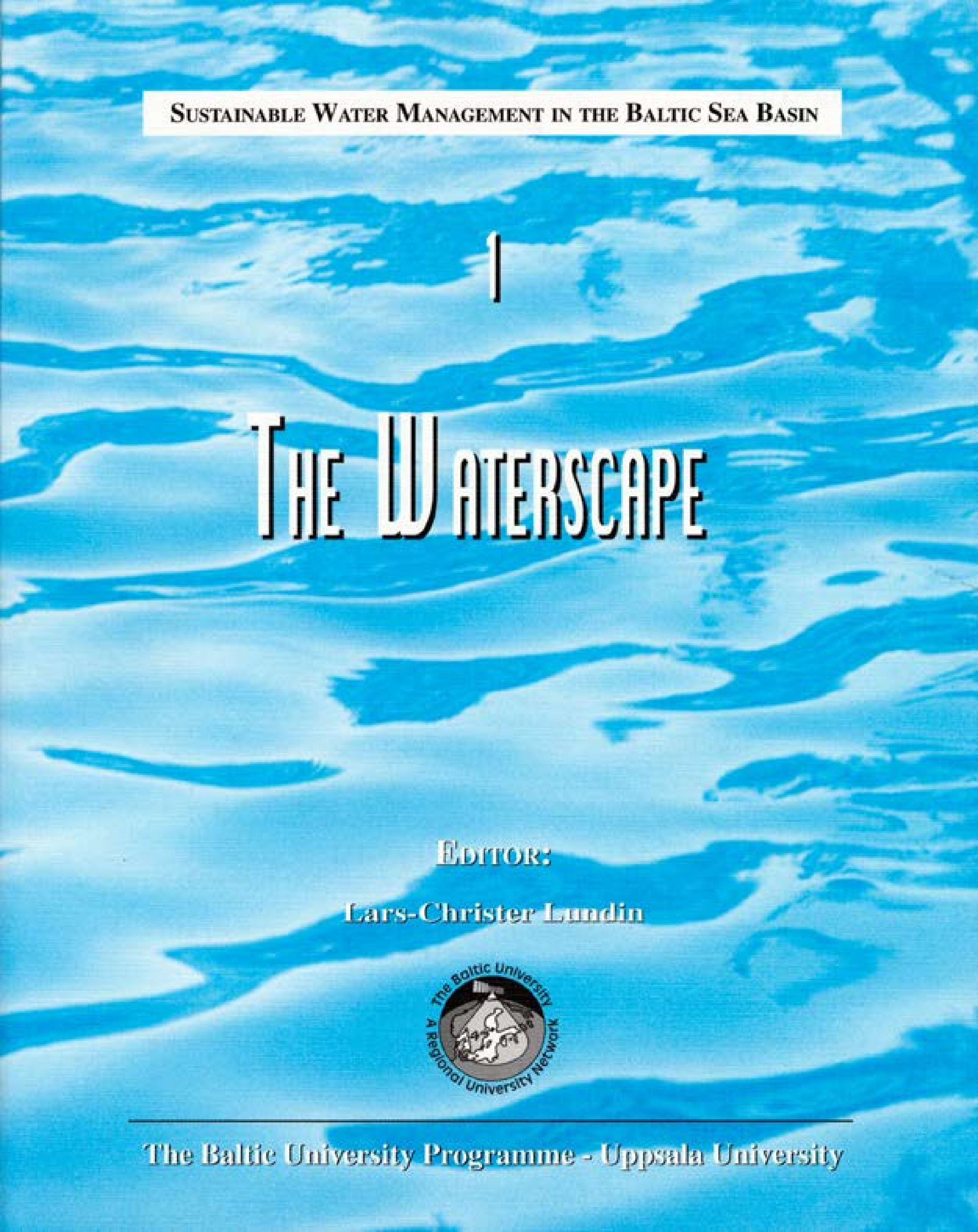

SUSTAINABLE WATER MANAGEMENT IN THE BALTIC SEA BASIN

1

THE WATERSCAPE

EDITOR:

Lars-Christer Lundin

The Baltic University Programme - Uppsala University

Sustainable Water Management in the Baltic Sea Basin

Book I.

