BALTIC SEA ENVIRONMENT PROCEEDINGS

No. 16

WATER BALANCE OF THE BALTIC SEA

A Regional Cooperation Project of the Baltic Sea States
International Summary Report

BALTIC MARINE ENVIRONMENT PROTECTION COMMISSION
– HELSINKI COMMISSION –

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June 1986

This International Summary Report has been edited for the purposes of the Helsinki Commission by Professor Malin Falkenmark, Executive Secretary of the Swedish IHP Committee.

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PREFACE

This document, published by the Helsinki Commission for the benefit of those interested in the marine environment of the Baltic Sea, presents extensive information on the hydrological background against which the ecological conditions of the different sub-basins should be seen. The report presents the average conditions of freshwater exchange, the time scales involved and the considerable fluctuations from month to month and from year to year. It constitutes the international summary bringing together the main results of fifteen years of joint work of a group of hydrological scientists from all the seven riparian countries.

The research has been carried out in the form of a regional project, WATER BALANCE OF THE BALTIC SEA, organized within Unesco's International Hydrological Decade (until 1974) and International Hydrological Programme (from 1975 onwards). The leadership has been provided by an international Group of Experts, convening intermittently during the project period. The final compilation of the balance is the work of experts in Poland and Sweden, who carried the burden of conceptual and coordinating work. The participating national committees distributed the work between themselves, so that the responsibility for each of the hydrological elements was delegated to one of the countries. The full reports on the individual sub-projects/elements have been published by the respective national committee or by the institution to which the committee transferred the scientific task.

In order to produce an international summary for the benefit of those involved in the ongoing work of the Helsinki Commission, the element coordinators were invited by the Group of Experts to submit texts to the individual chapters. The project coordinator invited Professor M. Falkenmark, Executive Secretary of the Swedish IHP Committee, to take on the task to edit the text to a balanced product. The publishing was made possible by financial support from the German IHP/OHP National Committee and the Swedish Committee for Hydrology. The drawings were prepared at the Finnish Institute of Marine Research.

The completed work constitutes an example of international co-operation among countries, characterized by different economic relations and different socio-political systems.

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The project can hopefully be treated as a model in stimulating scientists to undertake similar studies on other semi-enclosed seas. Although there remain some defects and some problems connected with the water balance of the sea that have not been solved, I am convinced that the results will be received with interest by people occupied with studies on the marine environment of the Baltic Sea.

Warsaw, October 1985

Prof.Dr. Zdzizlaw Mikulski
Project Coordinator

The Summary Report from the Regional Hydrological Research Project on Water Balance of the Baltic Sea is published in the Baltic Sea Environment Proceedings on the basis of the decision by the Helsinki Commission at its Fifth Meeting held on 13-16 March 1984 in Helsinki. The Helsinki Commission is not responsible for the content of the document but the contributors are considered to be responsible for all the opinions and conclusions presented in this publication.

LIST OF ELEMENT COORDINATORS AND MAIN REPORTS ON THE INDIVIDUAL WATER BALANCE ELEMENTS

ELEMENT	COORDINATOR	MAIN REPORT*
River inflow	Prof. Dr Zdzislaw Mikulski University of Warsaw Faculty of Geography and Regional Studies PL-00-927 WARSAW 64-Poland	Mikulski, Z (1982): River inflow to the Baltic Sea 1921-75. Summary List Warsaw (Mimeo)
Precipitation	Dr Bengt Dahlström Swedish Meteorological and Hydrological Institute S-601 76 NORRKÖPING Sweden	Dahlström, B (1983): Determination of areal precipitation for the Baltic Sea Internal report, Swedish Meteorological and Hydrological Institute
Evaporation	Dr Dieter Henning Staffelsgasse 36 D-5305 ALFTER - FRG	Henning, D (1985): Abschätzung der Verdunstung aus Oberflächendaten. Chapter 3.1.2 of an IHP-report of the Federal Republic of Germany on the Water and Material Balance of the Baltic Sea. Koblenz, in press.
Water storage	Dr Nikolai N Lazarenko State Oceanographic Institute 23 Linia 2a SU-199 026 LENINGRAD - USSR	Lazarenko, N N (1980): Variations of mean level and water volumes of the Baltic Sea. Leningrad (Mimeo)
Water exchange	Dr Torben Jacobsen The Marine Pollution Laboratory Jægersborg Allé 1 B DK - 2920 CHARLOTTENLUND Denmark	Jacobsen, T S (1980): Sea Water exchange of the Baltic. Measurements and methods. National Agency of Environmental Protection, Copenhagen
River input of suspended material	Dr Bengt Nilsson Hydroconsult Drottninggatan 4, S - 752 20 UPPSALA Sweden Dr Jerzy Cyberski University of Gdansk Dep. of Physical Oceanography Czolgistow Avenue No 45 81 - 378 GDYNIA - Poland	Final report included as Chapter 9 in this summary report

In addition to the above contributions, a study of the river input to the Baltic Sea of dissolved substances was carried out by Aarno Voipio and Vappu Tervo of the Finnish Institute of Marine Research. Unfortunately, very little experimental material was however available in the various countries. Shortly after the study period, the collection of relevant data in the various Baltic Sea countries was clearly intensified enabling more reliable estimates of river input. Since this publication series also includes such reports, the authors of the original IHP-study felt it unnecessary to publish their slightly aged contribution in this context.

* The report could be made available through the respective National Committees for the International Hydrological Programme.

Chapter 1

HISTORY OF THE PROJECT

Zdzislaw Mikulski (Poland)

1.1 EARLY WATER BALANCE STUDIES

Studies on the water balance of the Baltic Sea have a long-term tradition, dating back to the turn of 19th and 20th centuries. Studies were obviously favoured by the establishment in 1902 of the Commission for Studies of Northern Seas (later on transformed into the International Council for the Exploration of the Sea, which is still active). The first calculation of water balance elements of the Baltic was made by Krümmel who presented the results in 1903 at Institut für Meereskunde at the University of Berlin (Krümmel 1904). The calculations allowed to draft, for the first time, a complete water balance of the Baltic Sea. Later attempts at calculating were done by Spethmann (1912) and Witting (1918). Great contribution to the work on the water balance of the Baltic was made by Rundo, co-founder of the Russian Hydrological Institute (later State Hydrological Institute in Leningrad), an outstanding Polish hydrologist and chief of Polish hydrological service in the period 1937-39. At the annual meeting of the Russian hydrological Institute in 1922, he indicated the necessity to undertake studies on the water balance of the Baltic (Rundo 1922).

Organized studies on the balance were undertaken during the 1930's whithin the framework of Hydrological Conferences of the Baltic Countries. At the Third Conference in 1930 in Warsaw, Rundo presented his significant appeal to undertake studies on river inflow to the Baltic and other elements of the water balance (Rundo 1930). At the Fourth Conference in Leningrad in 1933, Sokolowsky presented a paper on the balance of the Baltic in which he gave the first water balance equation (Sokolovsky 1933). Following conferences patronized the studies so that after a few years, a lot of valuable material had been gathered. A turning-point was Brogmus work, published in 1952, which revised the water balance of the Baltic and which for the first time took into account also the share of ocean waters in the water balance (Brogmus 1952). Two years later, Wyrtki conducted detailed analysis of the seasonal changes of the water balance components as well as of the long-term variations (Wyrtki 1954).

In 1956 the Conferences of Baltic Oceanographers were started with the purpose to inspire joint coordinated research. Ten years later, at the Fifth Conference in 1966 in Leningrad, the Polish side presented a paper on variability of river inflow to the sea, and proposed to resume the water balance studies. The proposal was accepted and at the Sixth Conference in 1968 in Sopot, results of calculation of river inflow to the Baltic in the period 1951-1960 were presented (Mikulski 1970).

1.2 INTERNATIONAL HYDROLOGICAL DECADE

In the autum of that year in Warsaw, the First meeting of representatives of National Committees on the International Hydrological Decade (IHD) of the European Socialist Countries accepted Poland's proposal to undertake a project on "Water Balance of the Baltic Sea". The first alarming signs of pollution of the sea had just appeared, calling for a more intense study of the ecological situation.

Simultaneously, the issue was approached by the IHD National Committees of the Nordic Countries, which created a special working group for that purpose. In 1970 at the seventh Conference of Baltic Oceanographers in Helsinki, the group held its first meeting. Mikulski and Majewski (1970) presented a concept of the programme, and a new form of the balance equation, separating horizontal and vertical water exchange. Soon, the Polish National IHD-Committee approached all the Baltic countries with a concrete proposal to undertake the project "Water Balance of the Baltic Sea".

A first meeting of experts, from all the Baltic countries, on the Water Balance of the Baltic Sea was held in Gdynia 21-24 September 1971. The meeting was chaired by the Polish initiator, Professor Zdzislaw Mikulski, who was charged with the function of coordinator of the project. The chairman stressed in his foreword that

> "a full presentation of the water balance is far, but very often we observe dangerous changes in the marine environment of the Baltic. More and more often situations requiring an intervention occur, and this will be possible and effective only when the water balance is known. Thus, it depends on us if we are able to provide, in time, sufficient data for rational management and protection of the marine environment of the Baltic. The purpose of our meeting is to define the problem, its volume, possibilities and time of its preparation. The presented programme is of preliminary character and will be, as it is expected, amended, corrected and modified with time. But this is not the most important thing. The important thing is to discuss it thoroughly, with the importance of the problem in mind, and to distribute the tasks and set the obligatory time-table of works. Personally, I am convinced that despite many obvious difficulties we shall manage to close our first meeting, having undertaken concrete decisions and obligations."

During the meeting, a general programme to study the balance was approved, initial distribution of tasks among the participating countries was made, and resolutions taken, setting the first tasks to be completed, e.g. the need to define the sea area and volume (updating of barometric maps), the necessity to undertake studies on water exchange with the North Sea, and a permanent exchange of information and publications.

1.3 SHAPING THE PROJECT

At the second meeting of experts (Copenhagen, 5th-7th October, 1972) immediately following the Eight Conference of Baltic Oceanographers, the programme of the whole project was made as follows:

* Poland - water inflow from the catchment area and participation in estimation of inflow of suspended matter
* Sweden - morphometry of the sea, precipitation, and participation in estimation of inflow of suspended matter (together with Poland)
* FRG - evaporation
* USSR - changes of sea-level and volume
* Denmark - exchange of water and solid matter with the North Sea
* Finland - inflow of dissolved matter.

GDR restricted its participation to supplying indispensable material (later on it joined the statistical analysis of river inflow). At the same time, the project coordinator (Prof. Z. Mikulski) was granted authorization to present the general programme of studies on the water balance of the Baltic Sea at the UNESCO/WMO international conference on "Hydrological problems in Europe" (Bern, 22nd-27th August, 1973).

It is worth reminding that soon afterwards, two significant Baltic conventions were signed. In September 1973, on Poland's initiative, a diplomatic meeting on the Baltic was held in Gdansk (4th-13th September 1973) and as a result the Convention on Living Resources in the Baltic Sea and the Belts was signed, in short called the Gdansk Convention. To realize the aims of the convention, the International Baltic Sea Fishering Commission was set up, seated in Warsaw. Another step on the way to protect the Baltic environment was - in result of Finland's proposal - the Convention of the Marine Environment of the Baltic Sea, in short called the Helsinki Convention, which was the result of another diplomatic conference of the Baltic countries in Helsinki (18th-22nd March, 1974). Similarly to the previous case, the Baltic Marine Environment Protection Commission was set up, with the seat in Helsinki, in short called the Helsinki Commission. Both Conventions constitute an important step in the cooperation of the Baltic countries, on a correct management and protection of the Baltic and its marine environment; they constitute a formal basis also for scientific research.

In 1974 a state of the art report, elaborated by experts from Sweden and Poland, was published (Falkenmark and Mikulski 1974) which contained also outline of the project. The report was received with great interest. It was marked as "Project Document No 1" with an intention to publish a series of reports concerning various fields of studies resulting from the cooperation. Unfortunately, so far no more publications have appeared in that series.

1.4 METHODOLOGICAL STUDIES DURING PILOT STUDY YEAR

The third meeting of experts in Kiel, 22nd-24th April, 1974, was held just after the Ninth Conference of Baltic Oceanographers. The main point, besides permanent evaluation of the current state of work on the individual elements of the balance, was a project proposal on a new morphometric basis of the Baltic and its division into basic subregions, presented by a Swedish expert (Dr. Ulf Ehlin), and just approved by the preceding Conference of Baltic Oceanographers. Dr. Ehlin also proposed a project of methodological studies, "Pilot Study Year" (PSY), to be started in 1975. The basic aims of this project were approved to be:

- to explore the feasibility and to study the best methods of determining the different elements of the water and material balances on a current basis, and based on data which can be delivered by the different countries,

- to develop the best form of data exchange between the participating countries for the elaboration of the current water and material balances,

- to perform necessary methodological studies for certain elements, thereby facilitating the elaboration of the historical balance to be based on observational data already existing in the different countries.

The aims should be attained by determining all the individual water balance components independently, so that closing errors in the calculations could be estimated. The programme should be preceded by preliminary studies concerning methodology in order to select the network of stations and the frequency of measurements to be applied etc.*)

The PSY was carried out simultaneously with the large measurement action "Belt Project" (April 1974 - April 1978), undertaken by Denmark in order to evaluate the state of the marine environment of the Danish coastal waters. A cooperation of the two actions was considered to bring benefits to both projects.

In September 1974, at the UNESCO/WMO International Hydrological Conference in Paris, achievements of the International Hydrological Decade were summed up, and its follow-up, the International Hydrological Programme, was enforced. The international project "Water Balance of the Baltic Sea" was presented, and considered to be a good example of regional hydrological cooperation of countries with different socio-political systems.

The issues connected with starting the Pilot Study Year from 1 July, 1975 were specifically approached at the fourth meeting

*) Pilot Study Year on the Water and Material Balance of the Baltic Sea. Programme proposed by the Swedish delegation. Kiel, April 22-24, 1974.

of experts held at Hässelby, Stockholm, 11th-14th February, 1975. The PSY concept was presented also at the Third Soviet-Swedish Symposium on control of Baltic pollution (Rosenön, near Stockholm, 15th-21st September 1975) (Mikulski 1977).

Coordination of the PSY-action was taken over by Sweden, and individual countries undertook the task to supply the necessary data on a monthly basis. During operation of the PSY, a decision was taken to prolong the action until the end of 1976. Soon after its completion, a meeting of an ad hoc group of experts (Ad hoc Pilot Study Group of Experts) was held in Sweden (Norrköping, 15-17 February, 1977) at which the course of the whole action and the value of the obtained data were evaluated.

At the fifth meeting of experts (Rostock 23rd-27th May, 1977), results of the PSY were presented. The meeting recommended analysis of the results and to supply them to all the participating countries. Also, the state of elaboration of the historical balance 1951-70 was discussed, and further recommendations to speed up the calculations were accepted.

Meanwhile the project "Water Balance of the Baltic Sea" became widely known, due to information on it presented at various international conferences. At the Seminar on the Water Balance of Europe (Varna, 27th September - 2nd October, 1976), the coordinator presented a paper titled "Water Balance of the Baltic Sea in the light of other European semi-enclosed seas". Similarly, at the Second UNESCO/WMO Conference on Hydrological problems in Europe (Brussels, 19th-23rd September, 1977), a report was presented to the group on regional hydrological activity. The project has been discussed many times at meetings of the IHD/IHP National Committees both of the Nordic countries and of the European socialist countries. At a meeting of the ad hoc working group (Warsaw, 26th-28th November, 1978), results obtained concerning individual elements were discussed, and conclusions necessary for the elaboration of the historical water balance were drawn. At the sixth meeting of experts (Hanasaari, near Helsinki, 30th January-2nd February, 1979), the following issues were discussed: evaluation of the PSY, state of elaboration of the historical balance, plan of a monography on the water balance of the Baltic. East German specialists, jointly with the coordinator, presented statistical analysis of the river inflow th the sea, seen in a long-term time prespective.

1.5 FINAL PHASE

The international project "Water Balance of the Baltic Sea" now entered its final phase. A third meeting of the ad hoc working group (Copenhagen, 18th-20th February, 1980) was devoted to further analysis of the PSY results, to possibilities to draft the historical balance and to the draft on the intended monography. A seventh (last) meeting of experts was held (Leningrad, 17th-19th April, 1980), immediately following the

Twelfth Conference of Baltic Oceanographers in Leningrad. At the Conference, the coordinator presented a general paper on the state of works on the balance (Mikulski 1984a). The Conference approved the results of the 10-year work, and recommended to continue studies on the water balance of the Baltic Sea. The subject of the meeting was an evaluation of the complete performance of the tasks covered by the programme, as well as the state of preparations for publication of the monography. The resolutions of the Conference of Baltic Oceanographers were approved. Specially, it was considered purposeful to present the results of the studies to the Helsinki Commission.

At the beginning of the 1980s, the work intensity on compilation of the project results clearly dopped down. The experts were busy with preparation of the different chapters of the monography, and the elaboration of so-called national reports containing the detailed reports on the studies on the individual elements of the balance, for which individual countries were responsible. At the Fourteenth Conference of Baltic Oceanographers (Gdynia, 28th September-2nd October, 1984), the coordinator reported on the final results of the studies (Mikulski 1984b). Due to difficulties met in publishing the monography, it was decided - after consultations - to publish a joint international summary report of smaller volume. After the consent of the Helsinki Commission, this summary was to be included in the series published by the Commisson.

Chapter 2.

THE BALTIC AS A SYSTEM

Zdzislaw Mikulski (Poland)

The Baltic is an inland, shelf sea. Despite of its relatively small area (415,266 km^2), its meridional stretch is over 1,500 km and its latitudinal about 650 km. Length of the coast line (curcumference of the sea) is over 15,000 km. Connection with the North Sea through the narrow and relatively shallow Danish Straits makes it possible to treat the Baltic as part of the Atlantic Ocean. Thus, it is a typical, so-called semi-enclosed sea with limited contact with an ocean (the North Sea) but under the clear impact of that ocean.

The Baltic Sea is a hydrological object of very differentiated character; specific land configuration results in the occurrence of separate water regions and bays, cutting deeply into the land. There are great differences in the supply of river water. Also the exposure to influence from the open sea varies considerably from the outer to the inner end of the Baltic. Therefore, it cannot be treated as one water reservoir - rather, each of its water regions is to be seen as almost a separate hydrological object. Thus, in the system approach, the Baltic Sea can be considered as a cascade of connected sub-systems whose water relations are formed under strong influence of the whole drainage basin and, through the North Sea, also under the influence of the Atlantic Ocean.

2.1 REGIONAL DIVISION OF THE BALTIC

2.1.1 Western boundary of the Baltic Sea

As already mentioned, the Baltic Sea is made up of a number of distinctly marked sub-basins with rich sculptured coast and bottom. In many earlier studies, it has been divided into characteristic regions - different depending on the research needs. Thus e.g. Dietrich's division made on a "hydrographic basis" (Dietrich 1950) became quite common. Without analysing this division of the sea or later divisions in detail, we shall here discuss the division into characteristic regions done in the course of the present project. The division was done in the Swedish Meteorological and Hydrological Institute, and discussed at the Ninth Conference of Baltic Oceanographers in 1974 (Ehlin et. al 1974); it was finally approved at fourth meeting of experts on the Water Balance of the Baltic Sea in 1975.

First of all, a decision was taken to define the western boundary of the Baltic. After a wide discussion, and taking into consideration views existing among Baltic oceanographers, it was decided to set the sea's boundary as running from the line separating Kattegat from Skagerrak, i.e. the line connecting the northern tip of the Jutland peninsula (promontory of the Skagens Rev Cape, Grenen) with the lighthouse on the Pater Noster Skerries (Hammeskäran on the foreland of the Tjörn island, north of Göteborg, Sweden). The separation into sub-basins was based on their hydrological by distinct character which, in turn, results mainly from morphology of the bottom and coast.

2.1.2 Seven main sea regions

For detailed calculation, 19 smaller regions were separated which were then grouped into 7 main sub-basins, accepted as a basis for calculation of the water balance. As an adaption to computers, boundaries between sub-basins assumed the form of zigzag lines, marked as straight lines on the map. End points of boundary lines and their bends were defined by geographic coordinates. The regional division of the Baltic Sea gained general approval among the Baltic oceanographers, and was later approved as a basis of research works conducted within the framework of the Baltic Marine Environment Protection Commission - the Helsinki Commission.

The Gulf of Bothnia was divided into the Bothnian Bay and the Bothnian Sea, divided by the archipelago of the Kvarken islands. The archipelago of the Åland Islands is included in the Bothnian Sea. The Gulf of Finland is a separate sub-basin similarly to the Gulf of Riga, which is separated from the open sea by the islands of Saarenmaa and Muhu. The main region of The Baltic Sea is the Baltic Proper; the name has been commonly accepted in scientific literature, including the publications of the Helsinki Commission. The sub-basin formed by the Danish Straits includes three different straits: Öresund, Great Baelt and Little Baelt; the latter forming the Baelt Sea. The seventh region is Kattegat, whose boundary with Skagerrak constitutes the accepted boundary of the Baltic Sea. Boundaries of the regions are outlined in Fig. 2.1.

Sub-basin 1. The Bothnian Bay
($36,260\ km^2$), northernmost part of the sea, relatively shallow (max. depth 146 m); southern boundary is formed by the archipelagoes of the islands of Vallgrund, Ängersön and Holmön, divided by two straits Eastern Kvarken and Western Kvarken; the border line runs from the Finnish town of Vaasa to the Swedish town of Umeå.

Sub-basin 2. The Bothnian Sea
($79,257\ km^2$), much deeper (max. depth 294 m); its boundary with the middle part of the Baltic is constituted by the Southern tip of the Åland Islands archipelago so that the Åland Sea forms part of this region.

Sub-basin 3. The Gulf of Finland
($29,498\ km^2$) easternmost part of the sea, shallow (max. depth 123 m); its western boundary has been defined to run from the Hanko peninsula to the north-western tip of the Estonian coast, almost perpendicularly to the longitudinal axis of the gulf.

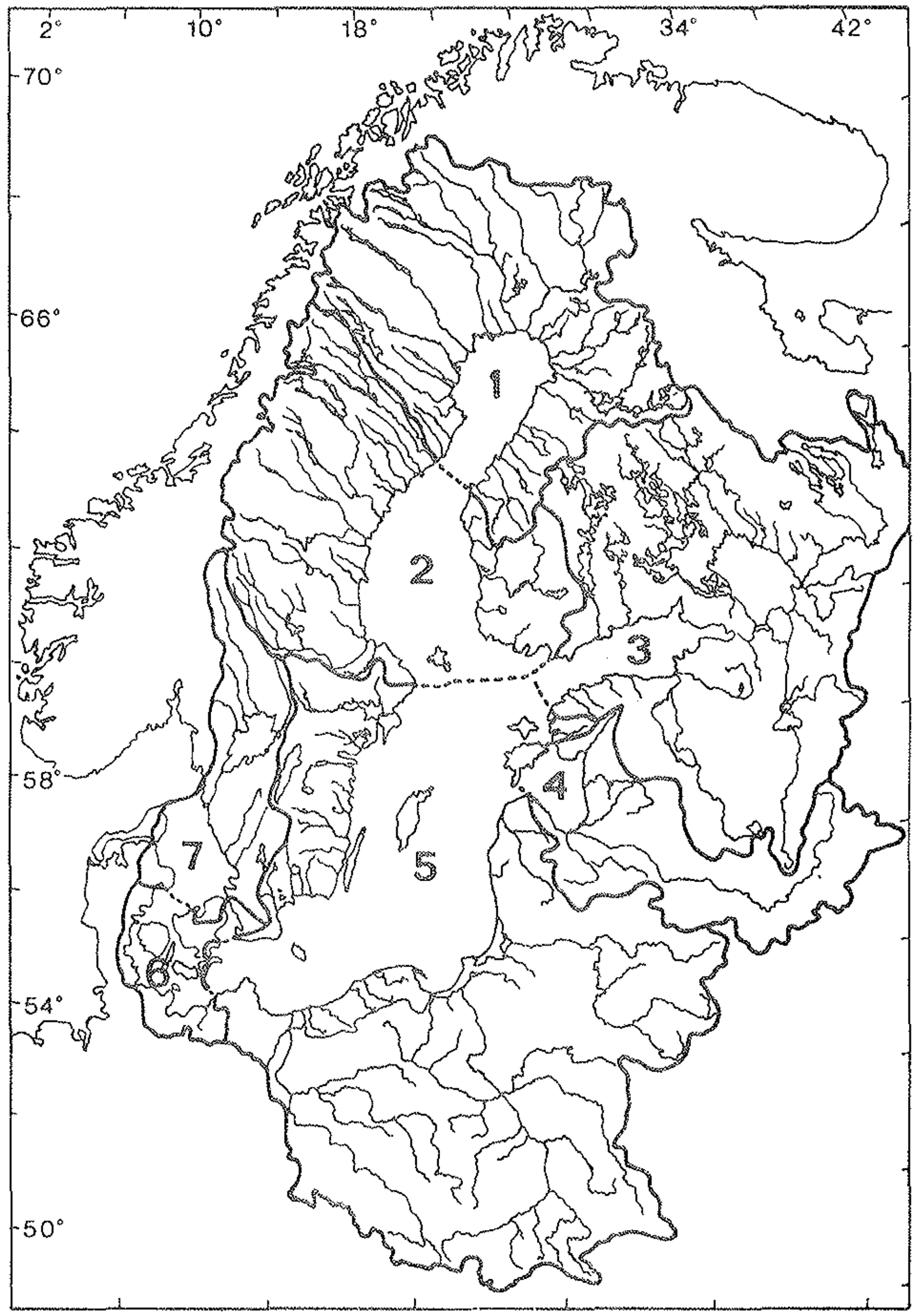
Sub-basin 4. The Gulf of Riga
($17,913\ km^2$), a water region protected from the central part of the Baltic by the islands Hiumaa, Muhu and Saaremaa; the border closing the gulf runs from the Estonian coast to the Muhu island, then to Saaremaa and then to the southern tip of the island (Sörve peninsula) to the Latvian coast (Kolka cape).

Sub-basin 5. The Baltic Proper
($209,930\ km^2$), main part of the sea covering the so-called central Baltic and southern Baltic, limited in the west by the Danish Straits; in its northern part there is the Gotland basin with the Landsort Depth (max. depth 459 m), deepest in the Baltic, and the Gotland depth (max. depth 249 m); its southern part includes the Gulf of Gdańsk with the Gdańsk Depth (max. depth 113 m), and the western part the Bornholm Basin with the Bornholm Depth (max. depth 105 m).

Sub-basin 6. The Danish Straits
($20,121\ km^2$) together with Kattegat constitute the so-called transitional region of the Baltic: the only way of water exchange with the North Sea and the Atlantic Ocean; the following straits are included: Öresund between the Scandinavian Peninsula and the Zeeland Island, the Great Baelt between the islands of Zeeland and Fyn, and the Little Baelt between Fyn and the Jutland Peninsula. The Danish Straits are separated from the Baltic Proper by a line running from the Swedish Falsterbo cape to the Danish Stevns Klitt cape (on Zeeland), and from the Gedser cape (Denmark) to the Darsser Ort cape (GDR), including also the whole Mecklenburg (Lübeck) Bay at the coast of GDR/FRG in the area of the Danish Straits.

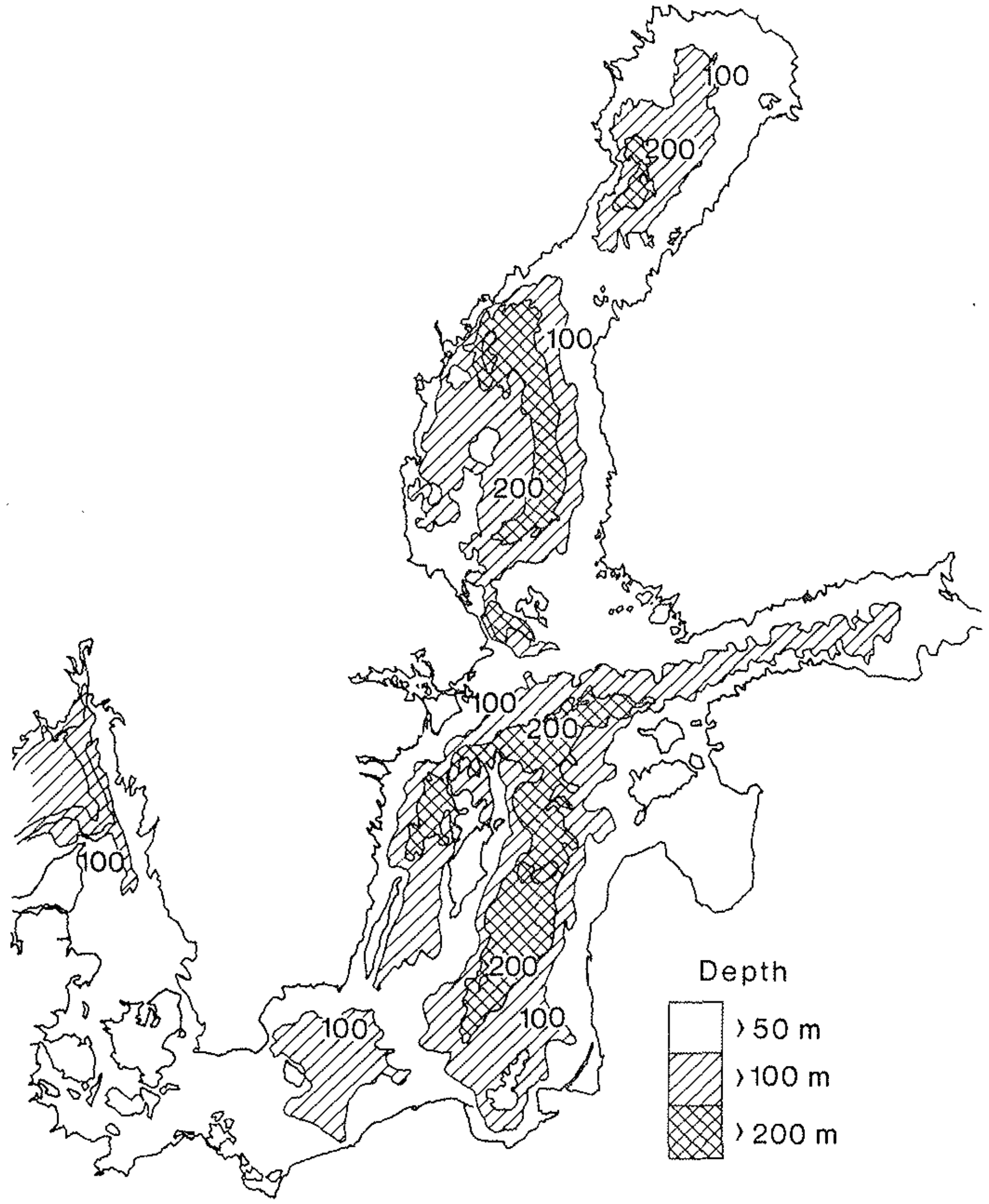
Sub-basin 7. Kattegat
($22,287\ km^2$) is one of the strait-seas (together with Skagerrak), separating the Baltic from the North Sea - a further part of the transitional region in which the basic water exchange of the Baltic and the North Sea takes place. Kattegat is separated from the Danish Straits by a line running at the northern edge of the Öresund strait from the Swedish Kullen cape to the city of Gilleleje on Zeeland, and then from the Gniben cape on Zeeland to the Ebeltoft promontory on the Djursland cape on the Jutland Peninsula. The northern border of Kattegat, and thus the Baltic's border at the same time, runs - as mentioned above - along the line from the Skagens Rev cape (Grene) on the northern tip of the Jutland Peninsula to the lighthouse on the Pater Noster skerries situated in the foreland of the Tjörn island, north of Göteborg (Sweden).

2.1 a)



2.1 Drainage basin (a), subregions depth characteristics (b) of the Baltic Sea and its transition areas.
Representative rivers indicated by names.
Dashed lines show boundaries between Baltic Sea subregions.
Thick lines show boundaries between corresponding drainage basins.
1. Bothnian Bay 2. Bothnian Sea 3. Gulf of Finland 4. Gulf of Riga 5. Baltic Proper 6. Danish Straits 7. Kattegat

2.1 b)



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2.1.3 Sea areas and volumes

These Baltic sub-basins constitute the basis for the water balance calculations. Due to existing earlier divergences in estimation of area and volume of the whole sea and its regions, attention was called already at the 1971 meeting of experts to the necessity to correct the values of area and volume of the sea sub-basins. The task was undertaken by Swedish specialists. Full cartographic material was gathered and controlled by random depth measurements; in some places differences were as much as 100 m. Due to the large amount of data, computers were used for the calculations. The area of the sea was covered with a net of 1' width and 2' length, thus creating 135,000 basic fields. So-called aggregate fields were made covering 25 basic fields each. In each of the basic fields, middle depths were marked, based on marine maps wherever possible; thus each aggregate field contained 25 middle depths. A data bank was created including also data from available maps. The middle depth in a basic field is the depth closest to the middle of the field. In case there was no information on the depth, the computer calculated it, based on data from other fields in the aggregate field.

The accuracy of the method was tested by comparing with detailed source maps; no systematic errors were noticed and distribution of accidental errors was considered moderate. The accuracy of calculated areas and volumes was determined with reference to the Gulf of Bothnia. It was found that the average relative error was 10^{-3} in an area of over 5,000 km^2; in smaller areas, the error grew significantly. Comparisons were also made in various areas, for which Swedish source maps were available, constituting background for marine maps. The comparisons between these two kind of maps showed that marine maps usually give lower values of area and volume than source maps. With depths less than about 100 m, average depths in the source maps appeared to be larger than in the marine maps, whereas in deeper regions the depths from the marine maps are larger.

This seems to be the result of a conscious selection in the editing of the marine maps of smaller depths in shallower areas with regard to the shipping interests and a selection of larger depths in deeper water perhaps as an estimate of moving depth etc.

Results of calculation of characteristic values of regions of the Valtic are presented in Main Table 1.

2.2 DRAINAGE BASIN OF THE BALTIC AND ITS SUB-BASINS

2.2.1 Geographical Extension

The drainage basin of the Baltic Sea ia 1,721,200 km^2,

corresponding to about 17 % of the European continent. Location of the drainage basin is limited by the following geographical coordinates:

- southern limit 49°00' northern latitude (the Opolonek peak in Bieszczady in the Eastern Carpathians, watershed of the San drainage-basin in the upstream part of Vistula river-basin, on the southern border of Poland and the USSR);
- northern limit 69°20' northern latitude (the Haltiantunturi peak in the northern part of the Scandinavian Mountains, in the Muonio drainage-basin in the Torne river basin, on the border of Norway and Finland);
- western limit 9°10' eastern longitude (central part of the Jutland Peninsula in the Vejle drainage-basin);
- eastern limit 38°00' eastern longitude (eastern edge of the South Karelian middle taiga hill- and ridge plain. *) Vodla drainage-basin in the catchment area of Lake Onega in the Neva river basin).

The determined geographical coordinates allow to define the linear extension: north - south 2,260 km, and east - west (along the 58° parallel) 1,700 km. The geometric centre of the drainage area is situated in the north-eastern part of the Baltic Proper, close to the Estonian island of Hiuma. The catchment area of the Baltic separates the so-called European watershed from the catchment areas of the Black Sea and the Adriatic Sea, both belonging to the catchment area of the Mediterranean Sea.

2.2.2 Subcatchments of the seven regions

The division of the Baltic Sea into characteristic sub-basins makes it necessary to divide also its catchment area into catchment areas of the sub-basins (second order catchment areas).

<u>1. Catchment area of Bothnian Bay</u>
(269,950 km^2) covers drainage areas of very effective rivers of the northern part of the Scandinavian Peninsula, and somewhat less effective small rivers of the Coastal Eastern Finland and the Maanselkä Upland. The runoff of the Swedish rivers is as high as 20 l/s km^2, whereas the Finnish rivers carry about 10 l/s km^2. Generally the outflow is damped as a result from substantial lake feed; this concerns in particular the rivers of the Scandinavian Mountains and the Norrland Plateau, where numerous and large mountain lakes act as storage reservoirs.

*)
In this paper geographic names in the English language are used that are found in the publication International Federation for Documentation (FID) (Regionalization of Europe, 1971).

2. Catchment area of Bothnian Sea
(229,700 km^2), where the main role is played by rivers of the central part of the Scandinavian Peninsula, passing through the lakes in the Scandinavian Mountains and the Norrland Plateaux, with a runoff well over 10 l/s km^2. Of less importance are small rivers of the Coastal Lowlands passing through the Eastern Finnish Lake District; the main tributary here is the Kokemäenjoki bringing the waters of numerous lakes around the city of Tampere. The runoff of this part of the catchment area is only 8 l/s km^2.

3. Catchment area of the Gulf of Finland
(419,200 km^2) has a much larger area than sub-basins 1 and 2 and therefore a considerable influence on the gulf. The flow from the Coastal Southern Finland and the Lake Plain of Central Finland passes a large group of lakes and delivers a runoff of about 8 l/s km^2. The main river is the Neva, which has the largest drainage area in the whole Baltic catchment area producing a runoff of almost 9 l/s km^2. The flow regime is in fluenced by the enormous lakes of Onega and Ladoga - its drainage basin, mostly located on the South Karelian Middle Taiga Hill- and Ridge Plain and in the northern part of the Prebaltic Moraine-Hill and Lake Plain constitutes 73 % of the gulf's catchment area, and contributes 76 % of the entire river inflow. Finally, the southern part of the catchment area is represented by the Narva, whose whole drainage-basin lies in the Prebaltic Moraine-Hill and Lake Plain, bringing a runoff below 7 l/s km^2. The whole catchment area is characterized by an even outlow.

4. Catchment area of the Gulf of Riga
(127,400 km^2) is mainly the Dvina drainage basin, covering 2/3 of the catchment area and lying almost totally in the Prebaltic Moraine-Hill and Lake Plain. Runoff is relatively high (7.5 l/s km^2) and quite even.

5. Catchment area of the Baltic Proper
(568,973 km^2; if catchment area of the Gulf of Riga is included 696,373 km^2) covers on the Swedish side drainage-basins of small rivers of the Middle Swedish Lake Lowland with runoff about 6-7 l/s km^2. The eastern part is covered by the catchment area of the Gulf of Riga, and the direct part includes mainly the drainage-basin of the Neman river, constituting 70 % of the area, with quite high runoff (6.6 l/s km^2), draining north-western part of the North Byelorussian Plains and western limit of Prebaltic Moraine-Hill and Lake Plain. The southern part of the catchment area is covered by the whole drainage basins of Vistula and Oder rivers, bringing water from the northern slopes of Western Carpathians and Outer Forelands, Sudeten Mountains and the sub-Sudeten Highland, Little Polish Uplands, Middle Polish Lowlands and finally the eastern part of Southern Baltic Hills and Lakes Plains. A small part of the catchment area covers the Southern Baltic Coastal Plains with a runoff of only about 5 l/s km^2.

6. Catchment area of the Danish Straits:
Öresund and the Belts (27,360 km^2) is the smallest sub-basin catchment area, covering the eastern part of the Jutland Peninsula and the Danish Islands as well as the western part of the Skania Peninsula. Runoff about 9 l/s km2.

7. Catchment area of Kattegat
(78, 650 km^2) is characterized by substantial asymmetry, with large quantities of fresh water supplied in the north-eastern part and considerably less in south-western part. The main river is the Götariver, bringing waters from lake Vänern (the largest among the Swedish lakes), originating from the Middle Swedish Lake Lowland and the southern part of the Norrland Plateau; its drainage- basin constitutes almost 2/3 of the catchment area. The catchment is characterized by high runoff, over 11 l/s km^2. However, attention should be paid to the fact that the Göta discharges itself at the northern limit of Kattegat. In case there is an outflow from the Baltic (much more frequent than inflows from the North Sea), the Götariver water flows directly to Skagerrak, without really participating in the exchange of the whole water mass of the Kattegat. In such cases the Götariver tributary to Kattegat should not be taken into account.

2.3 INTERNATIONAL CHARACTER OF THE DRAINAGE BASIN

The Baltic Sea catchment is divided into territories of seven Baltic countries: Sweden, Finland, the USSR, Poland, the GDR, the FRG and Denmark, all lying on the Baltic, and in addition also small parts of the territories of Norway and Czechoslovakia; totally nine countries. Out of them only Poland, Sweden and Finland are almost totally in the catchment area together with over half of the Danish territory. Both German states cover small parts of the catchment area; similarly, only 10 % of the area of the European part of the USSR is in the catchment. The share of the mentioned countries in the Baltic Sea catchment area is presented in Main Table 2.

Chapter 3

METHODOLOGY

Zdzislaw Mikulski (Poland), Malin Falkenmark (Sweden) and
Ulf Ehlin (Sweden)

3.1 INTRODUCTION

The Baltic Sea is claimed to be one of the most polluted sees of the world. Ecological impact assessments depend on good information on the water renewal of the different parts of the system. The necessity to determine the water balance was pointed out already by the beginning of the present century (Krümmel 1904, Spethman 1912, Witting 1918, Rundo 1922). However, well organized measurements had to wait for the foundation of the hydrological Conferences of the Baltic States in 1926 to be made possible.

Until 1939, only partially homogenous incomplete hydrological data were brought together, and the data had to wait for Worldwar II to end before compilation and analysis became possible (Brogmus 1952). Two years later, also the fluctuations of the water balance had been analyzed (Wyrtki 1954). Since then, continuously increased interest in the system has been generated by oceanographers and ecologists, in response to the environmental problems developing in the wake of ever increasing pollution loads from the countries bordering the sea.

3.2 WATER RENEWAL CONCEPTS

Oceanographers working with the Baltic mostly focus on internal water exchange processes, such as the mixing between layers and between subregions, mixing between coastal waters and the open water mass etc. They are further interested in the water exchange with the North Sea, the path followed by individual salt water inflows, the salinity distribution in the Baltic, and the development of the oxygen conditions in its deep water.

Hydrologists, on the other hand, tend to regard the semienclosed sea more as a whole, and to see it in close relation to the land area drained. They are occupied with the water storage in the basin and with the external water exchange, and take less notice of the salinity of the different water balance elements.

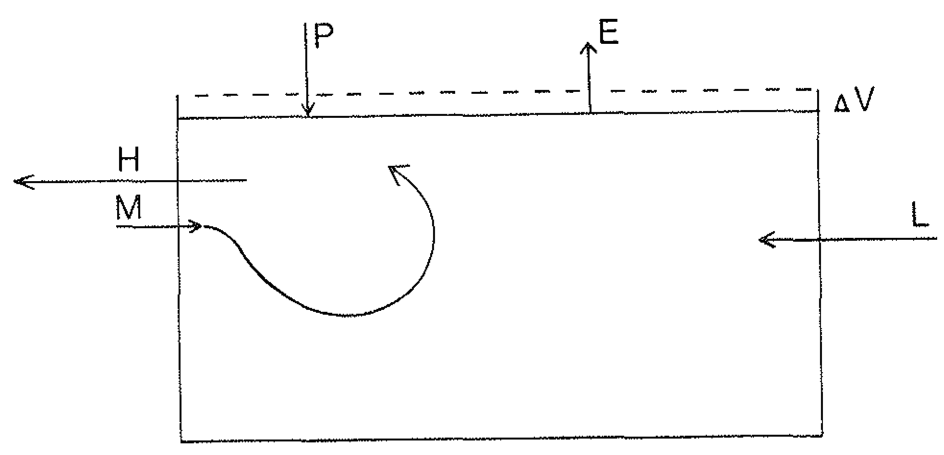
The Baltic Sea is, in general, characterized by a positive fresh water balance, and its water is therefore brackish. The basin is

in hydraulic contact with the North Sea over the shallow thresholds on the Danish Straits, which allow a restricted water exchange only. Basically, the water mass of the Baltic consists of an upper layer with continuous throughflow of fresh water from the rivers discharging into the Baltic, and a lower layer of higher salinity, where the water is renewed in an oscillatory manner through irregular salt water instrusions from the North Sea.

Basically, the dynamics can roughly be described by the simple exchange model in Fig. 3.1. The external forcing functions governing the water exchange are

* fresh water supply from the land drained
* outside sea level and salinity (North Sea)
* meteorological forcings.

The renewal of the water mass is described by the water balance, a concept quite extensively used by hydrologists. The concept includes the quantitative relationships and the different interconnections between all the elements responsible for the renewal of the water by different exterior processes: precipitation (P), evaporation (E), input by land runoff (L), salt water inflow through the straits connecting the semi-enclosed basin with the bordering sea (M), water storage or retention (ΔV), and water outflow (H).



P = precipitation
E = evaporation
L = river inflow
ΔV = storage difference
H-M = net outflow

3.1 Water exchange model

In combination, these water renewal processes are of primary importance for the retention time characteristic for any semi-conservative pollutants introduced from adjacent land areas, and therefore for the pace to be expected for advancing pollution in the Baltic Sea. They are also important for the ability of the system to recover, once that new pollutants are no longer introduced, and the remaining pollutants in the basin are successively swept out through the outlet with the waters leaving the Baltic system. When analyzing trends in the pollution or in the natural biological and chemical conditions, also long-term variations and trends in the water exchange elements have to be taken into account.

The water balance is composed of processes of vertical and horisontal exchange (Fig. 3.1). On a short-term basis, a change in water storage has also to be taken into account. The vertical and horisontal parts of the water exchange play different roles in different semi-enclosed basins. In some basins, the vertical exchange may dominate, in others the horisontal one may dominate. Any of these exchanges may be either positive or negative.

