and the degree of oxygen saturation off the Siikajoki astuary in April 1975. Oxygen saturation in the surface water (1 m) and near the bottom, total nitrogen (1 m) and total phosphorus (1 m) in April 1975.

eastern Bothnian Bay by the other rivers. The wintertime stratification of river water over sea water has been clear-cut, but the mixing of river water in sea water appears to be more intensive than was reported by Ryhänen (1962) (cf. Leinonen 1976). This is due to the lower salinity of the Bothnian Bay, which is why the differences in density between river water and sea water are smaller in the Bothnian Bay than further south in the Gulf of Bothnia. Owing to the more effective mixing, the layer influenced by river water is thicker (2–3 m) off the Siikajoki and the sea water content of the river water layer is greater than was the case in the aforesaid investigation.

The findings made during the open-water period showed that the masses of water off the Siikajoki were mixed down to the bottom and the area of river water influence was quite small.

The local flow of water masses in the Baltic Sea is affected by the average flow systems of surface water and deep water (Hela 1957), the currents caused directly by wind in summer (Lisitzin 1946, Hela 1957), the currents due to fluctuations in the sea level (Lisitzin 1946), the pressure due to the river waters flowing into the sea area, shallows and islands, and the force of the earth's rotation.

All these factors also influence the currents off the Siikajoki estuary. The last two factors remain constant, while the others vary according to e.g. the seasons.

The movements of water masses in the northern part of the Bothnian Bay are very slow (Palosuo 1966). In summertime, the deep water remains isolated and the movements of water masses mainly take place as surface currents. In late autumn, the stratification disappears (Fonselius 1971). The average direction of surface currents in the Finnish part of the Bothnian Bay is towards the north along the coast owing to the force of the earth's rotation (Palmen 1930). This system of currents probably brings about pressure of the water masses at the Siikajoki estuary towards Luodonselkä. Hydrochemical analyses have revealed average currents of this kind in summer (Alasaarela 1977b).

According to the flow measurements made by Sarkkula and Forsius (1977), wind is the primary factor causing currents in the sea areas off Oulu during the open-water period. In winter, the effect of the wind is eliminated and the rates of flow are consequently smaller than they are in open water. At that time the fluctuations of sea level are clearly related to the currents. Investigations have shown that the changes in sea level generally take place in 8-hour periods, which cause reciprocating flow. As the sea level rises, the Luodonselkä basin is filled via the two straits, and as the sea level goes down, the basin is correspondingly evacuated via the same routes. Flow measurements revealed a net flow towards the west in the strait off Karinkanta. The wintertime rate of flow in the strait was occasionally as high as 0.30 m/s.

Sarkkula and Forsius (1977) observed a net flow bringing water in winter from the Luodonselkä area into the area influenced by the Siikajoki water, which supports the observation made during the course of this work. Contrary to previous assumptions, water from the River Oulujoki is conveyed in winter into the area where water from the Siikajoki spreads. This is probably due to the pressure caused by the inflow of the Oulujoki water.

## 4.2 Structure of the river water layer

The movement of river water masses slows down in the sea area, and the river water simultaneously comes into contact with saline sea water. As the motion slows down, the particles present in the river water tend to fall to the bottom. According to Stokes' law, this downward movement depends on e.g. the size of the particle and the viscosity of water, which, in turn, depends on the temperature and salinity of the water. In practice the falling of the particle is influenced by the turbulence and density stratification of water.

The humus colloids contained by the river water are not in themselves sufficiently heavy for sedimentation. When the humus comes into contact with electrolytes in the sea area, it coagulates and, upon reaching a sufficient particle size, begins to sink towards the bottom (Ryhänen 1964).

The humus contained in water can be divided into a colloid fraction and an electrolyte fraction (Pennanen 1972). The molecular size of the latter is clearly smaller, and its sedimentation is therefore slower (Pennanen 1972, Kauppi 1975). The colloid fraction contains markedly more iron and phosphorus than the electrolyte fraction, while the factors responsible for the colour of the water, for example, are more evenly distributed (Pennanen 1972, Haapala et al. 1976). In the river water off the Siikajoki estuary there was less reduction of phosphorus than reduction of iron and colour. The reason for this is the high content of soluble phosphorus in the river water. Iron and colour were reduced in a nearly similar ratio. Owing to the shortage of the data available it is impossible to estimate the quantitative sedimentation of the two humus fractions on the basis of the ratio between iron and colour reduction. The results suggest, however, that the present method, when applied at the estuary of a suitable river, might be used to elucidate e.g. the following question: How is the reduction of phosphorus in the humus affected by the fact that most of the phosphorus is bound in the colloid fraction, whose sedimentation is more rapid than that of the electrolyte fraction.

The partial mixing of river water with sea water during the winter has a favourable effect on the state of the river water layer. The oxygen situation in the sea area is good, and oxygen consumption is low. The monthly oxygen consumption in the area off Oulu has been found to be as high as 3 mg/l, but the dilution of waters has precluded the imminent shortage of oxygen (Alasaarela 1977a). Oxygen consumption in the area off the Siikajoki is remarkably low, which signifies slow decomposition of humus. Moreover, mixing clearly improved the situation.