The Waterscape

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FOREWORD

Water and water management have a very special place in the efforts of countries in the Baltic Sea region and universities participating in the Baltic University network. A concern for our common water, the Baltic Sea, was almost the only unifying point of departure when we met for the first time in 1991 during the break up of the old system. It will remain an important dimension of our work as illustrated by declarations from prime ministers in the region and intensification of activities e.g. within the Helcom co-operation. When work to improve the environmental situation started on a larger scale a few years later, water was by far the most important point on the agenda. In 1995, for example, as much as 95 % of the Latvian investments in the environmental field were directed towards water issues, especially wastewater treatment. Reducing emission into the air, soil remediation and natural protection were all secondary to water. The situation was similar in other countries in the newly independent states in Central and Eastern Europe. On the western side of the region investments to improve water quality have been substantial for several decades, which happily have yielded some good results.

This is not difficult to understand. Like all lifeforms, we depend on water for our daily life and well-being. We drink it, we wash ourselves in it, we enjoy seeing it flowing by, enjoy living in the beautiful “waterscape” of our Baltic region. To have good and clean water is a first priority, as it always was.

The Baltic University Programme has selected water management for the first master level course on issues on sustainable development. In this context water has a special role. It is a renewable resource, and the access to this resource is quite well defined, not only globally or regionally, but also locally, based on the drainage area concept. It will also be the first resource to be managed on the basis of this concept, since European Union directives recommend drainage- area based water administration. Sustainable water management is a first goal in our development towards a sustainable society.

The course material for Sustainable Water Management is, as with all Baltic University course material, interdisciplinary in its approach. We strive to present the problems of water management from a more holistic point of view. This transdisciplinary approach is intended to give students, regardless of background – natural scientists, engineers, social scientists etc. – a platform for working with water issues in their professional career. It treats the system rather than its components so naturally all specialists will be disappointed with the treatment of “their” specialities. The objective is to connect the specialities rather than to teach them.

The three books are the result of the combined effort of more than 50 researchers/teachers in some ten countries. They could not have been written by any single person, university or even country. They are a true result of the network and hopefully they will be used and studied in the entire Baltic region.

Uppsala January, 1999

Lars Rydén
Director, the Baltic University Programme

PREFACE

The textbook series

The current textbook volume is the first in a series of three on sustainable water management. The prime purpose of the textbook series is to serve as reading material on the Sustainable Water Management courses co-ordinated by the Baltic University. The series build on the input from teachers and students from the pilot course given in 1998 and the second course in 1999, involving some 30 universities and 300 students in the Baltic region. However, the textbooks are quite general and may be useful on other courses on water management or as self-study material.

Although the focus throughout the series is the Baltic Sea basin, sustainable water management is a global issue and the ideas and problems are thus also introduced from a broader perspective, widening the scope of the books.

The “blue thread” of the series is carried forward by a multitude of authors, selected from a number of Baltic countries, and in some cases also outside the Baltic region. They all have the interest in the Baltic basin in common and they were invited to present their expertise views of the problems and processes.

It is thus up to the local course responsible teacher to guide the students along the main avenue, occasionally making excursions using texts describing local conditions and local problems. It is furthermore up to the students to form their own opinions and build their own understanding from the variety of presentations and view points presented. The discussions with the teacher and the fellow students should be central in this process. The video- and Internet-conferences complementing the course lectures are natural fora for this discussion.

The Waterscape

The waterscape is a landscape in which focus is put on water. The purpose of this first volume is thus to present the Baltic basin, it’s natural water resources and the basic principle governing the water resources at the surface, in the ground, in the lakes and rivers, and of course, in the Baltic Sea itself.

The reader is in *Part 1* introduced to the Baltic drainage basin and the waterscape of rivers, lakes, coasts, sea, and wetlands from various points of views.