In the international project, the water balance of the Baltic Sea was studied by comparing the individual inputs and outputs of freshwater, and the complementary inflow of salt water from the North Sea. The following balance equation expresses the water balance:

$$(P - E + L) + (H - M) = \Delta V$$

supply of fresh water	net exchange with the Sea	difference in retention

The net fresh water inflow (P - E + L) includes the three primary water balance elements precipitation (P), evaporation (E), and land runoff (L), and is influenced by climatic conditions and hydrography of the drainage basin. The net freshwater outflow (H - M), and the water retention in storage ΔV could be seen as secondary elements in their constituting the effects of the balancing of the primary elements with the sea water inflow (M) from the North Sea.

3.3 SEPARATE DETERMINATION OF INDIVIDUAL WATER BALANCE ELEMENTS

Specific for the international project was the effort to determine, separately, each of the individual elements of the water renewal of the system. By so doing, the water balance equation would give a closing error. The work was divided between the riparian states according to the main principle that each country took the main responsibility for one element each (Fig. 3.2).

Due to the temporal fluctuations between different time periods, it was decided to select a joint time period, for which all elements should be studied. The period 1951-70 was accepted as a basis to calculate the so-called historical balance. The period was divided into two decades to study differences between individual decades.

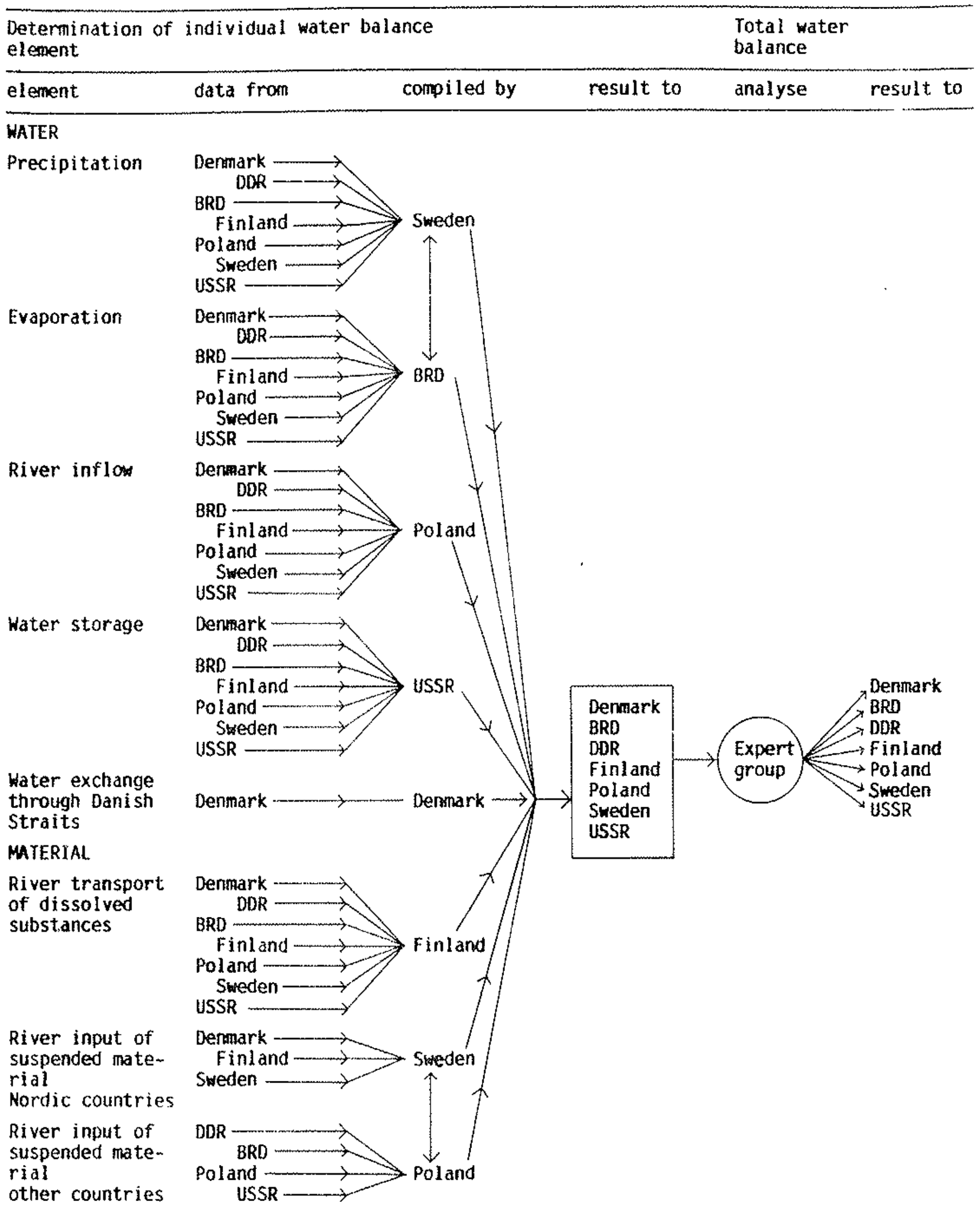
It was furthermore recommended to accept - as far as possible - the period 1931-60 as a period of reference, interesting for this specific purpose by the fact that it is widely used by climatologists and hydrologists for comparison.

By also studying variations between individual years of the historical period and the reference period, interannual fluctiations could be identified, and extreme years and situations illuminated and analyzed.

3.4 REGIONAL SUBDIVISION OF THE BALTIC SYSTEM

It was moreover decided that the water balance studies should be carried out separately for each of the seven subbasins, into which the Baltic system was subdivided, as closely described in Chapter 2. By such studies it should be possible to study the individualities of the different subbasins, and to arrive at an increased understanding of the water renewal of the different parts of the cascade system, both for longterm average conditions and for extreme years and seasons.

FIGURE 3.2. Work distribution and data flow between riparian countries



3.2 Work distribution and data flow between riparian countries

3.5 METHODOLOGY DEVELOPMENT

In this subsection, a short overview will be given on the methods used for the determination of the individual water balance elements and the results in general. The reader will find the details in the chapters, describing the work element by element (Chapters 4-9).

The studies involved in the calculation of the precipitation over the sea surfaces were performed by the Swedish Meteorological and Hydrological Institute (Dahlström 1983). Abundant observational data existed: over 200 observational posts for the period 1951-70, and about 300 posts for the period 1931-60. Special attention was paid to the spatial correlation of the precipitation measured at different localities. Estimation of the areal distribution of precipitation over the sea surface was considered a serious problem, taking into account that the majority of the data had been obtained at coastal stations along a wide strip of the Baltic coast. The spatial distribution could however be estimated thanks to the existence also of a number of posts on islands and of installations on lightships and other ships.

As further described in Chapter 5, the obtained results gave much higher values of precipitation than the ones accepted in earlier studies. This was mainly due to the introduction of corrections of the observed values (always in the positive direction due to gauge deficits). This considerably changes the proportion of this element in the total balance. In the spatial dimension, the precipitation grows from the Bothnian Bay towards the Danish Straits and the Kattegat. In the course of an average year, a growth takes place from a minimun in March to a maximum in August (sometimes in July).

One of the most difficult elements to estimate was the evaporation from the sea surface. In principle, there are both indirect methods of calculation, and direct methods of measurements. The latter are however, in the case of a vast sea surface, extremely difficult to conduct. The estimations had therefore to be based on meteorological data representing certain spots, such as islands, lightships and other ships, equipped with the necessary meteorological instruments. The most reliable methods utilized by the West German specialists (Henning 1983) was the so-called aerodynamical method. For comparative purposes, the relatively new aerological method was also tested, basing the estimates on data from the aerological network around the Baltic, by recording differences in water vapour content in the air moving over the sea. However, this method proved to give unsatisfactory results.

Although representing a time period of more than a century, the observational data available for calculations according to the aerodynamic method were extremely inhomogenous. The methodological difficulties involved induced the scientists to undertake a great measurement effort during the period July 1975 - December 1977.

Joint action in all the Baltic countries during this concentrated period produced a large data material, in effect corresponding to 75 % of the whole data material at disposal for the final estimations of the evaporation. Since, at the end, only 20 % of the data material available represented the period 1951-70, selected for the historical balance, the conditions during the pilot study year heavily influenced the final calculation of evaporation also for the historical period.

The results obtained in the evaporation study - as will be seen in Chapter 6 - are higher by more than 10 % than previous evaporation estimates for the Baltic Sea. Highest values were recorded during the autumn and early winter, whereas yearly minimum takes place during the spring. In the spatial dimension, the evaporation increases from Gulf of Bothnia towards the Danish Straits and Kattegat.

Poland undertook the responsibility to calculate the river inflow from the drainage basin of the Baltic Sea (Mikulski 1982). The studies were based on a very long period of observations in order to study also possible variability over time. The calculations were based on 17 rivers selected as representative for each one of the subbasins of the Baltic. In order to check the accuracy, calculations were carried out for the two decades composing the historical period 1951-70, based on respectively 65 and 71 controlled rivers. The error of calculation was found to be within the range of a few recent (exceptionally up to 10-13 %).

In the period 1921-75, the inflow during individual decades was noted to show a quite distinct stability (Mikulski 1982). As further developed in Chapter 4, river inflow culminates in spring (April-June) and takes on its lowest values in winter. A statistical analysis of the river inflow was performed in cooperation with specialists from GDR (Hupfer et.al 1979). The total inflow to the Baltic Sea is dominated by the inflow to the Bothnian Bay and the Bothnian Sea and the Gulf of Finland. Mean values for multiyear periods do not differ much from estimates in earlier balance calculations. There are however some differences to be noted in individual regions due to anthropogenic influence of flow control in the main rivers.

The water storage element of the water balance was given considerable efforts in the project by Soviet specialists (Lazarenko 1980). This element was determined from water stage observations at a large number of gauges around the Baltic. Based on an analysis of representativeness of existing observational gauges, 59 were selected as representative of the changing level of the open sea, i.e. not exposed to local influence. From mean daily levels, monthly average were determined for the five regions inside the Danish Straits. As all other water balance elements were studied by monthly averages, in order to keep free from short-term influences storage changes were also considered on a monthly basis. The annual course of water storage changes were therefore based on monthly changes of average sea-water level rather than on changes

from the first day in a month to the first day of the following month. Monthly volume increments were calculated by multiplying the sea-level change with the sea surface area of that specific subregion of the Baltic Sea.

During the Pilot Study Year July 1975 - December 1976, intensive field studies were undertaken in the Danish Straits in order to determine the water exchange between the Baltic and the North Sea. This operation was based on current measurements at 18 different verticals distributed over 9 cross sections in the different sounds. The work was done by Danish oceanographers within the framework of a five-year effort, known as the Belt Project (Jacobsen 1980).

As further discussed in Chapter 8, analysis of the results obtained showed that direct current measurements (given the present state of the measurement technique and the inhomogeneties of the velocity field) do not give a sufficient basis to allow the separate determination of the inflow M of salty water from the North Sea, and the outflow H of brackish water from the Baltic. Therefore it was decided to confine the studies only to estimations of differences between these two water exchange elements, i.e. to determine only the net outflow to the North Sea (H-M).

3.6 THE PILOT STUDY YEAR

In order to test the different methods to estimate the water balance elements and investigate the errors involved in the calculations, it was decided - as already indicated - to undertake a special Pilot Study. The study was planned to last for one year from July 1975 but since there were uncertainties with the data collection in the beginning the Pilot Study year was prolonged until December 1976.

During the Pilot Study year the Danish Belt Project, as already mentioned, undertook extensive current measurements in the Belt Sea and the Sound. These investigations were of great importance as a test of the possibilities of direct measurements of the complex water transports in the transition zone between the Baltic Proper and the North Sea. Good results of these measurements would have given an estimate of the closing error in the water balance calculations. Unfortunately the results were not of such a quality that this goal was reached. The results of the Danish study is reported in Chapter 8.

Another aim with the Pilot Study year was to test the possibilities to calculate the Baltic Water balance on an operational basis and with the estimations of the balance elements carried through in different countries. The conclusion of this test is that it might be possible to make the calculations on an operational way, with the work decentralized to the hydrological services within the Baltic countries.

The main results of the Pilot Study are reported in Chapter 10.

Chapter 4

INFLOW FROM DRAINAGE BASIN

Zdzislaw Mikulski (Poland)

4.1 METHOD OF CALCULATION

4.1.1 Selection of method

The Baltic drainage area is characterized by a large number of relatively small rivers, especially in its northern part (the drainage area of the Bothnian Bay and the Bothnian Sea). This makes the calculation of river inflow rather cumbersome. Although most of the rivers have, for a long time, been under hydrometric control, enabling precise determination of the inflow, the detailed calculations demanded in this case involves a large amount of work. On the other hand, an oversimplification would adversely affect the results of the determination. The method chosen for computation of the inflow is based on a selection of rivers, representative for individual regions and so that their drainage-basins cover a large part of the drainage area of the Baltic.

Systematic hydrometric control covered some of the more important Baltic Rivers as early as the first half of the previous century (the Göta 1807, the Neman 1811, the Vuoksi 1847, the Neva 1859); others at the end of the century (the Kymijoki, the Kemijoki, the Lule älv, the Ångerman älv). The existing data enable an analysis of long-term characteristic features of the flow.

It was first decided to calculate the river inflow for the 50-year period 1921-70, subsequently extending the period until 1975 (Mikulski 1980, 1982). Averaging calculations were made for the two decades fo the so-called "historical balance" period, 1951-60 and 1961-70; both periods were used for methodological comparison. Inflow was also calculated as five-year averages (1961-65 and 1966-70) in order to study the inflow variability. For calculating the inflow, initially 65, later extended to 71 partial river-basins were used, represented by 40-45 controlled rivers.

Calculation of the annual inflow in the period 1951-60 was made at the end of the 1960s, in other words before an organized cooperation in this field was begun and applying border lines and region areas, differing from the later defined ones, (corresponding to a total drainage area of 1,649,550 km^2). Left outside these studies were parts of the Danish Straits and Kattegat (Mikulski 1970).

For the period 1961-70 (Mikulski 1972) monthly inflow was determined, assuming a somewhat different size of the drainage area (1,634,823 km^2), but within the same border lines and for the same areas as earlier.

4.1.2 Selection of representative rivers

Once that the final borders of the subbasins and the western border of the Baltic had been determined (Ehlin et al 1974), and the conclusive borders of the corresponding drainage areas had been defined, uniform calculations of monthly river inflow were possible for the period 1921-75. In order to simplify and automatize the calculations, 17 rivers representative for the selected drainage areas were chosen. The selection was based on the runoff considered representative for a particular part of the drainage basin; the length of a river (preference for larger rivers of greater importance in the drainage); and finally, availability of data , preferably in hydrological annals, especially in the UNESCO/IHD/IHP yearbook.

The Bothnian Bay (269,950 km^2) was represented by the following rivers: Lule älv (25,250 km^2)*), Kemijoki (50,900 km^2) and Kalajoki (3,024 km^2); adding up to a controlled area of 79,174 km^2, which constitutes only 30 % of the drainage area of this subbasin.

The Bothnian Sea (229,700 km^2) was also represented by three rivers: Dalälven (29,040 km^2), Kokemäenjoki (26,025 km^2) and Ume älv (26,730 km^2) corresponding to a controlled area of 81,795 km^2, or 36 % of the drainage area.

The Gulf of Finland (419,200 km^2) was similarly represented by three rivers, although with a decisive supremacy of the Neva: Kymijoki (36,537 km^2), Neva (281,000 km^2) and Narva (56,000 km^2); the controlled area is thus 373,537 km^2, or 89 % of the drainage area.

The Gulf of Riga (127,400 km^2) is represented by the only large river - the Dvina (82,400 km^2) controlling 65 % of the drainage area.

Baltic proper (568,793 km^2), due to a big and varied drainage area was represented by six rivers: Mälaren-Norrström (22,600 km^2), Vättern-Motalaström (15,470 km^2), Alsterån (1,537 km^2), Neman (81,200 km^2), Vistula (193,866 km^2) and Oder (109,364 km^2); the controlled area amounts here to 424,037 km^2 which constitutes 75 % of the drainage area.

The Danish Straits (27,360 km^2) and Kattegat (78,650 km^2), due to only small rivers existing in the area, were represented only by Göta River (50,280 km^2) emptying into Kattegat at its northern end, i.e. at the westernmost end of the Baltic. The Oder River was additionally adopted as representative for the runoff from the drainage basin of the Danish Straits, assuming that runoff from the drainage area has intermediate values between the flows of the Oder and the Göta. Thus, the drainage area of Kattegat was in this case controlled to 64 %.

The Baltic Sea (1,721,233 km^2) is in other words represented by 17 rivers, controlling altogether an area of 1,091,223 km^2, i.e. 63% (less than two thirds) of the whole drainage basin.

*) the values in the parantheses are the sizes of river-basins controlled by a hydrometric profile

4.1.3 Precision achieved

Verification was made of the precision of calculation by comparing the results from the simplified method, i.e. based on the data from the 17 representative rivers, with the results of detailed calculations for both 10-year periods 1951-60 and 1961-70, taking as examples the Bothnian Bay and the Bothnian Sea - the least controlled (except for the Danish Straits) - as well as the Gulf of Finland and the Gulf of Riga - with a high degree of control. The borders and areas of these regions did not undergo significant changes.

Table 4.1 Riverflow precision according to different methods

	1951-1960 /m³/s/			1961-1970 /m³/s/		
	detailed	simpl.	error	detailed	simpl.	error
Bothnian Bay	3,224	3,105	- 6.1%	3,198	3,103	- 2.9%
Bothnian Sea	2,634	2,947	+ 10.6	2,668	2,062	+ 12.9
total	5,858	6,052	+ 3.2	5,866	6,165	+ 4.9
Gulf of Finland	3,738	3,722	- 0.4	3,482	3,464	- 0.5
Gulf of Riga	1,026	993	- 3.3	848	847	0

In conclusion, the error caused by using the simplified method in case of the Bothnian Bay and the Bothnian Sea reaches a maximum of 13 % which means that it exceeds only slightly the error of flow measurement accepted in hydrometry and estimated at about 10 %. The error could be either positive or negative and will thus in the result often be reduced. In the case of the Gulf of Finland and the Gulf of Riga, the calculation error is minimal - it reaches at the outmost a few percent.

4.1.4 Some adjustments

In the data materials, supplied by the Baltic countries, several flow values were missing, especially during World War II, mainly from the rivers in the USSR and Poland. The largest gaps were the following: the rivers Neman (Nov. 1943 - June 1946), Neva (Sept. 1942 - Febr. 1943), Narva (1944), Vistula (Jan. - Oct. 1945) and Dvina (July - Dec. 1944).

Connections between the flow values of these rivers and neighbouring rivers were used to supplement the data. This strategy was considered more advantageous than leaving gaps in the flow charts.

A particular difficulty was presented by zero flow in some representative rivers (mostly during winters) and sometimes even negative flows (in the case of the outflow of Lake Mälaren), caused by inflow of sea water up the river. In this case freshwater flow was calculated either from suitable dependences between neighbouring rivers (with reference to the Kalajoki and the Mälaren), or accepting the lowest value of flow $Q = 1\ m^3/s$ (degree of precision of the calculation) as the lowest value considered in the calculation (in the case of a small river - the Alsteran). In this way, zero values of inflow from the drainage area of a river, could be avoided.

For the calculations of river inflow, computers were used. The amount of data material, necessary for the calculations decreased considerably by allowing to use only hydrological annals of the Baltic countries. The method can be easily used in the future, as the basic data needed are available without difficulty. The chosen procedure is at the same time an attempt at automatising the water balance computations of the Baltic Sea, which will be of real importance when preparing an operative balance. The resulting river inflow data are presented in Main Table 3 (reference periods), Main Table 4 (1951-70) and Table 4.2 (Pilot Study Year).

4.2 ANALYSIS OF RIVER INFLOW TO THE BALTIC

4.2.1 Long-term fluctuation

The long-term average annual river inflow to the Baltic, exposed in Main Table 3, is characterized by a high degree of stability in time and amounts as a long-term average for the whole period 1921-75 to exactly 14,900 m^3/s; in the reference period 1931-60 it amounts to 14,600 m^3/s (461 km^3), which constituted 97 % in relation to the studied 55-year period. The annual mean inflow for the standard 20-year period 1951-70, selected for the joint water balance studies, was 14,970 m^3/s (473 km^3).

The interannual fluctuations of the annual inflow lies between 76 % (1942) and 130 % (1924). It is worth underlining that 1924 was characterized by an exceptionally high value of the inflow of 19,500 m^3/s (618 km^3) and the second highest yearly value (1931) is 17,700 m^3/s (560 km^3). Individual 10-year periods and the last 5-year period manifest the following irregularities in relation to the long-term average (cf. Main Table 3).

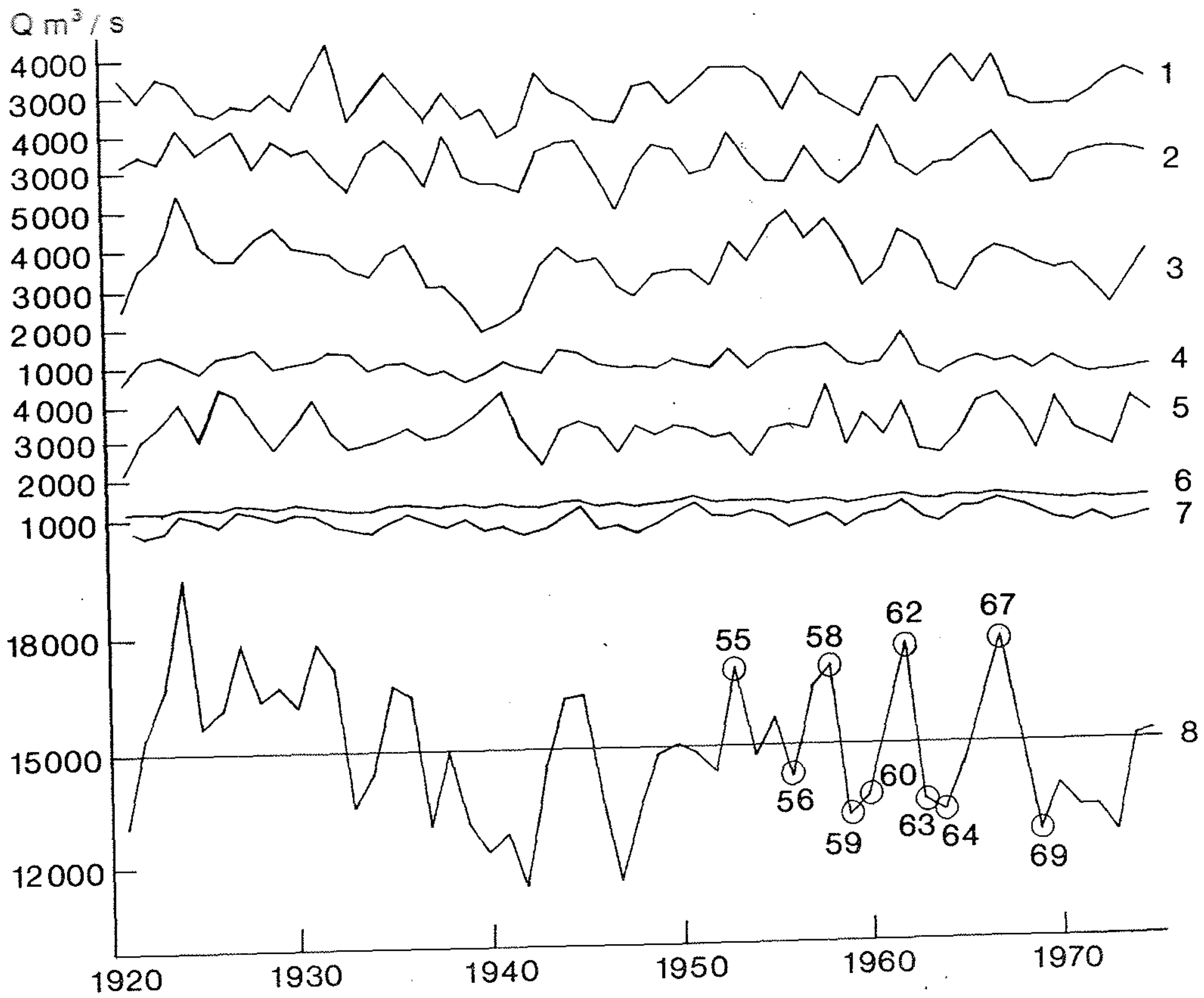
1921/30	1931/40	1941/50	1951/60	1961/70	1971/75
109 %	100 %	93 %	101 %	100 %	93 %

Table 4.2

RIVER INFLOW TO THE BALTIC SEA / mm/

Pilot Study Year

	1975							1976													SUM
	VII	VIII	IX	X	XI	XII	Sum	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year	PSY
1. Bothnian Bay	129	114	181	255	186	168	1033	166	162	153	188	516	232	130	151	122	121	141	139	2082	3115
2. Bothnian Sea	90	88	82	117	96	89	562	88	80	82	64	116	118	83	80	68	57	59	62	957	1519
3. Gulf of Finland	398	343	309	300	249	170	1769	161	158	182	254	325	315	318	311	300	296	272	221	3113	4882
4. Gulf of Riga	50	34	29	32	30	36	211	48	31	54	372	300	109	85	37	43	35	44	64	1222	1433
5. Baltic proper	32	35	22	24	25	26	164	40	31	43	60	36	33	20	18	17	21	22	31	372	536
6. Sund and Belts	20	24	22	16	16	16	114	22	17	22	19	18	17	12	13	13	13	12	15	193	307
7. Kattegat	59	82	81	52	48	47	369	55	42	62	52	54	54	41	42	40	40	32	37	551	920
1-7. Total Baltic	77	75	71	82	70	61	436	69	61	70	95	124	90	66	64	58	57	58	61	873	1309



4.1 Long-term variations of river inflow to the Baltic Sea during the period 1921 - 75

For the period as a whole, there is a declining tendency in the 1930s, and a slightly growing tendency in the 1940s; beginning with the 1950s, the inflow values oscillate around the long-term average (Fig. 4.1).

4.2.2 Seasonality

The annual regime of the long-term average inflow is characterized by an inflow of melted snow (Fig. 4.2).

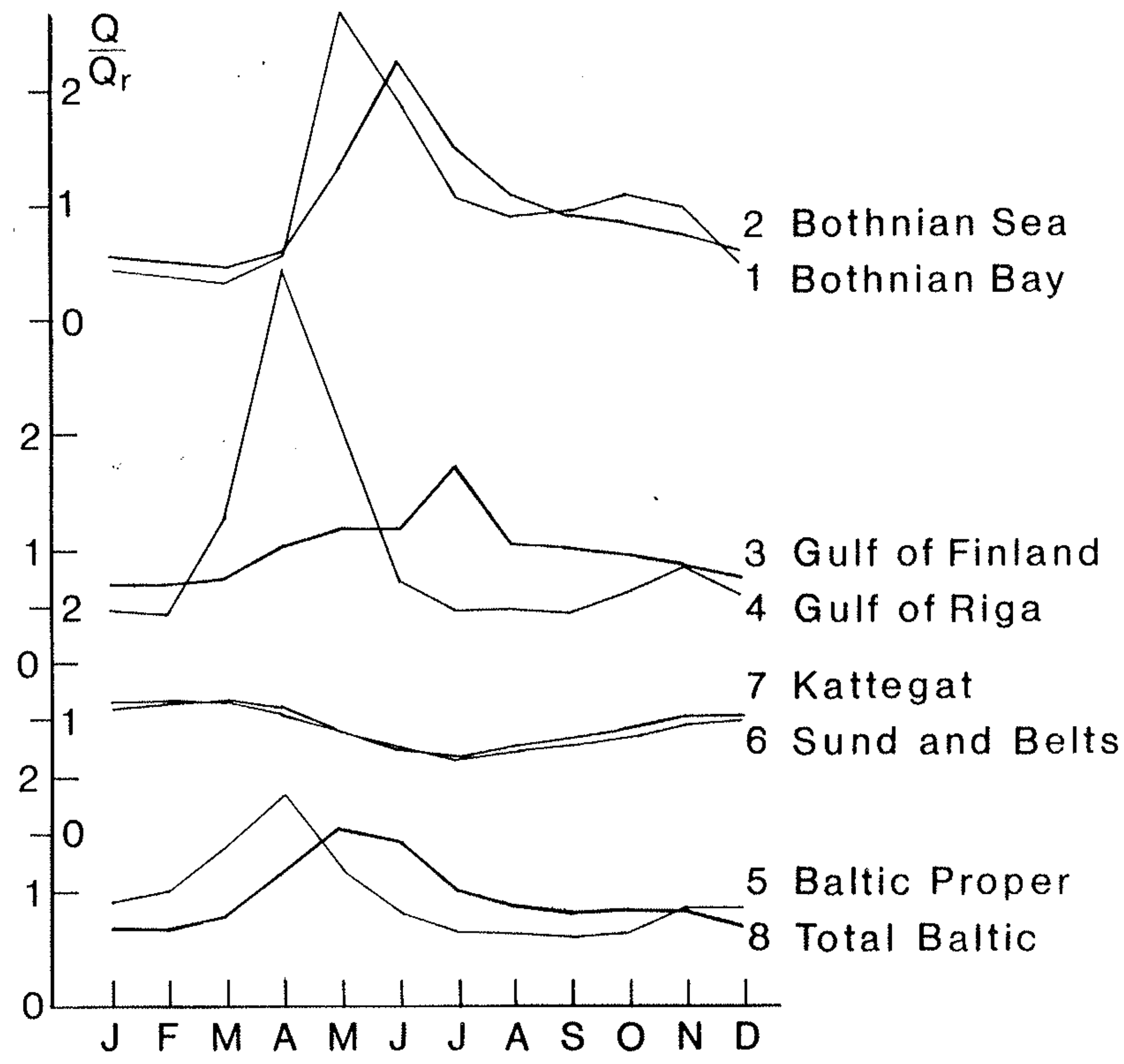
After a start with the lowest values at the beginning of the year (January and February, 69 % of the yearly inflow value each), there is in the spring a significant rise in the river inflow reaching a maximum in May (160 % of the annual mean). Also in June, the high inflow persists, after which a decline occurs down to the winter minimum.

The long-term fluctuations of the annual river inflow to individual subbasins of the Baltic during the period 1921-75 is exposed in Fig. 4.1. In general, the inflow remains at a stable level. The declining tendency during the 30's of the total inflow to the system is visible in the Gulf of Finland and obviously an influence of the river development of the Neva. It also indicates a significant share of that river in the total inflow to the Baltic.

Analysing the seasonal changeability of the inflow to individual subbasins of the sea, an influence of the river basin development in their drainage areas can be clearly noted (Main Table 4, Fig. 4.2). The Bothnian Bay shows the lowest value of inflow in March, followed by a rapid growth to a maximum in May; a small secondary growth is observed in October. A similar course is manifested by the inflow to the Bothnian Sea with a minimum also in March and a slightly lower maximum in June.

The Gulf of Finland is characterized by a different, quite stable course of the inflow with a very late maximum - as late as in July, and a minimum in January. A completely different course is shown by the inflow to the Gulf of Riga where, after a minimum in February, a rapid growth of inflow takes place with a maximum in April and a slightly marked secondary maximum in November; the spring maximum for the whole period reaches 348 % of the average yearly value, and is a result of comparatively early - as for the drainage area of the Baltic - inflow of water resulting from snow melting.

The course of the inflow to Baltic proper is similar, although much more stable. Starting with the winter months, there appears a slow and small increase of the inflow to a maximum in April (189%) , followed by a slow decrease of the inflow. From July till October low values of the inflow occur, reaching a minimum in September (66 % of the average value for the whole period). A very even course is shown by the river inflow to the Danish Straits and Kattegat; in this part of the Baltic



4.2 Seasonal variations of river inflow to the subbasins of the Baltic Sea. Long-term average 1921 - 75 high values occur during winter (with a slightly marked minimum in March) and low values in summer (with a minimum in July).

The annual course of river inflow to the Baltic Sea as a whole is the resultant of inflow to its individual subbasins. The predominating period when minimum occurs is winter (with an exception of the Danish Straits and Kattegat); the maximums of inflow occur over a longer period of time - from March (the Danish Straits and Kattegat) through April (the Gulf of Riga and Baltic Proper), May (the Bothnian Bay), June (the Bothnian Sea) till July (the Gulf of Finland - the Neva river-basin bordering the drainage area of the White Sea in the north-east).

4.2.3 Horisontal water renewal

What is the share of river water in the total water mass in the subbasins and in the Baltic as a whole (Table 4.3)? Undoubtedly, the biggest share is in the Gulf of Finland. Theoretically over a year, the new layer of river water would reach 3.73 m. A large share is also noted in the Gulf of Riga (7.1 %) where the layer would be 1.61 m; similarly in the Bothnian Bay (6.4 %), the analogous water layer would reach as much as 2.62 m. The smallest share of river waters is noted in Baltic Proper (0.8 %), where the layer would reach only 0.48 m, and also in the Danish Straits (2.6 %), the layer reaching only 0.38 m. For the system as a whole, the share of river water amounts to 2.2 %, which gives a layer of 1.13 m; undoubtedly, the low contribution from the drainage-area of the Baltic proper is reflected here (only 5.7 l/s km^2 combined with a large area and capacity of that region of the Baltic). It should be stressed that these remarks concern the annual contribution to the water volume, and not the share of river water in the water balance of the sea: this issue will be discussed separately in Chapter 10.

4.2.4 Statistical inflow analysis

A statistical analysis of the calculated river inflow was made based on the 50-year data material for the years 1921-70 (Hupfer et al. 1979).

It was found out, among other things, that the strongest regional correlation occurs between the inflow to the Bothnian Bay and the total inflow to the Baltic. Quite high correlation exists also between the inflows to the Gulf of Riga and Baltic Proper (two regions similar with respect to the climate). Correlations among values of the inflow to the whole Baltic show a dominant influence of the Bothnian Bay and the Bothnian Sea; a smaller influence is shown by the Gulf of Finland, the Gulf of Riga and Baltic proper. As a general conclusion, the Bothnian Bay and Bothnian Sea as well as the Gulf of Riga

Table 4.3
Share of river water in the watermass of the Baltic Sea and its seven subbasins. Period 1921-75.

Region	Inflow of river water				Contribution of river water
	m^3/s	1/s km^2	km^3	m	%
1. Gulf of Bothnia	3001	11,1	95,024	2,62	6,4
2. Bothnian Sea	3176	13,8	99,966	1,26	2,0
3. Gulf of Finland	3493	8,3	110,383	3,73	10,0
4. Gulf of Riga	913	7,2	28,791	1,61	7,1
5. Baltic proper	3226	5,7	101,801	0,48	0,8
6. Sund and Belts	248	9,0	7,585	0,38	2,6
7. Kattegat	859	10,9	27,087	1,21	5,3
Baltic Sea	14895	8,7	470,644	1,13	2,2

and Baltic proper behave relatively homogeneously, while the Gulf of Finland and the Danish Straits and Kattegat differ quite considerably from those regions.

4.2.5 Concluding remarks

The presented calculations of the river inflow to the Baltic Sea are based on a quite homogeneous data material covering a considerable period of time. The obtained results seem to be fully representative and can constitute a basis for calculating the normal water balance of the whole sea and its main subbasins. They also allow to define with some precision the long-term tendency of the inflow. Against that background, it is possible to state that most of the values obtained earlier do not show significant differences from the long-term average (55 years). For example, Spethmann (1912), Witting (1918) and Rundo (1930) obtained results with an error only within the range of ± 1 %; similar values were accepted by Brogmus (1952) in his revision of the water balance of the Baltic. Slightly bigger differences can be noted for individual regions, probably caused by acceptance of differing region boundaries and thus different drainage basin areas.

Determination of river inflow to the Baltic should be continued. This is strongly motivated by the role of this element in the present water balance of the sea, the role it plays in hydrological relations in general, and also by the anthropogenic changes of the inflow caused by progressive hydrotechnical development of the rivers in the drainage area (Ehlin and Zachrisson 1974) as well as intensification of land management in general, which would be expected to alter the runoff conditions.

Chapter 5

DETERMINATION OF AREAL PRECIPITATION FOR THE BALTIC SEA

Bengt Dahlström (Sweden)

5.1 INTRODUCTION

The main objective of this investigation is to estimate monthly areal precipitation over the subbasins of the Baltic Sea. In this report areal values have been estimated for the periods 1951-1970, 1931-60 and for the Pilot Study Year, covering the period July 1975 to December 1976.

The areal estimates computed in this report are based on corrected point precipitation data: it is a well-known fact that measurement by gauges gives systematic deficits in precipitation amounts. For each station corrections of the monthly values have been suggested by the respective country.

For the areal estimation of precipitation within the Baltic Sea and its subbasins statistical interpolation has been applied. The normalized fields have been extrapolated from the available climatological point data.

Methods for determination of areal precipitation have been discussed by Rainbird (1967) and by Dahlström (1976). The fact that the principal part of the point precipitation data are samples representing land conditions rather than the precipitation regime over the sea may lead to serious errors in the areal estimates. To reduce these effects of the inhomogeneities the statistical interpolation method is applied on normalized precipitation data.

5.2 METHODOLOGY

The data stocks delivered by the respective Baltic bordering countries consisted of monthly and yearly precipitation sums (uncorrected and in general also corrected data), from the following total number of stations:

Period	Number of stations
1931-60	299
1951-70	226
1975/76	464 (the Pilot Study Year)

Some countries have also submitted data for the period 1971-1975.

The data coverage was densiest in the region of Denmark and in the other coastal regions, the density of stations was roughly the same. Below are presented some further information about the data.

5.2.1 Error influences at point measurements

The conventional measurement of precipitation is a very simple procedure and consists in emptying a bucket and measuring the amount by using a graduated glass. In the case of solid precipitation the content of the gauge is melted and then measured. Despite this simple character of measurement the value obtained is influenced by a variety of errors.

Due to the fact that the error sources frequently interact in causing a deficiency in the precipitation amount it is important to find suitable amendments for the point measurements. As a lodestar when going through the jungle of possible error influences on point measurements the following mathematical model can be used (cf. B. Dahlström, 1970).

$$P' = P + \Delta P_E + \Delta P_S + \Delta P_A + \Delta P_W + \Delta P_P + \Delta P_D + \Delta P_R$$

errors due to meteorological and instrumental factors combined (ΔP_E to ΔP_P) — purely instrumental error (ΔP_D) — error caused by the observer or by unforeseen incidents (ΔP_R)

The error sources are of individual physical origin and consequently this 'additive' model has been formulated. Explanation of the formula: P' = observed precipitation amount, P = true amount, E = evaporation/condensation, S = splashing/drifting of snow, A = aerodynamic influence (the "wind effect"), W = wetting, P = unsuitable position (effects from interception etc), D = defects of the instrument, R = reading errors and unforeseen incidents.

In the normal case it is sufficient to correct the data for the aerodynamic influence (ΔP_A), the wetting error (ΔP_W) and the error due to evaporation (ΔP_E).

In general the magnitude of the corrections are based on special field investigations designed to reveal the error sources inherent with the respective precipitation equipment. A comprehensive survey of this research field is contained in WMO 1982.

The limited space available does not permit a description here on the individual correction methods applied in the respective country. However, part of this information can be obtained from the following references: Solantie (1974, 1977), Korhonen (1944), Struzer and Golubev (1976), Alleru and Madsen (1980), Karbaum (1969, 1970), Chomicz (1977), Wielbińska (1977), Dahlström (1973).

5.2.2 The quantitative correction effect obtained by the various methods

For the computation of statistical characteristics of the precipitation field it is important that fictitious patterns or large systematical errors are not introduced by the correction method applied.

Table 5.1 Comparison of the applied corrections in the respective country: Mean ratio between correction and corresponding corrected precipitation sums 1931-1960. The corrections have been determined by the respective country

	Month J	F	M	A	M	J	J	A	S	O	N	D	YEAR
Sweden 113 stations	0.20	0.21	0.21	0.16	0.11	0.08	0.09	0.10	0.09	0.12	0.14	0.18	0.14
Finland 58 grid points	0.30	0.30	0.29	0.18	0.11	0.06	0.05	0.06	0.08	0.13	0.19	0.23	0.15
USSR 20 stations	0.36	0.33	0.38	0.18	0.15	0.10	0.07	0.09	0.12	0.14	0.22	0.34	0.18
Poland 18 stations	0.18	0.21	0.15	0.16	0.13	0.09	0.09	0.09	0.10	0.13	0.16	0.17	0.13
DDR 25 stations	0.21	0.20	0.18	0.16	0.13	0.09	0.10	0.09	0.09	0.13	0.15	0.15	0.13
FRG 31 stations	0.19	0.20	0.17	0.17	0.12	0.09	0.09	0.09	0.09	0.14	0.17	0.16	0.14
Denmark 34 stations	0.20	0.20	0.17	0.17	0.12	0.08	0.10	0.09	0.09	0.13	0.16	0.18	0.14

In Table 5.1 above the mean relative corrections (expressed relative to the corrected sum) for the respective country are presented. Due to the fact that the estimates of the corrections are based on results from independent field studies the results seem to agree remarkably well. Due to the type of instrument and to the variability of the meteorological conditions the true percentages are not expected to be identical.

5.2.3 Some aspects on the areal estimation problem

The determination of areal precipitation over oceans respective over semiclosed seas, such as the Baltic Sea, consists basically of the same problems. However, the data coverage is more satisfactory within the region of the Baltic Sea than within the oceans.

The present investigation has been carried out on the basis of data from conventional precipitation measurements. The basic difference in approach between this investigation and the previous computations of the areal precipitation is that corrected point measurements have been used. The areal estimates have been obtained by simple extrapolation of the climatological field and by use of statistical interpolation.

5.2.4 Statistical interpolation of precipitation at sea

For the areal estimation of precipitation within the Baltic Sea and its subbasins the method of statistical interpolation has been applied on normalized precipitation fields. The normalized fields have been extrapolated from the available climatological point data.

The interpolation of grid values was applied by use of corrected point precipitation data. The deviation of the corrected measurements from the true point values was taken into account at the interpolation, see Gandin (1963, 1970).

There is limited information available on the statistical nature of the error in the corrected data. It is quite clear that besides the random error in the corrected values there are also probably systematic errors in all the point correction methods used by the respective country.

Due to the fact that no 'true' data sets are available it is difficult to reach quantitative conclusions on the magnitude of the error in the corrected point data.

To further evaluate the interpolation error some qualitative judgements are given below on the error characteristics of corrected data.

1. The spatial error correlation. In a set of neighbouring stations, used at the interpolation of a grid value, the following factors act towards less spatial correlation of errors in the adjusted data:

   a. The stations are - depending on their site - exposed to various meteorological conditions, especially differences in wind exposure of the rain gauge. Consequently, the corrections and the corresponding errors in the corrections are subjected to a certain 'random' influence, connected with the variation of wind speed and other parameters between stations used for the correction. This 'random' influence thus acts towards a low spatial error correlation.

   b. The available corrected point data are subjected to different correction methods depending on the techniques and way of application used in Denmark, Finland, Poland, Sweden and USSR. These methods seem to have been developed essentially independently. The fact that different methods have been in use acts partly towards a greater spatial independency of errors between points representing different countries.

   c. The point correction methods developed by the respective Baltic bordering country have been developed on the basis of information obtained by special field investigations on error sources at precipitation measurements. It seems consequently relevant to expect that the main systematic deficit in precipitation catch is eliminated by the developed point correction methods and that the inaccuracy of the adjusted data is dominated by a random error component.

   With reference to the items a-c above, spatially uncorrelated errors are assumed in the absence of the precise information of the nature of the errors.

5.2.5 Normalization of the precipitation field

One crucial problem at the interpolation of rainfall over the sea concerns the anisotrophy of the precipitation field. Especially the efficient production of rainfall at stations along the coast during the warm season contrasts strikingly to the moderate rainfall at sea. In the autumn the reverse climatological regime exists.

The normalized values used in the computations were obtained as the deviation of the observed rainfall quantities from the long term average and divided by estimates of standard deviation.

The method applied to determine the climatological fields can be characterized as a rough method based on linear, weighted interpolation with climatological adjustment for the land-sea precipitation gradients. The method consists of the following steps:

- The monthly precipitation measurements were allocated to the nearest points in a regular cartesian grid covering the Baltic

Sea and the nearby land areas. From qualitative judgements a grid distance of 50 km was selected. If more than one station was situated within a distance of 25 km from the specific grid point the arithmetic average of these neighbouring values was allocated to this grid point.

Part of the grid was thus filled with observational data.

The grid data, that were obtained by this step, were used for the estimation of data at the remaining 'empty' grid points.

- Distance weighting and linear interpolation within a 7 x 7 matrix, centered at the respective grid point.
- Adjustment according to a climatological precipitation land/sea gradient

Statistics on the mean rainfall land/sea gradient was computed for the coastal areas of the different subbasins and for different months. It turned out that this statistics is highly sensitive to what stations are selected for determination of these gradients.

On the basis of corrected point data from a few stations with acceptable locations the following annual gradients G(d), were computed:

Table 5.2

The precipitation gradient of the Baltic Sea. The annual relative reduction of the precipitation from shoreline.