Despite dilution, the effect of the Siikajoki water on the humus-like colour and nutrient content of the surface water of the sea area is remarkably great in winter. No similar local increase in the concentrations of these qualitative parameters has been noted anywhere in the northeastern Bothnian Bay. When we, furthermore, take into account the sudden effect of the spring flood on increasing and spreading the river water which has accumulated over the winter, we can assume that the water masses discharged by the Siikajoki provide a considerable store of nutrients for the bloom period of phytoplankton in the early summer. The phytoplankton population occurring in the Luodonselkä area in the early summer is the densest seen in the coastal waters near Oulu. It has been suggested (Alasaarela 1978) that one cause for this abundance of phytoplankton may be the Siikajoki water, which is transported by wind into this area after the break-up of the ice cover.

## 5. SUMMARY

The report dealt with the hydrodynamics and hydrochemistry of river and sea water off the Siikajoki estuary in 1975–1977. The main focus was on the situation prevailing in winter. The effect of the Siikajoki water on the sea area was limited in summer, and no stratification of water masses was noted.

In winter, the area influenced by the Siikajoki water is relatively large and the effect of the river water on the chemistry of the surface water of the sea area is considerable. The high substance concentrations of the water of the Siikajoki compensate for the low discharge. The area off the Siikajoki estuary hence displays a wintertime increase in the nutrient content and humus colouring which is greater than any other local increase in the northeastern Bothnian Bay. Some mixing of river water in sea water does, however, take place even in winter. The effect of this mixing is favourable on e.g. the oxygen balance of the surface water.

Measurements of electrolytic conductivity showed that the area off the Siikajoki estuary had a surface water layer consisting of river water, whose quantity was more than half of the amount of water discharged by the river during the winter. Hydrochemical analyses showed, however, that the area was influenced by not only the Siikajoki water, but also water from the Oulujoki. This observation was later confirmed by means of flow measurements. This phenomenon must be taken into consideration in planning protective measures on the waters of the Oulu region and the possible embankment for the Hailuoto road.

It is difficult to estimate the sedimentation of humus from the Siikajoki water by means of reductions in substance concentrations, because the other river waters flowing into the area tend to obscure the situation. The reduction of phosphorus is lower than that of colour and iron. The reason for this is the high concentration of soluble phosphorus in the Siikajoki water, while colour and iron are bound to humus.

One of the purposes of this study was to test the applicability of the methods described by Alasaarela (1976) to the investigation of the partially isolated sea area off the Siikajoki estuary. The findings show that the electrolytic conductivity values give a relatively reliable picture of the spreading of river waters. When the substance concentrations are viewed in the light of the river water proportion calculated by means of electrolytic conductivity, the material is clearly easier to interpret. Certain observations can be made which are impossible on the basis of the substance concentrations alone.

## LOPPUTIIVISTELMÄ

Selvityksessä käsitellään jokiveden ja meriveden dynamiikkaa ja kemiaa Siikajoen edustalla v. 1975–1977. Tutkimuksen pääpaino on talvitilanteessa, koska Siikajoen vesien vaikutus merialueella oli kesäaikana suppea-alainen eikä vesimassojen kerrostuneisuutta havaittu.

Talvella Siikajoen vesien vaikutusalue oli verrattain laaja ja vaikutus merialueen pintaveden kemiaan huomattava. Siikajoen veden suuret ainepitoisuudet kompensoivat vähäistä virtaamaa. Tämän vuoksi Siikajoen edustalla ravinnepitoisuuden ja humusväritteisyyden paikallinen lisäys talvella on suurempi kuin muualla Perämeren koillisosassa. Jokiveden sekoittumista meriveteen tapahtuu kuitenkin talvellakin. Tämä parantaa esimerkiksi päällysveden happitaloutta.

Sähkönjohtavuusmittauksien avulla voitiin havaita, että Siikajoen edustalle oli kerääntynyt talven aikana pintavesipatjaksi jokivesiä, joiden määrä oli selvästi yli puolet joen talven aikana tuomasta vesimäärästä. Toisaalta voitiin vesikemiallisten analyysien avulla osoittaa, että alueella oli Siikajoen vesien lisäksi myös Oulujoen vesien vaikutusta. Havainto vahvistettiin myöhemmin virtausmittausten avulla. Tämä on otettava huomioon mm. Oulun alueen vesiensuojelutoimenpiteitä ja Hailuodon pengertietä suunniteltaessa.

Siikajoen humuksen sedimentoitumisen arviointia ainepitoisuuksissa havaittavien reduktioiden avulla häiritsevät alueelle tulevat muut jokivedet. Fosforin reduktio oli alhaisempi kuin värin ja raudan. Tämä johtuu siitä, että fosfori on Siikajoen vedessä puoleksi liukoisessa muodossa, kun taas väri ja rauta ovat pääasiassa humukseen sitoutuneita.

Tämän selvityksen eräänä tarkoituksena oli testata sähkönjohtavuuden käyttöä jokivesiosuuden määrittämismenetelmänä Siikajoen edustan puoliavoimella merialueella. Tutkimuksen mukaan sähkönjohtavuusarvot antavat kohtalaisen hyvän kuvan jokivesien leviämisestä. Ainespitoisuuksien käsittely sähkönjohtavuudesta laskettavan jokiveden osuuden avulla avartaa selvästi aineiston tulkittavuutta. Tällöin voidaan tehdä havaintoja, joita ei pelkistä ainepitoisuuksista voida nähdä.

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