As a second step, in *Part II*, the hydrological cycle and the energy balance, giving the basis and limitations for sustainable water management, are presented in an introductory-level text. The following chapters present the processes instrumental in the hydrological cycle in more detail. The properties of the specific water storages, or reservoirs, being the basis for water management and use, are here described. The hydrological processes, groundwater, rivers and lakes in a catchment-perspective are presented. Part II ends with a review of hydrological models, including Internet addresses so that the interested reader can download and explore the models.

Finally, in *Part III*, Man is introduced into the system and human impact is discussed from various perspectives The large Lakes Ladoga and Onega are presented as specific objects and concrete examples of water resources. Human impact leads to the need for protection of water resources being dealt with in the final chapter. Note however, that part III is merely a smooth passage, or introduction, to the next volume, Water Use and Management.

L-C Lundin

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11. HYDROLOGICAL MODELS AND MODELLING

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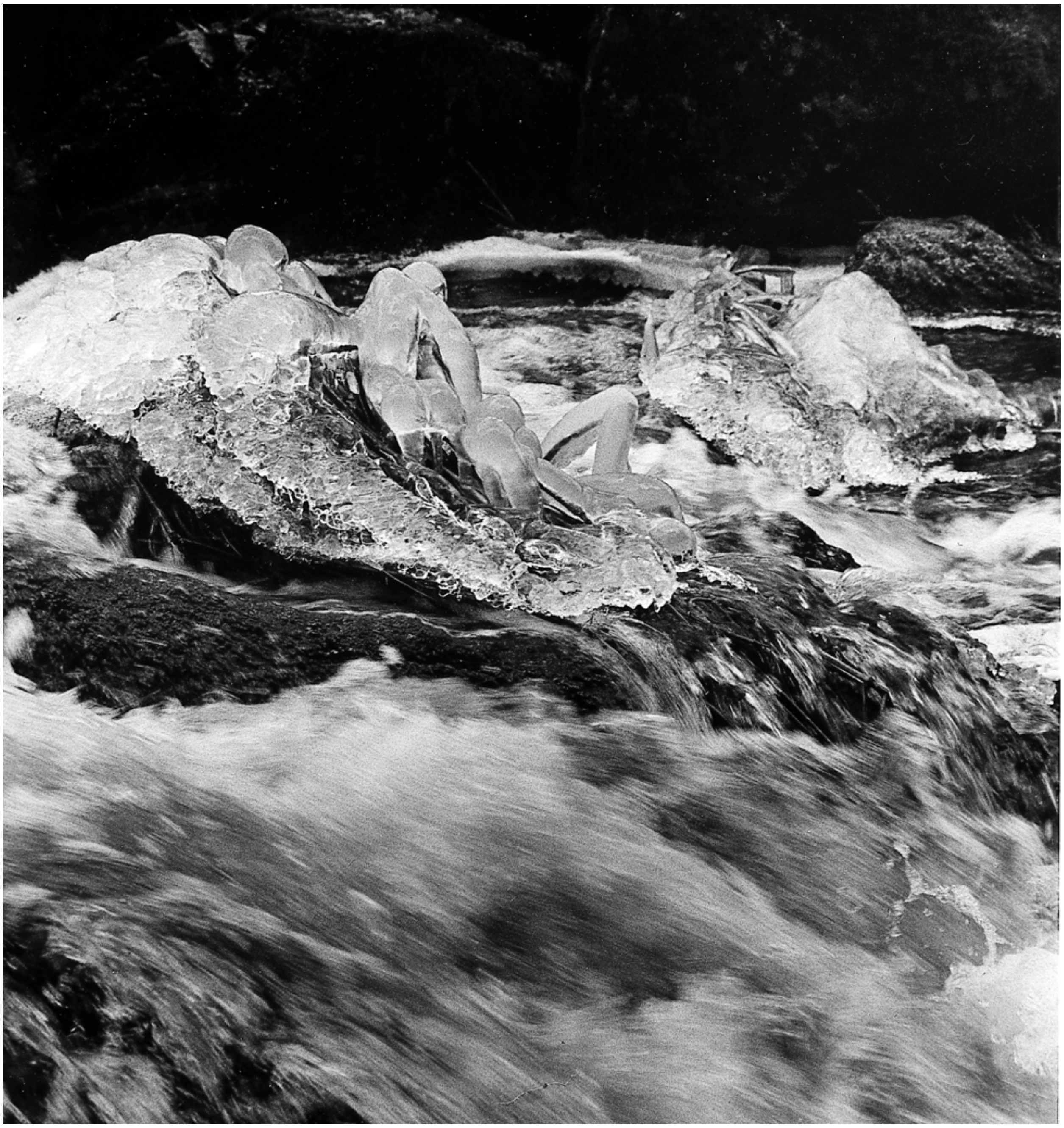

Photo, Inga-May Lehman Nådin.