Subbasin No	Precipitation gradient G(d) annual values d = distance from shoreline	
	d < 100 km	d ≥ 100 km
1-2	0.13	0.195
3-7	0.05	0.075

The relatively cold water in the subbasins 1 and 2 with a longer duration of ice cover gives a steeper gradient in these regions than in the other parts of the Baltic Sea. In addition coastal oroegenic effects on the western side of the northern Bothnian Sea make the gradient relatively steep.

The results in Table 5.2 indicate that the precipitation gradient is steeper close to the shoreline than more distant from the shore. This is in agreement with the result obtained by Andersson in his study of the precipitation in the region of southern Bothnian Sea, see Andersson (1963, p. 300).

5.2.6 Normalization due to variability

The information for the proper computation of the standard deviation at the location of the respective station was in general only available at certain stations. At grid points no relevant measurement data were available for the computing of statistical quantities.

In addition to this lack of information the relevant estimate of statistical measures of the variability of precipitation at coastal stations is not easy to determine due to the fictive variation caused by the error sources inherent with the measurement. It was therefore decided to normalize the observed values by regression estimates of standard deviation and by climatological averages of precipitation.

These regression estimates were obtained on a monthly and yearly basis by relating the standard deviation of the rainfall values, compared in the usual way at selected stations, to the climatological average of rainfall at the respective stations.

By use of the climatological averages a simple measure of the variability, here denoted s_i, then could be obtained using the regression relationships developed. The difference between the corrected point values and the climatological values were divided by the respective values s_i to get the normalized fields.

5.3. RESULT OF THE COMPUTATIONS

5.3.1 Areal estimates and comparison with previous results

The previous investigations on the areal precipitation within the Baltic Sea have not quantitatively taken the error sources inherent with point precipitation measurements into account. These error influences, dominated by the aerodynamic deflection of precipitation particles around the instrument, give the integrated effect of a deficit of precipitation. These error effects is of special importance for the determination of areal precipitation within the Baltic Sea due to the fact that the relevant stations, where data are available, are situated on wind exposed peninsulas, spits, islands and lighthouses.

The fact that corrected point measurements have been used in this project means that the areal estimates can be expected to be larger than the results from the previous investigations, where uncorrected point data in general have been processed.

Table 5.3.

Comparison of areal precipitation estimates for the Baltic Sea

Subbasin No	Areal precipitation (mm) - yearly averages				
	B.Dahlström*		W.Brogmus	H.Simojoki	R.Witting
	1931-60	1951-70	(1886-1935)	1886-1935	1898-1912
1	554	535	405	449	533
2	598	572	425	473	554
3	677	593	560	576	595
4	653	590	580	569	560
5	655	628	473	544	570
6	685	692	515		
7	684	701			
1 - 5	635	603	470	525	565
1 - 6	638	607	474		
1 - 7	639	613			

* present investigation

The circumstance that the estimates are made for different periods and the fact that no quantitative error estimate of the areal values has been presented in the previous investigations are factors that make a 'direct' comparison of the estimates difficult.

The relatively low values obtained by W. Brogmus are mainly explained by his assumption on the precipitation gradient between land and sea.

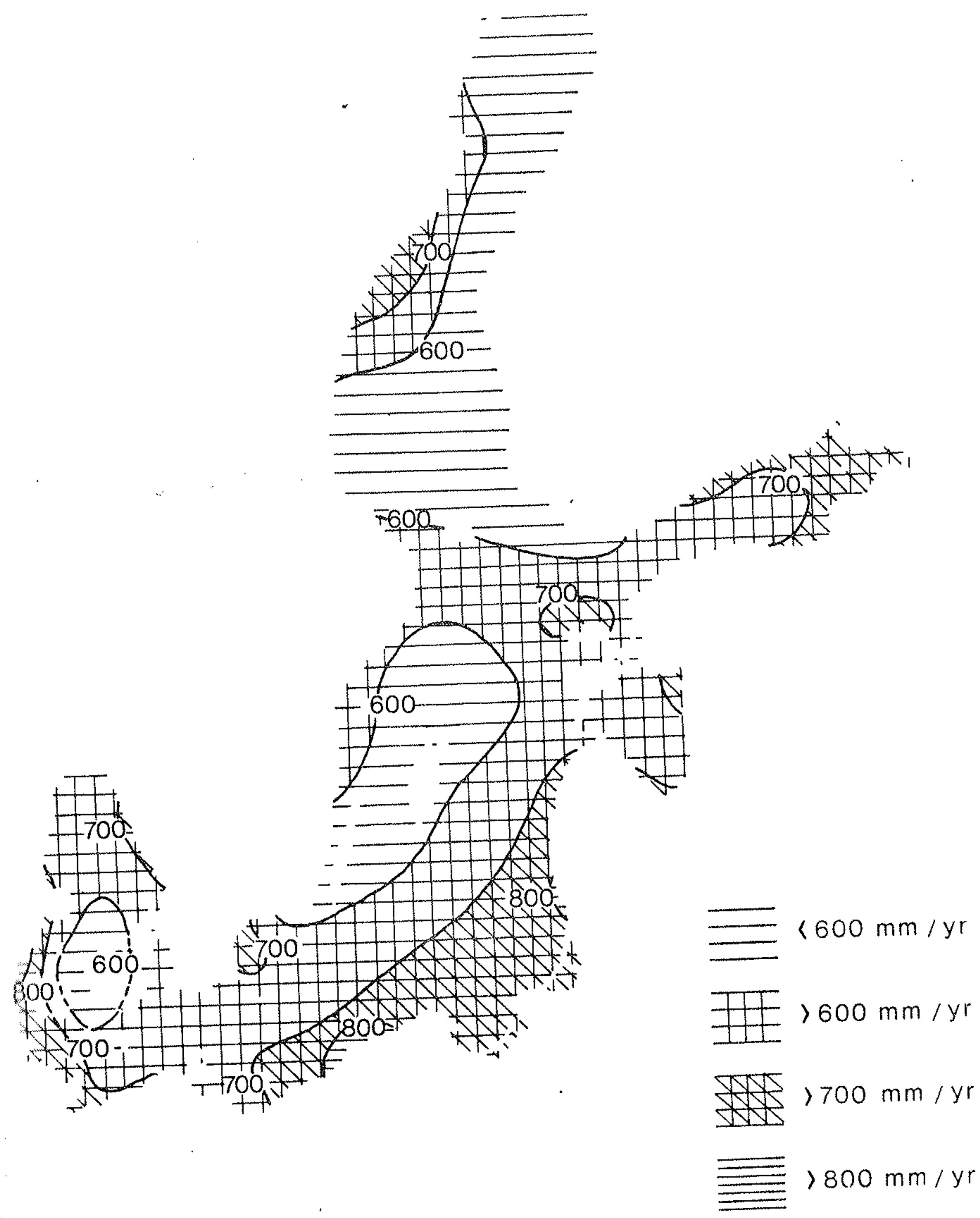
The final data on the precipitation from the areal estimation of the Baltic Sea and its subbasins are presented in Main Table 5 (1931-60) and 6 (1951-70).The areal distribution over the Baltic is illustrated in Fig. 5.1 (1931-60).

Precipitation during the Pilot Study Year are exposed in Table 5.4.

5.3.2 Verification of results

The uncertainty of the method applied for the estimation of the climatological areal precipitation is in particular connected with the weighting function applied and the adjustment of the precipitation gradient.

The verification, theoretically or experimentally, of the computations is not easy to perform. The accuracy of the estimation procedures is believed to be approximately the same



5.1 Areal distribution of annual precipitation. Long-term average 1931 - 60 . mm/yr

Table 5.4 Precipitation during the Pilot Study Year. Areal estimates on individual subbasins.

a. 1975

	Subbasins		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
1	Bothnian Bay	mm	54	14	14	27	42	32	16	80	71	38	52	51	491
		km³	1.96	0.51	0.51	0.98	1.52	1.16	0.58	2.90	2.57	1.38	1.89	1.85	17.81
2	Bothnian Sea	mm	46	18	25	28	46	40	28	50	67	32	38	41	459
		km³	3.65	1.43	1.98	2.22	3.65	3.17	2.22	3.96	5.31	2.54	3.01	3.25	36.39
3	Gulf of Finland	mm	51	23	29	72	42	44	43	59	47	34	55	68	567
		km³	1.60	0.68	0.86	2.12	1.24	1.30	1.27	1.74	1.39	1.00	1.62	2.01	16.73
4	Gulf of Riga	mm	48	15	34	66	47	22	41	25	44	38	46	87	513
		km³	0.86	0.27	0.61	1.18	0.84	0.39	0.73	0.45	0.79	0.68	0.82	1.56	9.18
5	Baltic Proper	mm	48	17	36	45	43	20	49	32	58	49	40	45	482
		km³	10.08	3.57	7.56	9.45	9.03	4.20	10.29	6.72	12.18	10.29	8.40	9.45	101.22
6	Sund and Belts	mm	77	15	31	61	32	20	57	27	68	36	58	35	517
		km³	1.55	0.30	0.62	1.23	0.64	0.40	1.15	0.54	1.37	0.72	1.17	0.70	10.39
7	Kattegat	mm	96	13	28	55	33	26	62	46	76	45	56	42	578
		km³	2.14	0.29	0.62	1.23	0.74	0.58	1.38	1.03	1.69	1.00	1.25	0.94	12.89
1-7	Total Baltic	mm	52	17	31	44	43	27	42	42	61	42	44	48	493
		km³	21.59	7.06	12.87	18.27	17.86	11.21	17.44	17.44	25.33	17.44	18.27	19.93	204.71

Table 5.4

b. 1976

	Subbasin		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
1	Bothnian Bay	mm	47	39	27	21	17	23	51	19	45	26	60	37	412
		km³	1.70	1.41	0.98	0.76	0.62	0.83	1.85	0.69	1.63	0.94	2.18	1.34	14.93
2	Bothnian Sea	mm	42	29	37	20	18	39	39	30	68	30	80	85	517
		km³	3.33	2.30	2.93	1.59	1.43	3.09	3.09	2.38	5.39	2.38	6.34	6.74	40.99
3	Gulf of Finland	mm	52	22	46	37	27	50	56	44	61	29	60	64	548
		km³	1.53	0.65	1.36	1.09	0.80	1.47	1.65	1.30	1.80	0.86	1.77	1.89	16.17
4	Gulf of Riga	mm	75	13	40	58	36	57	39	35	53	27	71	89	593
		km³	1.34	0.23	0.72	1.04	0.64	1.02	0.70	0.63	0.95	0.48	1.27	1.59	10.61
5	Baltic Proper	mm	79	14	36	41	46	32	45	27	51	41	54	101	567
		km³	16.58	2.94	7.56	8.61	9.66	6.72	9.45	5.67	10.71	8.61	11.34	21.20	119.05
6	Sund and Belts	mm	90	12	21	25	71	15	27	16	43	64	39	70	493
		km³	1.81	0.24	0.42	0.50	1.43	0.30	0.54	0.32	0.87	1.29	0.78	1.41	9.91
7	Kattegat	mm	66	19	17	25	51	21	22	19	48	113	58	82	541
		km³	1.47	0.42	0.38	0.56	1.14	0.47	0.49	0.42	1.07	2.52	1.29	1.83	12.06
1-7	Total Baltic	mm	67	20	35	34	38	33	43	27	54	41	60	87	539
		km³	27.82	8.31	14.53	14.12	15.78	13.70	17.86	11.21	22.42	17.03	24.92	36.13	223.83

for the coastal areas of all the subbasins. This qualitative statement emanates from the fact that the procedures that have been used for the estimation are basically the same for all subbasins. Sophistication of the method has to a great extent been avoided which somewhat 'facilitates' the verification. The proper verification of the results in the most data sparse areas, such as the interior of the Baltic proper, offers particularly great problems.

Verification by use of independent data. Data from 8 stations along the Swedish coast that were not used at the computation of the climatological grid fields were compared with the corresponding values interpolated from the computed grid fields. For the comparison the point measurements were corrected by the same point correction method which had been used for the point data involved at the estimation of grid values.

The following result was obtained:

The average monthly deviations range from 1% to 8% and the average yearly deviation is 4%. If the corrected point values thus would represent the true values for these 8 stations, then the spatial estimation would give an overestimate of 4% (if we neglect the above indicated 'displacement effect').

However, this limited amount of information does not permit any detailed conclusions on the reliability of the estimates.

From qualitative judgements it seems reasonable that a systematic error probably is less than 25% of the random part of the error influence. With an overestimate of systematic error influence = 0.25 the following overestimate is obtained on a monthly respective yearly basis.

Table 5.5.

The relative standard error, E*, of areal precipitation values - a probable overestimate. The figures are expressed in percentages (of the areal estimates). Period: individual months 1951-1970.

	Error estimate E*. Percentages error of respective areal estimate. Individual months 1951-1970							
Subbasin No	1	2	3	4	5	6	7	1-7
%	+12	+10	+11	+13	+8	+11	+10	+9

The values on E* presented in Table 5.5. represents an over-estimate of the areal relative error for an individual month 1951-1970. The variation between months was small.

5.4. CONCLUSIONS

5.4.1 The estimation problem

Within this project corrections of point precipitation data were - with some exception - applied by the respective Baltic bordering country. The methods of correction were of different kinds according to the type of precipitation gauge and the results from special investigations on error sources of precipitation measurement in the respective country.

Consequently the point correction can be regarded as a procedure independent from considerations of the spatial structure of precipitation within the Baltic Sea. This fact seems important with regard to the circumstance that the error sources at point measurements is one factor and the meteorological mechanisms that determine the yearly, spatial distribution of precipitation is another factor that influences the spatial pattern towards decreasing amounts with increasing distance from land. The two factors are thus compounded, but have been possible to separate from each other in a basically independent way in this investigation.

The paramount problem at the areal estimation concerns the lack of reliable observational evidence in the interior parts of the respective subbasin. Nevertheless, the study of the covariance field by use of monthly precipitation sums reveals that there is a considerable correlation between values from coastal stations and values well off from the coast. Consequently a large amount of climatological information on the conditions in the data sparse areas are contained in the data from stations on spits, lighthouses, islands etc.

5.4.2 The estimates

1. The areal estimates of the present investigation indicates that the long-term average of yearly precipitation amount for the whole Baltic Sea, with the subbasins 1-7 (Danish sounds and Kattegat included) is about 639 mm, (265.77 km^3), for the period 1931-1960 and 613 mm (254.25 km^3), for the period 1951-1970. With consideration to error limits the average precipitation on a long term basis is estimated to be within 600 mm to 650 mm per year and with a probable average of 625 mm (259.54 km^3).

The maximum areal value for the subbasins 1-7 for the period 1951-70 occurred in 1960 with 730 mm ($303\ km^3$) and the minimum value in 1964 with 481 mm ($200\ km^3$).

5.4.3 Urgent future activities

1. For future computations of areal precipitation it seems important to include information from remote sensing devices and also information contained in the quantitative numerical precipitation forecasts.

In particular it seems important to understand quantitatively the physical mechanisms that determine the efficiency of precipitation release in the coastal zone and at sea. Separate investigations on this topic by use of numerical models in connection with conventional data and new data sources are encouraged.

2. For environmental and economic reasons it is important that the precipitation element, as a component in the water balance, is determined on an operational basis. The main problem connected with this task concerns the flow of data between the Baltic bordering countries. It is here proposed that the feasibility of an operational evaluation is investigated by the relevant authorities.

Chapter 6

EVAPORATION FROM THE BALTIC

Dieter Henning (FRG)

6.1. INTRODUCTION

The evaporation from the surface of the Baltic Sea and its subbasins has been determined for true months (Januaries of 31 days, Februaries of 28.25 days. Marchs of 31 days and so on). Long-term averages were calculated as well as the evaporation heights for the individual months of the extended Pilot Study Year (July 1975 - December 1977). For the nineteen months of May 1976 to November 1977 two different procedures to estimate the Baltic evaporation could be applied: the bulk aerodynamic method (BAM) and the aerological method. The availability of aerological data during this period was the reason for extending the Pilot Study Year (PSY) by twelve months as far as the "atmospheric components" of the Baltic Sea water budget were concerned. Utilization of aerological data for the determination of areal means of evaporation also requires the availability of the respective precipitation data; these were provided by the Swedish Meteorological and Hydrological Institute.

6.2. THE DATA

6.2.1. Bulk aerodynamic method (BAM)

The surface data needed for application of the BAM - sea-surface temperature (SST), wind speed, and moisture content of the air at a certain level, characteristically 10 m - date from the years 1862 - 1978. (Quasi-)decal means of evaporation were calculated for the periods 1948 - 1960, 1961 - 1970 and 1971 - 1978. Also, the overall monthly averages were determined by utilizing the total number of nearly 200,000 data sets: these averages are considered as the best approximations of long-term or climatological mean values of the Baltic evaporation attainable at present.

The surface data of 1862 - June 1975 came from the archives of the Seewetteramt, Hamburg, of the Deutscher Wetterdienst. They represent measurements carried out aboard "ships of opportunity" (Friehe and Schmitt 1976), the light-vessel Fehmarnbelt (1968-1972) as well as along the lighthouse Kiel (1968-1972).

For the extended PSY, a special observational programme could be launched successfully; therefore 75 percent of the suitable data (compare Table 6.1) date from this period. Each of the Baltic countries took part in this programme in one way or another. The data came from ships of opportunity (merchant ships, ferries, warships), research vessels, icebreakers, the light-vessel Fehmarnbelt, and the lighthouse Kiel. In addition, the observations of 22 to 27 meteorological stations on islands or at the coast were made available by the Finnish and Swedish meteorological or/and hydrological services. In these cases, SST was estimated from hydrographic charts (showing SST distributions and ice phenomena) issued by the Institute for Marine Research, Helsinki, in winter and by the Swedish Meteorological and Hydrological Institute throughout the year. SST was estimated from these maps, too,

Table 6.1. Number of surface data sets available for application of the BAM

1862 - 1947*):	2792	*) actually, only 28 years were data-years
1948 - 1960:	8988	
1961 - 1970:	20063	
1971 - 1975/6:	12539	
1975/7 - 1977/12:	149717**)	**) about equal to an average of 120 data sets for an area of 100000 km^2 during an individual month
1978:	5467	
1862 - 1978:	199566	

in case that it was the only indispensable quantity missing in a ship's report. For the Gulf of Bothnia, measurements from coastal and island stations represent the majority of observations. It is believed that the results for the PSY do not suffer from any systematic errors by the utilization of these land-born observations to which no corrections were applied.

The data from the Hamburg Seewetteramt had been routinely error-checked. Additionally, all the data - PSY or historical - were once more comprehensively checked before processing. Erroneous data were corrected if possible in some way, otherwise they were deleted.

6.2.2. Aerological method

By the aerological method, the water vapour budget of the air above a polygonal area very similar to that of the Baltic - or any of its subbasins - had to be determined month by month. The data needed for this are the horizontal wind components and atmospheric humidity and pressure at the "standard levels" and "significant points" above the radiosonde stations of northern and north-central Europe up to 400 mbar. These data are normally available twice a day. They were received via the central office of the Deutscher Wetterdienst in Offenbach on Main and were processed by a working group in Kiel of which Prof. F. Defant[1] was

1) cf. Defant (1985)

the principal investigator. Sophisticated routines were developed by this group in order to eliminate erroneous observations. The drawbacks inherent to aerological observations with respect to large-scale flow investigations - time interval between two ascents as large as twelve hours, different moisture measuring equipment on different radiosonde types, horizontal drift of the radiosondes with strong winds - were considered to be of minor importance.

6.3. PROCEDURES

6.3.1. Bulk aerodynamic method (BAM)

The BAM is characterized by the bulk transfer equations. The equation for the vertical flux of water vapour - or evaporation E - reads

$$E = c_E \, \rho (q_s - q) \, v \qquad (6.1)$$

where c_E is water vapour transfer coefficient, ρ the density of moist air, q_s, q specific humidities of "air in contact with salt water" (Bunker 1976) and at a standard height assumed to be 10 m, and v wind speed at 10 m. Equation (6.1) means that the evaporation from an (extended) body of water is simply proportional to the product of the vertical slopes or gradients of specific humidity and wind speed. At the surface, wind speed is assumed not to differ from the amount of the given current velocity ($v_s = 0$), and the humidity q_s can be calculated as a function of the surface temperature t_s. The specific humidity q at 10 m is computed from the dry and wet bulb temperatures there.

Questions to be decided in applying equation (6.1) are a) selection of the transfer coefficient c_E, and b) the question whether the equation is to be applied to mean or to individual, or instantaneous, values of (q_s - q) and v, respectively. While in most of the numerous investigations in which use was made of the BAM, long-term monthly mean values of oceanic evaporation were calculated by applying long-term monthly averages of specific humidity and wind speed (compare, e.g., Hastenrath and Lamb 1978, 1979), here the evaporation from the Baltic was estimated by calculating instantaneous values of E from individual, simultaneously measured values of q_s, q and v. This, of course, excluded any observation from the evaluation in which even one of these quantities was missing. The long-term monthly mean values of E were then determined by arithmetically averaging all values of E found for a given area. In doing so, a recommendation of Britton et al. (1976) was observed. Recently, oceanwide investigations on water vapour and heat exchange have been carried out in the same way (Bunker 1976; compare also Bunker and Worthington 1976, Weare et al. 1980, 1981 and Esbensen and Kushnir 1981).

The transfer coefficient c_E is known to be dependent on wind speed and density stratification (thermodynamic (in)stability) of the air above the sea surface (compare, e.g., Deardorff 1968). Nevertheless, when operating with time-averaged values of q_s, q and v, normally a constant value of c_E somewhere between about $1.0\ 10^{-3}$ and $2.0\ 10^{-3}$ is applied. When applying equation (6.1) to individual data sets it becomes appropriate, however, also to utilize variable transfer coefficients c_E; otherwise the gain of information obtained from using individual observations would not be fully exploited. From a thorough evaluation of previous scientific experiments combined with the theoretical findings of Deardorff (1968), Bunker (1976) tabulated c_E-values for different wind speeds and vertical temperature differences $t_{10} - t_s$ (t_{10}: temperature in 10 m height). In the present investigation c_E-values were chosen according to his table with minor modifications.

Arithmetic averages of monthly evaporation were calculated for each 1-degree latitude-longitude field. Mean values for the subbasins were then calculated by double-weighted averaging of these 1^o-field mean values. The number of available observations per 1^o-field and month (up to a maximum of 248 observations for an individual month of the PSY) as well as the areas of these fields were taken as weights. To obtain areal averages for the entire Baltic, singleweighted averages of the subbasin-means were determined, using the subbasin-areas as weights. This means that the subbasin-averages of evaporation were considered as equally representative independent of the numbers of observations on which they were based. This principle was observed also in case of the Baltic Proper (BP) when the BP-averages were calculated from those of the BPN (BP North; north of 57^oN), BPC (BP Cental; south of 57^oN and east of 15^oE) and BPW (BP West; west of 15^oE). This subdivision was introduced in order not to exceed subbasin-areas of 100,000 km^2, and thus to make better allowance for regional differences.

In order to get realistic subbasin-averages of evaporation during the winter months, the extent of an ice cover had to be taken into account. Because practically no observations became available from ice-covered parts of the Baltic, their evaporation was supposed to be zero. From the Finnish and Swedish ice charts already mentioned, monthly averages of the areas covered by ice were estimated for each subbasin and each month of the extended PSY. The subbasin evaporation heights were calculated by multiplying the evaporation heights estimated for the ice-free parts of the respective subbasins with the ratios of the ice-free to the total subbasin-areas. The relative areas found covered by ice are given in Table 6.2. As a measure of emergency, the two- to three-year ice-cover averages were used in estimating the (quasi-)decadal and long-term mean evaporation heights for the respective months and subbasins.

6.3.2. Aerological method

Determination of the vertical water balance at the surface of a given area by utilization of aerological data has been described

Table 6.2

Relative ice cover on the Baltic Sea during the extended PSY Percentage of subbasin-areas as estimated from the ice charts of Institute for Marine Research, Helsinki, and Swedish Meteorological and Hydrological Institute.

Subbasin	Winter	Month N	D	J	F	M	A	M
1. Bothnian Bay	1975-1976	0	13.3	65.7	92.0	92.4	78.7	25.8
	1976-1977	10.5	22.8	63.5	99.3	92.7	87.7	33.6
	1977	1.2	21.7					
	Mean	3.9	19.3	64.6	95.6	92.6	83.2	29.7
2. Bothnian Sea	1975-1976	0	0	11.1	28.5	54.0	19.3	.4
	1976-1977	0	.4	12.5	53.9	60.4	20.1	1.4
	1977	0	1.4					
	Mean	0	.6	11.8	41.2	57.2	19.7	.9
3. Gulf of Finland	1975-1976	0	1.3	42.6	81.4	85.3	48.0	0
	1976-1977	0	2.4	56.6	97.8	85.6	50.9	.3
	1977	0	10.7					
	Mean	0	4.8	49.6	89.6	85.4	49.4	.2
4. Gulf of Riga	1975-1976	0	0	8.6	70.3	73.3	29.0	0
	1976-1977	0	0	21.1	82.1	79.7	12.4	0
	1977	0	1.4					
	Mean	0	.5	14.8	76.2	76.5	20.3	0
Baltic Proper North	1975-1976	0	0	1.7	7.9	5.0	1.6	0
	1976-1977	0	0	2.6	9.0	6.8	.9	0
	Mean	0	0	2.2	8.4	5.9	1.2	0
Baltic Proper Central	1975-1976	0	0	1.4	5.0	3.8	0	0
	1976-1977	0	0	3.7	4.6	1.7	0	0
	Mean	0	0	2.6	4.8	2.8	0	0
Baltic Proper West	1975-1976	0	0	.6	3.3	0	0	0
	1976-1977	0	0	3.0	.7	0	0	0
	Mean	0	0	1.8	2.0	0	0	0

in more or less detail e.g. by Palmén and Söderman (1966), Rasmusson (1977), Alestalo and Savijärvi (1977) or Alestalo and Holopainen (1980). Defant (1985) gives a detailed description of the work within the IHP-project to determine this difference over the Baltic for the period May 1976 to November 1977. In order to overcome the drawbacks of large spacing of the aerological stations and large intervals between two radiosonde-ascents compared to the extent and configuration of the Baltic, Defant hand-analysed the maps of the monthly averages of the zonal and meridional components of the vertically integrated water vapour flux over northern and north-central Europe. From these maps he plotted the flux components for the central points of the sections (of 110 km length) of a polygon fitted to the Baltic coastline and the open-sea borderline. The subbasins were treated correspondingly. Summation of the resultants of the flux components at each section then led to the differences of evaporation minus precipitation for the entire Baltic or its subbasins for a given month.

6.4. RESULTS

6.4.1. Figures from previous investigations

Selected results of previous investigations together with the climatological figures obtained by the present evaluation are shown in Table 6.3. In order to achieve maximum comparableness, all data are carefully related to relevant subbasins according to the present IHP-investigation.

As for the Baltic without Kattegat and without Beltsea, the findings concerning the estimated mean annual amount of evaporation have changed only slightly since 1918. The continued repetition of the 200 mm/year given by Spethmann (1912) is justified: Spethmann relying on the data of Witting (1908) for the Bothnian Bay (200 mm/year) and the Bothnian Sea (190 mm/year), assures that he did not expect any significant local change of the annual evaporation across the Baltic.

From Brogmus (1952) - whose investigation has to be taken as the forerunner of the present study - always two series of results are quoted in Table 6.3. The smaller figures represent Brogmus original results - which are directly comparable to those presented here - while the higher values are those normally quoted. The latter however, form a compromise between the results found by application of the Sverdrup approach and the data of Witting (1918): they were obtained by a water budget approach which was based on the data of net outflow through the Danish Straits given by J.P. Jacobsen (1936). These outflow data, however had been adjusted to Witting's evaporation figures.

Table 6.3
Monthly maximum and annual evaporation from the Baltic and its subbasins (mm). Summary of findings in chronological order. Table gives also evaporation during high-evaporation half-year (August-January) in percent of annual evaporation.

Subbasin	Krümmel 1904	Witting 1908 1904-1905	Spethmann 1912	Witting 1918 1898-1912	Sokolovski 1933 1926-1930	Schulz 1938 1926-1930	Simojoki 1949	Hela 1951 1923-1938	Brogmus 1952 a[1]	Brogmus 1952 b[2]	Strokina 1956 1904-1932	Hankimo 1964 March 1961-Febr 1962	Pomeranze 1928-1938 1947-1955	Sturm 1970 1947-1961	Alestalo & Savijärvi 1977 Nov 1968-Oct 1970	Mengelkamp 1980 Apr-Oct 1976	Present investigations 1862-1978
1. Bothnian Bay																	
Monthly max/month-mm		41.5/Nov		64/Oct					61/Nov	65.7/Nov							73.1/Sep
percent Aug-Jan-%		90.0		91.5					86.3	86.3							81.2
annual - mm		200	200	294			279		308	332			340				364
2. Bothnian Sea																	
Monthly max/month-mm		34.5/Nov		69.3/Nov				61.4/Aug	60.9/Dec	65.5/Dec		87.4/Dec					74.0/Sept
percent Aug-Jan-%		77.6		78.3				77.8	75.6	75.6		75.2					77.3
annual - mm		190	200	415			410	362	374	402		495	426		300		460
3. Gulf of Finland																	
Monthly max/month-mm				87/Aug					57/Aug	61.3/Aug	92.5/Nov						63.6/Sept
percent Aug-Jan-%				76.3					77.0	77.0	81.0						79.0
annual - mm			200	510			408		370	398	613		420				361
4. Gulf of Riga																	
Monthly max/month-mm				85/Aug					51/Oct	55/Oct	89.3/Nov						80.6/Nov
percent Aug-Jan-%				74.0					74.6	74.6	87.0						77.3
annual - mm			200	504		417	410		335	360	520		492				439
5. Baltic Proper																	
Monthly max/month-mm				77/Nov					78.6/Oct	84.6/Oct							86.6/Sept
percent Aug-Jan-%				74.2					72.5	72.5							73.4
annual - mm			200	566			522		508	546							551
Baltic inside Danish Straits																	
Monthly max/month-mm				71.6/Aug					65.5/Nov	70.6/Nov							78.9/Sept
percent Aug-Jan-%				76.2					74.5	74.5							75.2
annual - mm			200	498	500		460		439	473							493
6. Danish Straits																	
Monthly max/month-mm									74/Aug	79.5/Aug				78.6/Aug		119.9/July	88.4/Sept
percent Aug-Jan-%									70.6	70.6				63.5			64.1
annual - mm			200						469	505				562			541
7. Kattegat																	
Monthly max/month-mm																	91.6/Sept
percent Aug-Jan-%																	65.8
annual - mm			200														541
1-7 Total Baltic																	
Monthly max/month-mm																	80.0/Sept.
percent Aug-Jan-%																	74.1
annual - mm	183		200														498

1. Bulk aerodynamic approach after Sverdrup (1937) with a variable transfer co-efficient which decreases with increasing wind speed, vice versa.

2. The figures known as Brogmus-results. They were obtained by a 7.65 percent increase of the figures determined after Sverdrup (1937); compare text.

6.4.2. Long-term averages by application of BAM

The long-term monthly averages of the Baltic evaporation evaluated for different time period are presented in Main Tables 7 and 8. The figures for the quasi-decades 1948 to 1970 might, in the light of the numbers of observations of Table 6.2, appear to be of doubtful reliability. Nevertheless, their presentation in Main Table 8 was thought to be useful in order to give an idea of their differences from the climatological averages of Main Table 7 or, vice versa, of the degree by which they contribute to these averages. Indeed, the totals for the entire Baltic only vary between 491 and 519 mm/year or 203.8 and 215.4 km^3/year for 1948-1960 and 1971-1978, respectively.

A special feature of the Baltic evaporation is the occurrence of two maxima which are normally observed in September and in November/December. Only for the period 1961-1970 just the December-maximum exists which then is especially marked. Witting (1918) too, found two maxima, occurring in August and November, while Brogmus (1952) and Strokina (1956) just traced the November-maximum. The main reason for intense evaporation in August and/or September is a relatively strong vertical humidity difference at high temperatures, while evaporation maxima in November and/or December are caused essentially by high wind speeds. The minima of the Baltic evaporation occur mainly in April or May; only in the Beltsea, Kattegat and the Bothnian Bay are they observed already in March or February, on the average (compare Main Table 7).

In the Bothnian Sea and the Baltic Proper, the half-year period of maximum evaporation is that of August to January. This is true also for the entire Baltic, while in all the small subbasins (the small western part of the Baltic Proper included) July to December show this characteristic. The evaporative water loss of the entire Baltic from August to January - for 1862-1978 - amounts to 74.1% of its annual value, while the corresponding figure for July to December is 73.1%. The Bothnian Bay is the only subbasin where - during 1862-1978 - the loss of water to the atmosphere during the month of maximum evaporation exceeds 20% of the mean annual evaporation.

6.4.3. Evaporation during the extended Pilot Study Year

The monthly amounts of evaporation for the extended PSY as determined by application of the BAM are given in Table 6.4 (heights in mm) and the semi-annual and annual evaporation heights in Table 6.5. Analysis of the evaporation data shows that the extension of the PSY until the end of 1977 as far as the "atmospheric water budget" is concerned turned out to be very fortunate. The atmospheric and hydrographic conditions relevant for the Baltic evaporation during 1977 were extremely different from those during 1976. More precisely, the most contrary conditions existed during the twelve-months periods starting

Table 6.4 Evaporation of the Baltic and its subbasins during the extended PSY and, partly, 1978, as calculated by application of the bulk aerodynamic method in mm/month. (Maximum values underlined)

Subbasin	Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1. Bothnian Bay	'75							31.8	77.3	59.2	74.5	43.5	57.8
	'76	29.4	3.0	4.2	5.6	4.2	20.1	31.7	53.0	90.1	59.1	29.7	35.2
	'77	14.5	0.5	4.6	3.9	6.0	21.6	32.1	42.7	69.8	45.1	36.4	36.3
2.Bothnia Sea	'75							28.6	80.2	63.8	71.8	62.2	78.3
	'76	64.0	24.1	19.7	14.0	6.4	21.1	37.6	49.5	85.3	80.5	39.2	63.8
	'77	30.8	21.4	9.9	9.2	9.3	15.0	29.7	39.7	73.7	36.1	47.2	53.9
	'78	47.6	39.2	-5.1	15.1	16.9	11.4	14.2	39.7	120.0	43.5	19.2	91.6
3. Gulf of Finland	'75							16.7	65.3	43.5	56.2	55.4	38.9
	'76	28.9	12.4	6.9	6.6	7.5	21.0	32.5	52.6	68.3	87.8	27.2	48.4
	'77	12.1	0	3.3	-1.1	3.1	31.2	18.8	41.6	70.2	26.8	36.4	48.2
4. Gulf of Riga	'75							16.5	80.4	65.3	107.3	96.0	102.2
	'76	59.2	9.2	28.0	7.6	10.7	23.2	39.0	51.3	83.4	115.3	29.9	73.1
	'77	23.9	7.4	1.0	2.3	8.3	31.4	32.2	45.7	78.0	51.5	55.2	65.7
Baltic Proper North North of 57°N	'75							22.6	73.5	82.8	73.6	87.2	91.0
	'76	71.3	30.8	42.2	13.2	9.2	14.7	43.3	55.6	102.7	115.9	47.9	82.6
	'77	33.9	39.6	18.0	6.0	8.7	23.1	32.7	47.2	86.8	37.4	55.8	67.4
	'78	55.3	58.9	26.8	17.7	16.4	20.1	25.3	103.0	98.2	51.1	28.8	92.1
Baltic Proper Central/South of 57°N and East of 15°E	'75							33.6	93.3	79.4	69.6	89.5	91.4
	'76	69.0	28.7	40.6	13.4	17.2	11.1	48.7	53.9	116.0	134.1	42.8	71.6
	'77	31.4	28.9	16.7	3.2	11.4	26.8	52.7	65.3	117.0	46.8	96.4	60.0
	'78	41.0	39.7	20.1	20.5	26.3	27.1	36.6	79.2	88.5	-	-	-
Baltic Proper West/West of 15°E	'75							37.3	55.6	93.2	83.8	94.9	75.5
	'76	54.7	27.2	22.9	13.5	13.2	15.4	75.5	49.0	98.2	98.5	50.0	71.0
	'77	19.7	15.9	8.1	10.7	12.0	29.1	52.1	44.9	114.0	41.0	89.5	61.9
	'78	48.3	29.4	11.9	17.9	16.6	43.2	51.6	62.9	53.7	35.8	81.2	56.0
5. Baltic Proper	'75							29.5	80.1	82.6	73.1	89.3	89.1
	'76	68.1	29.4	38.9	13.3	13.4	13.1	50.0	54.0	108.1	121.9	45.9	76.2
	'77	30.9	31.6	16.1	5.4	10.4	25.6	44.3	55.1	104.1	42.1	78.6	63.3
	'78	47.9	46.3	21.8	19.0	20.9	26.3	33.9	87.0	85.7	-	-	-
6. Danish Straits	'75							64.1	56.4	98.2	90.7	75.8	37.9
	'76	34.9	14.7	19.6	23.1	17.1	37.5	116.9	61.8	85.9	70.0	38.6	56.7
	'77	10.2	10.5	4.8	18.2	20.1	42.1	70.8	44.8	97.4	31.8	75.0	33.4
	'78	34.5	31.8	7.7	25.4	14.7	71.7	68.4	79.9	88.5	50.1	57.3	90.5
7. Kattegat	'75							70.2	78.1	103.9	57.2	67.8	48.9
	'76	38.6	7.0	14.6	26.3	19.7	44.7	50.6	46.9	78.3	50.8	24.1	55.7
	'77	5.8	12.4	8.5	23.5	27.4	40.5	51.6	35.0	81.1	23.0	51.8	25.5
Total Baltic -6-7	'75							27.9	78.7	72.4	73.2	76.7	80.4
	'76	59.9	23.4	28.4	11.9	10.4	16.6	43.6	52.7	97.2	104.0	40.6	67.2
	'77	27.5	22.8	11.9	5.4	9.0	23.7	37.4	49.1	90.4	40.4	63.4	57.6
Total Baltic -7	'75							29.8	77.6	73.7	74.1	76.7	78.2
	'76	58.6	22.9	27.9	12.5	10.7	17.7	47.4	53.2	96.6	102.2	40.5	66.7
	'77	26.6	22.1	11.6	6.0	9.6	24.6	39.1	48.9	90.7	39.9	64.0	56.4
Total Baltic	'75							31.9	77.6	75.4	73.2	76.2	76.7
	'76	57.6	22.1	27.2	13.2	11.2	19.1	47.6	52.8	95.6	99.5	39.7	66.1
	'77	25.5	21.6	11.4	7.0	10.6	25.5	39.8	48.2	90.2	39.0	63.3	54.7

Table 6.5

Six-months totals of the evaporation from the Baltic in mm. (Maximum values underlined)

Subbasin	Low-evaporation half-year: Jan.-June			High-evaporation half-year: July-December			
	1976	1977	1978	1975	1976	1977	1978
1. Bothnian Bay	66.5	51.2	-	344.2	298.8	262.4	-
2. Bothnian Sea	149.3	95.6	125.0	384.9	355.8	280.4	328.1
3. Gulf of Finland	83.3	48.7	-	276.7	316.7	241.9	-
4. Gulf of Riga	137.8	74.3	-	467.6	391.9	328.4	-
Baltic Proper North	181.3	129.3	195.2	430.7	448.2	327.3	398.5
Baltic Proper Central	179.9	118.5	174.7	456.7	467.1	438.2	-
Baltic Proper West	146.9	95.7	167.3	440.3	442.3	403.4	431.1
5. Baltic Proper	176.1	119.9	182.3	443.8	456.0	387.7	-
6. Danish Straits	147.0	105.8	185.7	423.2	429.8	353.3	434.9
7. Kattegat	150.8	118.1	-	426.1	306.4	268.1	-
Total Baltic -6-7	150.6	100.3	-	409.4	405.3	338.3	-
Total Baltic -7	150.4	100.5	-	410.1	406.6	339.1	-
Total Baltic	150.4	101.5	-	411.0	401.2	335.3	-

November 1975 and November 1976, respectively. This is especially true for the Gulf of Finland and the Baltic Proper. For the entire Baltic, from November 1976 until October 1977, the evaporative water loss amounted to only 70 percent of that of the preceding twelve-months period. This gives evidence that the evaporation of even the entire Baltic may deviate, in each direction, by about 25 % from its long-term average - which is a considerable amount for a conservative quantity like marine evaporation. The extreme twelve-months totals are 713 mm (November 1975 - October 1976) for the central or southeastern part of Baltic Proper, and 282 mm for the period November 1976 - October 1977 for the Gulf of Finland.

In many cases, the differences between the monthly evaporation totals are likewise conspicuous, compare in particular the months of August, October and November of 1975 to 1977 (1978) in Table 6.4. In October 1977 the evaporative water loss of the entire Baltic amounted to only 39.2% of that of October 1976; the corresponding figures for the Baltic Proper and the Gulf of Finland are 34.6 % and 30.5 %, respectively. For November, the conditions are similar: for August, the evaporation was extremely variable in the Bothnian Bay and Kattegat. Also, the low-evaporation half-year (January to June) of 1977 contributed considerably to the evaporation deficit of that year, compare Table 6.5; during the first six months of 1977, the evaporation from the entire Baltic amounted to just 67.5 percent of that of the preceding "winter half-year", and for the Gulf of Riga this ratio came up with mere 53.9%.

The most conspicuous evaporation changes during consecutive months took place between August 1976 and January 1977: 53, 96, 100, 40, 66 and 26 mm were the evaporation heights of the entire Baltic during these months (see Table 6.4). So, Tables 6.4 and 6.5 demonstrate in particular the unexpectedly (?) high intra- as well as interannual variability of the Baltic evaporation.

Evaporation from the Baltic and precipitation on to the surface of this sea show about contrary lapses in time. While, for the entire Baltic, summer evaporation (July to December) was decreasing continuously from 1975 to 1977, summer-precipitation, indeed, was increasing from year to year during that time. There was found some evidence that 30-day totals of both quantities would be significantly correlated if a time-lag of about 10 to 15 days (with precipitation preceding evaporation) would be taken into account.

A sharpening of the sense of magnitudes with respect to the Baltic water budget might be achieved by the following comparison: The month of minimum evaporation during the extended PSY was April 1977 when the evaporative water loss of the entire Baltic amounted to 2.89 km^3 only. Vice versa, October 1976 was the month with the most intense evaporation during the PSY. The Gulfs of Finland and Riga, the Baltic Proper and the entire Baltic, too, then suffered from their strongest evaporative water losses. During this month, the Gulf of Riga came up with an evaporation of 2.07 km^3 or 71.4% of the evaporation of the entire Baltic six months later.

6.4.4 Estimates for the Pilot Study Year achieved by the aerological method [1)]

The figures found by means of the aerological method are compiled in Table 6.6 column (1). Columns (2) and (3) always show the deviations - in absolute and relative values - from the results which were derived from the surface data. The millimeter-values of columns (1) were calculated by division of the water vapour divergences by its respective polygon areas (and not by the "true" areas according to Ehlin and Mattisson, 1976).

Table 6.6 is very encouraging. For the entire Baltic, the relative difference (columns (3)) between the two types of results exceeds 5 %, by amount, only in four months: July, November 1976, June, August 1977. In all cases, these "large" percentage figures are caused by small values of the differences between the respective evaporation and precipitation heights. In absolute values, the difference $(E-P)_a$ - (E-P) (column (2)) for the entire Baltic never exceeds 1.7 mm. During nine of the nineteen months, the ratio $((E-P)_a - (E-P))/(E-P)$ is, for the entire Baltic, less than 2.5 %, with absolute differences of 1.0 mm or less.

Relative differences (columns (3)) of more than 10 % are only observed - with one exception (Bothnian Sea, May 1976) - in the small subbasins: in 12 months in the Gulf or Riga, 8 months in the Beltsea, 5 months in the Kattegat, and during one month in the Bothnian Bay. Apparently, the aerological method looses some of its power for areas of less than 40,000 km^2. Arithmetic averaging of the amounts of the relative deviations given in columns (3) of Table 6.6 yields 1.21% for the Baltic Proper, 3.72% for the Bothnian Bay, 4.49% for the Bothnian Sea, 4.76% for the Gulf of Finland, 7.92% for the Kattegat, 9.28% for the Gulf of Riga, 11.21% for the Beltsea, and 4.42% for the Baltic in total.

Further, it can be seen from Table 6.6 that during 17 of the 19 months under consideration the aerological data produce somewhat larger - or less negative - differences of evaporation minus precipitation for the entire Baltic than the surface data (exceptions: May and August 1977). This means - the aerological method supposed to be immaculate - that either the BAM yields somewhat too low values of evaporation or that the extrapolations and corrections of the precipitation data resulted in somewhat too large figures of this element.

6.5. CONCLUSIONS

The quasi-agreement of the results demonstrates that any of the three components of the "atmospheric water budget" of the Baltic could be derived from the two others preconditioned, however,

1) see Defant (1985)

Table 6.6

Comparison of the difference evaporation (E) minus precipitation (P), from and on to the surface of the Baltic and its subbasins, as determined from surface data (E-P) and from aerological data $(E-P)_a$ for May 1976 to November 1977.