Water is essential for all life on the Earth. We may even say that it is the lifeblood of the biosphere. There is plenty of water on Earth's surface and this truly wonderful substance connects us to one another as well as to other forms of life and to the entire planet. Indeed, we live on a water planet, since about 70 percent of the Earth's surface is covered by oceans and seas. But this water is salty, or at any rate brackish, while all terrestrial ecosystems and humans depends on fresh water, the supply of which is much more limited – less than one percent of the global water supply.

Despite its importance water is one of the most poorly managed resources on the earth. In many situations humans are overdrawing and depleting water resources, and water scarcity is rapidly emerging in many parts of the world. Rivers, lakes, reservoirs and underground aquifers show widespread signs of degradation and depletion whereas human demands for water continue to rise. Moreover we not only waste water and pollute it, but we also charge too little for making it available, encouraging even greater waste and pollution of this vital renewable resource.

This practice jeopardises sustainability and human security in different ways: through threats to food production in many areas (and even human habitation in some), human health, ecological integrity, and political stability. Failure to address these threats directly and very soon will greatly compromise human well-being in the 21st century, as well as diminish prospects for achieving sustainable patterns of water use on the planet, including our Baltic region.

Addressing these threats and achieving sustainable patterns of water use will not be easy. It will take the deployment of new technologies, policies and management strategies. It will require a new kind of mentality and unprecedented co-operation both within and between countries, and of course it will take a new ethics of sharing water – not only with each other, but with nature as well. To protect water is a fundamental ecological support function.

We have four main objectives in this context. The first is to understand the natural water cycle (i.e. the hydrological cycle), its capacities and its limitations in conformity with surface water resources use and demands on fresh water. The second is to understand how we are overdrawing certain water resources and the consequences of this action. The third is to understand our influence on water quality and the environmental consequences of waste and pollution. And the fourth is to understand how water resources should be managed if we are to achieve sustainable supplies.

Nikolas Rolley
St. Petersburg Technical University

Part I

The Baltic Waterscape and Water Resources

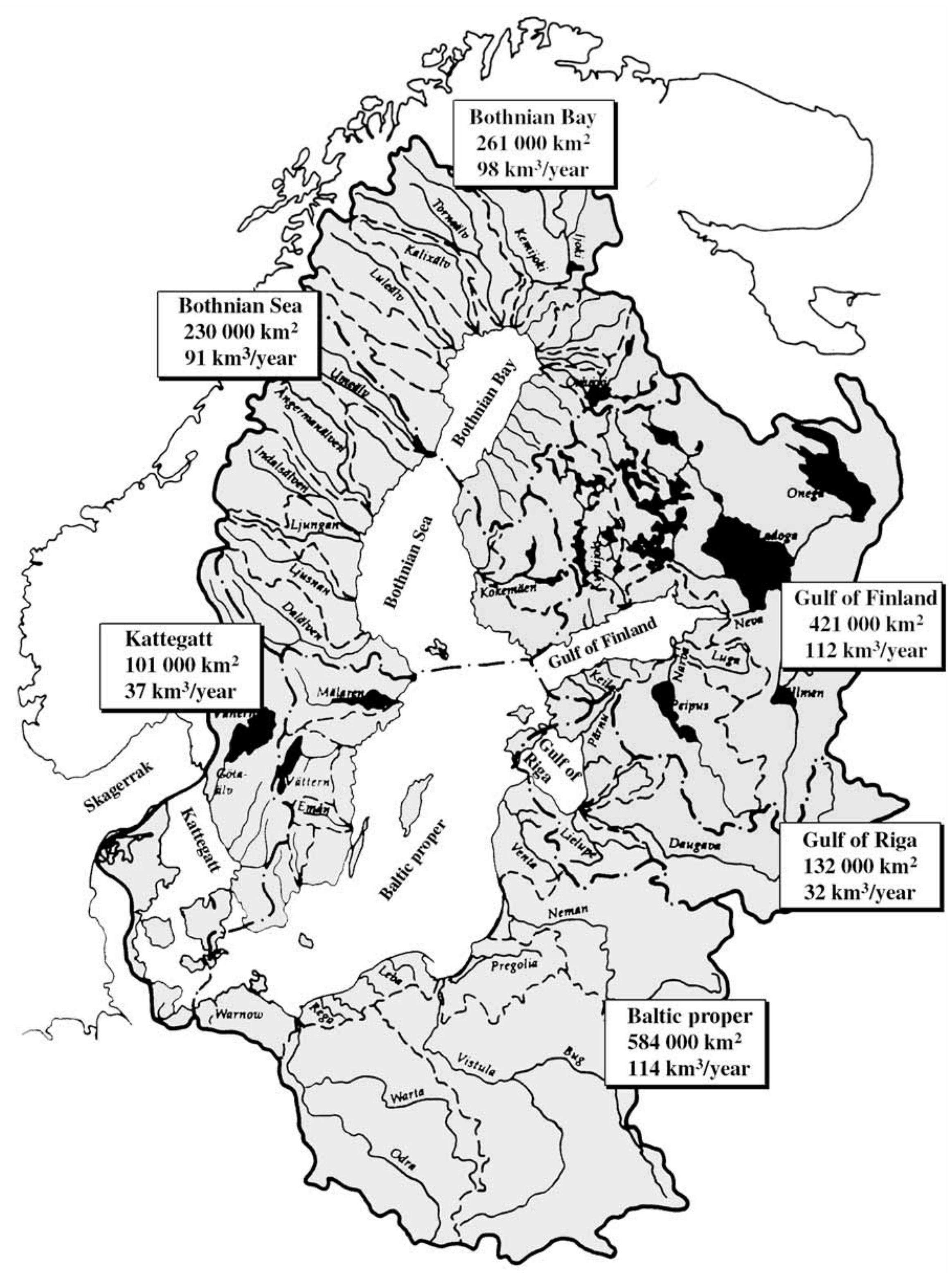

Figure 1.1. The main surface water resources of the Baltic Sea catchment. The inflow of fresh water to the various sub-basins for the period 1950-1990 and their respective areas are given in boxes. The water divides of the sub-basins are given as dot-dashed lines and some smaller-scale water divides are given as dashed lines (from Bergström & Carlsson, 1993).

1.

THE BALTIC BASIN - RIVERS, LAKES AND CLIMATE

Sten Bergström, Nicolai Filatov, Dimitry Pozdnjakov, Artur Magnuszewski & Hans Bergström[1]

Introduction

The total land area of the Baltic drainage basin covers approximately 1.7 million km^2 and includes territories from altogether 14 nations with more than 80 million inhabitants. Of environmental significance are also some major cities in the basin such as Saint Petersburg, Helsinki, Tallinn, Riga, Vilnius, Warsaw, Copenhagen and Stockholm, among others.

The natural habitat of the Baltic drainage basin is characterised by boreal forests in the north, agriculture in the south and mountains on the western and southern divide. There is an abundance of lakes in the northern half of the basin, some of them the largest in Europe, such as Lakes Ladoga, Onega and Vänern. Altogether lakes cover 9 % of the land areas of Finland and Sweden. Some of the largest rivers are the Neva, Vistula, Daugava, Kemijoki and Luleälven Rivers, among many others (Figure 1.1).

Due to its semi-enclosed character the Baltic Sea is very vulnerable to pollution and its environmental status is of major concern. The water body is affected by contributions of fresh water and nutrients from rivers, pollution from industries, municipalities and shipping and by direct atmospheric deposition. The inflow of water with high salinity and oxygen concentrations via the Danish Sounds is another critical factor for the ecosystem of the Baltic Sea.