Column (0): Subbasin

Column (1): $(E-P)_a$ in mm, as determined by the Kiel-group of Prof. F. Defant

Column (2): The difference $(E-P)_a$ - (E - P) in mm

Column (3): The ratio, in percent, of the value of column (2) divided by the amount of (E-P) as calculated from the surface data

(0)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
	May 1976			June 1976			July 1976			August 1976		
1. Bothnian Bay	-12.5	0.3	2.3	-2.9	0	0	-18.3	1.0	5.2	37.1	3.1	9.1
2. Bothnian Sea	-10.4	1.2	10.3	-16.4	1.5	8.4	-1.4	0	0	20.5	1.0	5.1
3. Gulf of Finland	-21.2	-1.7	-8.7	-26.9	2.1	7.2	-21.9	1.6	6.8	9.3	0.7	8.1
4. Gulf of Riga	-22.2	3.1	12.3	-29.2	4.6	13.6	1.8	1.8		14.6	-1.7	-10.4
5. Baltic Proper	-32.2	0.4	1.2	-18.5	0.4	2.1	5.1	0.1	2.0	27.4	0.4	1.5
6. Danish Straits	-58.1	-4.2	-7.8	25.6	3.1	13.8	96.3	6.4	7.1	49.9	4.1	9.0
7. Kattegat	-27.8	3.5	11.2	23.3	-0.4	-1.7	28.3	-0.3	-1.0	27.3	-0.6	-2.2
Total Baltic	-26.6	0.2	0.7	-13.4	0.5	3.6	5.8	1.2	26.1	26.4	0.6	2.3
	September 1976			October 1976			November 1976			December 1976		
1. Bothnian Bay	45.6	0.5	1.1	35.5	2.4	7.3	-28.9	1.4	4.6	-1.8	0	0
2. Bothnian Sea	18.2	0.9	5.2	52.5	2.0	4.0	-38.1	2.7	6.6	-20.8	0.4	1.9
3. Gulf of Finland	8.0	0.7	9.6	58.1	-0.7	-1.2	-30.5	2.3	7.0	-14.6	1.0	6.4
4. Gulf of Riga	26.9	-3.5	-11.5	83.5	-4.8	-5.4	-37.4	3.7	9.0	-14.0	1.9	11.9
5. Baltic Proper	57.4	0.3	0.5	81.2	0.3	0.4	-8.0	0.1	1.2	-25.0	-0.2	-0.8
6. Danish Straits	46.8	3.9	9.1	7.4	1.4	23.3	-4.3	-0.3	-7.5	-15.6	-2.3	-17.3
7. Kattegat	29.8	-0.5	-1.7	-52.6	9.6	15.4	-33.3	0.6	1.7	-21.8	4.5	17.1
Total	42.8	1.2	2.9	60.2	1.7	2.9	-18.8	1.5	7.4	-20.4	0.5	2.4

Table 6.6 cont.

(0)	January 1977 (1)	(2)	(3)	February 1977 (1)	(2)	(3)	March 1977 (1)	(2)	(3)	April 1977 (1)	(2)	(3)
1. Bothnian Bay	-75.9	-2.4	-3.4	-42.2	-2.7	-6.8	-42.9	-0.5	-1.2	-87.0	-3.9	-4.7
2. Bothnian Sea	-46.6	0.6	1.3	-19.0	1.6	7.8	-21.7	0.4	1.8	-63.7	0.1	0.2
3. Gulf of Finland	-26.5	0.4	1.5	-48.4	-1.4	-3.0	-30.9	-1.2	-4.0	-82.6	-2.5	-3.1
4. Gulf of Riga	-12.3	1.8	12.8	-26.9	3.7	12.1	-15.8	1.2	7.1	-67.2	5.5	7.6
5. Baltic Proper	-20.0	0.1	0.5	-10.0	0.4	3.8	-16.7	0.2	1.2	-44.7	-0.1	-0.2
6. Danish Straits	-57.7	-3.9	-7.2	-71.1	-3.6	-5.3	-39.5	-5.3	-15.5	-53.3	-3.5	-7.0
7. Kattegat	-84.4	6.8	7.5	-43.2	3.4	7.3	-37.7	2.8	6.9	-42.7	2.8	6.2
Total	-34.9	0.6	1.7	-22.8	0.6	2.6	-23.1	0.5	2.1	-55.6	0.4	0.7

(0)	May 1977 (1)	(2)	(3)	June 1977 (1)	(2)	(3)	July 1977 (1)	(2)	(3)	August 1977 (1)	(2)	(3)
1. Bothnian Bay	-36.9	-1.9	-5.4	-18.8	-0.4	-2.2	-44.3	-0.4	-0.9	12.7	0	0
2. Bothnian Sea	-22.3	1.4	5.9	-34.1	1.9	5.3	-73.2	1.1	1.5	4.3	-0.4	-8.5
3. Gulf of Finland	-36.2	-1.3	-3.7	-11.6	0.2	1.7	-94.2	-3.0	-3.3	8.3	-0.3	-3.5
4. Gulf of Riga	-29.8	3.9	11.6	-19.3	2.3	10.6	-56.1	7.7	12.1	15.2	-1.5	-9.0
5. Baltic proper	-19.0	0	0	-8.4	0	0	-39.5	0.2	0.5	13.5	-0.6	-4.3
6. Danish Straits	-9.1	-1.2	-15.2	-1.7	0.2	10.5	17.8	3.0	20.3	-16.0	-1.8	-12.7
7. Kattegat	-1.5	0.1	6. 25	-13.9	0.6	4.1	-16.9	1.5	8.2	1.9	-0.1	-5.0
Total	-21.8	-0.4	-1.9	-14.5	1.0	6.5	-46.3	0.9	1.9	9.3	-0.9	-8.8

(0)	September 1977 (1)	(2)	(3)	October 1977 (1)	(2)	(3)	November 1977 (1)	(2)	(3)
1. Bothnian Bay	21.8	2.0	10.1	11.4	0.3	2.7	-28.6	-1.0	-3.6
2. Bothnian Sea	34.1	1.4	4.3	-23.9	-1.0	-4.4	-36.8	-1.0	-2.8
3. Gulf of Finland	-0.83	-0.03	-3.8	-55.4	-2.2	-4.1	-42.1	-1.5	-3.7
4. Gulf of Riga	2.7	-0.3	-10.0	-28.0	2.5	8.2	-25.1	-0.3	-1.2
5. Baltic Proper	56.7	-0.4	-0.7	5.0	-0.1	-2.0	2.6	0	0
6. Danish Straits	66.8	5.4	8.8	-3.5	-0.3	-9.4	-19.1	-1.1	-6.1
7. Kattegat	20.8	4.7	29.2	-38.2	4.8	11.2	-50.6	3.6	6.6
Total	42.2	1.0	2.4	-7.7	0.3	3.8	-15.2	0.5	3.2

that the analyses are carried out with the same carefulness as that observed when the PSY-data were processed. Here, the prominent point concerning the aerological method seems to be that the moisture fluxes were determined - from hand-analysed maps (!) - across the sections of polygons which were skilfully fitted to the coast- and bordering lines of the Baltic and its subbasins - instead of across polygon edges which just represent the connecting lines between existing aerological stations.

Also, the experiences gained by this investigation give rise to the conjecture that the components of the "atmospheric water budget" of the Baltic Sea could be successfully estimated for periods of less than a month, e.g., for ten days or a week.

After all, the evaporation data estimated for the PSY may claim a certain reliability: this is especially supported by the figures of Table 6.6. In fact, the accuracy of the evaporation data for the PSY for at least the Baltic in total and the large subbasins - Baltic Proper and the Bothnian Sea - may be assumed to arrive at about plus or minus five percent.

Notwithstanding the importance of efforts to determine the Baltic evaporation with a high degree of accuracy, it should be realized, however, that the 233 km^3 of water which evaporated from the Baltic from July 1975 until June 1976 represent not so much as five percent of the water released to the atmosphere by the ocean between 55^oN and 65^oN during an average year (see Baumgartner and Reichel, 1975).

Chapter 7.

VARIATIONS OF MEAN LEVEL AND WATER VOLUME OF THE BALTIC SEA

N.N. Lazarenko (USSR)

7.1. EARLIER STUDIES

Systematic investigations of mean sea levels in the Baltic were initiated early in the 19th century for various purposes (sea port projects, hydrographic surveys, studies of recent coastal vertical movements (RCVM), selection of gauge datum for a highly accurate adjustment of the national networks in the Baltic countries, selection of depth datum for sea charts, etc.)

In a fundamental monograph, Rudovits (1917) presented a detailed analysis of the Russian tide-gauge and mareograph network operation; a first attempt to analyse homogeneity of data on sea levels; and computed mean level for some of the gauges.

Among other scientists who investigated mean levels of the Baltic Sea are Blomqvist and Renqvist (1914), Madsen (1914), Bergsten (1925), Hela (1944, 1947), and Lisitzin (1953). Particular attention should be paid to the work of R. Witting (1918, 1945). He was the first to substantiate and evaluate the surface slope of the mean Baltic Sea level; he prepared one of the first maps of the recent movements of the sea shores, and he tried to combine the heights of the Baltic levelling polygon (BLP) with the position of the mean sea-level surface.

Mean sea level investigations made before World War II showed that the position of the surface of the mean sea level deviated from the geoid of the Earth and changed its height in time. Therefore, much efforts were concentrated around this problem considering its particular practical and scientific importance. In 1938-1940 the scientists of Leningrad collected data to adjust the Baltic levelling polygon system, with the aim at achieving a complete uniformity in sea-level records.

After World War II, work on the problem of the Baltic mean sea level continued in the USSR.

At the first stage of this work the following was implemented (Lazarenko, 1951):

- development of methodology for a reliable reduction of mean annual levels of the entire system of sea-level gauges since the start of observations till 1937 to complete uniformity

- compilation of the RCVM map of the Baltic Sea coast on the basis of observations before 1938, reduced to complete uniformity

- accurate geodetic adjustment of the BLP polygon system above the initial gauge datum of the Kronstadt gauge by the dynamic method (BLP, 1950) with the account of RCVM at the bench mark sites during the organization of national levelling networks in other countries

- compilation of the map of mean level position of the Baltic Sea surface for 1901-1937.

The second research stage included the following (Lazarenko, 1961):

- determination of mean daily, mean monthly and mean annual levels of the Baltic Sea for 1901-1940 from the results of observations at 26 level gauges reduced to complete uniformity

- compilation of monthly mean sea level maps both for average conditions for the period 1901-1940 and for extreme conditions

- investigations of the main peculiarities of sea-level fluctuations in the Baltic.

An attempt was made to reduce sea-level records before and after World War II to uniformity. This problem could, however, be solved only for some of the level gauges because of the short duration of post-war observation at that time.

7.2 IHP PROJECT ACTIVITIES

The third stage which took place within the framework of the international project on the water balance of the Baltic Sea had the following main results:

- sea-level records before and after World War II were produced to uniformity

- the RCVM map for the Baltic Sea coast was compiled on the basis of uniform level records

- mean monthly and mean annual sea levels and water volume increments for the five subbasins and for the Baltic as a whole were determined for the historic period (1951 - June 1975) and for the Pilot Study Year (June 1975 - December 1976)

- mean daily levels and water volume increments were determined for the Pilot Study Year (July 1975 - December 1976).

7.3 SEA-LEVEL OBSERVATIONS OF THE BALTIC

The network of sea-level gauges in the Baltic is older and of a higher density than any other network of the World Ocean: by 1 January 1977, 110 level gauges were under operation, out of which 68 sites were equipped with mareographs, while tide gauges were installed at the rest of the sites. Data are available on 8 level gauges for 1804-1811. For 20 level gauges data are available for 80-100 years.

The oldest sea-level gauges in the Baltic are: Kronshtadt, Tallinn, Klaipeda, Baltyisk, Nowyport, Kolobrzeg, Swinoujscie and Stockholm. Before 1869, sea levels were observed by tide-gauges only. In 1869, the first observations were made by a mareograph in Swinoujscie. The equipment of measuring sites with mareographs was most intensive in 1880-1900 and 1920-1940. In 1940, 60 sites with mareographs were in operation, In 1950, there were 48 mareographs only, while in 1970 the number of mareographs installed exceeded 68.

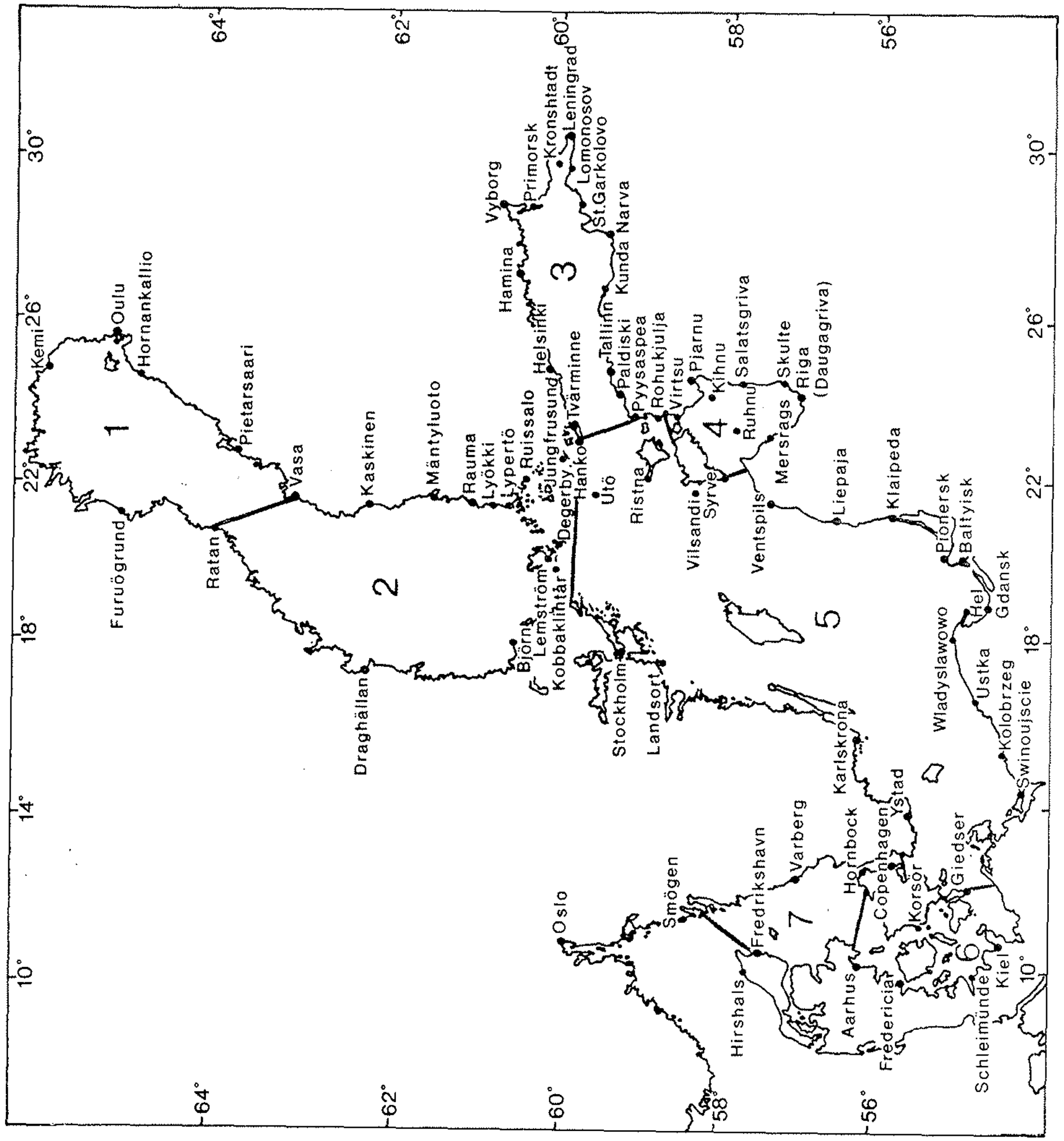
During World War I, and in particular World War II, many level gauges in the area of hostilities did not operate. Gaps in the observation series of such gauges were 4-6 years or even longer. In some cases gauges and benchmarks were destroyed and previous level records were lost. Hostilities and intensive ground water pumpage at the sites of level gauges in the post-war period (for example, in Tallinn) explain a disturbance in permanent bench-mark heights and cause great difficulties in the level records reduction to uniformity.

Fig. 7.1. shows the base network of level gauges with mareographs used to determine mean sea levels for the period 1951-1976.

7.4. REDUCTION OF SEA-LEVEL RECORDS TO UNIFORMITY

The reliability of sea-level results and in particular mean position of the sea-level, depends on the degree of uniformity in the basic records. Therefore, particular attention has been paid to the problem of reducing the basic data to uniformity. By this operation, maximum accuracy is provided for the comparison of level records of any gauge, and any observation period. Completely uniform records on sea levels have to satisfy the following conditions:

1 - observations made at the same time and dates
2 - no errors observed during observations and processing
3 - records reduced to a single epoch with the accuracy required
4 - records taken from the single zero point of the heights of national levelling networks strictly adjusted by the dynamic method.



7.1 Schematic base network distribution of level gauges with mareographs

The reduction of sea level data to uniformity is made in a strict and definite sequence, with every subsequent stage of the work closely related to the results of the previous stage.

At the start of the research, the problem was considered to satisfy the first uniformity condition - i.e. proper reduction of the basic records to uniform time and date. In the next step, the reduced records were analysed to satisfy the second uniformity condition, i.e. to eliminate observation and data processing errors and to reduce to uniform height datums during the observation period.

The third condition of uniformity - i.e. to reduce level records to a single epoch - could be satisfied only by the use of records which satisfied the first and the second conditions of uniformity. In the opposite case there might be errors in determining RCVM from the basic level records non-reduced to the first and the second conditions of uniformity.

The fourth condition of uniformity was satisfied on the basis of the Baltic levelling polygon operation (BLP, 1950).

For details of the reduction procedure inline with these four conditions, the leader is referred to the main project report on this element of the water balance (Lazarenko 1980).

The accuracy of data reduction to complete uniformity may be evaluated from mean root-square error m_o by the following equation:

$$m_o = \pm \sqrt{(m_1^I)^2 + (m_1^{II})^2 + (m_2)^2 + (m_3)^2 + (m_4)^2} \qquad (7.1)$$

where: m_1^I - accuracy of initial data reduction to uniform time;

m_1^{II} - accuracy of reduction to uniform dates;

m_2 - accuracy of excluding errors of observation and processing and reduction to a single height of every gauge datum;

m_3 - accuracy of reduction to a single epoch;

m_4 - accuracy of bench mark height reduction to the single initial datum of the Kronshtadt gauge in the BLP system (1950)

Table 7.1. gives m_o values computed by equation (7.1).

Table 7.1. Accuracy of data reduction

Levels	Accuracy of height determination in the BLP system, m_o		
	I*	II*	III*
At particular dates	± 2-4	± 3-5	± 4-6
Mean daily for 6 dates	± 1-3	± 2-4	± 2-5
Mean daily for 24 dates	± 1-3	± 2-4	± 2-5
Mean monthly	± 1-3	± 2-4	± 2-5
Mean annual	± 1-2	± 1-2	± 1-3
Mean long term	± 1-2	± 1-2	± 1-3

* I - heights obtained by direct accurate levelling above bench mark stations entering into BLP system;

II - heights obtained by levelling from the bench marks of the BLP system by unclosed levelling lines of different lenght (up to several dozens of kilometers, e.g. Hanko);

III - heights obtained by water levelling.

7.5 SEA -LEVEL SURFACE

The methods of control and reduction provided completely uniform sea-level data and made possible for a new trend in the research on a sea-level fluctuations - i.e. to study the dynamics of spatial changes in the sea surface shape.

7.5.1 Sea-level surface reliability

The reliability of maps of sea-level surface depends on a number of factors:

- representativeness of level gauge location from the point of view of the whole sea surface
- peculiarities of basic forms of sea-level surface fluctuations
- time of sea-level averaging for map compilation.

Level gauges in the Baltic Sea are mainly distributed along the coast (Fig. 7.1) and they provide incoherent information on the regime of level fluctuations in the open sea. The maximum representativeness is provided by the observations on small islands of the Åland archipelago, at the level gauges of Degerby, Lemström, Kobbaklintar and Utö. It is reasonable to mention observation sites at Björn, Landsort, Öland-Norra-Udde, Draghällan and Karlskrona, located along the western (Swedish) coast on small islands 5-20 km far from the continent, and the stations at Kronshtadt, Gogland, Ristna, Jungfrusund, Hanko, Vilsandi, Syrve, Ruhnu, Hel, Giedser and Korsör located either on islands or on peninsulas and shoals extending far off into the open sea.

When observation records from other stations are used it is necessary to take into account some specific features of their location. For example, stations in the river mouths may overestimate water levels during floods compared with the levels in the open sea.

7.5.2 Extreme monthly sea-level surfaces

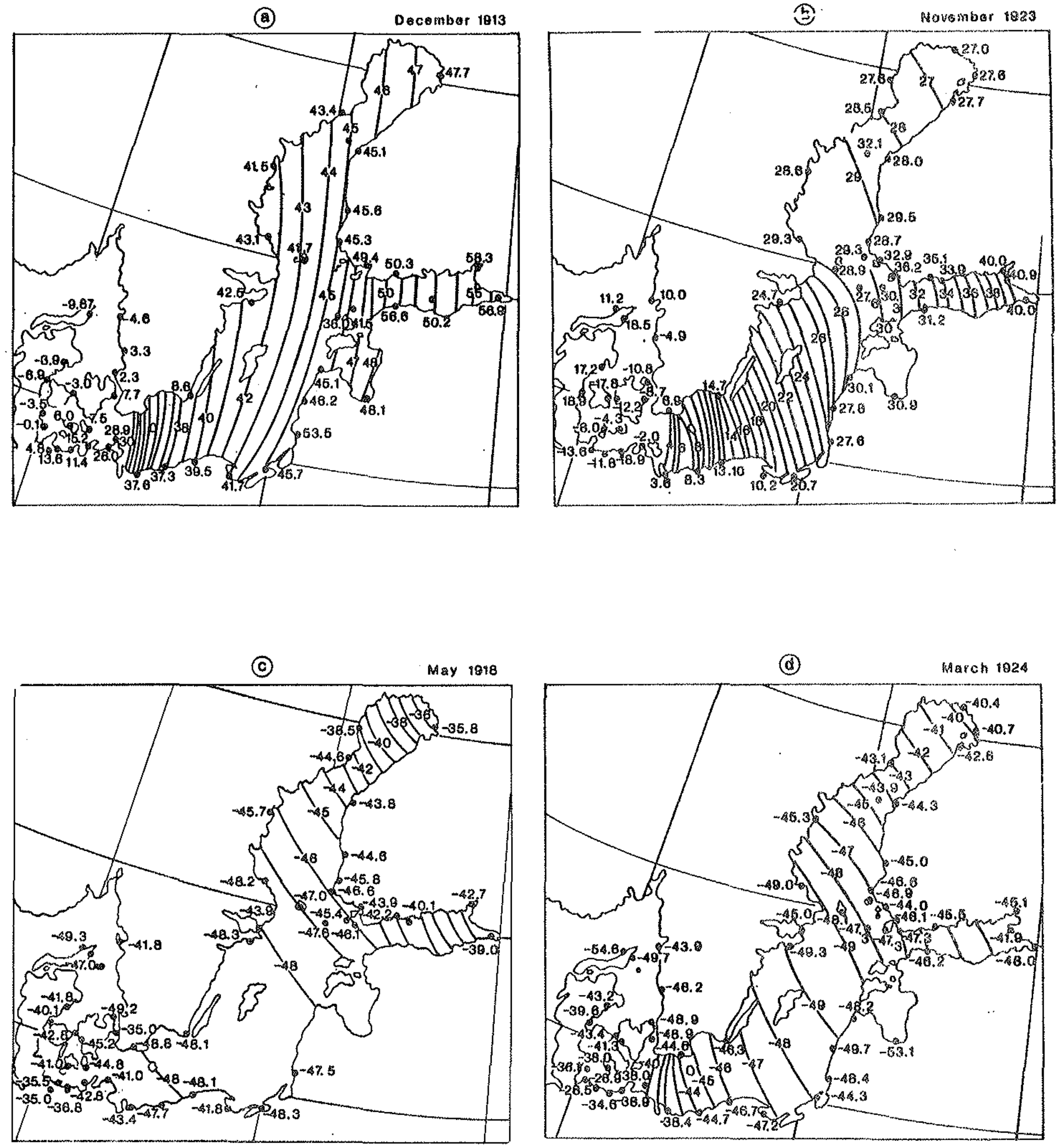
Fig. 7.2 a-d shows the maps of the surface position of mean monthly extreme sea levels for 1901-1940. In December 1913 the observed mean monthly level was the highest during 40 years of observations (H_m = 43.1 cm) (Fig. 7.2a). In November 1923 (Fig. 7.2b) a high mean monthly water level was observed (H_m = 24.7 cm). In both cases the gauge at Utö and Kobbaklintar in the central part of the sea do not show any deviation from the general position of the mean level surface of the sea. A similar situation is observed for the lowest mean monthly water levels in May 1918 (H_m = -46.8 cm) and in March 1924 (H_m = -46.7 cm), see Fig. 7.2c.

In case of a low water level, however, almost a horizontal mean level surface in the central sea is observed. It is evident from Fig. 7.2c that the mean level surface from the Ventspils - Landsort line to the Ustka - Ystad line deviates from mean levels at individual gauges quite insignificantly (± 0.5 cm) and its total height is 48.0 cm.

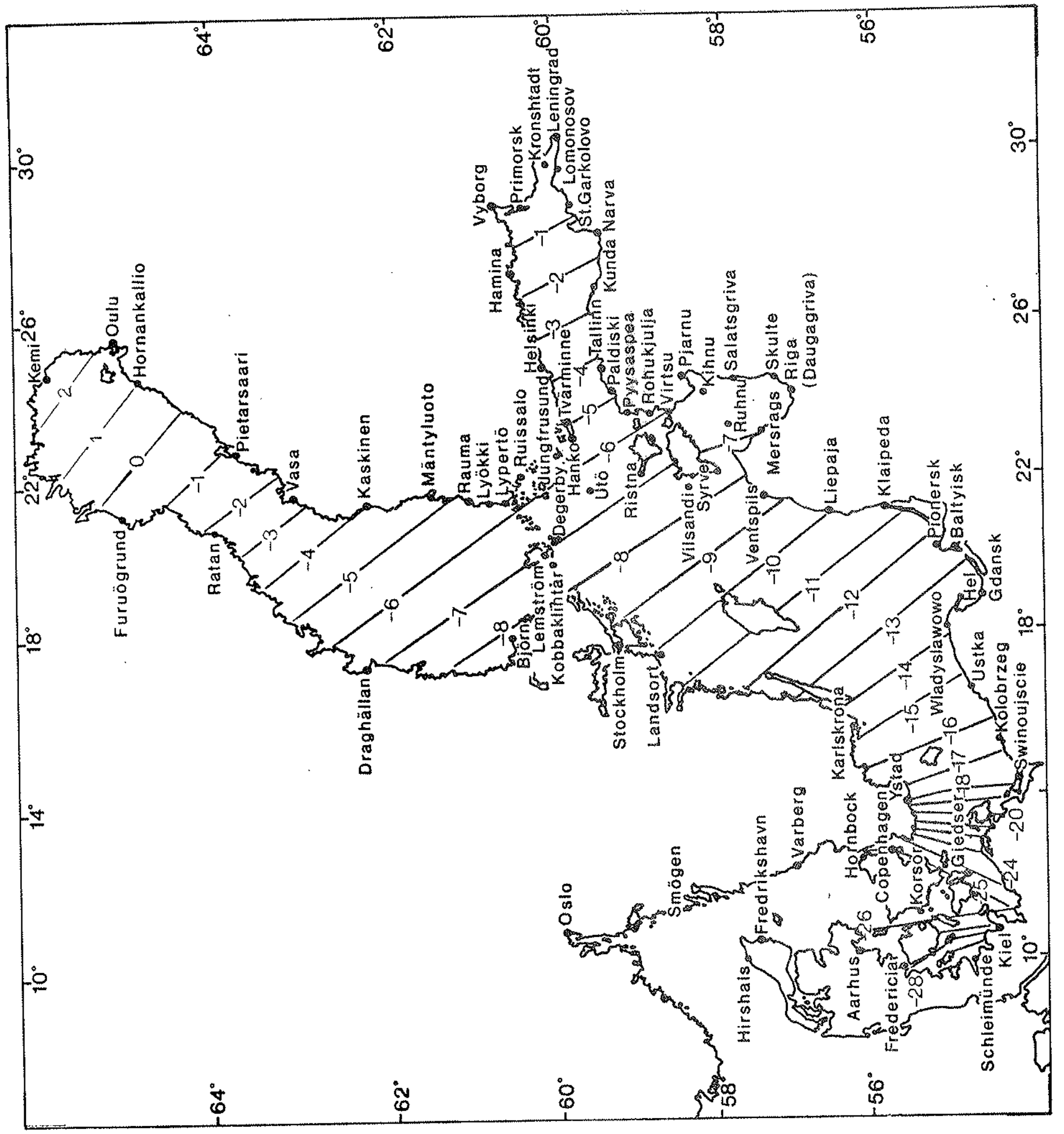
7.5.3 Long-term average sea-level surfaces

A map of mean sea level surface for 1901-1937 is given in Lazarenko (1951). Mean sea levels for 1901-1937 for all the gauges (except Yxpila and Pietarsaari) obtained independently above the single zero height of the Kronshtadt gauge in the BLP system are in a good agreement (BLP, 1950). Deviations from mean level at some points are within ± 1.0 - 2.0 cm and may be explained by the effects of river runoff, prevailing winds, etc. For example, gauges on the coasts with the dominant eastward winds, in the heads of gulfs and bays as well as in river mouths give mean levels by 1.5 - 2.5 cm higher. On the contrary, gauges at the sites with prevailing westward winds show mean levels by 1-2 cm lower.

The nature of the surface slope of the mean levels in the proper sea, in the gulfs and in straits is different. The mean level surface slope from Kemi to Ystad is 18 cm, while from Kronshtadt to Ystad it is 16 cm. The slope in straits is across the straits and it is up to 4-5 cm, while in Kattegat it is up to 7-8 cm. In the Gulf of Viborg the slope is several times larger than in the Gulf of Finland.



7.2 Maps of surface position of mean monthly extreme sea levels for 1901 - 40



7.3 Map of surface position of the mean water level for 1951 - 76

The mean water level for 1951-1976 (Fig. 7.3) is practically similar to the map for 1901-1937 (Lazarenko, 1951). Inadequate information, however, for Denmark and partially for FRG, the straits and Kattegat, makes it impossible to compile a map as detailed as that for 1901-1937. Both maps are quite accurate though. It is possible to assume that the total surface slope of the mean sea level is 18-20 cm and the error does not exceed ± 1-3 cm.

7.5.4 Water volume increments

With the area of the Baltic Sea (areas 1-5) accepted to be 392,228 km^2, according to U. Ehlin, water volume increments for a sea-level change of 1.0 cm, are 3.92 km^3.

Daily increments of mean Baltic Sea level for 1926-1935 are subject to variations within ± 1 à 3 cm on the average, and may attain ± 8 à 10 cm/day in extreme situations (Hela 1944). Such daily sea level increments correspond to daily sea volume increments from ± 3.9 à 11.8 km^3 up to ± 31 à 39 km^3. In the latter case, the water volume increment attains ± 7 à 9 % of the annual water discharge from the whole drainage area, or 45 à 50 % of the annual discharge of the Neva River.

7.6. RESULTS

7.6.1 Mean sea level for the period 1951-70

The methodology for mean sea-level computation for the sea or its specified areas, described in Lazarenko,(1961), made it possible to compute mean monthly and mean annual sea levels for the five subbasins and for the Baltic as a whole for 1951-1976. A comparison was made with mean monthly and annual levels for 1901-1940, computed from uniform observations at the base network of sea level gauges. The comparison showed that, for Stockholm, for instance, mean deviations of annual gauge levels from annual levels of the sea were ± 0.5 cm, and the maximum deviations attained ± 1.5 cm. For Utö this deviation is ± 0.6 cm and ± 2.0 cm respectively.

Better correlation was obtained by using mean sliding values for 11 years for Utö and the Baltic Sea. Hence, mean deviation of those levels for 1901-1940 was ± 0.1 cm only, while the maximum deviation was ± 0.4 cm.

7.6.2 Water levels in the five subbasins

Table 7.2 contains some information (for comparison) on the Baltic Sea and on its 5 areas.

The highest annual water level for individual sea areas and for the sea as a whole during 1951-1976 was observed in 1967, the lowest one in 1960. The maximum level fluctuations were in the Bothnian Bay (27.7 cm), and the minimum level fluctuations in the Baltic proper (17.7 cm).

The highest mean monthly level was observed in January 1975, except the Baltic proper, where it was fixed in January 1976.

The lowest mean monthly levels were observed in three areas and for the whole sea in March 1960, and in the Gulfs of Finland and Riga in December 1959.

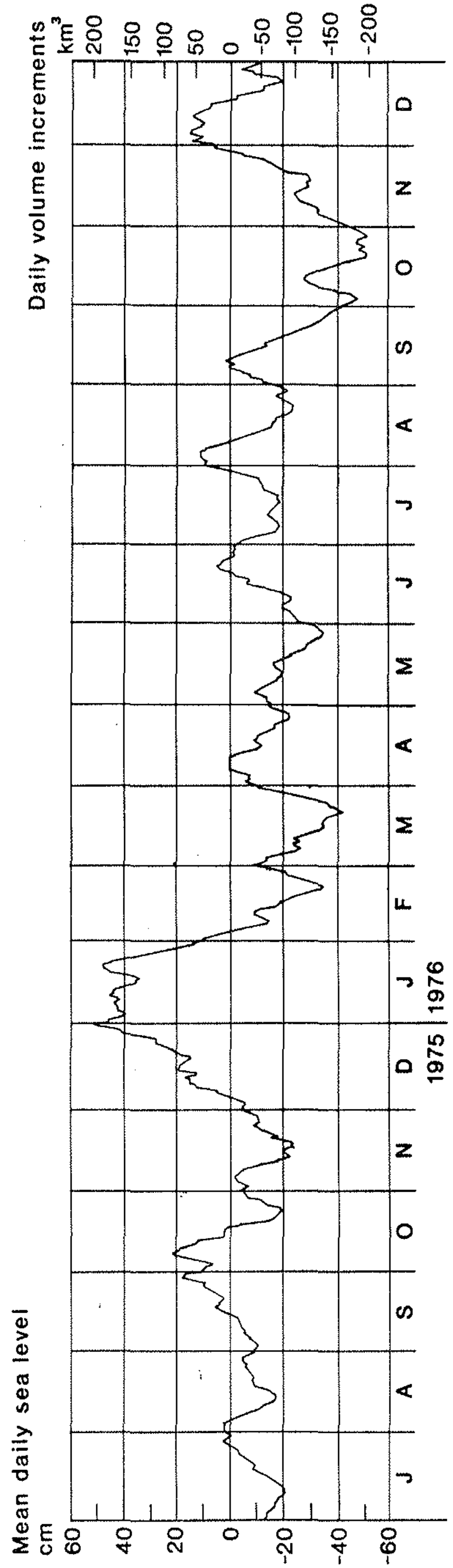
7.6.3 Sea-levels during Pilot Study Year

Mean daily levels for July 1975 - December 1976 were computed for the same level gauges, for which mean monthly and annual levels were computed for 1951-1976.

For Poland and Finland mean daily levels were used on the basis of mareograph data obtained 6 times a day; at the other gauges mareograph data were obtained 24 hours a day. At the sites equipped with tide-gauges, measurements were made 4 times a day.

Fig. 7.4 shows chronological variations of mean daily sea levels for July 1975 - December 1976. During a year and a half, 13 main sea level waves were observed, and secondary waves were marked on this background. The most significant wave took place during the period 17 November 1975 - 23 February 1976 (98 days). Water level rise lasted from 17 November, when the mean daily level was 27.37 cm, till 31 December when mean daily level attained 49.54 cm. This was the maximum level attained for the whole period of computation. Consequently, mean sea level for 44 rose by 76.91 cm. Average rate of mean sea level increment for the whole period was 1.98 cm/day. During the period 9 till 20 December the level did not rise. Between 20 and 31 December the level attained its maximum. The rate of level rise for this period was 3.7 cm/day, and on 27-28 December the daily level increment was 7.77 cm/day. When the maximum level was attained, during 31 December - 22 January 1976, mean daily levels of the sea varied within 49.54-32.16 cm. During 22 January - 9 February (19 days) the sea level fell from + 46.93 cm to - 15.78 cm, i.e. by 62.71 cm, corresponding to a mean fall of the level by 3.48 cm/day.

The maximum amplitude of mean daily levels for the period from July 1975 to December 1976 were 101.15 cm.



7.4 Chronological variations of mean daily sea levels during Pilot Study Year

Table 7.2

Water level extremes 1951 - 76 in different subbasins

	Period (years)	Mean long-term level, cm	Annual level, cm: highest (year)	lowest (year)	Max.	Monthly level, cm: highest (year)	lowest (year)	Max.
1. Bothnian Bay	1951-1976	0.6	14.4 (1976)	-13.7 (1960)	27.7	64.0 (Jan.1975)	-42.3 (Mar.1960)	106.3
2. Bothnian Sea	-"-	-6.0	6.6 (1967)	-16.7 (1960)	23.3	48.8 (Jan.1975)	-48.7 (Mar.1960)	97.5
3. Gulf of Finland	-"-	-3.7	9.7 (1967)	-15.6 (1960)	25.3	54.7 (Jan.1975)	-51.3 (Dec.1959)	106.0
4. Gulf of Riga	-"-	-5.0	6.2 (1967)	-18.4 (1960)	24.6	47.5 (Jan.1975)	-58.2 (Dec.1959)	105.7
5. Baltic Proper	-"-	-11.3	-0.9 (1967)	-18.6 (1960)	17.7	35.3 (Jan.1975)	-49.0 (Mar.1960)	84.3
Baltic Sea (Regions III-V)	-"-	-8.4	3.4 (1967)	-17.4 (1960)	20.8	42.0 (Jan.1975)	-48.2 (Mar.1960)	90.2
Baltic Sea (Regions I-V)	1901-1940	-8.2	2.1 (1903)	-17.7 (1939)	19.8	43.1 (Dec.1913)	-46.8 (May 1918) (Feb.1929) (Mar.1923)	89.9

7.6.4 Water storage changes in the five subbasins

Based on the sizes of individual subbasins and the Baltic as a whole, according to Ehlin et al (1974) and as recommended at the fifth meeting of experts on the water balance (cf. Main Table 1), water volume increment were determined from the following equation:

$$\Delta W_M = \Delta Hcp \cdot F \qquad (7.2)$$

where: W_M - water volume increment for a certain time interval;
Hcp - sea level rise for that interval;
F - area of the sea surface.

Results on mean monthly water volume changes for the five subbasins during the period 1951-70 are given in Main Table 9.

The interannual fluctuations during the period 1951-75 are shown in Fig. 7.5 for the entire Baltic and the five subbasins inside the Danish Straits.

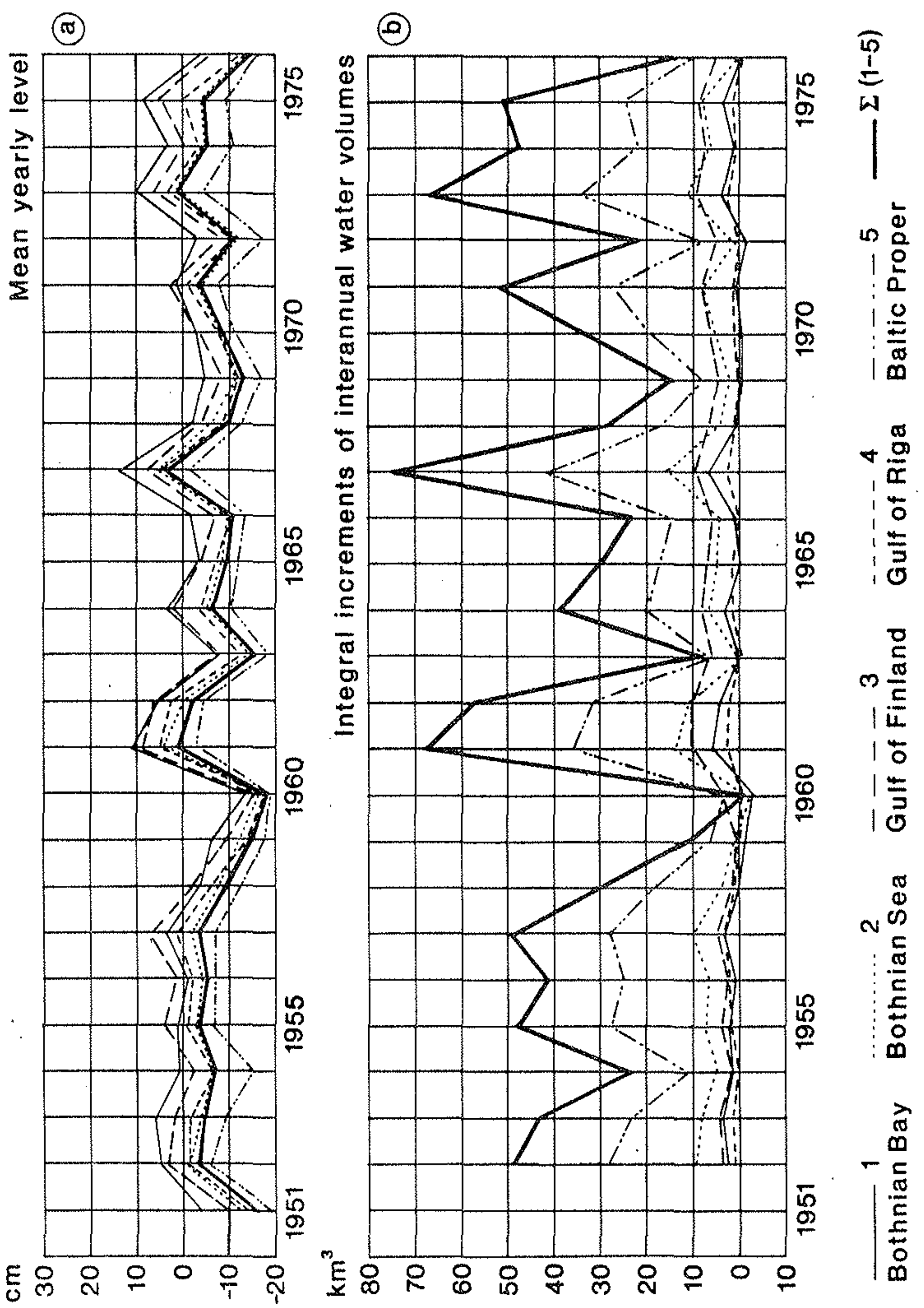
Variations of mean daily water volume increments (in km^3) for July 1975 - December 1976 are shown in Fig. 7.4 (the right scale).

Based on the cross-section areas of the Danish Straits according to Hela (1944) (80.10^3 m^2 for Öresund, $255 \cdot 10^3$ m^2 for Great Belt and 16.10^3 m^2 for Little Belt) the discharges corresponding to the obtained daily sea volume changes during the Pilot Study Year could be estimated (Table 7.3). Daily volume increments, exceeding 30 km^3 were obtained 6 time during that period or in 1.1 % of all the cases of daily intervals observed.

Table 7.3

Largest daily sea volume changes during Pilot Study Year and the corresponding discharges through Danish Straits

Nos	Day	Daily increment, km^3	Discharge m^3/s	Mean velocity in straits m/s
1	from 7 to 8 December, 1975	31.64	368040	1.04
2	from 27 to 28 December, 1975	30.54	351000	1.00
3	from 30 to 31 December, 1975	31.05	351351	1.01
4	from 26 to 27 September, 1976	-31.72	368550	-1.05
5	from 1 to 2 December, 1976	36.60	442260	1.26
6	from 27 to 28 December, 1976	33.41	386100	1.10



7.5 Mean yearly levels a) and integral increments of interannual water volumes b) of the whole Baltic and its subbasins for the historical time period 1951 - 76.

The analysis, made by Hela (1944) on water velocities in the Danish Straits during maximum daily discharges for the period 1926-1935, shows that water discharges during the Pilot Study Year are close to maximum possible discharges. Out of the 6 cases of major water transport, only one (26 to 27 September 1976) was observed during a phase of water volume decrease, i.e. release of stored water.

Daily increments from 20 km^3 to 28 km^3 were registered 34 times or in 6.2 % of cases. During those cases, mean flow velocity varied between 0.66 m/s to 0.92 m/s and discharges through the Straits from 232000 m^3/s to 323000 m^3/s. Out of 34 cases, water inflow to the Baltic Sea from the North Sea was observed 23 times, and water outflow to the North Sea 11 times.

The most intensive fall of sea level occurred during the period 22 January - 9 February, when the water level fell by 62.75 cm during 18 days, corresponding to a release from storage of 246 km^3.

During 24 hours, water discharge to the North Sea was on the average 13.72 km^3/day or 158000 m^3/s.

From 19 to 29 November, 1976 water inflow to the Baltic Sea was 145 km^3 for a 10-day period, and the mean sea level rose by 33.7 cm. On the average water inflow amounted to 14.5 km^3/day or 168000 m^3/s.

An even more intensive water inflow to the Baltic Sea occurred during the period 26-31 March 1976 (98 km^3 in 5 days, or on the average 19.6 km^3/day or 228000 m^3/s.

7.7. CONCLUSIONS AND PROPOSALS

The investigations of mean level and water volume changes in the Baltic Sea gave the following results:

- further methodological development for reducing water level records to complete uniformity;
- computation of mean monthly and annual levels of the Baltic Sea for 1951-1976, and mean daily levels and water volumes of the Baltic for July 1975 - December 1976 on the basis of uniform records;
- preparation of a realistic basis to compute actual changes of mean levels and water volumes for different time intervals (24 hours and longer) to provide operational water balance of the Baltic;
- demonstration of hydrosynoptic sea level maps with daily, monthly, annual and long-term surfaces of the mean sea level to study the regime of water level fluctiations.

Based on the results provided the following proposals are made:

- the Baltic countries should discuss the possibility to develop a uniform methodology for organization, collection and processing of records on the Baltic Sea levels which would satisfy the conditions of a complete uniformity of level records;
- it is reasonable to discuss a new levelling of the BLP system by the dynamic method (BLP-2) on the basis of results of relevelling of the national levelling networks which form the polygon, completed after World War II;
- it is recommended to study the possibility for a compilation of operational hydronynoptic maps of the level surface position; to this end it is reasonable to organize additional level gauges on islands and in the open sea;
- it is recommended to study the possibility of a cooperative programme of continuous operational monthly computations of the water balance of the Baltic Sea.

Chapter 8

WATER EXCHANGE THROUGH THE DANISH STRAITS

Torben Schelde Jacobsen (Denmark)

8.1. ON THE CONCEPT OF SEAWATER EXCHANGE

The term "water exchange" has been used with various meanings in the past decades of investigation of the water renewal of the Baltic. A short discussion of the methods employed and their interpretation is considered to be relevant.

8.1.1. Early studies

As earlier indicated the Baltic has a positive water balance, i.e. on the average the amounts of fresh water received by river inflow and precipitation exceeds the loss by evaporation. This surplus amount is denoted Q_o.

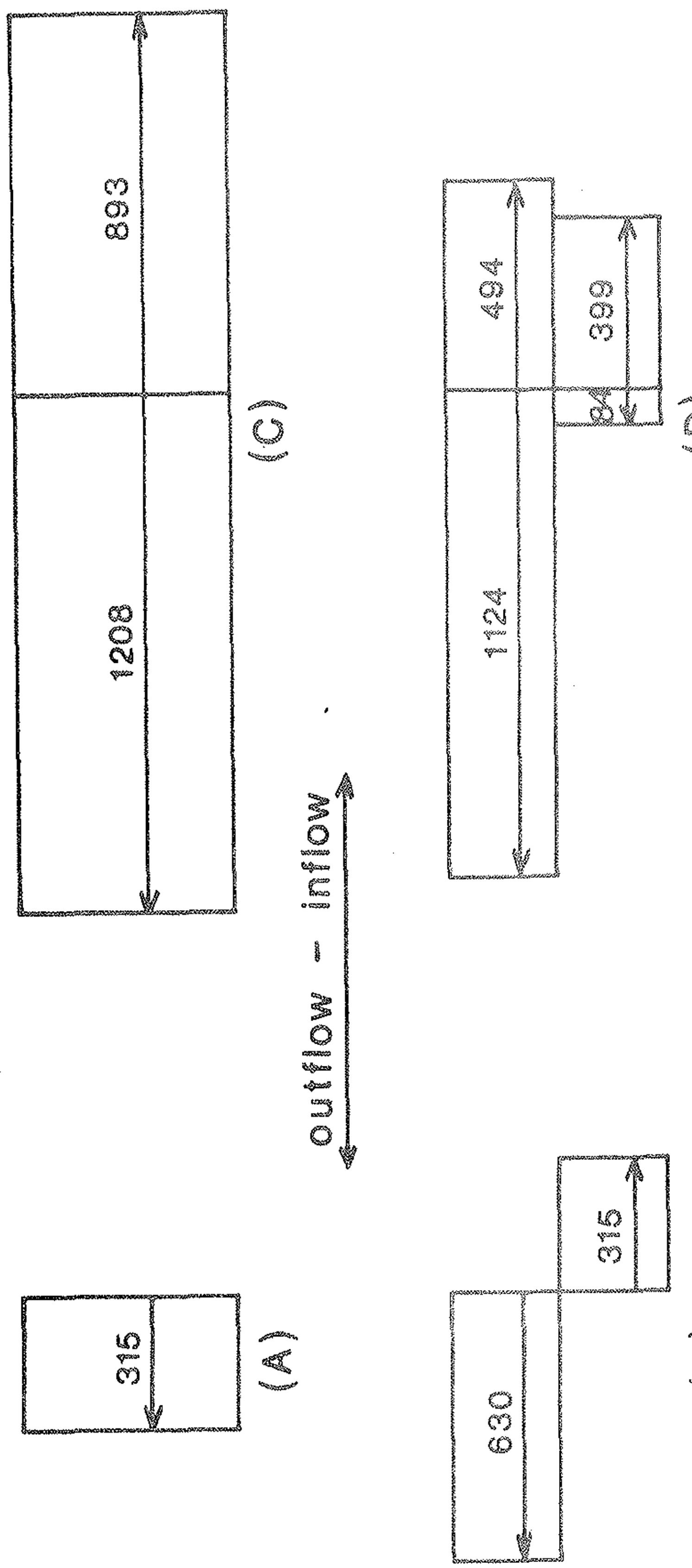
If the Belt Sea and the Kattegat are included in the Baltic, Q_o is about 8 % higher than without these areas. If only the Belt Sea is included, the rise is 2 %.

For the Baltic without the Belt Sea and the Kattegat, the mean value of Q_o is about 14,000 m^3/s, assuming that evaporation and precipitation balances in the annual budget. The basin area is taken as 273,000 km^2 and the volume as 201,900 km^3, (Ehlin et al., 1974). Q_o is found to make up 2 % of the volume over a year, corresponding to a sea level rise of 1.2 m.

The first studies on the water balance of the Baltic were mainly concerned with estimation of Q_o (Krümmel, 1907, Keller, 1911, and Spethmann, 1912). Their estimates differ not much from more recent studies.

In order to achieve more insight in the distribution of flows in the Transition Area, Knudsen (1899, 1900) decomposed the flow into an upper layer of outflowing brackish light Baltic water and a deep inflowing layer of higher salinity of Atlantic origin (Fig. 8.1.B). This is to be understood as average conditions. For the section Gedser-Darss, Knudsen proposed an outflowing upper layer transport of $Q_1=2Q_o$, and a deep layer inflowing transport of $Q_2=-Q_o$, utilizing conservation of mass and salt in steady state conditions.

Moving from the Gedser-Darss section towards the mouth of the estuary, i.e. through Fehmarn Belt and the Great Belt, the mean discharge of the upper layer increases due to entrainment from the bottom layer. The net loss of water from the bottom layer is



8.1 Different models for water exchange through Danish Straits. Explanation in text. Inflow and outflow in km^3/yr

compensated for by a corresponding increase in the mean rate of inflow towards the estuary mouth. The size of the mean flows in the two layers, exemplified for Gedser-Darss in Fig. 8.1 b will thus both become larger if a similar section is constructed, say, in the Great Belt.

It was early recognized that Q_o does not leave the Transition Area undisturbed. Tidal excursions are present in the Belt Sea, although not very pronounced. The amplitude of the most prominent component, the semi-diurnal tide M_2, is reduced from 12 cm at Frederikshavn to about 4 cm at Gedser. Meteorologically forced oscillations with duration from a few days to some weeks cause, however, a considerable water exchange. It was also observed that the mean current in the deeps of the straits is directed towards the Baltic due to the baroclinic pressure field created by the outflowing light water.

The Sound and the Belts are channels through which the barotropic part of the flow is determined by the sea level difference between the Kattegat and the western Baltic. Westerly winds cause inflows, and easterly winds outflows. Outflows also occur during calms because of the positive water balance. Therefore it is not the local wind but the large scale wind field which determines the direction of the flow, not directly through the windstress, but indirectly by means of the piling up of water, and the creation of barotropic pressure gradients. This is why the surface current often runs in opposite direction to the local wind. The flow in the sound and the Belts is mainly frictionally balanced, (Wyrtki, 1954 Pedersen, 1978; Jacobsen 1978, 1980).

8.1.2. Studies based on lightship observations

Jacobsen (1925) tried to relate the exchange of water to surface observations of the current at the lightships in the Transition Area. He suggested that the total exchange Q is proportional to the surface current at Brogden lightship in the Sound. Wyrtki (1954) improved the method by estimating the exchange through the Great and the Little Belt by means of current observations at Halsskov Rev lightship in the Great Belt. He found, however, that the coefficient of proportionality between the surface current at Halsskov Rev and transport Q_B through the Belts varied by a factor of two between different periods.

Soskin (1963) regarded the in- and outflow periods separately and related the exchange of water in the Belts to the mean value of current observations from the lightships Halsskov Rev, and Lappegrund in the northern Sound. He found a linear relationship for outflow and a non-linear for inflow. However, the mean outflow computed from these relations became suspiciously low, even negative, in the beginning of the 40's Both Wyrtki and Soskin estimated the exchange through the Sound with the formula proposed by Jacobsen (1925), and both authors calibrated their coefficients for the Belts against the water balance equation of the Baltic.

Assuming that the lightship observations, which are carried out mainly by visual estimation, contain no errors which are correlated to the direction of the flow, two explanations are proposed for the discrepancies encountered:

1) The strong alternative inflows and outflows caused by atmospheric forcing leave the net outflow Q_o to be measured as a small difference between large volumes of in- and outflowing water. The existence of even a small horizontal residual circulation in the upper layer, where the lightship is located, will invalidate the assumption of proportionality between the long term mean value of the observed current and the corresponding net flow.

   This residual circulation may arise from the density structure, the Coriolis force or become inducted by the local wind. The lighsthip observations are sensitive to the wind effect, as they deal only with the current in the upper few centimetres.

   Wyrtki was aware of the possibility of such a bias in the computed net flow, and Soskin tried to avoid it by establishing different relationships for in- and outflow.

2) The baroclinic (density driven) component of the water exchange represents a vertical residual circulation. The surface current can therefore never describe the average conditions in the deep layer.

In the discussion above, the intricate problem of reducing the surface current vector to a scalar quantity has not been discussed Although the currents in the straits are distinctly bi-directional, the current direction can assume all values. Jacobsen (1913) defined a scalar quantity, the "resulting mean current", as the numerical value of the in-going vector's sum subtracted from the outgoing ditto, the difference to be divided by the total number of observations. The two distinct minima in the directional distribution served to define the sectors of in- and outflow. The author has derived scalar currents suitable for exchange studies by projecting the current vector on a direction which is in reasonable accordance with the directional distribution, and the geometry and orientation of the strait. The different methods are, however, almost certain to yield different results with respect to long term averages.

8.1.3. Time variability of the seawater exchange

The coefficient of variation for the exchange, C_v (Q), is the ratio of the standard deviation to the mean value

$$C_v \ (Q) \equiv SD(Q)/\langle Q\rangle \qquad (8.1)$$

Results from the project on the water balance of the Baltic have shown that C_v varies in the range from 8 to 10, when daily averages of the total exchange in the Transition Area are used

as input data. It is therefore not surprising that attempts to extract the mean outflow from lightship observations have failed on many occasions.

Four ways of interpreting the sea water exchange are shown in Fig. 8.1. The first (A) shows the concept of a mean outflow equal to Q_o and averaged over such a long time that the importance of the meteorological short term forcing vanishes. No information is obtained about the density driven currents in the Transition Area, and the result is only little affected by displacement of the section chosen, because no large rivers have their outlet in the Belt Sea.

In (B) the decomposition into mean outflow in the upper layer and inflow in the deep layer below the density interface is demonstrated. This is Knudsen's approach, but because of entrainment the magnitude of the resulting flows is sensitive to the choice of the section. The sum of the two flows should equal the net average outflow Q_o.

Fig. 8.1A shows a decomposition of the vertically averaged flow into total outflow and total inflow, which are a measure of the barotropic pulsations. The density stratification is thus entirely ignored. Results of this type can partly be inferred from the changes of the sea level in the basin. Lisitzin (1967) and Soskin (1963) followed this approach and found the sum of inflowing and outflowing water to be 3000 and 2850 km^3 respectively on a yearly base. Their computations are, however, sensitive to the position of the section, and also to the kind of time averaging performed. It is clear that if the original flow data are averaged over a sufficiently long time before the separate sums of inflow and outflow are formed, one ends finally up with just a mean outflow of Q_o.

Finally, one might describe both the effect of the average baroclinic field and the barotropic oscillations as suggested in Fig. 8.1D. Again, the choice of the section and the averaging performed affect the results.

The illustrations A-D have been exemplified with numerical values for the section Gedser-Darss with the following assumptions:

Q_o is taken as 450 km^3/year and 70 % of the water exchange of the Baltic is assumed to take place through this section. The sum of the total amounts of in- and outflowing water is 3000 km^3/year (derived from daily averages) and the mean vertical distribution of the exchange at the section follows the ideas of Knudsen, i.e. the mean outflow in the upper layer is 70 % of $2Q_o$. The partition of the total flows in Fig. 8.1D (sum of out- and inflow) between the upper and lower layer has been taken as the ratio of the areas above and below the mean halocline depth at 11 m. These areas are 30 x 10^4 and 9 x 10^4 m^2 respectively (Wyrtki, 1954).

In the older literature on the water exchange a distinction is made between inflowing water, outflowing water and net flow, while in modern analysis of geophysical time series it seems to be more appropriate to describe the process by its mean value, variance, and spectral characteristics. Higher moments of the process can be included if there is a significant deviation from a normal distribution. The usefulness of the former concepts should, however, not be overlooked, as the direction of the flow is of importance for the displacement of hydrographical fronts and for the associated environmental effects.

8.1.4. Some methodological conclusions

It is concluded that in an estuary having a high time variability of the flow one should attempt to describe the water exchange by the following methods:

1) The variability of the barotropic (not vertically resolved) exchange is measured in the channel. A few instruments or a suitable flow model will suffice as the net long term average flow is not to be determined.

2) The net long term average outflow is determined from the hydrological characteristics of the upstream basin.

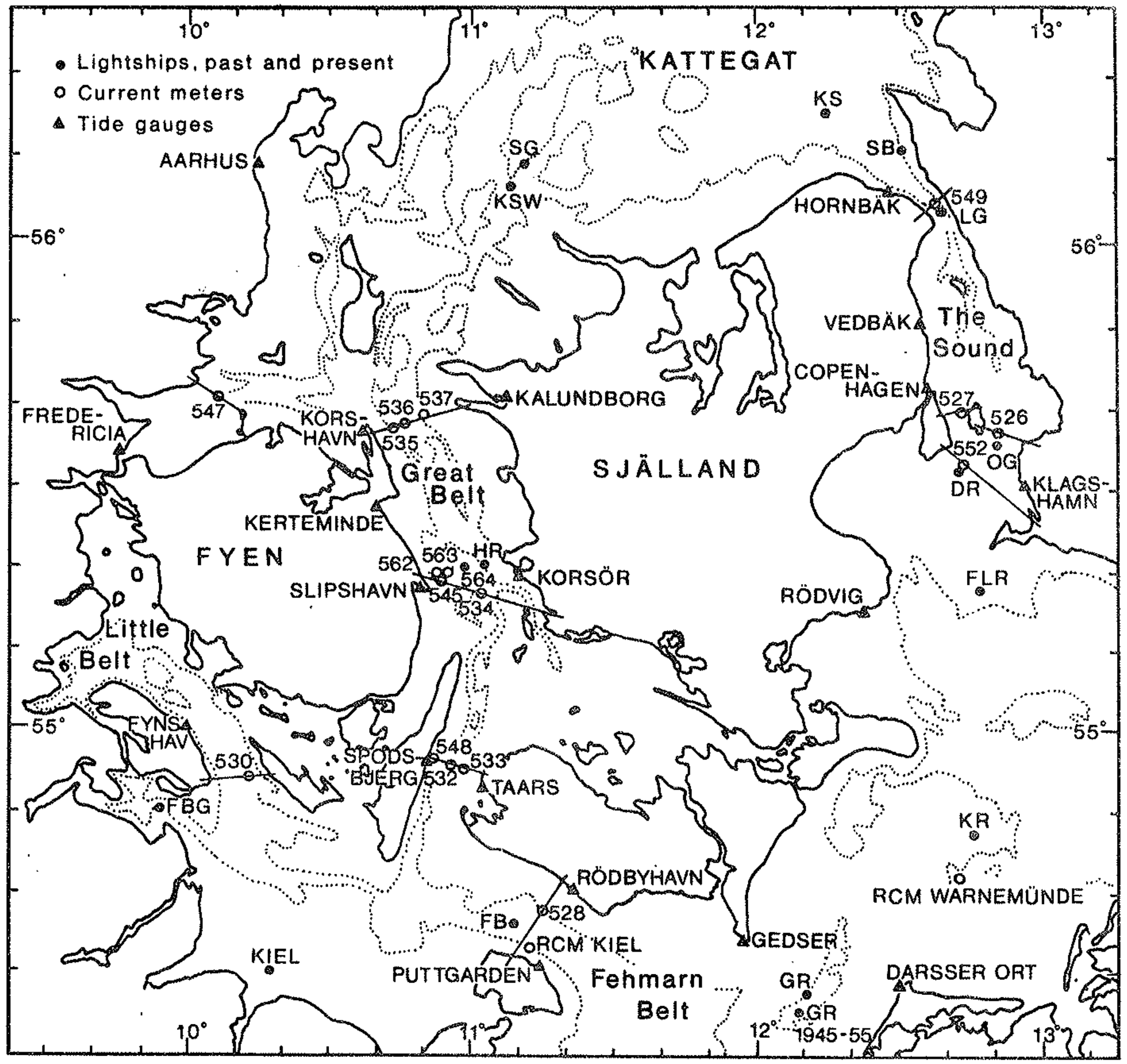
3) The baroclinic mean flow systems are determined from the salinity distribution.

Attempts to describe the variability of the flow in the channel from basin measurements or to measure the long term net outflow directly in the channel are both certain to meet with difficulties. In this chapter only oscillations in the period ranging from a few days to approximately one month will be examined. These oscillations are called "meso-scale oscillations".

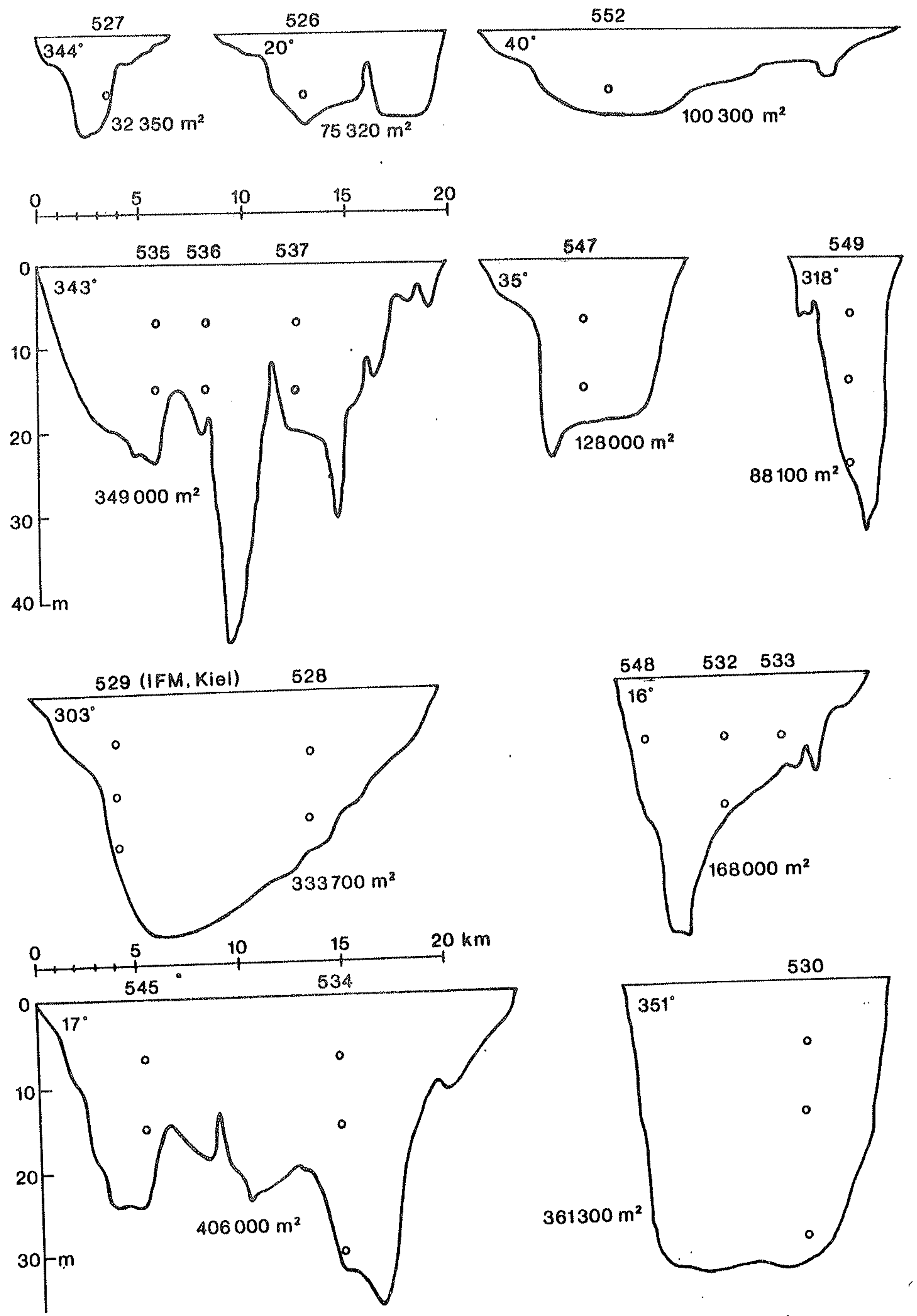
8.2. FIELD MEASUREMENTS OF THE SEAWATER EXCHANGE

This section deals only with the Danish measurements which took place during the Pilot Study Year in the Sound and the Belt Sea. An independent investigation in the Kattegat was carried out by the Swedish National Board of Fisheries (Szaron, 1979). Previous estimates and models of the exchange have been reviewed by Jacobsen (1980).

In August 1974 the Belt Project, sponsored by the Danish Ministry of the Environment, the National Agency of Environmental Protection, placed subsurface moorings with Aanderaa current meters in a number of sections, see Fig. 8.2., 8.3. The stations shown are the maximum number at any time. The depths shown in Fig. 8.3 are the recording depths aimed at, but on many occasions the instruments have actually been placed somewhat deeper, 1-2 metres. From month to month variations in the actual recording depth within 1-2 metres have occurred when the instruments have been replaced in the moorings.



8.2 Map over current meter sites



8.3 Distribution of current meters in the respective sections

A detailed description of the measurements has been prepared for the final reporting of the Belt Project. It includes a graphical representation of the current meter data (current, salinity, temperature, and depth of the instrument), reduced to daily mean values (Kruse, Jacobsen and Nielsen, 1980).

8.2.1. Calculation of the sea water exchange

No attempt has been made to use theoretical models of the velocity profiles in order to improve the calculations. There exists at present no theory on stratified non-steady flow which can be of help with the limited observational material available. Therefore the simplest possible box model was applied. It is realized that the strong vertical mean shear in the horizontal velocity field will make the resultant long term net flow very dependent on the choice of the boxes. The implications of this problem are discussed in section 8.3.

The transport calculation took place by dividing the cross section into boxes followed by multiplication of the velocity component normal to the box with the box area, i.e. by assuming the current measured to be equal to the average of the current over the entire box.

The boxes were separated by horizontal lines placed half-way between the instruments (nominal depths, and by vertical lines placed half-way between stations).

Missing data were substituted by means of linear regression from the adjacent instrument which showed the highest correlation to the missing one. When a substantial part (more than half) of the recording in the upper (high velocity) layer were missing, the discharge calculation was not carried out for the series of daily water exchange, but less restrictions were imposed on the calculations of the monthly exchange.

In a previous analysis of daily averages of the resulting series (Jacobsen, 1976) it was shown that the calculated discharges in the three sections in the Great Belt deviate in a systematic way. They have for reasons of continuity to yield the same discharge rates with a minor correction for the accumulation of water between the sections, but calculations for the middle section give transport rates almost 40 % higher than the northern section, while the southern section gives lower estimates and also bears a lower correlation to the northern section. The residual variation of points around the line of regression between transports in the middle and the northern section is 2-3 km^3/day and is taken to be an estimate of the standard deviation of error of the method used, even if box areas could become optimized.

8.2.2. The Belt sections

Without further information about the amounts of water passing the Great Belt it is not possible to decide which section to rely upon (if any) for extended studies. Because of poor instrumentation in the southern section and because of the discrepancies of the calculations from this section when compared to the other two it was, however, decided to reject results from the southern section. Of the two remaining, the northern section was preferred because it had six instruments and also because the flow was expected to be of a simpler and more uniform structure than further south. The island of Sprogo rises just north of the middle section, and the ridge divides the Great Belt into two parts, Vesterrenden and Osterrenden. This choice was confirmed later by results from the equation of water balance (Jacobsen, 1980).

Transports in the Little Belt were calculated at the northern section (station 547), as the currents at station 530 in the southern Little Belt cannot be considered as representative of the movement of the water through this strait (Jacobsen 1980).

The Fehmarn Belt section could not be used until the Institute of Marine Research, Kiel, on October 12, 1976 moored an additional station (529) with three instruments at the 20 m contour outside Fehmarn. The last two and a half month of the Pilot Study Year has, however, not been included in the calculations as data from the Danish station 528 were very scanty.

8.2.3. The sections of the Sound

In the section in the southern part of the sound (stations 526, 527, 552) continuous recordings failed because of frequent interference of the mechanical part of the current meters (the rotors) with drifting sea weed.

The section in the northern part of the Sound (station 549) was not established until November 1975, and the highly irregular current which frequently consists of a narrow northgoing swift surface current of low salinity, embedded in denser water of small velocities (Jacobsen and Nielsen, 1978) did not encourage calculations, when only two instruments (7 and 25 metres) covered the section. The 15 metre instrument was added in February 1977.

In the preliminary tables of the water exchange, presented in Rostock 1977 (Nielsen and Jacobsen, 1977) use was made of the estimates of the surface current from the lighttower Drogden, and Q_S was calculated according to:

$$Q_S \text{ (km}^3\text{/month)} = 1.5\, V_{DR} \text{ (cm/s)} \quad (8.2)$$

The formula has been proposed by Jacobsen (1925). V_{DR} is almost always reported in directions 50° (outgoing) or 230° (ingoing). A later investigation based on intensive current measurements during September 1976 showed that the factor of proportionality between Q_S and V_{DR} has increased almost monotonically since 1931 and is now about doubled (3 instead of 1.5), (Jacobsen 1978, 1980). No safe explanation of this has yet been found. It should also be pointed out that the annual average of the current from Drogden has been ingoing on many occasions since 1943. It is, however, hard to accept that the annual net exchange through the Sound should also have been negative.

In consequence of this the previous presented monthly values for Q_S (Nielsen and Jacobsen, 1977) are too small. It was not considered safe to utilize the observations from Drogden with a larger constant of proportionality, as long as the question of the change in the constant not has been settled. Alternatively, a simple model has been established which permits Q_S to be calculated from a frictionally balanced barotropic flow over the shallow area north of Drogden (Jacobsen 1978, 1980). The barotropic pressure gradient is calculated from the sea level difference between Klagshamn and Copenhagen:

$$Q_S = K(\Delta h + D)/|\Delta h + D|^{\frac{1}{2}} \quad (8.3)$$

where $\Delta h = h_{Klagshamn} - h_{Copenhagen}$

$D = 0.078$ m
$K = 9 \times 10^4\ m^{5/2} s^{-1}$

$h_{Klagshamn}$ is measured relative to the Swedish "heightsystem 1900" and $h_{Copenhagen}$ relative to DNN (Danish Normal Zero).
D accounts for the expected difference between the Swedish and the Danish levelling zeroes.

The model was calibrated to give a good description of the exchange during periods of uniform flow of moderate to high intensity. It is likely to fail during situations with small sea level differences, and also if the transport is averaged over many current reversals. It has, however, owing to lack of better data been used to reproduce the monthly values of Q_S for the Pilot Study Year.

The Danish Meteorological Institute and the Swedish Meteorological and Hydrological Institute kindly supplied the hourly readings from the two tide gauges. During March 1976, the tide gauge in Copenhagen was out of order, and tentatively was substituted:

$$Q_S \text{ (km}^3\text{/month)} = 3.0\, V_{DR} \text{ (cm/s)} \quad (8.4)$$

8.2.4. Results

Results are given in Table 8.1. The monthly values of Q_{GB} could not be evaluated for January and February 1976 at the northern section in the Great Belt because of lack of data. Similar calculations from the middle section (stations 545 and 534) were used after multiplication with the factor 0.71, which is the mean ratio between the discharges calculated at the two sections (Jacobsen, 1976). This was done in order not to leave the table of monthly values incomplete, but the method is not entirely satisfactory. All daily values reported in this chapter stem on the other hand only from the northern section, and rather many gaps are for that reason unfortunatley introduced.

The monthly values of the exchange in Table 8.1 fulfil the requirements of the project on the water balance, but the high variability of the exchange made it desirable to study the process also from daily values. The hourly averages of the water exchange calculated at the sections in the northern Great Belt and the northern Little Belt, and from the barotropic model of the Sound, were filtered with a triangular (Bartlett) filter over 48 hours and resampled at midnight with an interval of one day. The reason for this procedure is that they should be comparable to the volume changes calculated from the daily mean sea level (Jacobsen, 1980).

8.3. DISCUSSION OF RESULTS

The daily mean sea level of the Baltic was calculated with data from 44 tide gauges in order to provide a provisional basis for comparison with the series of the daily sea water exchange (Fig. 8.4). Results derived from a larger number of tide gauges were presented by the Soviet element coordinator at the seventh meeting on the water balance of the Baltic in 1980. The values of Q_O stem from the preliminary results of the sixth meeting in Helsinki, 1979. Altogether 433 km^3 was in this way found to have left the Baltic during Pilot Study Year (Jacobsen, 1980).

With regard to the amplitude of single in- and outflows, Q_{LB} has the smallest and Q_{GB} the largest. But the long term average is apparently positive for Q_S in the Sound, while the two others are zero or even slightly negative. Two comments can be given already at this stage:

1) Q_S is derived from a barotropic model of which the long term average is very dependent on small inaccuracies in the absolute difference of the tide gauge zeroes, and this difference has not been adjusted in order to produce a reasonable long term net flow. The mean outflow $\langle Q_S \rangle$ will become reduced to half of its present value if the parameter D in eq. 8.3 is reduced by only 2 cm, which is well within the uncertainty of the knowledge of D. At the same time $\langle |Q_S| \rangle$ will be left almost unchanged, i.e. the mesoscale oscillations are just slightly distorted

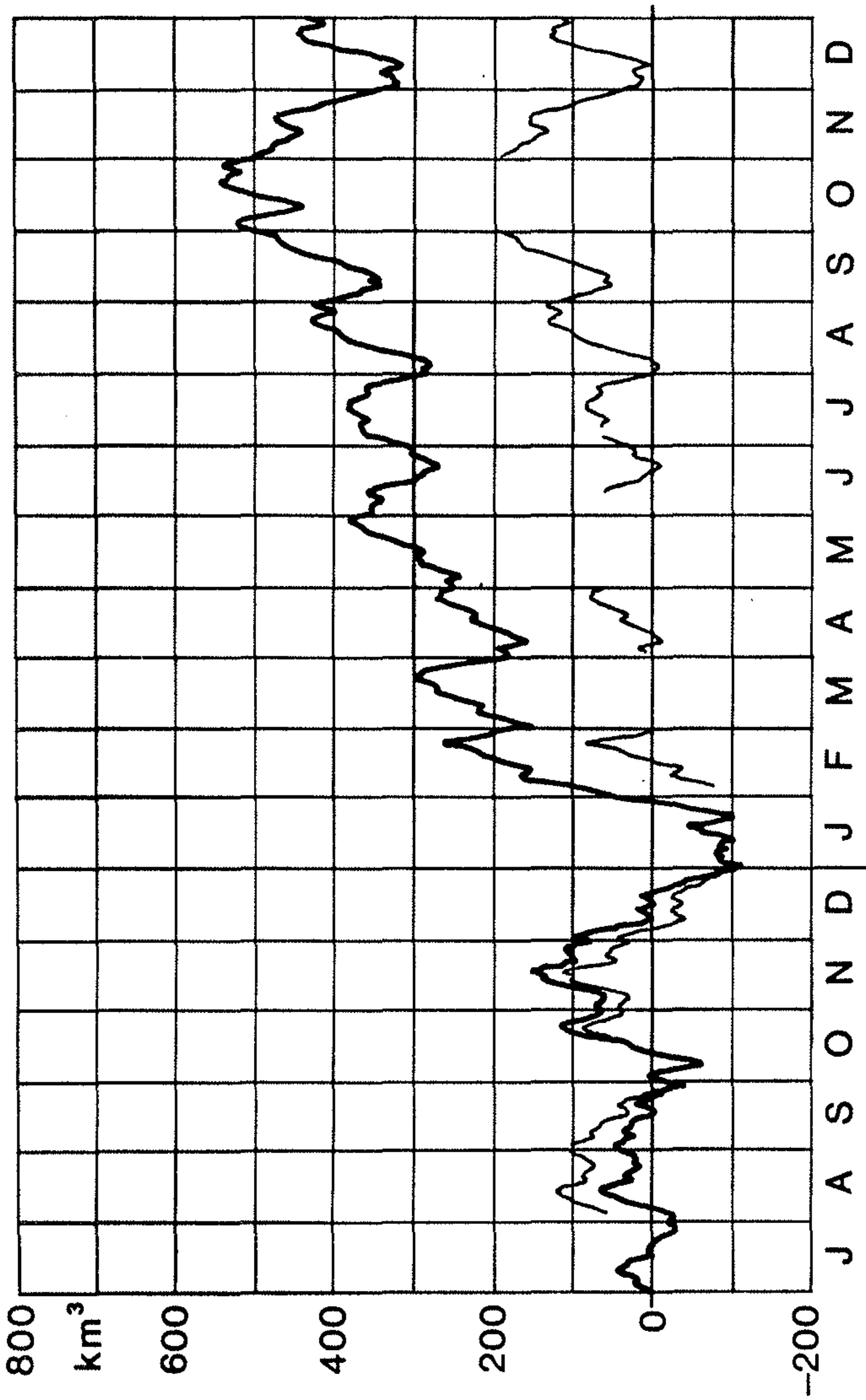
Table 8.1 Net water transports in Danish Straits during Pilot Study Year (July 1975 - December 1976)

Units in km^3. Flow to the Kattegat is positive

Subbasin	VII	VIII	IX	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
The Sound	9.9	27.6	-3.0	25.5	14.4	-34.8	58.4	32.8	-17.4**	42.5	39.9	0.2	14.9	38.2	32.4	0.9	-20.1	45.5
The Great Belt	-22.0	50.5	-70.2	55.2	-21.0	-93.9	56.4	51.1	35.0	22.6	57.0	-48.2	-10.8	75.7	27.6	-15.3	-114.9	36.8
The Little Belt	-	-0.9	-18.8	-4.0	-2.7	-24.1	5.8	6.7	-8.2	-2.8	1.7	-8.5	-1.3	16.2	-3.1	-17.0	-34.6	9.7
Total	-12.1*	77.2	-92.0	76.7	-9.3	-152.8	120.6	90.6	9.4	62.3	98.3	-56.5	2.8	140.1	56.9	-31.4	-169.6	92.0

* Little Belt not included

** Calculated as 3 V_{DR} (see text)



8.4 Cumulated estimated outflow Qo-ΔV (heavy line) and directly measured discharge H-M (thin line) during Pilot Study Year. Units in km^3

each to yield a lower outflow and a higher inflow. For an investigation of the sensitivity of the simple non-linear model of the Sound, see Jacobsen (1980).

2) There are many gaps in the series. When cumulated this will affect the position of the end point, because the cumulated discharge for computational reasons has been kept constant during periods with no data. The effect of the gaps for the sum of the mean discharges in the three straits has been estimated indirectly from the equation of water balance and produces a deficit of 227 km^3. See Fig. 8.4. and Table 8.2. The actual deficit thus left is only about 90 km^3 when compared to Q_o and the volume change ΔV.

8.3.1 Time lapse of the exchange

The time lapse of the exchange during the Pilot Study Year is described from the integrated value of (Q_o - ΔV) (Fig. 8.4, heavy line). The most prominent features are the strong inflow by the end of 1975 followed by a full month of intense outflow, and the quasi-periodic oscillations of about once months duration during 1976.

The inflow begins by the middle of November 1975 and continues with minor interruptions of outflow until early in January. The rate of inflow is particularly high during the first and last third of December. This is in good agreement with the east-west component of the wind stress (Jacobsen, 1980).

About the 3rd and the 23rd of January severe storms passed Denmark; there were flood-warnings for southwest Jutland, and the Transition Area experienced some extreme sea level oscillations. A strong outflow started after the second storm at January 23rd and lasted a full month with a single small interruption. About 370 km^3 left the Baltic during this outflow which corresponds to 140,000 m^3/s.

Alternating in- and outflows of smaller size followed, each representing the pendling of characteristically 100 km^3.

The integrated curve of the directly measured total discharge Q is also shown in Fig. 8.4, but is far from complete. The fragments which are present do, however, conform to a high degree with (Q_o - ΔV), even in very small details.

8.3.2. Differences observed between the Belts and the Sound

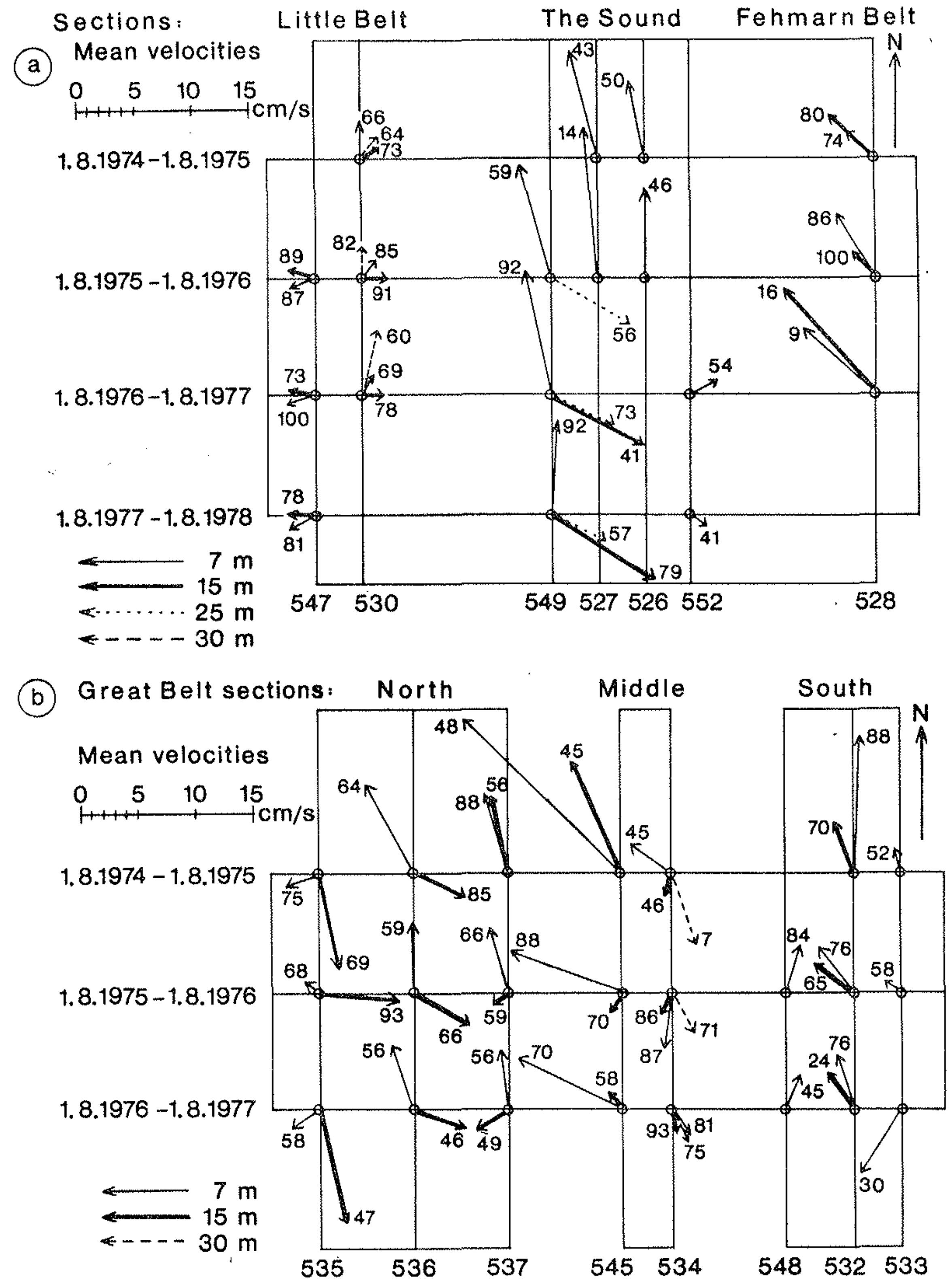
Three types of filtering have been applied (hourly simple averages, 24-hour simple averages, and the before mentioned 48-hourly triangular filtered values). The mean value, the standard deviation, the mean of the absolute values, and the ratio of the latter parameter to the standard deviation have been calculated.

From the mean of the absolute values, it is seen that the flushing ratio between the Sound, the Great Belt and the Little Belt is 3:7:1 for all three filters. The ratio $<|Q|>/SD(Q)$ is seen to be a little higher than 0.8, cf. section 8.2.3. The ratio for Q_S is even close to 0.9, but it is to be remembered that Q_S is calculated from a crude hydraulic model while Q_{GB} and Q_{LB} are calculated from direct current measurements; deviations in the amplitude distributions must be expected. If the 1-hour means of the absolute values of the exchanges through the Sound and the Belts are assumed to be representative, we find that the sum of the flushings is about 3500 km^3/year. For 24-hourly simple means this is reduced to 3000 km^3/year. The absolute value of the total exchange Q equals the sum of the flushings of the single straits only if they are always of the same sign (direction). This is known not to be the case and the flushing of Q is consequently smaller than the numbers just given.

It should be mentioned that both current meters at station 547 in the northern Little Belt were moored about 3 metres deeper than planned, i.e. at 10 and 18 metres. Calculation of the vector of the mean current, Fig.8.5 a, shows persistent inflow at both depths with velocities about 2 cm/s. The salinity is seldom lower than 20 o/oo at the upper instrument. It is concluded that the mean outflow takes place above 10 metres depth.

Fig. 8.5.b shows the mean current vectors for the Great Belt sections. The mean current at 7 metres depth on station 535 is small during 1.8.1975 - 1.8.1976. The depth of the instrument has varied from 6 to 8 metres. Its projection at right angles to the section gives an outflow of 1 cm/s. It should be noticed that the data representation is only 68 % and that the period selected is only 12 months of the Pilot Study Year. Nevertheless it seems very likely that the instrument is moored too deep to represent the mean outflow in the western part of the Great Belt. Due to the Coriolis force, the deep layer rises at the western side of the Belt, and this could possibly explain why the outflow has not been recorded, while at the same time the instrument at station 537 on the east side records an outflow of 5-7 cm/s, although actually moored at appr. 9 metres. The other two annual mean currents at 535/7 m are slightly negative when projected on the normal to the section. Salinities are usually 1-2 o/oo higher than at the corresponding instrument placed in the eastern part of the section.

The box allocated to 535/7 m represents 20 % of the total cross section area and 36 % of the area shared by the three upper boxes. It it is assumed that the representative velocity in the box is appr. 5 cm/s (cf. 536 and 537), this would raise the calculated mean outflow in the Great Belt with 3500 m^3/s or 710 km^3/year. At the same time, the total expected net outflow corresponding to 70 % of the fresh water surplus is only a little more than 300 km^3/year. This demonstrates the extreme difficulty in estimating the long term net outflow from direct measurements.



8.5 Mean current vectors for different sections

8.3.3. Long-term mean discharge

It is concluded that the long term mean discharge through the Belts has been underestimated, while through the Sound it is too large. In the sum <Q>, however, these errors partly cancel. The results are presented as they were originally calculated, i.e. without adjustment to the known total outflow ($Q_o - \Delta V$), because it was agreed upon from the beginning of the project that all water balance elements should be evaluated independently.

8.3.4. Modelling the seawater exchange

There have been many more or less successful attempts to model the sea water exchange. Most have been reviewed by Svansson (1976) and Jacobsen (1979, 1980). Modelling of the data obtained during the Belt Project has been attempted by the Danish Hydraulic Institute (1977), Pedersen (1978), Nielsen (1979), and Jacobsen (1978, 1980).

Most of the models seem to indicate that the best results are obtained with a non-linear bottom friction law, which has the advantage that it inhibits unrealistic large flow rates to develop for large sea level gradients.

All these models give uncertain results when the rate of flow is small, and also they are unable to produce reliable long term mean values. On the other hand, they give fair results for moderate to high exchanges.