The environmental problems of the Baltic drainage basin and the Baltic Sea are very complex and require interdisciplinary approaches, where hydrology plays a central role. River runoff to the Baltic Sea has been identified as one of the key factors influencing the ecosystem of this semi-enclosed basin. It is also a key factor for the understanding of the energy and water cycle of the Baltic basin, which is a key to more reliable climate modelling.

Climate and water resources

The range of climate is wide in the Baltic basin. Long, cold winters dominate in the north while there are more variable conditions in the south. Precipitation has its maximum in the northwest and the highest evapotranspiration occurs in the southern parts of the basin. The interaction of the storage of water and the dynamics of climate creates a complex runoff pattern of the available water resources (Figure 1.2).

In the northernmost parts of the basin more than half of the precipitation may be accumulated as snow and released during melt in spring, whereas the runoff has its peak during winter in the south. The mean

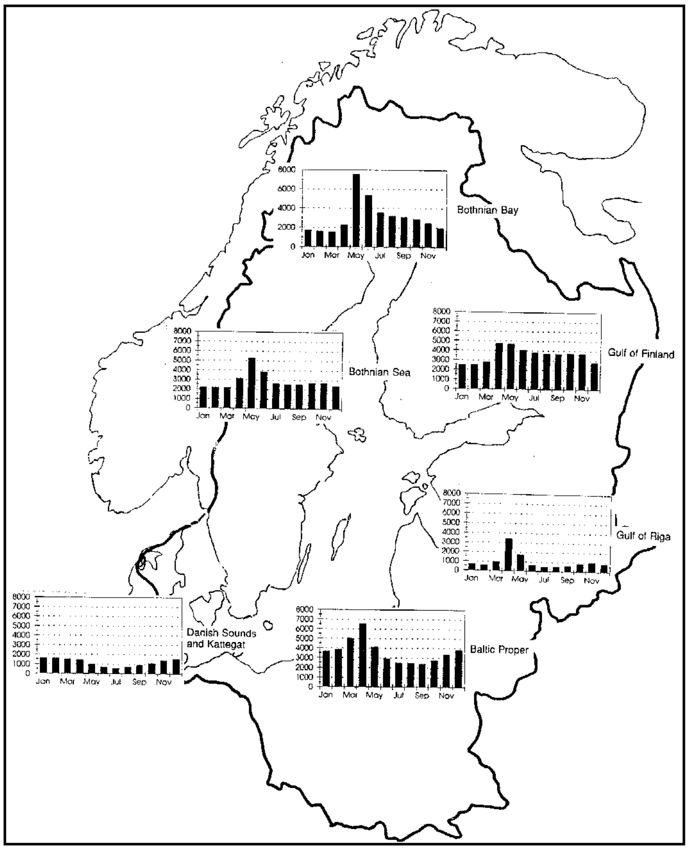

Figure 1.2. Average river runoff (m^3/s) for the subbasins of the Baltic drainage basin (data from Bergström & Carlsson, 1994).

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[1] Sten Bergström is the main author. Nicolai Filatov, Dimitry Pozdnjakov, and Hans Bergström contributed with Climate in the Baltic basin, and Artur Magnuszewski contributed with European climate

LAND USE AND POPULATION

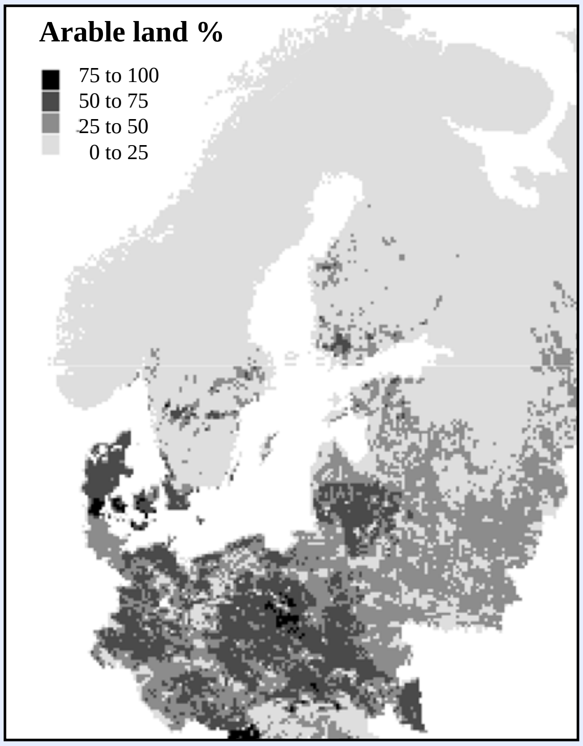

Figure 1.3. Arable land.