It appears to be possible to monitor the sea water exchange in a rather simple way with observations of the sea level in the southern Kattegat and in the western Baltic, but the long term mean requires adjustment from the other terms of the equation of water balance, ($Q_o - \Delta V$).

8.4. CONCLUSIONS

The present chapter describes the results of the direct measurements of the sea water exchange through the Transition Area (the Sound and the Belts) during the Pilot Study Year. The results are given for each of the 18 months in Table 8.2.

The difficulties encountered when attempting to measure the average net outflow of an oscillating fluid of changing stratification are discussed. The time lapse of the series of daily values of the total exchange (Fig. 8.4) shows the presence of a strong oscillation with a period close to one month. A monthly cycle in the water exchange will not appear in the series of monthly net exchanges.

Table 8.2

Caps in measured total outflow Q

Days	Period	Simultaneous value of $(Q_o - \Delta V)\,km^3$
24	13 Jul - 5 Aug 1975	-62.7
2	2 Sep - 3 Sep 1975	4.2
32	5 Jan - 5 Feb 1976	189.5
34	1 Mar - 3 Apr 1976	-14.2
41	2 May - 11 Jun 1976	106.9
4	6 Jul - 9 Jul 1976	14.7
31	3 Oct - 2 Nov 1976	-11.1
Total 168		227.3

The distribution of the current over the cross section depends much on the density stratification, which again is intercorrelated to the direction of the flow. Outflow is usually connected with stratified flow, while the fronts during strong inflow move south to the sills of Drogden and Darss, and the stratification may virtually disappear in the Belt Sea. This systematic change in the flow pattern is likely to introduce a bias in the net exchange, which is calculated over an entire cycle of inflow and outflow, and the bias is expected to be of the same order of magnitude as the long term net flow.

It seems therefore justified also to study the water exchange on a time scale which resolves all important modes of motion and it is useful to introduce the average exchange regardless of the direction, $\langle |Q| \rangle$. It has not been attempted to obtain a vertical resolution of the exchange from the direct current measurements. To be useful it requires a more detailed knowledge about the position and stability of the density interface than could be obtained from the relatively few moored selfrecording instruments.

Chapter 9

RIVER INPUT OF SUSPENDED MATTERS

Bengt Nilsson (Sweden)

9.1. INTRODUCTION

In the countries bordering the Baltic Sea investigations on sediment transport have been going on for a long time. The purpose of the measurements, however have varied widely and different methods of sampling, analysing and data processing have been used. In Sweden the studies have often been initiated because of building operations, water regulations, dredgings or other artificial measures in the rivers.

The observations and the measurements often cover a fairly short period, as the aim has been to determine the concentration of suspended material during the period of disturbance, an information of great importance for instance for water supply plants and paper mills. The rate of silting in reservoirs and the sedimentation in river channels are also of interest.

Lately special attention has been paid to the fact that the suspended material is often contaminated with dissolved, colloidal and solid matter from waste material. This implies a serious environmental problem, as the waste material often contains heavy metals, toxic substances and other undesired contaminants, which affect the sediments, especially within the coastal depositional areas.

Thus there was a great interest of a joint study on the sediment transport within the research project "The water balance of the Baltic Sea". The problems involved were the following:

- intercalibrate the different methods used in water sampling and water analysing
- measure the transport during a Pilot Study Year (July 1975 to December 1976)
- calculate the transport of suspended matter into the Baltic Sea during the period 1961-70 (second decade of the historical 20-year period chosen for the project).

According to differences in drainage pattern and, to some extent, also to river regime differences, the drainage basin of the Baltic Sea may be divided into two main regions. In one region, Finland and Sweden, the numerous medium size rivers create problems in terms of the network density and the cost factors involved in an investigation. In the south and south-eastern part of the drainage basin the rivers are few with very large drainage areas, and the measurement problems will be of another kind.

Considering this fact and also other practical reasons, Dr. J. Cyberski, Poland, was responsible for data from the USSR, Poland, GDR and FRG, and Dr. B. Nilsson, Sweden was responsible for data from Denmark, Finland and Sweden.

9.2. NETWORK DENSITY

As mentioned above, a dense station network is needed in the northern region, whereas in the southern region a few stations registering the net transport from a large inland area are often sufficient.

In Denmark there were no regular observations on sediment transport. However, some investigations have been carried out on Jylland (Hasholt 1974, 1975; Neiss 1974; Höst-Madsen and Edens 1974), one small river on Själland (Bihlet 1971) and a pilot study in nine small rivers on Själland (Hasholt 1977).

In Finland a network for studies of the chemical composition of river water was in operation (Wartiovaara 1975, 1978). Though not especially designed for sediment transport the concentration of suspended sediment could be obtained from that investigation. Twentyone stations, located near the river mouths, cover 85 % of the area drained along the Finnish coast. The sampling frequency was 12 samples a year.

In Sweden a network particularly designed for sediment transport studies was started by the national IHD-Committee 1966-67 (Nilsson 1972). The observations were since the middle of 1975, carried out by the Swedish Meteorological and Hydrological Institute. Before 1966 only irregular investigations were undertaken in some rivers (Arnborg 1958, 1967, 1969; Nilsson and Martvall 1972; Sundborg and Norrman 1963). The IHD network covers about 34 % of the total Swedish drainage area and about 30 % of the total water discharge from Sweden into the Baltic Sea. A sampling frequency of about 50 samples a year makes it possible to analyse about 10 % of the total water discharge from Sweden if one sample is supposed to represent the conditions during one day.

In the USSR there was a network covering most of the drainage area of the Gulf of Riga. The network covers also about 60 % of the area which is drained to the Baltic proper.

In Poland the network covers almost the entire area from which the water is discharged to the Baltic. Data from the river Odra also reflect the transport from most of the area which is drained to the Baltic from GDR.

The sampling frequency in the USSR and in Poland varies from daily samples at some stations, for instance in the Vistula river, to every fifth day at some other stations.

The names of the rivers and the stations are listed in Table 9.1 and a map of the Baltic and the drainage area covered are shown in Fig. 9.1.

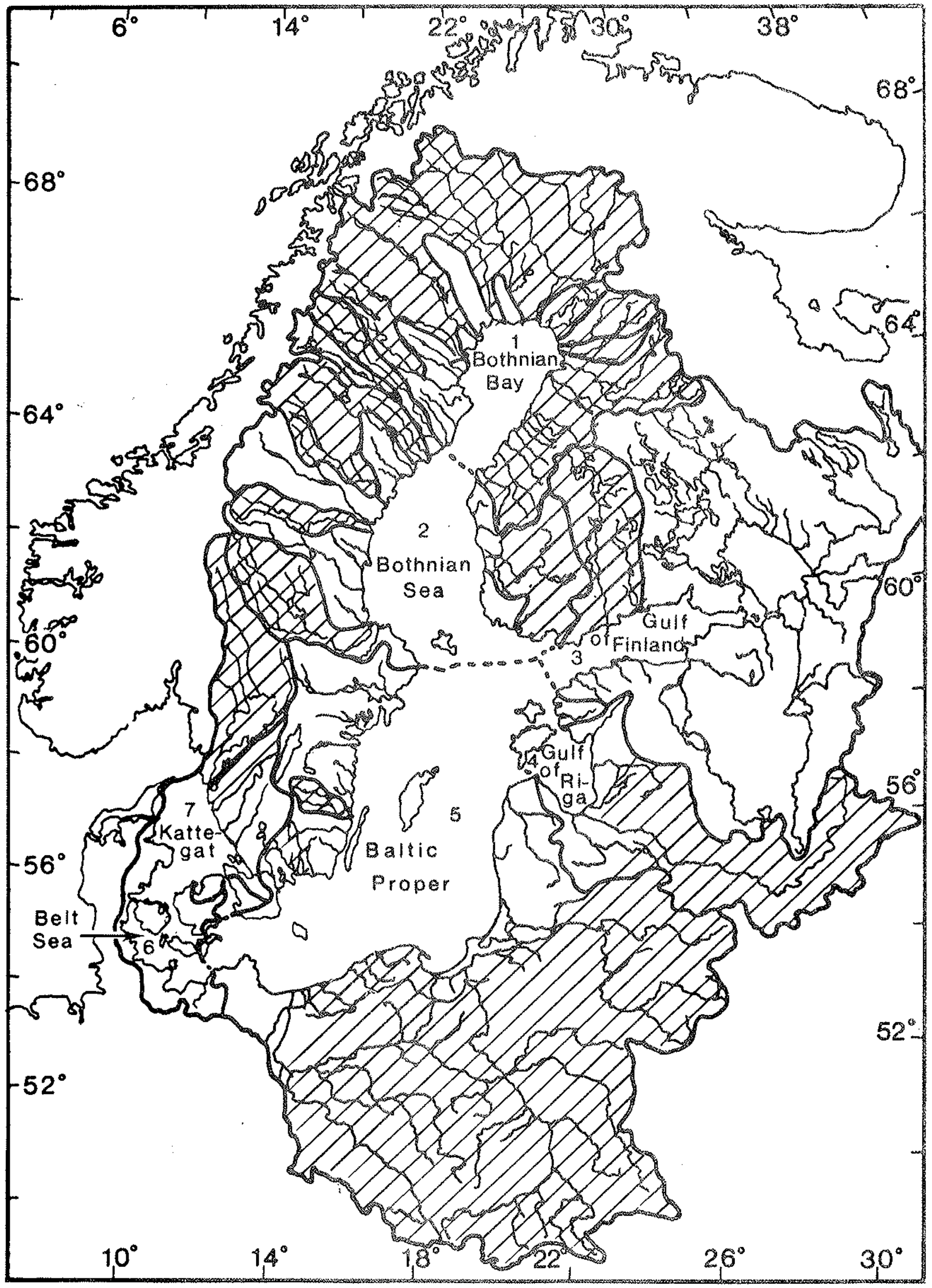
Table 9.1
List of investigated rivers draining to the different subbasins of the Baltic (underscored stations see text in section 9.4.1)

River	Drainage area km^2	River outflow (longterm mean) m^3/s	Sampling station	Drainage area at sampling station km^2	Lake area upstream sampling station percent
1. BOTHNIAN BAY					
Sweden					
Torne älv [1)]	34 800	350	Övertorneå	32 700	4.3
Kalix älv [1)]	23 400	290	Kalix	23 700	3.0
Lule älv	25 250	508	Gäddvik	25 250	7.8
Pite älv	11 220	170	Bölebyn	11 093	6.8
Skellefte älv	11 690	160	Rengård	9 640	13.0
Finland					
Kemijoki	51 400	578	Kemin mlk	50 900	2.9
Iijoki	14 385	170	Ii	14 315	5.8
Oulujoki	22 925	234	Oulu	22 900	11.4
Siikajoki	4 400	34	Revonlahti	4 395	1.5
Pyhäjoki	3 680	24	Pyhäjoki	3 400	5.7
Kalajoki	4 200	25	Kalajoki	3 025	1.8
Lapuanjoki	4 110	30	Uusikaarlepyy	3 955	2.8
Kyrönjoki	4 900	43	Mustasaari	4 805	0.9
2. BOTHNIAN SEA					
Sweden					
Öre älv	3 030	35	Torrböle	2 880	2.4
Lögde älv	1 610	19	Lögdeå	1 610	2.4
Ångermanälven	31 890	490	Nyland	31 700	7.4
Ljungan	12 850	140	Njurunda	12 850	7.1
Dalälven	29 040	370	Älvkarleby	29 030	6.2
Finland					
Isojoki	1 125	10.6		1 035	0.4
Kokemäenjoki	27 100	206	Pori	26 025	11.8
Aurajoki	885	6.2	Kaarina	730	0.0
Paimionjoki	1 080	8.3	Paimio	790	2.2
Uskelanjoki	585		Salo	520	1.3
3. GULF OF FINLAND					
Finland					
Karjaanjoki	2 010	17.8	Karjaa	1 925	12.2
Vantaanjoki	1 685	13.7	Helsinki	1 235	2.8
Porvoonjoki	1 260	10.9	Porvoon mlk	1 135	1.7
Kymijoki	37 235	183	Kymi	36 535	19.4
Virojoki	360	3.4	Virolahti	345	4.8
4. GULF OF RIGA					
USSR					
Gauja		49	Valimiera	6 150	
Daugava	88 000	465	Jekabpilis	70 200	(0.6)
5. BALTIC PROPER					
Sweden					
Emån	4 460	30	Emsfors	4 446	6.8
Mörrumsån	3 380	27	Mörrum	3 374	13.3
USSR					
Neman	98 100	546	Smalininkai	81 200	1.0
Pregoła	14 677	87	Gwardiejsk	13 600	2.7
Poland					
Pasłeka	2 330	14.8	Braniewo	2 290	2.0
Wisła (Vistula)	198 510	1010	Tczew	193 866	0.7
Łeba	1 789	6.0	Lebork	436	5.2
Łupawa	964	8.2	Smołdzino	830	4.2

Table 9.1 cont.

River	Drainage area km^2	River outflow (longterm mean)	Sampling station	Drainage area at sampling station km^2	Lake area upstream sampling station percent
Słupia	1 652	16.7	Słupsk	1 470	2.0
Wieprza	2 173	16.0	Stary Krakow	1 510	1.1
Parseta	3 145	27.5	Bardy	2 944	0.7
Rega	2 672	20.9	Trzebiatow	2 551	1.4
Odra	118 388	522	Gozdowice	109 364	0.9
6. THE BELT SEA AND ÖRESUND					
Sweden					
Rönneå	1 890	21	Klippan	952	5.3
7. KATTEGAT					
Sweden					
Viskan	2 200	33	Åsbro	2 160	6.2
Göta älv	50 180	575	Ormo-Agnesberg	48 200	18.0

1) The drainage areas are divided according to mean water discharge through the bifurcation. The Finnish area of the Torne rivers drainage area is 14 900 km^2.



9.1 Map of areas of the drainage basin surveyed by the chosen stations network

9.3. METHODS USED IN MEASUREMENTS AND CALCULATIONS

9.3.1 Water sampling

In Finland water samples were collected with a Ruttner sampler at midpoint of the stream and at about 1 m below the surface. The sampling stations were located close to the hydrological gauging stations.

In Sweden a depth intgrating sampler was used within the IHD network (Nilsson 1969). The sampler allows a discharge-weighted sample consisting of the water column from the surface down to 0.3 m above the bed to be collected. The ordinary sampling vertical was located near the vertical where the mean transport of the cross section is prevailing. Cross section measurements of water velocity and suspended sediment concentration were carried out once or twice a year. Depending on water velocity and water depth the sample volume may vary between 0.5 l to 0.8 l. The lower limit of the sample volume is stated because of analysing accuracy and the higher volume because it prevents throughflow of water in the sampler.

In Poland and in the USSR the measurements of suspended load were done by the government hydrological services in selected cross sections. In these measurements, in addition to the water sampling with a bathymeter, water discharge and daily observations or continuous water stage recording is performed. In the majority of stations water was sampled every day (at some of the stations the sampling is every two to five days) from a depth of 1 m and invariantly at the same site.

Cross section measurements of the suspended sediment concentration and the water velocity were carried out from a few to over ten times a year. Then the sampling was done at every other depth gauging point inclusive of the midstream and the nearest bank points. In case of an even number of points more sampling points were chosen in the midstream. At every bathymetric point samples were withdrawn at 0.2, 0.4, and at 0.8 of the depth. As the load measurements were completed, a single reference sample was collected at the site of constant sampling.

The Swedish sampling method was compared with the Finnish method in two rivers in Finland. The results showed that the Swedish sampler gave a 2 % higher concentration than the Finnish one in one river, and in the other river the samplers gave almost the same values within the concentration range investigated. Comparisons with the Polish method have not yet been performed.

9.3.2 Methods of analysing

In Finland the analysis followed SFS-3037 standard methods (SIS-028112, Wartiovaara 1978). This means that a water sample

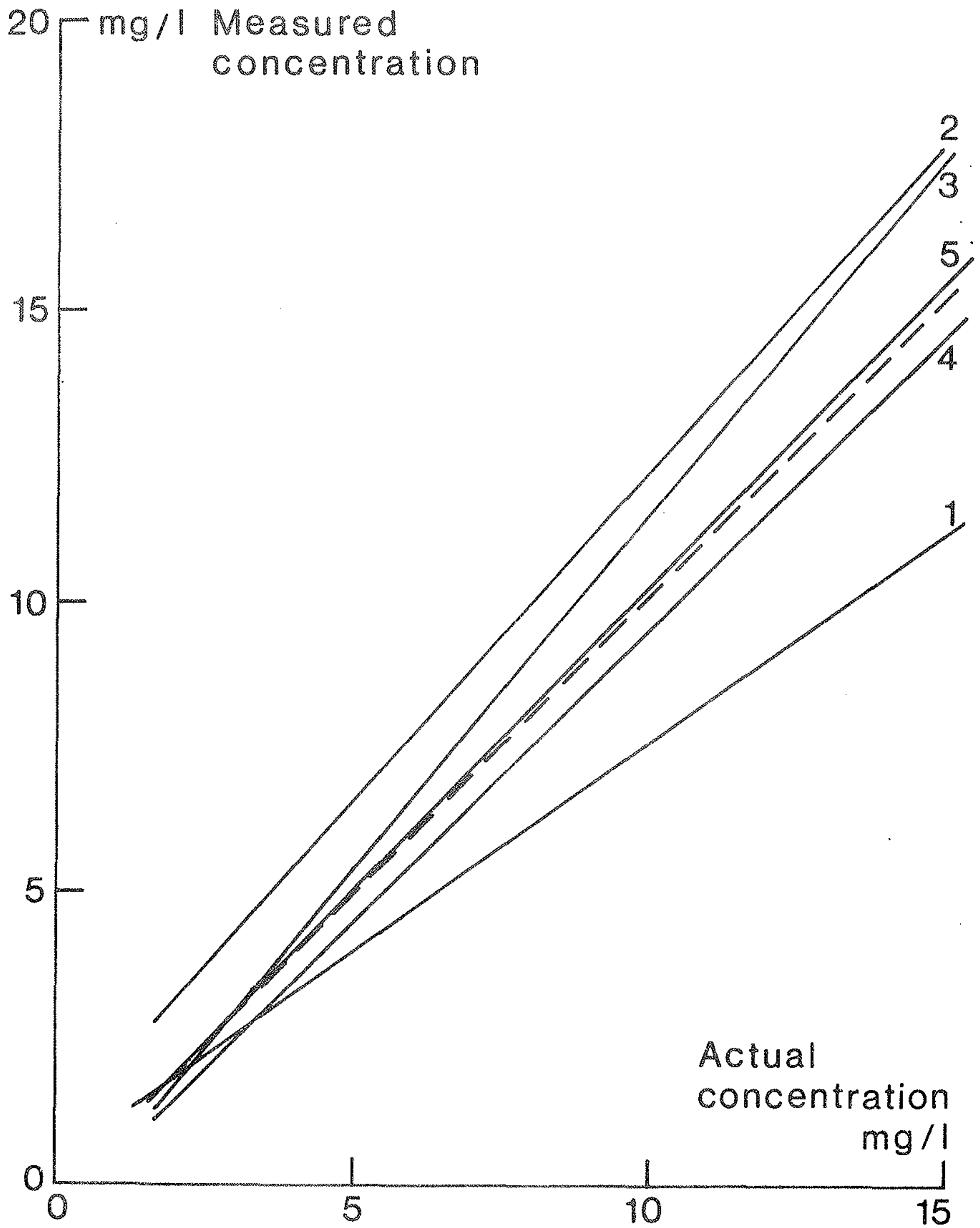
of 50-100 ml was filtrated through Whatman GFC 45 filter with a pore size of 1 micron. The filter was then dried in 105°C. The amount of material was obtained by the difference of weight before and after filtering.

In the Swedish IHD-project the whole water sample was filtrated through a membrane filter of 100 mm diameter with a pore size of 0.05 microns (Nilsson 1971). The material was washed down to a crucible and dried at 105°C. After cooling in a dessicator, during 2 hours the material was weighted on an analytical balance with 0.1 mg accuracy. The concentration of the sample was then adjusted to mg/l.

In Poland and in the USSR the water samples were filtrated through no. 389 paper filters of the GDR make having 185 mm in diameter, medium wide pores and medium fast filtering capacity and designed for crystalline deposits. The value of the suspended sediment concentration per unit volume was found from the difference in weight of the filter prior to and after filtration, followed by drying at a temperature of 105°C and weighed on an analytical balance with 0.1 mg accuracy. In view of an increasing measurement error with lower water turbidity, a principle mandatory in the USSR, according to which at $P > 100$ mg/l the minimum sample volume is 1 liter, for $50 < P \leq 100$ mg/l the corresponding value is 2 liters, for $20 < P \leq 50$ mg/l it is 5 liters and for $P < 20$ mg/l a sample volume of 10 liters is needed (Pasławski 1973). This is a very accurate method, but the disadvantage is the increasing costs. Furthermore it is difficult to determine the concentration of the water during the sampling and thus also to determine the sample volume.

The analysing methods were calibrated between laboratories in Denmark, Finland and Sweden. Sediment samples were prepared in a recirculating flume at the laboratory of the Department of Physical Geography, University of Uppsala. During one hour the water was fed by material ranging in size between 100 - 5 microns. After the feeding was stopped the suspended sediment concentration and the median grain size decreased along the time until an equilibrium was established. During that time samples were collected every other minute. Samples no 1, 7, 13, ... 31 and 2, 8, 14 ... 32 and so on were sent to laboratories in Denmark, Finland and Sweden. The sample volumes were ranging between 400 - 500 ml.

According to the values from the different laboratories there were no relation between the obtained deviations from the expected values and grain size. Fig. 9.2. shows the relation between the expected values (dashed line) and those obtained by the different laboratories. In this case the results from Denmark (2) and Finland (3) show too high concentrations. The Swedish laboratories no 4 and 5 using the IHD analysing method described, gave results rather near the expected values.



9.2 Intercalibration of analyses of suspended inorganic sediment. Dashed line shows the expected values. Line 1, 4 and 5 are the results from Swedish laboratories, line 2 from Danish and line 3 from Finnish laboratory

9.3.3 Data processing

The processing of data from Finland is described by Wartiovaara (1975, 1978). A regression analysis using the formula

$$T = a + bQ + cQ^2$$

where T is mass transport, a, b and c are coefficients and Q is daily mean water discharge was carried out for every river investigated. The annual load of material was obtained by adding the daily amounts.
A second method to estimate the annual discharge was based on the annual means of concentration and runoff. In a third method the water quality was weighted in relation to length of intervals between the water quality observations. The concentration was weighted by the total runoff recorded during the period represented by each quality observation.

The mass discharge values calculated by these three different methods were very similar for dissolved matters. However, the discharge values of suspended matter could deviate with more than 100 % in single rivers.

In Sweden a regression alaysis between water discharge and mass transport was established for every river investigated. Suspended sediment discharge rating curves were constructed. Using the power function

$$T = aQ^b$$

where T is mass transport, Q is the daily mean water discharge, a and b are coefficients. These curves were used in order to calculate the mass transport during days when no data on sediment concentration were available. The daily transport amounts were calculated and summed every month (Nilsson 1972).

In Poland and in the USSR with their dense sample frequency the interpolation in time was easier and the mass transport probably more accurately determined. Having found the daily suspended sediment concentration, the daily mass transport was evaluated using the formula

$$T_i = 10^{-3} C_i Q_i$$

where C_i is the daily suspended sediment concentration in g/m^3, Q_i is the rate of mean water flow in m^3/s, and T_i is the mass transport rate in g/s. The value of mean monthly transport and the mean annual transport were evaluated as an arithmetic mean:

$$T = \sum_{i=1}^{n} T_i/n$$

where n is the number of days in a month or in a year.

The mean monthly or annual suspended sediment concentration were calculated as weighted means, in which the weights are the rate of daily water flow, from the formula:

$$C = 10^3\ T/Q$$

The monthly values of the suspended sediment transport, R, in tonnes, were evaluated using the expression

$$R = 86{,}4 \sum_{i=1}^{n} T_i$$

As the suspended sediment concentrations were found from the analysis of single water samples, a correction should be made in the form of a coefficient k calculated from the relation between the mean suspended sediment concentration at the hydrometric cross section, C_w, and the concentration at the site of ordinary sampling, C_p, viz.

$$C_w = kC_p$$

Finally the values of the suspended sediment characteristics were obtained by multiplying T, C, and R by the k-coefficient which was determined for individual bathymetric stations and was updated every year.

Besides the use of sediment discharge rating curves the Polish and Swedish methods are rather similar. However, in Sweden it was found that the k-coefficient varies almost along the range of water discharge. Any safe relationships have not yet been found. Therefore the Swedish mass transport values are not yet corrected for representativity deficiencies of the conditions at the ordinary sampling point in relation to the conditions at the whole cross section. Due to this fact the Swedish daily transport values were estimated within ± 10 % accuracy. At some stations the correction of the transport should be about ± 20 % (Nilsson 1972).

9.4. CALCULATION OF INPUT OF SUSPENDED MATTERS INTO THE BALTIC SEA

9.4.1. Pilot study

As mentioned before the calculation techniques differ between Finland/Sweden and Poland/USSR. In order to make the transport values from Finland and Sweden comparable the basic data from Finland were calculated with the Swedish method. This was not because the Swedish method was considered to be more accurate but simply because of the fact that Swedish computer routines were available.

If the correlation (r^2) obtained from the regression analysis was

less than 0.5, the transport estimations were carried out by means of linear interpolation. This method was used for the estimates of the rivers Karsjaanjoki, Kokemäenjoki and Oulujoki. In some cases one sample was considered to be representative for a whole month. The transport during that month was then calculated as the sum of the monthly mean water discharge multiplied by the concentration and the time.

The transport estimations from areas where no data were available are rather rough (Nilsson 1976). In the northern part of Sweden it was possible to take into certain consideration different soil regions and land use. The areal transport from similar basins was then applied to the unmeasured areas. In Finland the mean areal transport of the surrounding rivers was applied directly to the unmeasured area. This measure is not good as, for instance, the drainage area of some of the adjacent rivers included large lake areas, while the unmeasured areas often were small areas, located along the coast between the mouths of the main rivers, and had very few lakes.

In the southern part of Sweden the weighted mean concentration of the rivers Hargsån, Emån, Mörrumsån, Rönneå and Viskan, and the annual mean water discharge from the different areas, calculated by Mikulski (1975), were applied to the unmeasured coast regions. The two large drainage basins, Mälaren-Norrström and Motalaström, include large lakes acting as sediment traps close to the outlets of the basins. The mean annual concentration of those two rivers was estimated to 7 ppm.

The unmeasured areas were named "coast region" even if they included rivers with a drainage area amounting to 6000 km^2 of size. The mass transport of the river Torne älv which constitutes the border between Finland and Sweden is based on Swedish data.

For the calculation of the suspended load into the individual basins of the southern Baltic a method was used which assumes a linear relation of the mass transport rate and the unit discharge for semiannual and annual periods within the subbasins under study. Averaged values of the annual totals of the suspended load collected for a multi-year period were taken. As the pilot study extended from July 1975 till December 1976, the contribution of the half year in the entire year transport value was evaluated for individual subbasins, i.e.

$$K_R = \frac{\sum R_{VII-XII}}{\sum R_{I-XII}}$$

On the basis of the multi-year data it was found that the contribution varied from 0.2 to 0.45 increasing from NE toward SW. The highest value of 0.49 was attained in the Parseta river basin.

In turn the coefficient K_Q was evaluated for the July-December half year of 1975 and for the year 1976 (I-XII 1976) as follows:

$$K_Q = \frac{M_Q\ (\text{PS VII-XII 1975})}{M_Q\ (\text{VII-XII 1956-70})}$$

and a corresponding expression for 1976.

Accordingly the suspended sediment transport from the subbasins under consideration during the pilot study could be evaluated as:

$$R_{PS} = R\ K_R\ K_Q$$

Data from the underscored stations in Table 9.1 were used in these calculations. The results of the calculations of the input to the Baltic during the Pilot Study Year are summarized in Table 9.2.

Because of uneven distribution of the gauging network, unequal sampling frequency and to some simplifications in the calculations that had to be made, the accuracy of the results obtained differs from region to region. For instance the estimates from the unmeasured areas, coast regions, of Sweden and especially those of Finland could certainly be more reasonably estimated by means of better knowledge of the physical conditions of the areas. The estimates are however considered to be reasonable.

The mass transport values of the year 1976 are very low depending on very low runoff.

9.4.2 Input of material during the period 1961-70

There are very few data published on sediment transport in Finnish rivers during the period 1961-70. By using the data published for the years 1970-72 and 1974-76 (Wartiovaara 1975, 1978), an attempt was made to estimate the transport. The sediment transport of different rivers displays quite varying dependence on streamflow conditions. Because of this fact, a method was used in which different river transport characteristics were considered.

Values on denudation (t/km^2) were plotted versus runoff for the rivers of each subbasin of the Baltic. The annual mean water discharge for 1961-70, calculated by Mikulski (1975), was then used to estimate the denudation. As the water discharge was calculated for four representative rivers (Kalajoki and Kemijoki representing the discharge to the Bothnian Bay, Kokemäenjoki to the Bothnian Sea and Kymijoki to the Gulf of Finland), the water discharges of these rivers were distributed to the other rivers according to drainage area. The annual mean water discharges (m^3/s) thus obtained were then transformed to the specific annual runoff ($l/s\ km^2$). The denudation from each river basin could then be estimated from the plot of the river in study. If the runoff values fell outside the plotted range, the denudation was obtained by means of linear extrapolation.

Table 9.2

Input of suspended matters to the Baltic Sea during the Pilot Study Year July 1975 - December 1976.

Subbasin	Year	Drainage area km^2	Denmark	Sweden	Finland	USSR	Poland	GDR	FRG	Total
			Contribution from countries (10^3 tons)							
1. Bothnian Bay	Jul.'75 - Dec.'76	269 950	-	180	140	-	-	-	-	320
	'77		-	580	183	-	-	-	-	763
2. Bothnian Sea	Jul.'75 - Dec.'76	229 700	-	190	45	-	-	-	-	235
	'77		-	550	68	-	-	-	-	618
3. Gulf of Finland	Jul.'75 - Dec.'76	419 200	-	-	42	96	-	-	-	138
	'77		-	-	41	492	-	-	-	533
4. Gulf of Riga	Jul.'75 - Dec.'76	127 400	-	-	-	81	-	-	-	81
	'77		-	-	-	510	-	-	-	510
5. Baltic Proper	Jul.'75 - Dec.'76	568 973	?	95	-	300	600	- 60	-	1055
	'77		?	90	-	400	1900	-150	-	2540
6. Danish Straits	Jul.'75 - Dec.'76	27 360	?	5	-	-	-	- 12	-	17
	'77		?	20	-	-	-	- 18	-	38
7. Kattegat	Jul.'75 - Dec.'76	106 010	?	100	-	-	-	-	-	100
	'77		?	170	-	-	-	-	-	170
1 - 7 Total Baltic	Jul.'75 Dec.'76	1 721 233	?	570	227	477	600	- 72	-	1946
	'77		?	1410	292	1402	1900	-168	-	5172

The same technique was applied to the Swedish data. The temporal extrapolations extended however only between the years 1961-66. The transport values from the river Ångermanälven were available for the whole period (Nilsson 1974). The transport from the unmeasured areas was estimated in the same way as for the pilot study.

The transport from the Danish islands and from Jylland to the Baltic Sea and to Kattegat was difficult to estimate. Irregular measurements in nine small rivers on Själland gave transport values ranging between 5 - 20 kg/day and km^2. Taking the different water discharges during the investigation into consideration, an estimate of about 15 kg/day and km^2, or in round number an annual transport of about 6 t/km^2, seems to be a reasonable value for the mass transport condition on Själland. This estimate could also be valid for the conditions of the rest of the islands, i.e. an area of about 12,000 km^2.

In Jylland some investigations during 1969-74 gave sediment discharge amounts ranging between 10 - 27 t/km^2 in rivers discharging to the North Sea (Hasholt 1974, Höst-Madsen and Edens 1974). These values seem to be too high compared to the Swedish river Viskan, which in the lower part of its drainage basin flows through soils rather similar to the soils of Jylland. Annual mean transport during the years 1967-77 of the river Viskan was 7.3 t/km^2. Taking into account the soil distribution of the Viskan basin, with 20 % exposed bedrock and 40 % till which is comparatively resistant to erosion, the contribution from the rest of the basin to the total transport would be about 12 t/km^2. This amount was considered to be a reasonable value of the annual transport from Jylland.

Rough estimates of the areas of the different drainage basins were made. According to these estimates, about 1,000 km^2 of the area is drained to the Baltic, 9,000 km^2 to the Belt Sea and 2,000 km^2 to Kattegat; from Jylland water from about 2,000 km^2 is discharged to the Belt Sea and from about 6,000 km^2 to Kattegat.

For the calculation of the mean annual suspended sediment transport for individual rivers of the southern and eastern parts of the drainage basin of the Baltic Sea, data from various sources were used (Branski 1974, 1975; IAHS 1974; Lisitsina and Aleksandrŏva 1972; Lvovic 1971; GGI 1975-76; Mikulski 1975). This refers to the rivers on which the transport is gauged. The data are rather inconsistent and collected in different periods. Most of the data come from the years 1950-70.

In collecting the supplementary data for the areas for which no information was available, the following approach was made:

1. for a portion of the drainage basin of the Gulf of Finland, a unit denudation index (M_R in t/km^2 year) was evaluated after Lisitsina and Aleksandrŏva (1972)

$$M_R = 0.005\, M_Q^{3.3}$$

where M_Q is the specific annual runoff in $l/s\ km^2$.

The M_Q value was found from the data according to Mikulski (1975).

2. for the drainage basins of the Baltic for which the measurements do not cover the entire drainage area under study, the M_R value for the missing area was estimated from the gauged basin, i.e.

$$M_{R(basin)} = \sum RA \,/ \sum A$$

The difference between the drainage area considered and the gauged drainage area was multiplied by the M_R value found.

3. as concerns the drainage basin of the Baltic proper, on the GDR territory and on the Belt Sea area, as well as that on the GDR and FRG territories calculation of the unit denudation index M_R was based on the analogy to the western part of the Pommeranian Lake Country in Poland, i.e. to the basins of the Rega, Parseta and Wieprza rivers according to

$$M_R = \frac{\sum RA \text{ (Rega + Parseta + Wieprza)}}{\sum A \text{ (Rega + Parseta + Wieprza)}}$$

The results of all the calculations of the input of suspended matters to the Baltic Sea during the decade 1961-70 are summarized in the Main Table 10.

9.4.3 Discussion of the results

Due to very unevenly distribuated measurements, geographically as well as in time, an estimation of the total suspended transport to the Baltic must have a limited accuracy.

From some regions no transport data were available at all and from other regions there were data series of one to twenty years of length. Besides the poor network and data series for different periods of time, also the fact that many power plants were constructed during 1960's, implying a complete change of transport conditions, contributed in making the estimation of the mass transport a mere guesswork. Furthermore, the techniques of sampling, of analysing and of data evaluation often varied from one investigation to an other.

Certainly some intercalibrations of methods were carried out in Denmark, Finland and Sweden. Still a lot of work remains to be done before the calibrations are statistically proved.

According to the estimates given the total input of suspended matters to the Baltic is in order of 7.5 million tons a year. The input per km^2 is from Denmark 8.4 t/km^2, from Poland 6.7 t/km^2, from Sweden 4.5 t/km^2, from Finland 4.0 t/km^2 and from the USSR 3.6 t/km^2.

Though sligthly disturbed by the large lake areas of middle Sweden, central Finland and of the Neva drainage basin, the geographical pattern of the denudation in the individual river basins shows an increase from the north to the south. In view of this fact, the estimated denudation of Denmark, which is high, might be rather reasonable.

Chapter 10

CALCULATED FRESHWATER BUDGET OF THE BALTIC AS A SYSTEM

Zdzislaw Mikulski (Sweden) and Malin Falkenmark (Sweden)

10.1. INTRODUCTION

As described in Chapter 3, the basic aim of the Baltic Sea project was to arrive at separate determination of all the individual water balance elements for the joint "historical" time period, 1951-70. This effort would give homogenous and mutually comparable data and would better reflect the water balance in its various details than earlier studies which have had to operate with data for different time periods, i.e. non-homogenous data. By comparing the long term averages of the individual elements and their relations, earlier conclusions could be cheked for reliability. Interannual variations between years of different character could be studied. This would give a good idea also of various extreme conditions in the Baltic system.

The main part of the study was to be based on monthly averages of the different water balance elements. During the 18-month-period of intensified synchronous studies, the so-called Pilot Study Year (July 1975 - December 1976), some elements were even analysed on a day-by-day basis. During the pilot study, the closing error should be evaluated, and the basic phenomena characterizing the water exchange through the Danish Straits be illuminated.

By basing all the element studies on a regional differentiation of the Baltic, composed of five different subbasins inside the thresholds in the Danish straits, and two additional areas in the transitional estuary region, a deeper understanding should be arrived at. Conditions in the different subregions or subbasins could be compared, and an increased understanding achieved of the water renewal of the different parts of the Baltic. The conditions should be studied both as long-term average conditions, and as conditions during extreme years and extreme monthly situations on the whole.

The studies performed on the individual elements have been reported in some detail in the earlier chapters 4-9 of this International Summary Report. In this chapter, the whole budget will be discussed and analyzed.

For easy reference, the final data on water balance elements are exposed in a separate data annex to this report, according to the following key table (Table 10.1).

Table 10.1 Key table on data for the individual water balance elements

Legend: Main Tables are marked with an M, text tables with a T

Element	Reference period 1931-60 subbasins	Reference period 1931-60 entire system	Historical period 1951-70 subbasins	Historical period 1951-70 entire system	Pilot study year subbasins	Pilot study year entire system
Precipitation	M 5	M 5	M 6	M 6	T 5.4	T 5.4
Evaporation	M 7*	M 7*	M 8	M 8	T 6.4	T 6.4
River inflow	-	M 3	M 4	M 4	T 4.1	T 4.1
Water volume changes	-	-	M 9	M 9	-	-
Net water exchanges	-	-	-	-	-	T 8.1
Suspended sediments	-	-	T 9.3	-	T 9.2	-
Dissolved transport						
Water balance components	-	T 10.2	M 11	M 11	-	T 10.4

* period 1862-1978

The Group of Experts already in 1971 decided that homogenous data on all water balance elements should be compiled for two ten year periods (1951-60, 1961-70). It was also considered desirable to extend the analyses to the climatological 30-year reference period of WMO 1931-60. When the joint work had started, it turned out that long series are possible to bring together for certain elements (precipitation, runoff), whereas for others difficulties emerged already with the two historical decades. This was the case for evaporation, for exchange with the North Sea and for suspended substances.

For certain elements, data are available also for periods others than those reproduced in the present report. The reader is referred to the full reports of the element coordinators in this respect. For instance, a 55 year data series is now available for river inflow, and a 100 year average for evaporation (although not homogeneous with the other elements).

For the Pilot Study Year (July 1975 - December 1976), monthly data were gathered on a continuous basis, including water exchange through cooperation with the Danish Belt Project.

10.2 LONG TERM AVERAGE CONDITIONS

10.2.1 Average annual water budget of the Baltic as a system

In bringing together the different long-term averages for the main elements of the water balance of the Baltic Sea, the seven riparian countries have made possible a thorough analysis of homogenous data. Comparisons can now be made with earlier studies, which have to this point of time been considered as "classical" water balance data of the Baltic Sea, and used as a basis for a considerable amount of ecological and oceanographical studies of the Baltic.

Water balance of the historical period 1951-70

The elements of the freshwater balance of the Baltic Sea, for subbasins 1-5 and 1-6 respectively, averaged over the 20-year period 1951-70, are exhibited in Table 10.2. Setting the net freshwater inflow $Q_0 = P - E + L$ to areas 1-5 at 100 % (476 km^3/yr), it could be seen that this inflow is composed of a horisontal component of 436 km^3, coming from the drainage basin and carried by the rivers (92 %), and a vertical component of 40 km^3 or 8 %. The latter forms the difference between precipitation (224 km^3) and evaporation (184 km^3).

Of the net freshwater inflow, 99 % is reflected as net freshwater outflow and 1 % is kept in temporary storage in the Baltic. It could be seen that precipitation dominates over evaporation (22 % higher), and that the river inflow is the dominating source of freshwater (92 % of the net freshwater input). The fact that the storage change during the period is so low, is explained by the averaging over 20 years with variable storage conditions.

Average sea level for the period 1951-70 was -7.8 cm. Highest annual mean level (3.4 cm occurred in 1967, a wet year, see below) and the lowest (-17.4 cm) in 1960. Amplitude of average annual level was accordingly 20.8 cm.

Reference period 1931-60

Table 10.2 also allows a direct comparison between the historical 20-year period and the 30-year reference period 1931-60. The differences are quite moderate (less than 6 %) and vary in size: whereas precipitation was 6 % larger during the reference period, the river inflow was 2 % lower. It might be recalled that the period 1931-60 is considered to be a rather dry 30-year period, at least in Sweden. The storage change has been assumed to even out totally for the 30-year period, as a working hypothesis. The higher net freshwater input is reflected in a somewhat higher net outflow.

Table 10.2. Water balance components (km^3/yr)

	Without Belt Sea and Kattegat (1–5) A = 372 858 km^2 1951–70	1931–60	Brogmus		Without Kattegat (1–6) A = 392 979 km^2 1951–70	1931–60	Brogmus
Precipitation P	224	237	172	77 %	239	250	183
Evaporation E	184	(184)	172	93 %	193	195 *	183
River inflow L	436	428	472	108 %	444	436	479
Net freshwater input $Q_o = P - E + L$	476	481	472	99 %	490	491	479
Storage change ΔV	+ 5	0	0		+ 5	0	0
Net outflow $Q_o - \Delta V = H - M$	471	481	472	100 %	485	491	479

* Longterm average 1868-1978. From Henning (1985)

Comparison with earlier water balance estimates

The standard values generally used by oceanographers during the last 30 years are those of Brogmus (1952), also exhibited in Table 10.2. A comparison shows that, for regions 1-5, precipitation has been underestimated by some 23%. Also evaporation has been underestimated by about 7%. About 2% of those 23 and 7% respectively are due to sea area differences in the calculations. It is interesting to note that the remaining underestimations took place in spite of the fact that Brogmus used data from the wet 20's. His working hypothesis was that precipitation and evaporation evened out to a vertical balance term of zero. The large underestimation of the precipitation in the past is due to a missing correction of precipitation observations for the aerodynamic deficit, introduced by the measuring device itself.

The evaporation determinations made by Henning (1985) show that, although the basic hypothesis of Borgmus was bad, the estimated value in itself turned out to be rather realistic. It should be stressed, though, that the present estimate still remains unprecise; the pilot study year in fact provides the main data core from which extrapolation backwards in time has taken place as earlier indicated (Chapter 6).

In Table 10.3 the historical development of water balance estimations is demonstrated. The table indicates that, although the estimate of Spethman (1912) and Witting (1919) of the net freshwater inflow was larger than the final IHD/IHP values, they still underestimated the precipitation heavily. Witting's estimate of evaporation is quite acceptable, however.

Table 10.3
Water balance of the Baltic Sea/after different authors

Elements of water balance	Krümmel (1904) A= 431 000 km^2 mm	km^3	%	Spethmann (1912) A= 406 720 km^2 mm	km^3	%	Witting (1918) A= 386 000 km^2 mm	km^3	%	Sokolovsky (1933) A= 375 000 km^2 mm	km^3	%
Precipitation /P/	550	(237)	42	400	163	26	565	206	31	550	211	32
Evaporation /E/	183	(80)	14	(197)	80	13	498	182	27	500	193	30
River inflow /L/	(773)	333	58	(1150)	467	74	(1278)	467	69	1172	440	68
Net freshwater inflow $Q_o = P - E + L$	1140	490	86	1353	550	87	1345	491	73	1222	458	70
Inflow from the North Sea /M/												
Outflow to the North Sea /H/												
Balance total P + L + M = E + H	1223	570	100	1550	630	100	1843	673	100	1722	651	100

Elements of water balance	Brogmus (1952) A= 386 000 km^2 mm	km^3	%	A= 365 000 km^2 mm	km^3	%	IHD/IHP (1931–50) A= 392 979 km^2 1–6 mm	km^3	%	A= 372 858 km^2 1–5 mm	km^3	%
Precipitation /P/	474	183	13	471	172	15	637	250	17.5	636	237	21
Evaporation /E/	474	183	13	471	172	15	497	195	13	493	184	16
River inflow /L/	1240	479	34	1290	472	42.5	1110	436	30	1147	428	37
Net freshwater inflow $Q_o = P - E + L$	1240	479	34	1290	472	42.5	1250	491	34	1290	481	42
Inflow from the North Sea /M/	(1910)	737	53	(1290)	(472)	42.5	(1920)	(755)	52.5	(1290)	(481)	42
Outflow to the North Sea /H/	(3150)	(1216)	87	(2580)	(944)	85	(3170)	(1246)	87	(2580)	(962)	84
Balance total P + L + M = E + H	3624	1399	100	3051	1116	100	3667	1441	100	3073	1146	100

* Evaporation 1862 - 78

10.2.2 Interannual fluctuations

Benefitting from the fact that data on both river inflow and sea volume increments are now available also for the individual years of the historical period 1951-70 - see the full reports from the element coordinators on these two elements (Mikulski 1982, Lazarenko 1980) - the interannual fluctuations of the water balance could be studied at least approximately (Fig. 10.1). As annual data are unfortunately missing on both precipitation and evaporation, it has been assumed that precipitation exceeds evaporation with on the average 40 km^3/yr. This is a very crude assumption, though, because in dry years evaporation tends to be markedly above average (cf section 10.3.2), while in wet years evaporation remains significantly below average values.

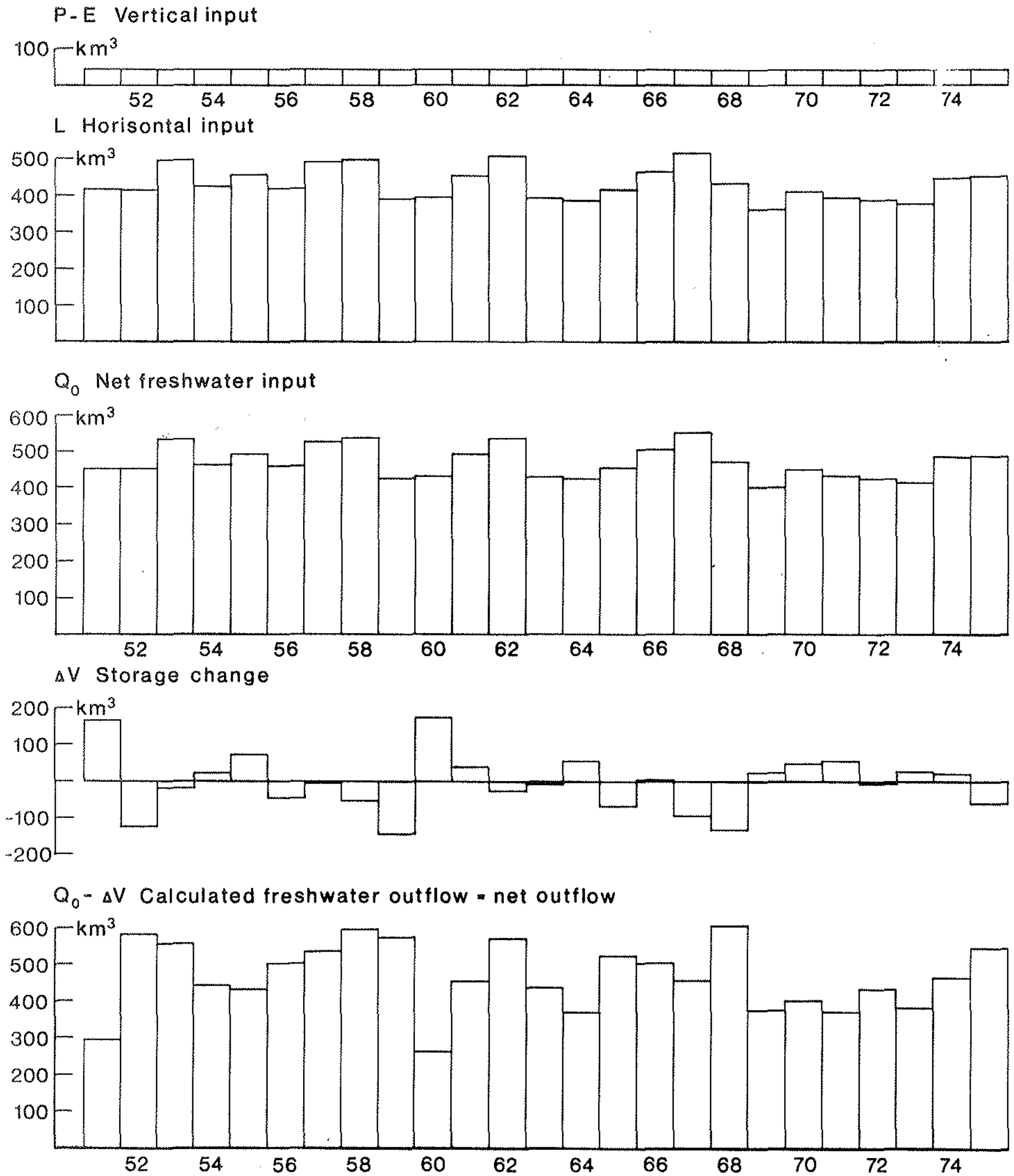
The water volume increment from one year to the next varies between an increase of over 60 km^3 and a decrease of 140 km^3, when added up for subbasins 1-5 (Lazarenko 1980). The annual river inflow, during the individual years of the 20 year period, fluctuated between a minimum of 360 km^3 (1969) and a maximum of 511 (1967), i.e. within an interval of plus minus 17 % around the average. This means that the freshwater inflow has varied between a minimum of 400 and a maximum of 550 km^3. We may conclude that the freshwater outflow has varied between about 250 and 600 km^3, or between 54 % and 127 % of the average.

From the interannual course of storage change (ΔV) and net outflow (H - M), exhibited in Fig. 10.1, we can see that large net outflows have generally occurred in combination with negative sea volume increments. In other words, the large outflows have been partly composed of a contribution released from the sea storage. Also the opposite is true: the years 1951 and 1960, when the net outflow took on its lowest values during the 20-year preriod, the storage increased in the Baltic with around 160 km^3 on both occasions. Certain years, more than 40 % of the river inflow may remain in storage, whereas during other years, a sea water storage release corresponding to 40 % of the inflow may add to the outflow.

Studying the river inflow during the different years (cf Fig. 4.1.), it can be seen that wet years were 1953, 1958, 1962 and 1967. Dry were on the other hand the years 1959, 1960, 1963, 1964 and 1969. From Fig. 10.1 we can see that years with low net outflow were 1951 and 1960, whereas the net outflow culminated in 1952, 1958 and 1968.

In conclusion, there are considerable differences between individual years both in the relations between individual elements and in the water volumes involved in the water balance. When averaging over a long-term period, these differences are wiped out. Such extreme conditions as can be seen during individual years evidently influence the ecological situation in the Baltic system considerably. Therefore, the water balance should be continuously monitored.

Before ending this discussion on interannual fluctuations, we may observe that the two most extreme years of the 20-year period in terms of river inflow were 1967 (inflow to subbasins 1-5 511 km^3) and 1969 (inflow 360 km^3). However, it turns out that the pilot



10.1 Composition of water balance for Baltic Sea (subbasins 1-5) Interannual fluctuations 1951 - 75. Vertical input, see text year 1976 was even drier, with a river inflow close to two standard deviations beneath the long term average (Jacobsen 1980). We will therefore come back later on the analysis of extreme conditions in terms of water balance elements and their relations.

10.2.3 Seasonal variations of water balance elements

Individual elements

The water balance elements, averaged for the period 1951-70, month by month, are given in Main table 11 and Fig. 10.2a. It could be seen that the precipitation culminates during July-September and has its minimum in March-April.

The evaporation exhibits a somewhat revolutionary difference in relation to land: the evaporation is high during September-December and low April-June, i.e. 2-3 months phase difference relative to precipitation.

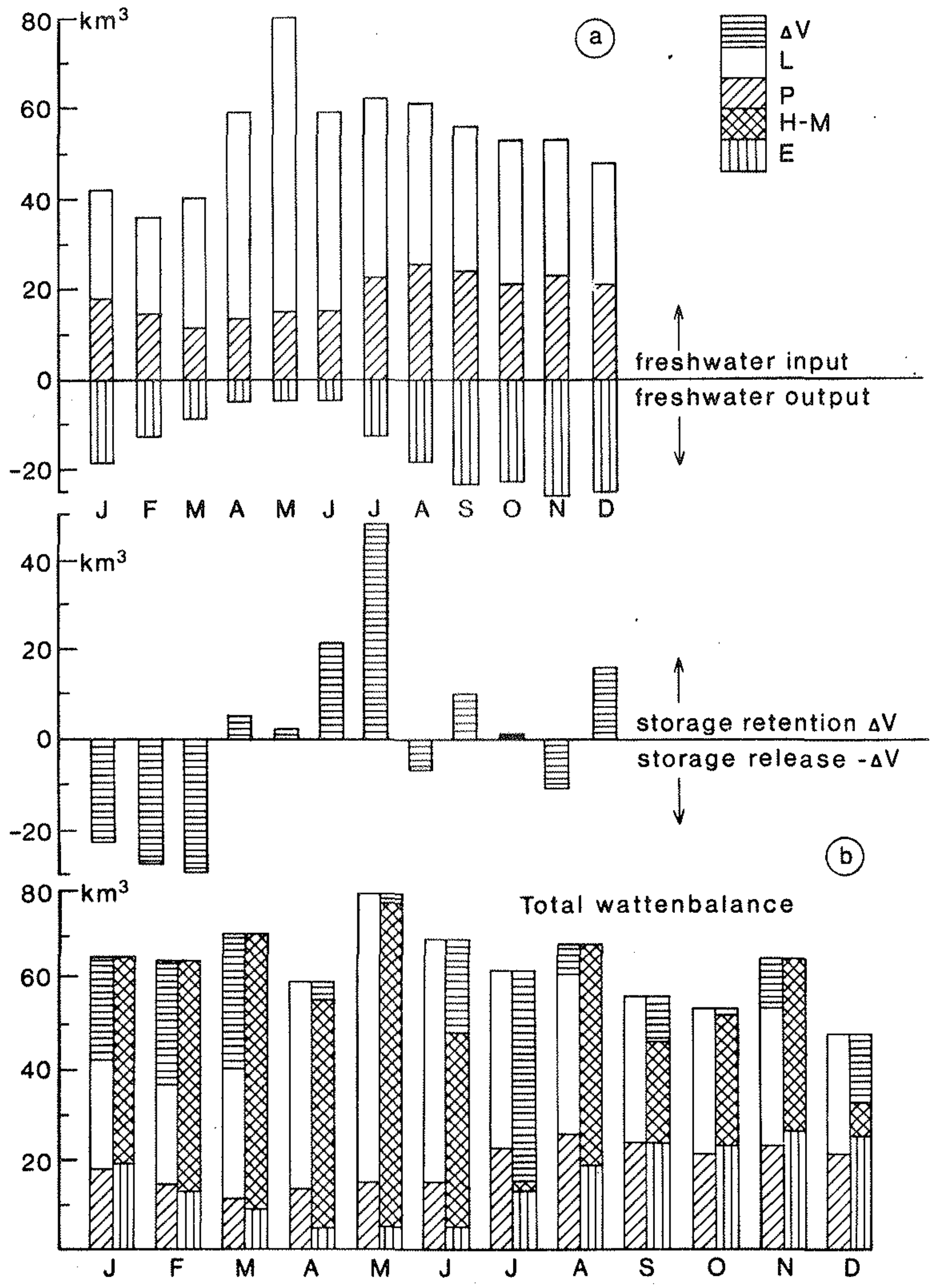
The seasonal variation in sea water retention (sea volume increment) shows a systematic release of retained water during the winter months January-March, whereas water is retained in the Baltic during April-July with maximum retention in July. During the autumn, conditions are less regular, due to autumn storms.

Annual course of the total water balance

The annual course of the total water balance is shown in Fig. 10.2b, visualizing the size of the water masses in movement in the Baltic sea during different parts of the year. During autumn and winter (Oct.-Jan.), evaporation predominates over rainfall, certainly promoting a decrease in storage. A temporary water storage in December decreases the net water outflow during this month. However, in spring, the considerable increase in river inflow with maximum in May, causes in this month the highest value of net water outflow. The low evaporation and the low storage change promotes this development.

The net outflow similarly culminates in the spring when water storage is quite inactive. The opposite configuration is observed in July, when the freshwater outflow is practically zero due to large scale water retention in the Baltic Sea. A complementary combination takes place during winter months (Jan.-March) when the outflow receives a large contribution from released water, stored in the sea from the preceding summer and autumn.

The net water outflow varies between 1 and 70 km^3 with minimum by summer culmination and maximum in May. The most extreme feature during the average year is indeed the summer culmination in July, when all water is retained as water storage.



10.2 Annual course of the water balance of subbasins 1-5 (Average conditions 1951 - 70)
a) Water balance elements
b) Total water balance

10.3. SHORT TERM VARIATIONS OF THE WATER BALANCE

10.3.1 Pilot study year

Thanks to the independent and synchronous measurements of all the individual water balance elements during the 18-month period July 1975 - December 1976, good precision data are available for this period of time. Evaporation was much better estimated than during earlier periods. The estimated accuracy of the monthly evaporation for at least the entire Baltic and the large subbasins (Baltic Proper and the Bothnian Sea) was (in Chapter 6) assumed to be within plus or minus 5 %.

Within the Danish Belt Project, efforts were made to determine the transport through the Danish Straits through direct current measurements. However, the information gained through this study demonstrated the extreme difficulty in estimating the long-term net outflow from direct measurements, i.e. the average net outflow of an oscillating fluid of changing stratification. It was concluded that the monthly net outflow was more reliably determined from the water balance than from direct measurements (Chapter 8).

The sea water retention was also followed with great accuracy during this period of 18 months, when daily values were recorded (Chapter 7).

Individual elements

The monthly data for the individual elements have been brought together in Table 10.4 and are visualized in Fig. 10.3a.

The precipitation varied between 7 and 33 km^3/month, culminating in December 1976 with minimum in February 1976.

The river inflow fluctuated between 23 and 50 km^3/month with lowest inflow in November 1976 and the highest in May 1976.

The evaporation fluctuated between 4 and almost 40 km^3/month with minimum in May 1976 and maximum in October 1976. During autumn months both years, the high evaporation produced negative vertical balance.

The net fresh water inflow varied between almost 60 km^3/month in May 1976 and a net loss of 3 km^3 in October 1976, when the large evaporation dominated over the fresh water input from precipitation and river inflow added together.

The sea water volume changes alternated between storages and releases. Largest monthly storage increase was 116 km^3 (Dec. 1975), and largest release of stored sea water was 213 km^3 in February 1976.

When comparing these fluctuations with the long-term average conditions, the large divergences characterizing individual years are clearly illustrated. The regular course with storage

Table 10.4

Water balance of the Baltic Sea inside Danish Straits
Pilot study Year July 1975 - December 1976 [1)]
Sub-areas 1-5, units in km^3

Elements of water balance/km^3	VII	VIII	IX	X	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Total	Jul.-Dec. '75	Jan.-Dec. '76
Precipitation /P/	15.1	15.8	22.2	15.9	15.7	18.1	24.5	7.5	13.6	13.1	13.2	13.1	16.7	10.7	20.5	13.3	22.9	32.8	304.7	102.8	201.9
Evaporation /E/	10.4	29.4	27.0	27.3	28.6	30.0	22.3	8.7	10.6	4.4	3.9	6.2	16.3	19.7	36.2	38.8	15.2	25.1	360.1	152.7	207.4
River inflow /L/	30.1	28.8	27.1	32.6	27.2	24.0	27.0	24.0	27.2	37.8	49.7	35.7	26.1	25.3	22.8	22.6	23.2	24.0	515.2	169.8	345.4
Net freshwater input $Q_0 = P - E + L$	34.8	15.2	22.3	21.2	14.3	12.1	29.2	22.8	30.2	46.5	59.0	42.6	26.5	16.3	7.1	-2.9	30.9	31.7	459.8	119.9	339.9
Storage difference ΔV/	0.2	12.1	28.8	-2.4	-47.9	116.3	82.8	-213.5	-37.4	57.1	-37.4	37.7	0.0	9.9	-25.1	-102.0	72.7	100.1	52.0	107.1	-55.1
Net outflow meas.	-12.1 [2)]	77.2	-92.0	76.6	-9.3	-152.8	120.6	90.6	9.4	62.3	98.3	-56.5	2.8	140.1	56.9	-31.4	-169.6	92.0	303.2	-112.3	718.7
calc. $Q_0 - \Delta V = H - M$	34.6	3.1	-6.5	23.6	62.2	-104.2	-53.6	236.3	67.6	-10.6	96.4	4.9	26.5	6.4	32.2	99.1	-41.8	-68.4	407.8	12.8	395.0

1) Table compiled by Ulf Eblin (Sweden)
2) Little Belt not included

predominating in summertime, and release predominating during winter does not hold for this period. There were large releases in both February and October 1976, and very small storage changes both summers 1975 and 1976. Large retentions occurred in December both years.

Within the Belt Project which included also the Pilot Study Year, Danish oceanographers carried out intensive measurements of the currents in the Danish Straits (Chapter 8). The measurements obtained during this period were used to calculate the "observed outflow" and compared with the expected outflow as calculated from the IHP project. The measured outflow turned out to be systematically lower than the expected outflow, with an accumulated deviation during the Pilot Study Year of the order of 300 km^3. The large size of the standard deviation of the discharge - one order of magnitude larger than its mean value - makes it difficult to get reasonable estimates of the long-term net outflow not only from direct current meters but also by indirect determination from lightships observations, or hydrodynamic modelling of the discharge in the transition area. The conclusion from the Belt Project was therefore that "long-term mean values are best determined from the fresh water components of the water balance" (Jacobsen 1980), i.e. hydrologic water budget studies.

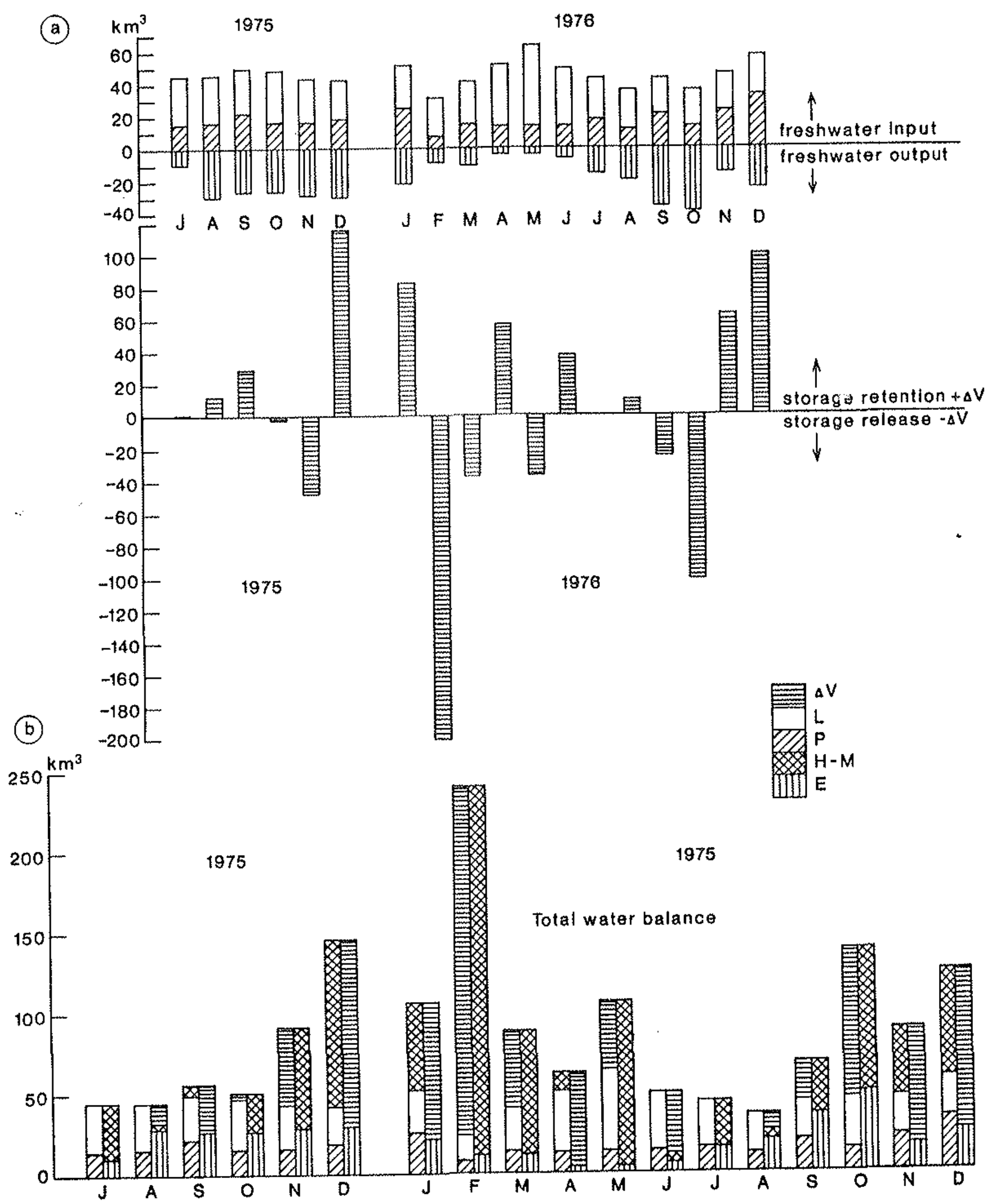
According to Jacobsen in Chapter 8, the net outflow is a function of the time scale. The water movements in the Straits are quite complicated, being the end result of a number of driving forces, out of which the freshwater surplus is just one factor. The size and the directions of the in- and outgoing flows vary with time. Measurements in the Belts have shown that values are by 10-20 % higher for hourly averages of discharge than for daily averages. Averages over prolonged periods converge to a long-term meanvalue, given a stationary process determined by the water balance equation.

Annual course of the total water balance

The annual course of the water balance, when combining the input and the output elements, is exposed in Fig. 10.3b. It is interesting to note, besides the negative vertical water balance during the autumn months both years (Aug. to Oct.) already discussed, that the two following months (Nov. and Dec.) have opposite character, with negative vertical balance in 1975 but positive in 1976. During five of the 18 months, evaporation was even greater than the river inflow (Nov.-Dec. 1975; Sept., Oct., Dec. 1976).

The net outflow was small in summer months both years, and took on large negative values in late autumn and early winter. This is equivalent to large net inflows of water from the North Sea during those months of more than 100 km^3 in December 1975, more than 50 km^3 in January and December 1976, and just over 30 km^3 in November 1976.

During all these months the net inflow from the North Sea resulted in large amounts of water stored in the sea. On the other hand, the huge net water outflow in February 1976 was a contribution from released storage of more than 200 km^3.



10.3 Water balance during Pilot Study Year (July 1975 - Dec 1976) for Baltic Sea (subbasins 1-5)
a) Water balance elements
b) Total water balance

10.3.2 Seasonal variations during extreme years

If we now compare the conditions during 1976 with the conditions during individual years of the historical period 1951-70, we note that the river inflow during 1976 was even lower than in the driest year of the 20-year historical period. By comparing the two years 1967, which was the wettest year of the 20 year period, with 1976 which was an extremely dry year, we may get an idea of extreme conditions, as summarized in the following table (Table 10.5).

Table 10.5. Comparison of extreme years

	wet (1967)	dry (1976)	historical (1951-70)	% of historical wet	% of historical dry
Precipitation	263	202	224	117	90
Evaporation	(189)*	207	184	–	112
River inflow	511	345	436	117	79
Net freshwater input	585	340	476	123	71
Storage	+94	-33	+ 5		
Net water outflow	491	405	471	104	86

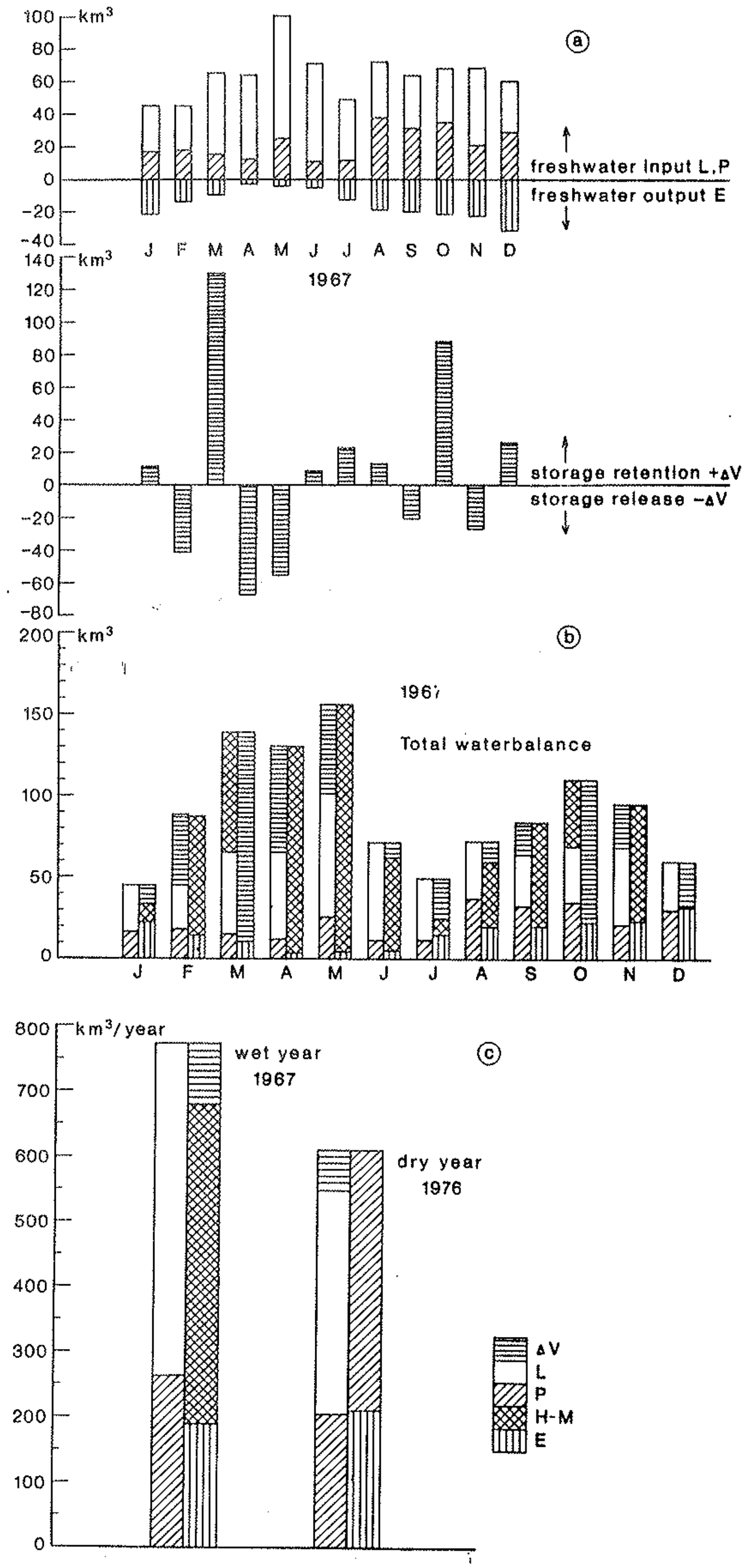
* 10 year average 1961-70 from Henning (1985) [1)]

The water balance during 1967 is shown in Fig. 10.4a (elements) and Fig. 10.4b (total water balance). Similar illustration for the dry year (1976) was already shown in Fig. 10.3a-b. In Fig. 10.4c a comparison is made between wet year and dry year water balances.

During the wet year, precipitation and river inflow are both 17 % above long-term average. The dry year evaporation is 12 % above average. The net water outflow is just 4 % above average during the wet year, and 14 % below during the dry year. The sea storage contributed about 8 % of the net outflow during the dry year, whereas a water volume corresponding to 18 % of the net outflow was kept in storage when wet year ended, to be later released.

During the wet year, there were two months of net inflow from the North Sea (March and Oct.) as compared to four months of inflow during the dry year, as already mentioned. For both years, storage and release from storage alternated during the course of the year.

1) By using, as an alternative, Henning's measured value for the wet year 1977 (163 km^3/yr) reality might have been better approximated. The net freshwater input and the net outflow during the wet year might therefore be underestimated about 5%.



10.4 Water balance during 1967 (a wet year) and comparison of overall balance with a dry year (1976) for Baltic Sea (subbasins 1-5)
a) Water balance components 1967
b) Total water balance 1967
c) Annual water balance 1967 as compared to 1976

10.4. REGIONAL DIFFERENTIATION OF THE WATER BUDGET

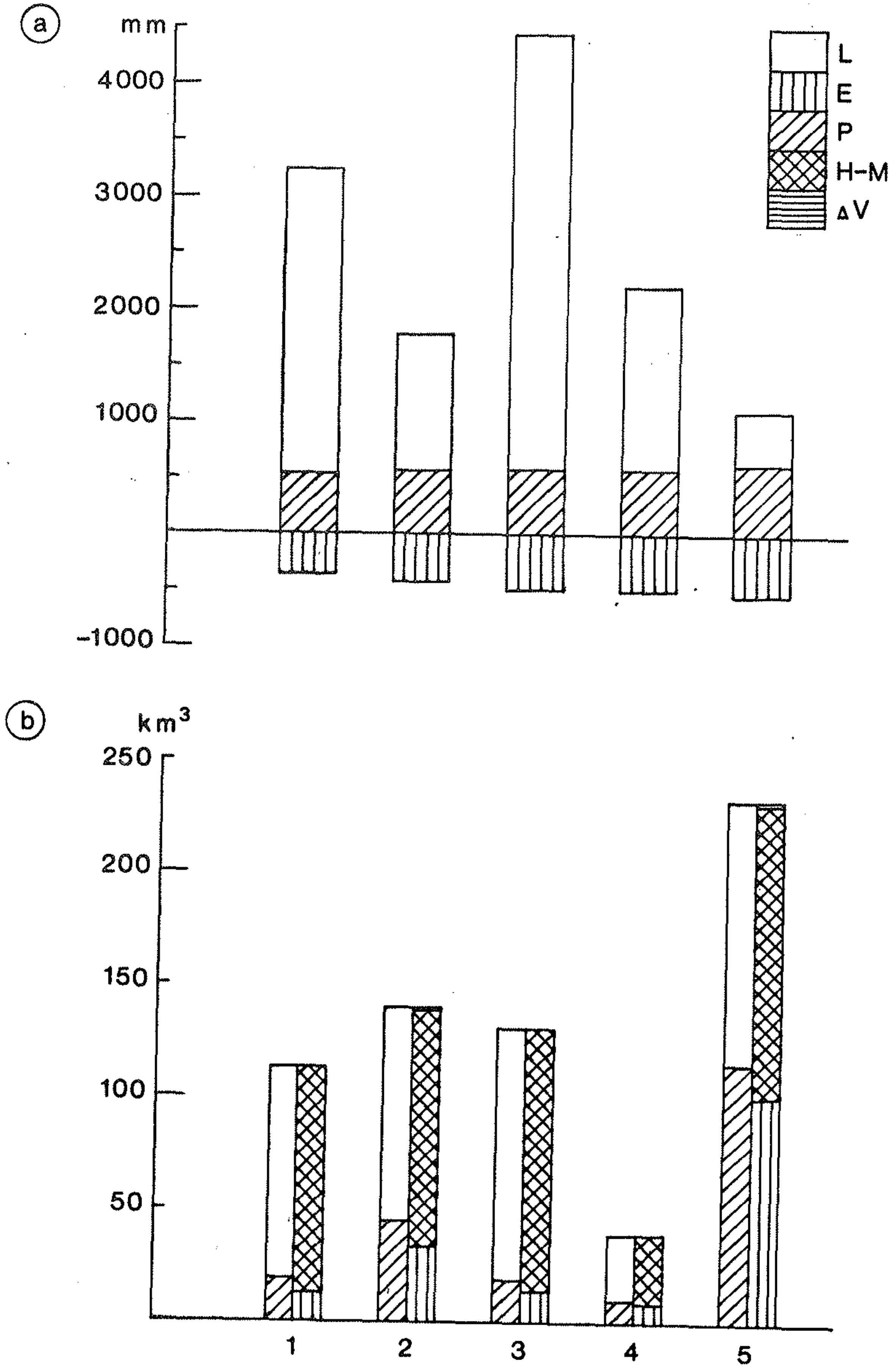
10.4.1. Baltic Sea a cascade of interconnected subsystems

It is evident from the map in Chapter 2 that the Baltic Sea is not a unity but the sum of a number of individual subbasins, defined by the plan and morphometrty of the whole system. In this respect one could talk of the Baltic as a cascade of interconnected subsystems. In this section, the implications of this fact will be closer analyzed, based on the data in Main Table 11. The water balances as summarized on a monthly basis in Fig. 10.2 is in other words the sum of the balances of the individual subbasins.

10.4.2. Hydrological comparison of individual subbasins of the Baltic

We will start this subbasin analysis by comparing, from a purely hydrological viewpoint, the individual subbasins based on data averaged over the period 1951-70 (Fig. 10.5a). The diagram indicates the layer thickness in mm when evenly distributed over the subbasin area. The vertical balance is consistently positive in all subbasins (of the order of 100-200 mm), largest in Bothnian Bay and Bothnian Sea, smallest in Baltic Proper. Both precipitation and evaporation increase to the South, but evaporation more. The largest input by river inflow takes place in Gulf of Finland due to Neva (of the order of 4000 mm). In Baltic Proper the vertical input dominates over the river inflow, basically caused by the large area. Bothnian Bay receives large amounts of river inflow (2800 mm), Bothnian Sea and Gulf or Riga about 1000-1500 mm/yr.

Fig. 10.5b exhibits the complete endogenous balance elements of the individual subbasins, now expressed in km^3/yr, showing that the net outflow, formed by the fresh water input to the basin is practically the same in all subbasins except Gulf of Riga, where it is of the order of one third of that water mass. The endogenous outflow is not extremely large from Baltic Proper in spite of the large area. This is due to moderate inflow in relation to the area. The composition of the total water balance in horisontal and vertical elements shows that the horisontal elements dominate in all except Baltic Proper, where the vertical elements is of the same order of magnitude as the horisontal ones. In short, subbasins 1-4 (Bothnian Bay, Bothnian Sea, Gulf of Finland and Gulf of Riga) are all throughflow basins already from endogenous aspects, whereas subbasin 5 (Baltic Proper) has a more static character.



10.5 Endogenous water balance of the individual subbasins (average 1951 - 70)
a) Water balance elements
b) Total water balance

10.4.3 Seasonal fluctuations of the endogenous water balance

Fig. 10.6a-e demonstrates the regime of the seasonal variations for all the subbasins, when averaged for the 20 year period 1051-70. It shows that the subbasins have consistently positive balance even when seen on a monthly basins, with the only exception of the Baltic Proper in July, which receives a large inflow of water that month. Two other similar phenomena (Gulf of Riga in July, Baltic Proper in December) are so small that they may be within the limits of precision. It may be recalled that in the combined balance of the whole system, the net outflow is practically zero for July (cf. Fig. 10.2b)

During the winter months, the storage change is systematically negative in each one of the individual subbasins 1-5, releasing stored water to contribute to the outflow. This element is evidently a secundary element in the water balance, phenomenologically determined from the other ones. The diagrams also show that subbasins 1, 2 and 3 (Bothnian Bay, Bothnian Sea and Gulf of Finland) are typical throughflow basins during the main part of the year due to inflowing large rivers, with the horisontal terms dominating over the vertical ones.

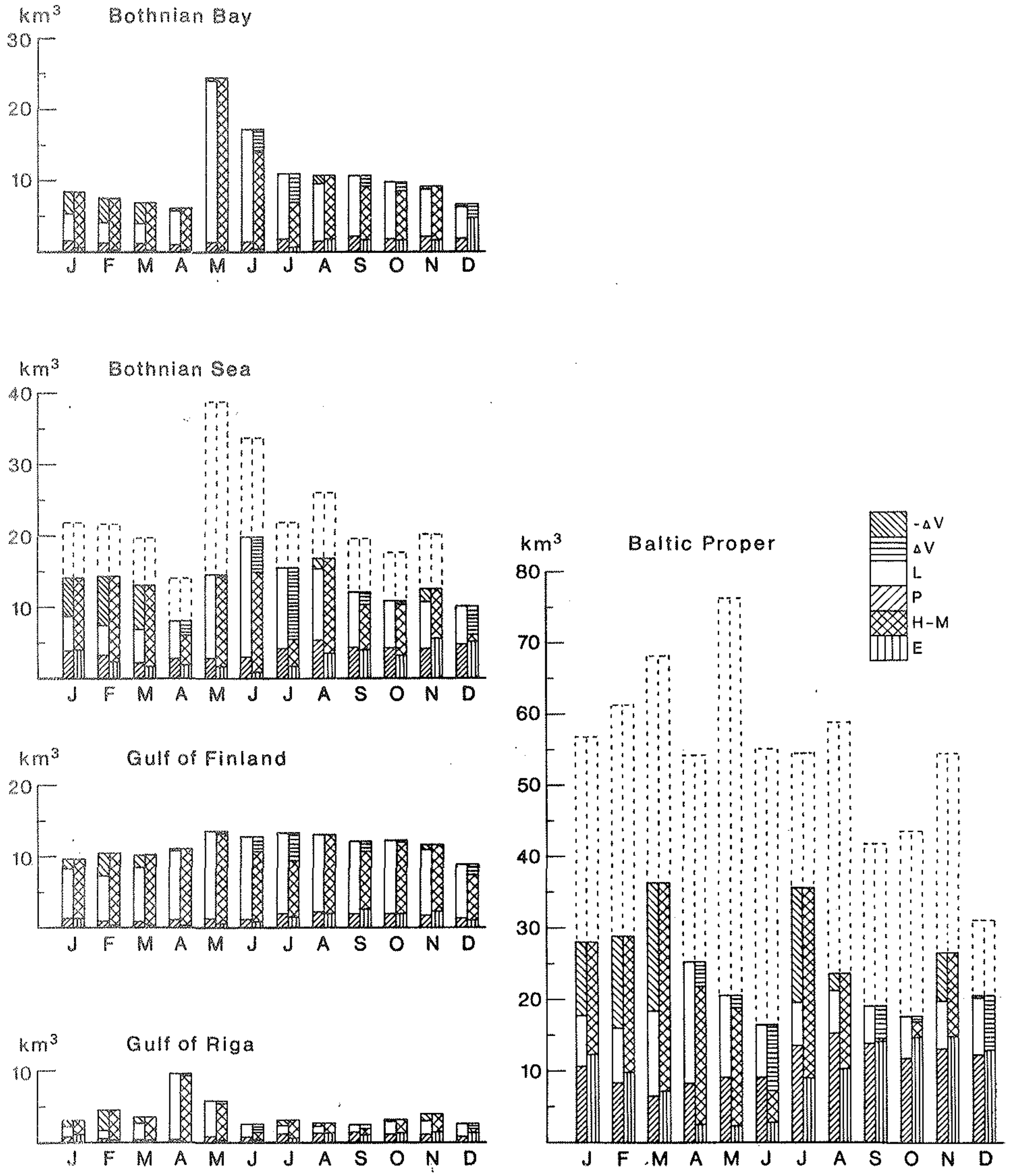
Conditions are less regular in Baltic Proper (subbasin 5), as expected. The vertical balance dominates in autumn and early winter (Aug.-Dec.). In the other subbasins, the vertical balance plays a smaller role.

10.4.4 Real water exchange, considering also the freshwater throughflow

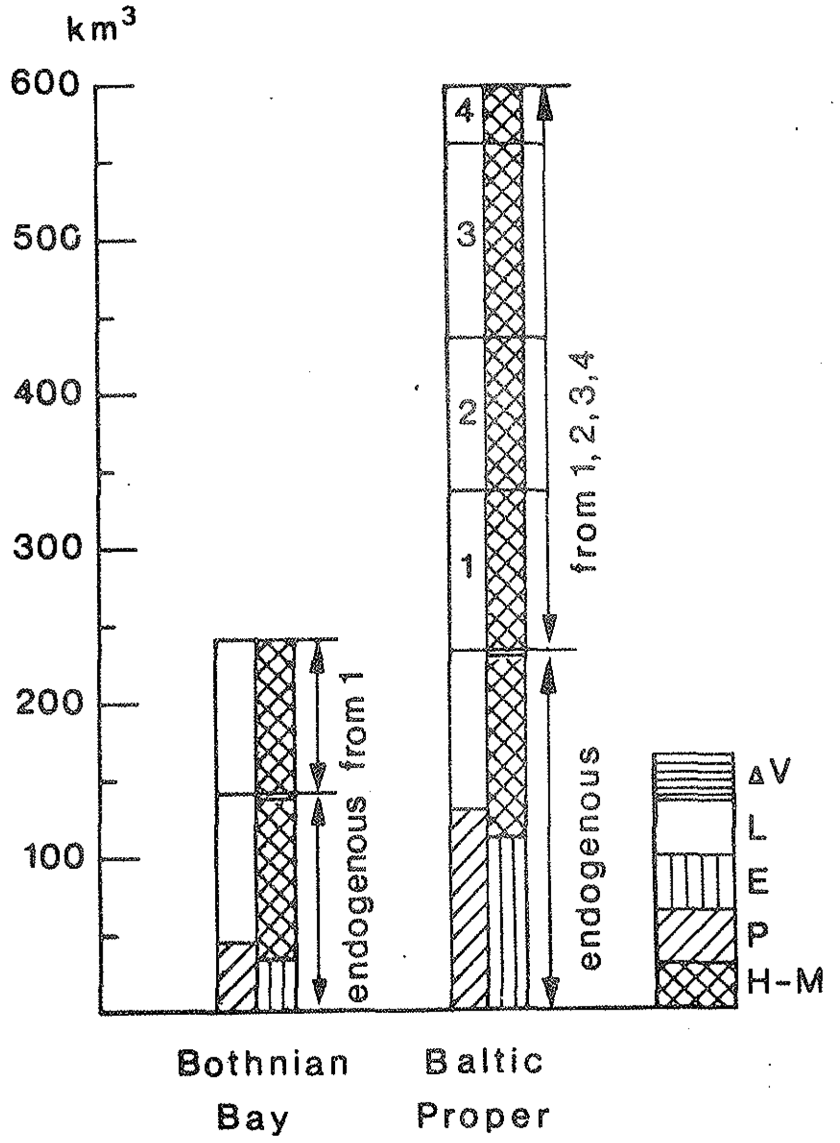
Up til now we have been considering the subbasins as individual subsystems under horisontal influence only from their own drainage basins. We are now turning to the composite system by interconnecting these subsystems to a cascade, thereby exposing them to a throughflow component of exogenous fresh-water emerging from subbasins further upstream in the system, i.e. to the influence from "upstream" drainage basins.

The real fresh-water exchange conditions are also reflected in Fig. 10.7 where attention is paid also to the throughflow component. Seen on an annual basis the exogenous throughflow of Bothnian Sea is practically doubling the endogenous net freshwater output. In Baltic Proper, the outflow is multiplied by a factor 4 through the considerable exogenous additions from all the subbasins further up the cascade. The total water exchange of this subbasin increases from the endogenous 240 km^3/yr to 580.

When seen on a monthly basis, it is evident from Fig. 10.6 that for the Bothnian Sea, the endogenous water exchange dominates during most of the year. Equivalence characterizes June, whereas the exogenous contribution dominates in May. For Baltic Proper,



10.6 Annual course of total water balances of individual subbasins (average 1951 - 70). Hatched column = contribution due to throughflow from subbasins higher up in the cascade



10.7 Composition of total water balance of throughflow subbasins (average 1951 - 70)

balance generally holds between endogenous and exogenous water exchange, whereas the exogenous dominates during spring and early summer (April-June) when the spring flood passes through. The endogenous exchange varies with a factor 2, the endogenous contribution to the outflow with a factor 60. The endogenous and exogenous contributions sum up to a total water exchange, subject to only moderate seasonal variations. In March, the endogenous contribution is about 40% of the total. Most extreme is September with practically no endogenous contribution.

From Baltic Proper, the water flows northwards through the down-stream subbasins 6 and 7 with practically no more endogenous contribution (< 3 km^3).

10.4.5 Overall freshwater exchange of the whole system

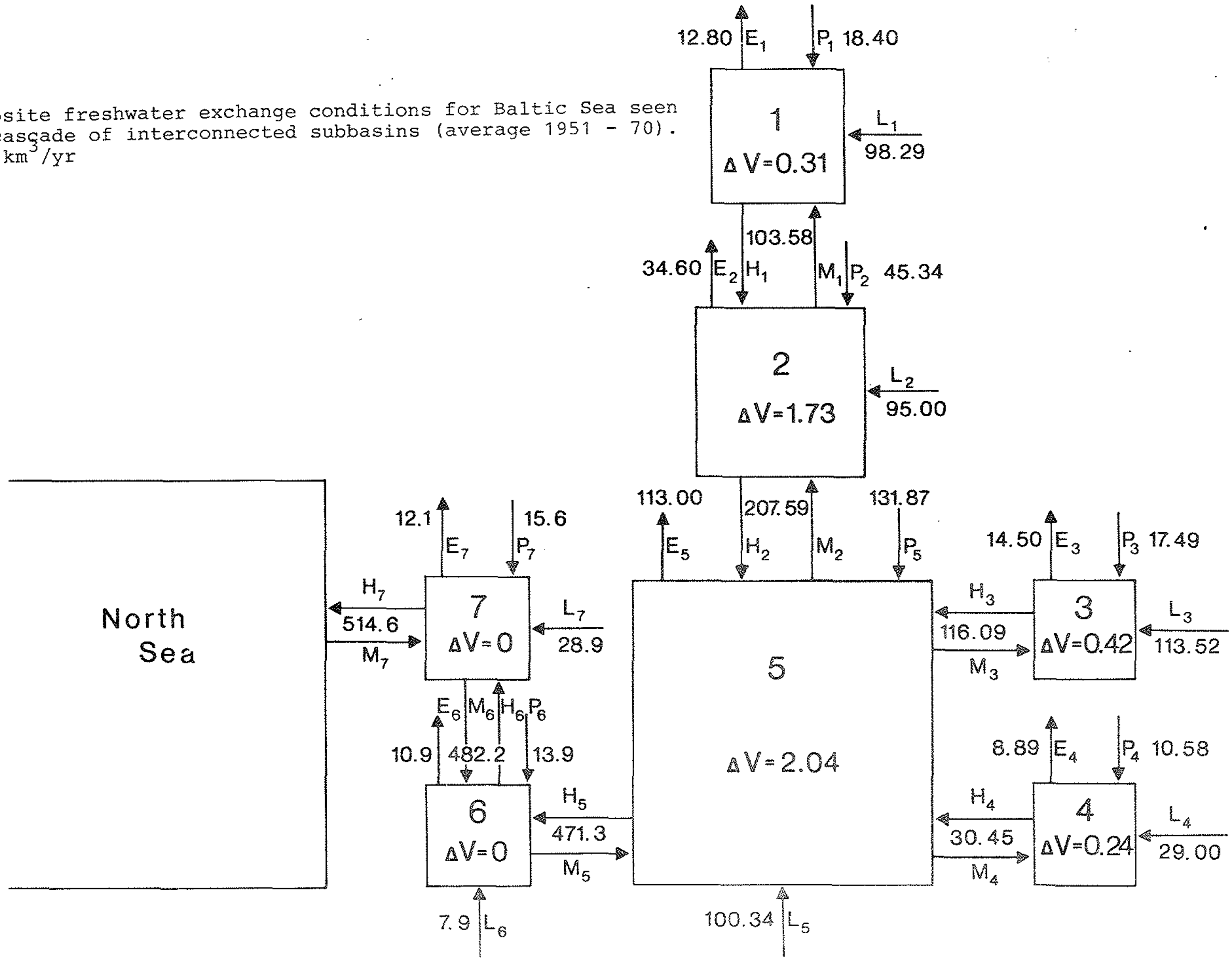
The composite freshwater exchange conditions of the whol cascade system is summarized for the historical period 1951-70 in Fig. 10.8, showing how the horisontal and vertical contributions from the various subbasins add up - subbasin by subbasin - to the final net outflow of ca. 520 km^3/yr.

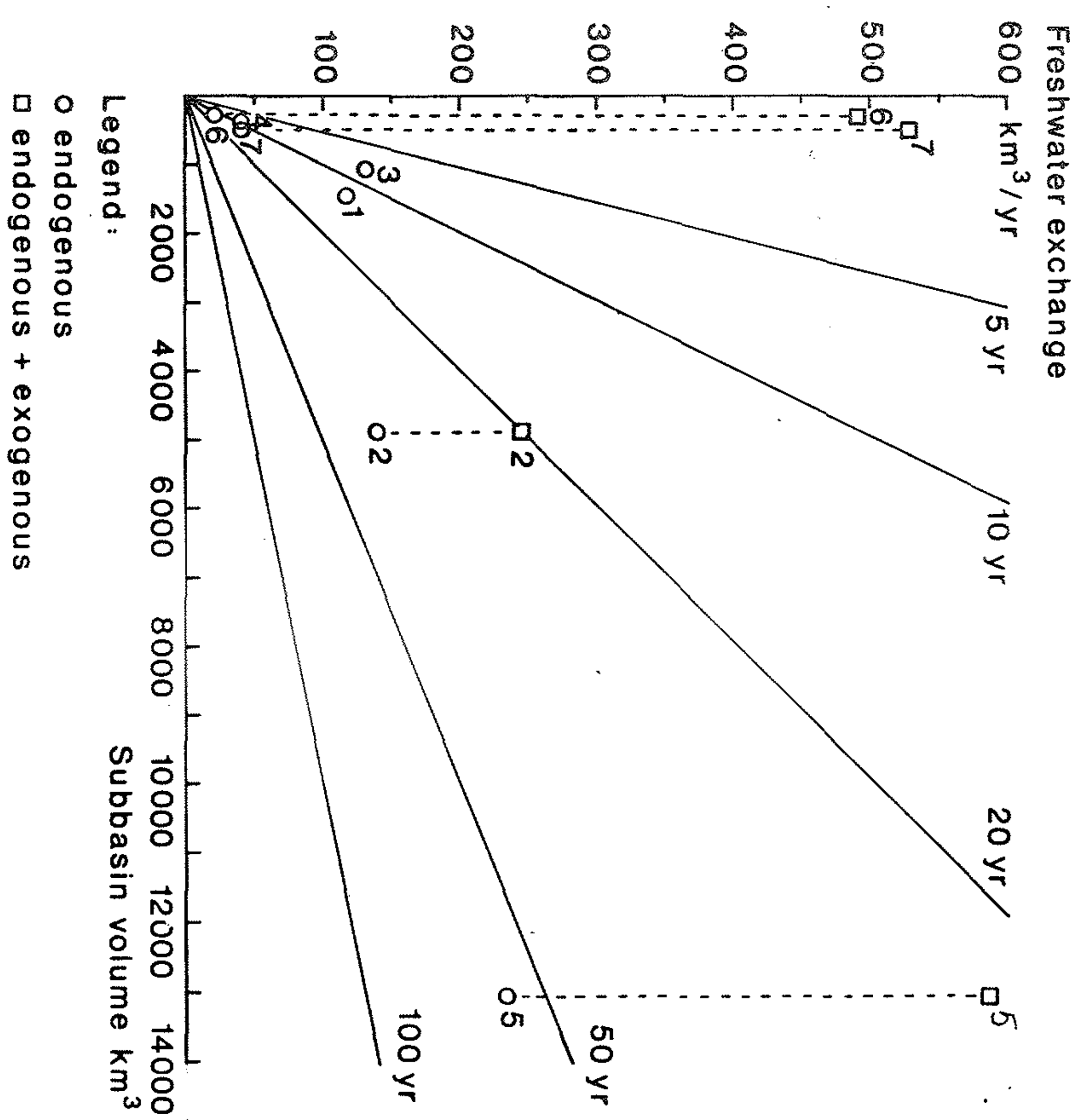
Fig. 10.9 finally illustrates the hydrological character of the various subbasins in terms of time characteristics under the assumption of complete mixing (exchange times). For example, the endogenous freshwater balance of the Bothnian Sea would alone need just under 50 years to exchange the whole water mass. Thanks to the freshwater throughflow from the Bothnian Bay, the exchange time is reduced to about 25 years. Likewise, the Baltic Proper, if only supplied with the endogenous freshwater contributions, would be practically stagnant with an exchange time of a whole century. All the freshwater from upstream parts of the cascade system, however, speed up the water exchange considerably to an average exchange time of about 25 years.

It should be noted that this water exchange takes place irrespective of the salt water inflow through the Danish Straits. Thus, in addition to the freshwater generated water exchange, there is an additional water exchange, generated by the salt water inflow. The total outflow (H) is therefore composed of a freshwater component (H-M) of about 470 km^3/yr at the outflow of Baltic Proper and a salt water component (M), determined by the size of the inflow.

10.8.

Composite freshwater exchange conditions for Baltic Sea seen as a cascade of interconnected subbasins (average 1951 - 70). Unit: km^3/yr





10.9 Hydrological character of the individual subbasins of the Baltic Sea. Crossing lines indicate exchange time (assuming complete mixing)

Chapter 11

CONCLUSIONS

Zdzislaw Mikulski (Poland) and Malin Falkenmark (Sweden)

11.1. INTERDISCIPLINARY PROBLEMS OF THE SEMI-ENCLOSED BASIN

The water balance of a semi-enclosed sea implies the comparison of two different types of water: freshwater from the land, and salt water from the adjacent ocean. The freshwater budgeting constitutes an important tool to determine the long-term water renewal and the water exchange conditions in the sea, based on real measurements in the field. The Baltic Sea can be seen as an excellent example of an interior sea, connected to the ocean through a constricted sound area, i.e. a semi-enclosed sea. Although the Baltic is extremely wellknown through a great number of studies since the beginning of the 20th century, its water balance has not been determined more than approximately in the past, due to lack of complete and homogenous data on the different components.

It is indeed quite a complicated task to pursue such a water balance excercise on an international water system: numerous elements are involved; some elements are particularly difficult to estimate; for most of the elements, data have to be brought together from all the bordering countries. Long data series are needed to arrive at a good estimation of long-term average conditions, and at conclusions regarding variability and general trends. Even if it is extremely complicated, it is however indeed necessary to determine the water balance, in order to be able to understand the long-term water renewal and the various ways in which it influences the sea environment.

In other words, oceanographers wishing to get a full understanding of the dynamics of the sea system, depend on hydrologists to determine the freshwater balance in its various details. To solve this problem, a close cooperation between hydrologists and oceanographers is needed - none of them is able to solve the water exchange problem on his own. In the past, these two groups of professions have represented vastly different standpoints. Today, however, it is generally accepted that, in order to solve the interdisciplinary problems involved in semi-enclosed seas, they have to work close together.

It is therefore fully logical, that the present project on the Water Balance of the Baltic Sea was indeed initiated by the Baltic Oceanographers. At the meeting in 1966 in Leningrad, the participating oceanographers decided to invite hydrologists to embark on a thorough study on the individual water balance elements of the Baltic. The aim was to arrive at more reliable reference values on the water balance elements as a base for

solving oceanographical and ecological problems, related to the environment of the Baltic sea, and to clarify the variability both in time and space of these elements.

11.2. THE INTERNATIONAL PROJECT

What has characterized the IHD/IHP project on the Water Balance of the Baltic Sea has been the organized bringing-together of multiannual, homogenous data on all the individual water balance elements. The cooperation was made possible through the framework of the IHD/IHP worldwide program. The main counterparts in the different countries have therefore been the national committees for the International Hydrological Decade (IHD) and the International Hydrological Programme (IHP). Besides a coordinated data gathering, the cooperation included a series of Expert Meetings for methodological discussions and joint solving of methodological problems, in particular regarding the exchange with the North Sea and the fluctuations in water storage.

Within the study, 20 years of system-wide homogenous data on all the individual water balance components, covering the period 1951-70, have been compiled. Efforts were made to arrive at the closing error of the water balance by separate and independent determination of all the individual components. The homogenous data-base produced resulted in new and more precise reference values on the freshwater balance components. The 20 year series also allowed some studies of the variability in time and, in particular, during extreme years.

By the large stress put on inflow studies, a new and more hydrological view has been introduced. The earlier borderline of the Baltic Sea, considered to be the coastline, has been moved to the water divide on the land areas, separating the land drained to the Baltic Sea from the land areas drained to other water systems.

The study included a separate consideration of the seven interconnected subbasins of the Baltic, linked together in a complex cascade system. Analysis of the individual subbasins contributes in increasing our understanding of the water balance specificities of semi-enclosed seas.

It was furthermore possible to discreticize - even on a monthly basis - the water balance from different aspects. On one hand, the vertical and horisontal water balances have been studied both separately and in combination. On the other hand, it has been possible to distinguish between the endogenous, or local freshwater input to a subbasin, in other words the input from the "own" drainage basin, and the exogenous input, originating from water balances of subbasins further upstream in the cascade system. Also, by relating the water exchange of the different subbasins to their water volumes, the time characteristics, i.e. the average or theoretical time of renewal of the individual subbasin volumes, have been determined.

11.3. SOME CONCLUSIONS

The Pilot Study was organized to make possible concentrated and synchronous measurements of all the individual water balance components. By cooperation with the Danish Belt Project it included also field measurements of the water exchange with the North Sea. New and more precise methods were applied for determination of evaporation. Thanks to this, more reliable data were achieved on the sea evaporation. It was concluded that earlier calculations had underestimated the evaporation by about 7 %. A theoretically based earlier hypothesis that the sea evaporation culminates in late autumn and early winter was confirmed.

In spite of the large efforts directed towards the water exchange with the North Sea that element remains the weak point of the water balance. It was concluded that the most reliable method for determination of the long-term water exchange remained the water balance equation. This is due to the methodological problems involved in current measurements in a complicated system of straits, characterized by complex water movements back and forth and successive entrainment of ingoing water in the outgoing water mass, as one moves downstream through the straits. At the present level of methodological development, the errors involved in current measurements remain rather large, and the instruments are not yet reliable enough to produce continuous data. Unfortunately, the time gaps in the final data series made it impossible to arrive at determining the closing errors.

The project produced the conclusion that in earlier studies, precipitation had been severely underestimated, due to neglect of errors involved in point measurement of precipitation.

For river inflow it was possible to study a 55 year data series, thereby allowing even better insight into the time variability, especially as the river inflow, when seen in a long-term perspective, plays a dominating role over the vertical balance. A statistical study on the 55 year series illuminated the characteristics and the long-term variations in the input of river flow. It was concluded that consecutive decade averages did not differ very much from each other during that period.

The sea water storage represents a quite dominating factor in the water balance when seen on a monthly or daily basis. When averaged over a 20-year period, however, the storage change tends to vanish in the water balance, in line with the general hydrological water balance hypothesis.

11.4. CLOSING REMARKS

The project represents 15 years of close cooperation and work of a great number of experts in the seven countries participating in the project. The experts involved have achieved the best knowledge

now available on the individual components of the water balance of the Baltic Sea. Now that the hydrologists have finalized their part of the relay-race, it is our hope that their results will be absorbed by the scientific community in the bordering countries, in order to make the best possible use of the new understanding achieved. The oceanographers, who initiated the study by asking for more reliable data on the freshwater balance, are now provided with such data, together with new information on the characteristics of the different parts of the cascade, and on the variability in time and space characterizing the different elements. Oceanographers should therefore now have a better basis than earlier for understanding the peculiarities of the different subregions composing the Baltic system.

Ecologists, on the other hand, may now also be in a position to deepen their understanding of the Baltic sea and its different subregions from an environmental viewpoint. We now know much more than earlier about the input and output of freshwater, and some substances that they carry to the system. The study included the input of suspended material to the various subbasins of the system. Also, the input of dissolved substances with the rivers was appreciated within the project. The accelerating interest in these elements within the Helsinki Convention work have, however already produced later data, thereby outdating the preliminary studies performed within the IHD/IHP-project.

When ecologists and oceanographers end by understanding the large role played by the freshwater budget, they will become interested in trying to follow, on a continuous basis, the freshwater balance and its components, as a measure of keeping control over the Baltic as an environment of considerable value for all the bordering states. This would make it desirable to keep the Baltic Sea under continuous observation through an operational water budget monitoring. Such a control program could very well be organized, based on the methodological experiences gained within the IHD/IHP project, as a matter of cooperation between the operational hydrological services in the countries involved.

The experiences gained through this study of a semi-enclosed sea could probably be helpful also in the study of other semi-enclosed seas. It is particularly interesting to note that a semi-enclosed sea may not be as homogenous as earlier considered. The complications due to mixing processes have been better explained by the differentiation of the Baltic sea in its seven subbasins.

In this regard, there is a considerable difference between the complex cascade of partial seas composing the Baltic, and an inland sea like the Black Sea. For instance, the Bothnian Bay is practically influenced only by freshwater, and the same holds for the Gulf of Finland and the Gulf of Riga. In the Bothnian Sea and the Baltic Proper, conditions are vastly different: the water balance gets much more complex. These throughflow subbasins receive water both from the land areas drained, and as inflow from upstream subbasins. On a short term basis, the back and forth movement of water masses between neighbouring subbasins may be considerable, but in the long-term perspective, they converge to the net water exchange determined by the freshwater balances. This basic fact, that the hydrological factors have such considerable influence, as soon as the long-term perspective is applied, is what makes the freshwater budget so important in the study of semi-enclosed seas.

It is sincerely hoped that the Baltic Sea study may be followed by similar studies in other semi-enclosed seas around the world, benefitting from the methodological development in this international cooperation between seven participating countries belonging to different political groupings in Northern Europe.

Chapter 12

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12.2.10. Chapter 10

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Mikulski, Z., 1982: see reference under chapter 3.

M A I N T A B L E S

Table No.	D a t a	Responsible
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3.	River inflow to the Baltic Sea and its seven subbasins. Monthly and annual means for different time periods	Mikulski
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8.	d:o a) Decade averages 1948-60, 61-70 b) 20 year averages 1948-70	Henning Henning
9.	Sea volume changes of the Baltic Sea and five of its subbasins. Averages 1951-70	Mikulski/ Lazarenko
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11.	Water balance of the Baltic Sea and five of its subbasins. 20-year averages 1951-70	Mikulski

a) Subbasin 1. Bothnian Bay
b) Subbasin 2. Bothnian Sea
c) Subbasins 1-2. Gulf of Bothnia
d) Subbasin 3. Gulf of Finland
e) Subbasin 4. Gulf of Riga
f) Subbasin 5. Baltic Proper
g) Subbasins 1-5. Baltic Sea inside Danish Straits

MAIN TABLE 1. CHARACTERISTIC DATA ON THE BALTIC SEA AND ITS SEVEN SUBBASINS
Table compiled by Zdzislaw Mikulski (Poland)

Region	Basin area km^2	Sea area km^2	Sea capacity km^3	Maximal depth m	Mean depth m
1 Bothnian Bay	269 950	36 260	1 481	156	40.8
2 Bothnian Sea	229 700	79 257	4 889	294	61.7
Sum 1-2	499 650	115 517	6 370	-	55.1
3 Gulf of Finland	419 200	29 498	1 098	123	37.2
4 Gulf of Riga	127 400	17 913	406	51	22.7
5 Baltic proper	568 973	209 930	13 045	459	62.1
Sum 1-5	1 615 223	372 858	20 919	-	56.1
6 Sund and Belts	27 360	20 121	287	38	14.3
Sum 1-6	1 642 583	392 979	21 206	-	54.0
7 Kattegat	78 650	22 287	515	109	23.1
Sum 6 + 7	106 010	42 408	802	-	18.9
Baltic Sea					
Sum 1-7	1 721 233	415 266	21 721	459	52.3

MAIN TABLE 2. SHARE OF THE BALTIC COUNTRIES IN THE DRAINAGE AREA OF THE BALTIC SEA
Table compiled by Zdzislaw Mikulski (Poland)

No.	Country	Drainage area		Area of Country		Length of shore line**)	
		km^2	%	km^2	%	km	%
1	USSR	594 600	34.5	5 570 000*)	10.7	2 670	17.6
2	Sweden	445 300	25.8	449 964	99.0	5 450	35.8
3	Poland	310 950	18.1	312 683	99.5	590	3.9
4	Finland	303 400	17.6	337 032	90.0	2 970	19.5
5	Denmark	23 400	1.4	43 075	54.4	2 480	16.3
6	GDR	18 260	1.1	108 178	16.9	660	4.3
7	FRG	5 130	0.3	248 611	2.1	400	2.6
8	Norway	12 000	0.7	323 886	3.7	-	-
9	Czechoslovakia	8 200	0.5	127 977	6.4	-	-

*) = European part

**) = Evaluated on basis of 1:1.7 min map/Bathymetric map, Helsinki 1981 - obtained valued are aproximated to 10 km/.

MAIN TABLE 3. RIVER INFLOW TO THE BALTIC SEA (SUBBASINS 1-7)
Monthly and annual means for different time periods. Table compiled by Zdzislaw Mikulski (Poland)

Years/Month		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I-XII
1921-1930	m^3/s	10877	9983	11906	17388	24705	25988	19142	15772	15084	15250	16084	12939	16260
	km^3	29.134	24.343	31.891	45.070	66.171	57.361	51.271	42.252	39.105	40.844	41.690	34.658	513.792
1931-1940	m^3/s	9942	9522	12490	17470	23823	21955	16139	14295	13624	14202	13760	11172	14866
	km^3	26.602	23.279	33.452	45.284	63.808	56.906	43.228	38.288	35.311	38.040	35.668	29.925	469.952
1941-1950	m^3/s	9042	9423	11078	17931	22256	21758	15500	12713	11855	12417	11994	11178	13929
	km^3	24.191	22.993	29.670	46.478	59.611	56.374	41.518	34.049	30.727	33.256	31.095	29.939	439.907
1951-1960	m^3/s	9948	10212	11454	18507	25052	22344	16756	14942	13932	13568	12599	10961	15023
	km^3	26.648	24.921	30.655	47.974	67.090	57.904	44.870	40.016	35.971	36.338	32.652	29.358	474.425
1961-1970	m^3/s	10682	10931	12016	19746	25061	20707	13640	13334	13184	12905	13948	11992	14929
	km^3	28.612	26.647	34.863	51.181	67.124	53.672	36.534	35.711	34.174	34.567	36.156	32.118	471.357
1971-1975	m^3/s	12228	12743	12431	15571	21221	17961	13420	11832	11177	12581	12614	12214	13832
	km^3	32.893	31.151	34.109	40.707	56.931	46.584	35.912	31.909	28.983	33.686	32.650	32.702	438.220
1921-1975	m^3/s	10292	10262	11847	17969	23911	22133	15980	13995	13321	13570	13580	11700	14895
	km^3	21.570	25.047	32.288	46.607	64.049	57.365	42.796	37.504	34.505	36.343	35.197	31.336	470.644
1931-1960	m^3/s	9644	9719	11674	17969	23710	22019	16132	13983	13137	13396	12784	11104	14606
	km^3	25.814	23.731	31.269	46.579	63.503	57.061	43.207	37.451	34.003	35.877	33.138	29.741	461.428
1951-1975	m^3/s	10952	11295	11967	17941	23778	20337	14605	13369	12764	13018	13054	11772	14595
	km^3	29.384	27.573	33.219	46.621	63.713	52.720	39.107	35.879	33.043	34.863	33.819	31.393	461.332

MAIN TABLE 4. RIVER INFLOW TO THE BALTIC SEA AND ITS SEVEN SUBBASINS

20-year averages for the period 1951-70. Table compiled by Zdzislaw Mikulski (Poland)

Region		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I-XII
1. Bothnian Bay	m^3/s	1348	1190	1100	1816	8616	6174	3486	3039	3304	3005	2570	1622	3106
	km^3	3.544	2.902	2.944	4.706	23.077	16.014	9.339	8.140	8.563	8.048	6.662	4.348	98.287
2. Bothnian Sea	m^3/s	1822	1714	1661	2078	4472	6572	4242	3729	2937	2476	2336	2023	3004
	km^3	4.854	4.182	4.450	5.388	11.978	17.034	11.360	10.018	7.612	6.634	6.054	5.432	94.996
3. Gulf of Finland	m^3/s	2445	2580	2827	3754	4584	4467	4296	4016	3874	3802	3574	2808	3582
	km^3	6.878	6.292	7.598	9.730	12.275	11.579	11.401	10.756	10.042	10.182	9.262	7.522	113.517
4. Gulf of Riga	m^3/s	482	422	694	3450	2076	678	426	378	465	645	717	605	920
	km^3	1.292	1.026	1.860	8.943	5.560	1.755	1.142	1.010	1.205	1.727	1.858	1.620	28.998
5. Baltic Proper	m^3/s	2680	3143	4414	6617	4277	2895	2204	2230	2018	2116	2664	2968	3186
	km^3	7.179	7.659	11.821	17.152	11.456	7.504	5.902	5.972	5.162	5.669	6. 08	7.952	100.336
Sum 1-5	m^3/s	8767	9049	10696	17715	24025	20786	14614	13392	12598	12044	11861	10026	13798
	km^3	23.747	22.061	28.673	45.918	64.345	53.886	39.144	35.896	32.584	32.260	30.744	26.874	436.134
6. Belts and Sund	m^3/s	302	322	332	314	236	173	140	167	203	244	290	302	252
	km^3	0.810	0.790	0.893	0.816	0.627	0.442	0.368	0.444	0.524	0.656	0.750	0.808	7.928
Sum 1-6	m^3/s	9069	9371	11028	18029	24261	20959	14754	13559	12801	12288	12151	10328	14050
	km^3	24.557	22.851	29.566	46.734	64.972	54.328	39.512	36.340	33.108	32.916	31.494	27.682	444.062
7. Kattegat	m^3/s	1146	1202	1198	1097	796	563	444	580	758	947	1122	1147	917
	km^3	3.072	2.934	3.206	2.843	2.132	1.456	1.191	1.554	1.969	2.536	2.910	3.071	28.874
Sum 6-7	m^3/s	1448	1524	1530	1411	1032	736	584	747	961	1191	1412	1449	1168
	km^3	3.882	3.724	4.099	3.659	2.759	1.898	1.559	1.998	2.493	3.192	3.660	3.879	36.802
8. Baltic Sea Sum 1-7	m^3/s	10315	10572	11735	19126	25056	21526	15198	14138	13558	13236	13274	11476	14967
	km^3	27.630	25.784	32.759	49.578	67.107	55.788	40.702	37.864	35.072	35.452	34.404	30.738	472.936

MAIN TABLE 5. PRECIPITATION ON THE BALTIC SEA AND ITS SEVEN SUBBASINS

Long-term averages for the reference period 1931-60. Data from Bengt Dahlström (Sweden)

Region		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
1	mm	43	33	29	34	30	46	57	64	62	53	55	48	554
	km^3	1.56	1.20	1.05	1.23	1.09	1.67	2.07	2.32	2.25	1.92	1.99	1.74	20.09
2	mm	52	35	29	33	45	45	58	69	63	57	64	57	598
	km^3	4.12	2.77	2.30	2.85	2.62	3.57	4.60	5.47	4.99	4.52	5.07	4.52	47.40
3	mm	57	41	33	41	45	56	70	79	68	67	64	56	677
	km^3	1.65	1.21	0.97	1.21	1.33	1.65	2.06	2.33	2.01	1.98	1.89	1.65	19.97
4	mm	55	40	33	36	41	50	73	73	72	64	58	58	653
	km^3	0.99	0.72	0.59	0.64	0.73	0.90	1.31	1.31	1.29	1.15	1.04	1.04	11.71
5	mm	57	44	35	39	40	47	70	72	66	64	61	60	655
	km^3	11.97	9.24	7.35	8.19	8.40	9.87	14.70	15.11	13.86	13.44	12.81	12.60	137.54
6	mm	58	45	38	46	46	53	75	81	65	65	53	55	685
	km^3	1.17	0.91	0.76	0.93	0.93	1.07	1.51	1.63	1.31	1.31	1.17	1.11	13.81
7	mm	57	43	34	41	39	51	79	78	73	69	63	57	684
	km^3	1.27	0.96	0.76	0.91	0.87	1.14	1.76	1.74	1.63	1.54	1.40	1.27	15.25
1-7	mm	55	41	33	38	38	48	67	72	66	62	61	58	639
	km^3	22.84	17.03	13.70	15.78	15.78	19.93	27.86	29.90	27.41	25.75	25.33	24.09	265.36

MAIN TABLE 6. PRECIPITATION ON THE BALTIC SEA AND ITS SEVEN SUBBASINS.
20-year averages for the period 1951-70. Data from Bengt Dahlström (Sweden)

Region		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
1	mm	41	35	33	29	34	37	48	66	57	48	56	51	535
	km^3	1.49	1.27	1.20	1.05	1.23	1.34	1.74	1.39	2.07	1.74	2.03	1.85	18.40
2	mm	47	40	30	33	34	37	52	68	56	54	62	59	572
	km^3	3.73	3.17	2.38	2.62	2.69	2.93	4.12	5.39	4.44	4.28	4.91	4.68	45.34
3	mm	43	33	28	35	40	40	66	71	66	64	57	50	593
	km^3	1.27	0.97	0.83	1.03	1.18	1.18	1.95	2.09	1.95	1.89	1.68	1.47	17.49
4	mm	41	31	25	34	40	41	66	68	73	63	58	50	590
	km^3	0.73	0.56	0.45	0.61	0.72	0.73	1.18	1.22	1.31	1.13	1.04	0.90	10.58
5	mm	51	40	31	39	43	43	65	73	66	57	62	58	628
	km^3	10.71	8.40	6.51	8.19	9.03	9.03	13.65	15.32	13.86	11.97	13.02	12.18	131.87
6	mm	54	44	37	46	50	52	76	82	61	62	68	60	692
	km^3	1.09	0.89	0.74	0.93	1.01	1.05	1.53	1.65	1.23	1.25	1.37	1.21	13.95
7	mm	57	42	36	46	45	49	72	85	66	74	68	61	701
	km^3	1.27	0.94	0.80	1.03	1.00	1.09	1.60	1.89	1.47	1.65	1.52	1.36	15.62
1-7	mm	49	39	31	37	41	42	62	72	63	58	62	57	613
	km^3	20.35	16.20	12.87	15.36	17.03	17.44	25.75	29.90	26.16	24.09	25.75	23.67	254.57

MAIN TABLE 7. EVAPORATION FROM THE BALTIC SEA AND ITS SEVEN SUBBASINS
Long-term averages for the period 1862- 1978. Data from Dieter Henning (FRG)

Region		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
1	mm	23.4	2.7	4.3	4.7	4.9	20.7	31.2	58.1	73.1	60.6	36.5	43.6	363.7
	km^3	0.848	0.097	0.157	0.170	0.177	0.751	1.13	2.11	2.65	2.20	1.32	1.58	13.19
2	mm	49.9	22.0	15.1	11.8	7.4	17.5	30.8	52.9	74.0	63.0	49.3	66.6	460.4
	km^3	3.96	1.74	1.20	0.939	0.590	1.39	2.44	4.20	5.86	4.99	3.91	5.28	36.49
3	mm	22.1	6.7	6.2	4.1	6.0	25.9	26.8	56.1	63.6	57.3	41.4	44.5	360.5
	km^3	0.652	0.196	0.182	0.120	0.176	0.765	0.790	1.65	1.88	1.69	1.22	1.31	10.63
4	mm	35.8	17.1	16.6	-0.1	13.3	16.1	36.5	45.8	46.8	51.8	80.6	78.2	438.5
	km^3	0.641	0.306	0.298	-0.002	0.238	0.289	0.654	0.821	0.838	0.928	1.44	1.40	7.85
5	mm	52.1	37.1	32.0	9.7	10.1	16.9	41.1	52.2	86.6	73.8	67.6	72.1	551.2
	km^3	10.95	7.78	6.71	2.03	2.13	3.54	8.62	10.96	18.18	15.50	14.19	15.13	115.72
1-5	mm	45.7	27.1	22.9	8.7	8.9	18.1	36.6	52.9	78.9	67.9	59.2	66.2	493.2
	km^3	17.04	10.12	8.54	3.25	3.31	6.74	13.64	19.74	29.41	25.30	22.09	24.70	183.89
6	mm	26.3	30.3	14.6	17.1	19.4	42.1	70.9	56.2	88.4	65.8	63.4	46.4	540.9
	km^3	0.530	0.609	0.293	0.345	0.390	0.848	1.43	1.13	1.78	1.32	1.28	0.930	10.88
7	mm	37.3	14.5	16.2	27.5	24.8	42.8	62.3	62.4	91.6	54.5	59.0	52.3	541.0
	km^3	0.831	0.324	0.360	0.523	0.553	0.953	1.39	1.39	2.04	1.21	1.31	1.16	12.06
1-7	mm	44.3	26.6	22.1	9.9	10.2	20.6	39.6	53.6	80.0	67.0	59.4	64.5	498.1
	km^3	18.40	11.05	9.20	4.12	4.25	8.54	16.45	22.26	33.23	27.84	24.68	26.79	206.83

MAIN TABLE 8. EVAPORATION FROM THE BALTIC SEA AND ITS SEVEN SUBBASINS

a) Decade averages for the periods 1948-60 and 1961-70.
Data from Dieter Henning (FRG)

Region			I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
1	mm	48-60	(23.4)[1]	(2.7)[1]	(4.3)[1]	(4.7)[1]	(4.9)[1]	(20.7)[1]	25.3	48.3	(73.1)[1]	(60.5)[1]	(36.5)[1]	(43.6)[1]	348.0
		61-70	0	0	0	0	0	-1.1	10.2	41.7	14.6	23.8	52.2	218.8	360.2
2	mm	48-60	27.2	17.7	7.6	24.2	18.1	11.5	23.6	62.4	62.5	64.7	91.8	48.4	459.6
		61-70	73.6	44.3	26.5	19.6	15.9	7.0	15.7	26.3	39.9	16.2	50.1	78.9	413.9
3	mm	48-60	47.8	(6.7)	(6.2)	7.6	15.5	21.0	36.4	47.6	87.3	66.5	99.3	24.9	466.7
		61-70	39.2	8.8	4.0	4.0	20.9	32.3	68.2	86.4	85.3	68.5	49.6	48.1	515.3
4	mm	48-60	57.0	12.5	16.1	-0.9	16.7	16.6	37.4	45.2	44.6	51.1	63.9	53.9	413.8
		61-70	55.3	27.4	14.0	3.3	15.2	27.9	18.0	91.1	65.7	83.2	82.5	101.2	584.6
5	mm	48-60	51.4	46.1	34.3	16.2	15.6	14.5	39.3	43.7	72.5	61.2	74.0	51.3	520.2
		61-70	67.1	47.4	33.9	8.0	7.7	12.8	45.7	55.4	61.3	79.2	68.1	71.6	558.1
1-5	mm	48-60	43.6	31.1	22.6	15.3	15.1	15.1	34.2	48.5	70.3	61.8	75.7	48.0	481.2
		61-70	59.2	38.1	25.7	9.2	10.1	12.5	36.3	52.0	54.3	59.7	62.0	87.0	506.1
6	mm	48-60	37.2	15.2	27.2	12.4	18.8	51.6	36.1	52.8	84.6	63.6	61.4	51.9	512.9
		61-70	23.5	19.6	14.1	6.1	9.7	28.2	54.6	42.9	69.1	55.6	55.2	47.5	426.3
7	mm	48-60	45.5	19.8	24.3	22.4	29.6	39.7	119.2	34.9	127.0	69.7	49.2	47.7	629.0
		61-70	59.2	49.4	28.3	17.0	29.5	44.0	50.4	66.0	68.8	93.1	76.4	66.7	648.7
1-7	mm	48-60	43.3	29.7	22.9	15.5	16.1	18.2	38.9	48.0	74.0	62.3	73.6	48.1	490.7
		61-70	57.4	37.8	25.3	9.4	11.1	14.9	37.9	52.3	55.8	61.3	62.4	84.0	509.9

1) parenthesis = long term average 1862-1978

MAIN TABLE 8. b) 20-year averages for the period 1948-70. Data from Dieter Henning (FRG).

Region		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
1	km^3	0.42	0.05	0.08	0.08	0.09	0.36	0.64	1.63	1.59	1.53	1.61	4.76	12.8
2	km^3	3.99	2.46	1.35	1.74	1.35	0.73	1.56	3.52	4.06	3.21	5.62	5.04	34.6
3	km^3	1.28	0.23	0.15	0.17	0.54	0.79	1.54	1.98	2.55	1.99	2.20	1.08	14.5
4	km^3	1.01	0.36	0.27	-0.05	0.29	0.40	0.50	1.22	0.99	1.20	1.31	1.39	8.89
5	km^3	12.4	9.81	7.16	2.45	2.45	2.87	8.92	10.4	14.0	17.7	14.9	12.9	113.0
1-5	km^3	19.1	12.9	9.01	4.39	4.72	5.15	13.2	18.8	23.2	22.6	25.6	25.2	183.9
6	km^3	0.61	0.35	0.42	0.19	0.29	0.60	0.91	0.96	1.55	1.20	1.17	1.00	9.45
7	km^3	1.17	0.77	0.59	0.44	0.66	0.92	1.89	1.12	2.18	1.81	1.40	1.28	14.2
1-7	km^3	20.9	14.0	10.0	5.17	5.67	6.88	16.0	20.9	27.0	25.6	28.2	27.5	207.6

MAIN TABLE 9. SEA VOLUME CHANGES OF THE BALTIC SEA AND FIVE OF ITS SUBBASINS

20-year averages for the period 1951-70. Table compiled by Zdzislaw Mikulski (Poland) from data by N.N. Lazarenko (USSR).

Region	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I - XII
1. Bothnian Bay km^3	-3.24	-3.275	-2.675	-0.265	-0.235	3.42	4.10	-1.19	1.285	1.21	-0.69	1.865	0.31
2. Bothnian Sea km^3	-5.57	-7.70	-6.19	1.425	0.290	5.10	10.12	-1.365	1.90	0.595	-1.60	4.105	1.73
3. Gulf of Finland km^3	-1.82	-3.125	-1.855	-0.150	0.375	2.18	4.14	-0.61	1.305	0.055	-1.71	1.62	0.42
4. Gulf of Riga km^3	-1.065	-1.785	-1.195	0.195	0.285	1.095	2.66	-0.34	0.765	-0.19	-0.995	0.815	0.24
5. Baltic Proper km^3	-10.21	-12.81	-18.07	3.65	1.615	8.81	26.75	-2.32	4.72	0.72	-6.73	7.36	2.04
Baltic Sea 1 - 5	-21.90	-28.06	-29.065	4.855	2.33	20.6	47.77	-5.82	9.975	0.955	-11.72	15.765	4.74

MAIN TABLE 10. ANNUAL MEAN INPUT OF SUSPENDED MATERIAL TO THE BALTIC SEA AND ITS SEVEN SUBBASINS

Ten-year average 1961-70. Compiled by Bengt Nilsson (Sweden). Data from USSR, Poland, GDR and Federal Republic of Germany contributed by J. Cyberski (Poland)

Subbasin	Contribution from countries (10^3 tonnes/year)							
	Denmark	Sweden	Finland	USSR	Poland	GDR	FRG	Total
1	-	625	455	-	-	-	-	1080
2	-	890	290	-	-	-	-	1180
3	-	-	170	545	-	-	-	715
4	-	-	-	810	-	-	-	810
5	6	225	-	800	~2100	-	-	3131
6	78	-	-	-	-	-35	-	113
7	84	335	-	-	-	-	-	419
Total	168	2075	915	2155	~2100~	-35-		7448

MAIN TABLE 11. WATER BALANCE OF THE BALTIC SEA AND FIVE OF ITS SUBBASINS

20-year averages for the period 1951-70. Tables compiled by Zdzislaw Mikulski (Poland) based on data from all element coordinators.

Main Table 11.a: Subbasin 1. Bothnian Bay (A = 36 260 km^2)

Elements of water balance /km^3/	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I - XII
Precipitation /P/	1.49	1.27	1.20	1.05	1.23	1.34	1.74	1.39	2.07	1.74	2.03	1.85	18.40
Evaporation /E/	0.42	0.05	0.08	0.08	0.09	0.36	0.64	1.63	1.59	1.53	1.61	4.76	12.80
River inflow /L/	3.54	2.90	2.94	4.71	23.08	16.01	9.34	8.14	8.56	8.05	6.66	4.35	98.29
Net freshwater input Q_o=P-E+L	4.61	4.12	4.06	5.68	24.22	16.99	10.44	7.90	9.04	8.26	7.08	1.44	103.89
Storage difference /ΔV/	-3.24	-3.28	-2.68	-0.26	-0.24	3.42	4.10	-1.19	1.28	1.21	-0.69	1.86	0.31
Net outflow Q_o-ΔV=H-M	7.85	7.40	6.74	5.94	24.46	13.57	6.34	9.09	7.76	7.05	7.77	-0.42	103.58

Main Table 11.b: Subbasin 2. Bothnian Sea (A = 79 257 km^2)

Elements of water balance /km^3/	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I - XII
Precipitation /P/	3.73	3.17	2.38	2.62	2.69	2.93	4.12	5.39	4.44	4.28	4.91	4.68	45.34
Evaporation /E/	3.99	2.46	1.35	1.74	1.35	0.73	1.56	3.52	4.06	3.21	5.62	5.04	34.60
River inflow /L/	4.85	4.18	4.45	5.39	11.98	17.03	11.36	10.02	7.61	6.63	6.05	5.43	95.00
Net freshwater input Q_o=P-E+L	4.59	4.89	5.48	6.27	13.32	19.23	13.95	11.89	7.99	7.70	5.34	5.07	105.74
Storage difference /ΔV/	-5.57	-7.07	-6.19	1.42	0.29	5.10	10.12	-1.36	1.90	0.60	-1.60	4.10	1.73
Net outflow Q_o-ΔV=H-M	10.16	11.96	11.67	4.85	13.03	14.13	3.83	13.25	6.09	7.10	6.94	0.97	104.01

Main Table 11c: Subbasins 1-2. Gulf of Bothnia (A = 115 517 km^2)

Elements of water balance /km^3/	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I - XII
Precipitation /P/	5.22	4.44	3.58	3.67	3.92	4.27	5.86	6.78	6.51	6.02	6.94	6.53	63.74
Evaporation /E/	4.41	2.51	1.43	1.82	1.44	1.29	2.17	5.15	5.65	4.74	7.23	9.80	47.40
River inflow /L/	8.39	7.08	7.39	10.10	35.06	33.04	20.70	18.16	16.17	14.68	12.71	9.78	193.29
Net freshwater input Q_o=P-E+L	9.20	9.01	9.54	11.95	37.54	36.02	24.39	19.79	17.03	15.96	12.42	6.51	209.63
Storage difference /ΔV/	-8.81	-10.38	-8.87	1.16	0.05	8.52	14.22	-2.55	3.18	1.81	-2.29	5.96	2.04
Net outflow Q_o-ΔV=H-M	18.01	19.39	18.41	10.79	37.49	27.50	10.17	22.34	13.85	14.15	14.71	0.55	207.59

Main Table 11.d: Subbasin 3. Gulf of Finland (A = 29 498 km^2)

Elements of water balance /km^3/	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I - XII
Precipitation /P/	1.27	0.97	0.83	1.03	1.18	1.18	1.95	2.09	1.95	1.89	1.68	1.47	17.49
Evaporation /E/	1.28	0.23	0.15	0.17	0.54	0.79	1.54	1.98	2.55	1.99	2.20	1.08	14.50
River inflow /L/	6.88	6.29	7.60	9.73	12.28	11.58	11.40	10.76	10.04	10.18	9.26	7.52	113.52
Net freshwater input Q_o=P-E+L	6.87	7.03	8.28	10.59	12.92	11.97	11.81	10.87	9.44	10.08	8.74	7.91	116.51
Storage difference /ΔV/	-1.82	-3.12	-1.86	-0.15	0.38	2.18	4.14	-0.61	1.30	0.06	-1.71	1.62	0.42
Net outflow Q_o-ΔV=H-M	8.69	10.15	10.14	10.74	12.54	9.79	7.67	11.48	8.14	10.02	10.45	6.29	116.09

Main Table 11.e: Subbasin 4. Gulf of Riga (A = 17 913 km^2)

Elements of water balance /km^3/	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I - XII
Precipitation /P/	0.73	0.56	0.45	0.61	0.72	0.73	1.18	1.22	1.31	1.13	1.04	0.90	10.58
Evaporation /E/	1.01	0.36	0.27	-0.05	0.29	0.40	0.50	1.22	0.99	1.20	1.31	1.39	8.89
River inflow /L/	1.29	1.03	1.86	8.94	5.56	1.76	1.14	1.01	1.20	1.73	1.86	1.62	29.00
Net freshwater input Q_o=P-E+L	1.01	1.23	2.04	9.60	5.99	2.09	1.82	1.01	1.52	1.66	1.59	1.13	30.69
Storage difference /$\triangle$V/	-1.06	-1.78	-1.19	0.19	0.28	1.10	2.66	-0.34	0.76	-0.19	-0.99	0.82	0.24
Net outflow Q_o-$\triangle$V=H-M	2.07	3.01	3.23	9.41	5.71	0.99	-0.84	1.35	0.76	1.85	2.58	0.31	30.45

Main Table 11.f: Subbasin 5. Baltic proper (A = 209 930 km^2)

Elements of water balance /km^3/	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I - XII
Precipitation /P/	10.71	8.40	6.51	8.19	9.03	9.03	13.65	15.32	13.86	11.97	13.02	12.18	131.87
Evaporation /E/	12.40	9.81	7.16	2.45	2.45	2.87	8.92	10.40	14.00	14.70	14.90	12.90	113.00
River inflow /L/	7.18	7.66	11.82	17.17	11.46	7.50	5.90	5.97	5.16	5.67	6.91	7.95	100.34
Net freshwater input Q_o=P-E+L	5.49	6.25	11.17	22.89	18.04	13.66	10.63	10.89	5.02	2.94	5.03	7.23	119.21
Storage difference /$\triangle$V/	-10.22	-12.81	-18.07	3.65	1.62	8.81	26.75	-2.32	4.72	0.72	-6.73	7.36	2.04
Net outflow Q_o-$\triangle$V=H-M	15.71	19.06	29.24	19.24	16.42	4.85	-16.12	13.21	0.30	2.22	11.76	-0.13	117.17

Main Table 11.g: Subbasins 1-5. Baltic Sea inside Danish Straits (without Belt Sea and Kattegat. A = 372 858 km^2)

Elements of water balance (km^3)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I-XII
Precipitation /P/	17.9	14.4	11.4	13.5	14.8	15.2	22.6	25.4	23.6	21.0	22.7	21.1	223.6
Evaporation /E/	19.1	12.9	9.0	4.4	4.7	5.2	13.2	18.8	23.2	22.6	25.6	25.2	183.9
River inflow /L/	23.7	22.1	28.7	45.9	64.3	53.9	39.1	35.9	32.6	32.3	30.7	26.9	436.1
Net freshwater input $Q_o=P-E+L$	22.5	23.6	31.1	55.0	74.4	63.9	48.5	42.5	33.0	30.7	27.8	22.8	475.8
Storage difference /$\triangle V$/	-21.9	-28.1	-30.0	4.8	2.3	20.6	47.8	-5.8	10.0	0.9	-11.7	15.8	4.7
Net outflow $Q_o-\triangle V=H-M$	44.4	51.7	61.1	50.2	72.1	43.3	0.7	48.3	23.0	29.8	39.5	7.0	471.1

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