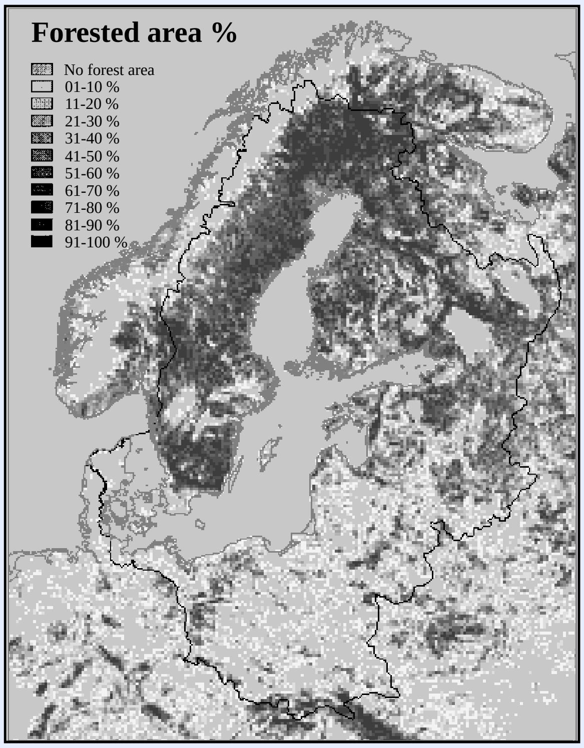

Figure 1.4. Forested area.

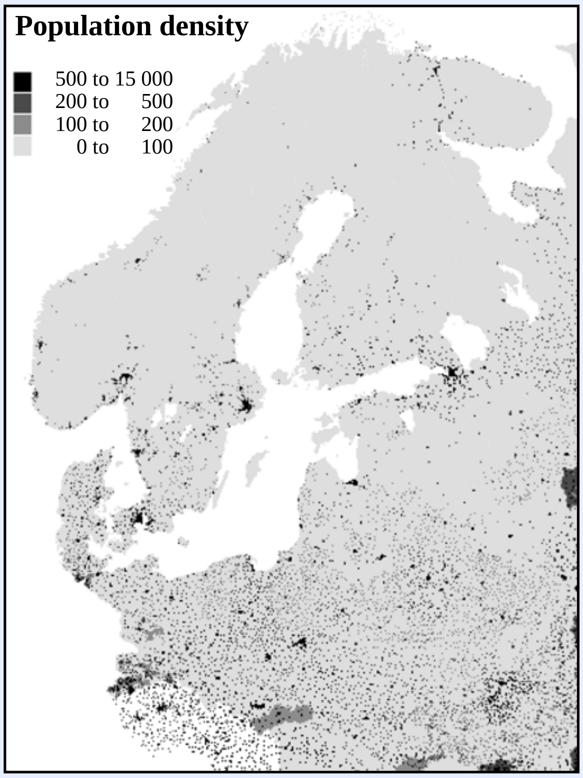

Figure 1.5. Population density.

Forests cover the whole northern part of the region. Although the forest accounts for 48 % of the total drainage basin, just three countries dominate: Sweden has 35 %, Finland 25 % and north-western Russia 19 % of the forested area.

In these three countries we also find the major proportion of the lakes. Finland, the land of a thousand lakes, accounts for 24 % of inland water, while north-western Russia, due to its great lakes, the Ladoga and the Onega Lakes, contributes with 36 %, while Sweden with its almost 100 000 lakes contributes with 28 %. This is a total of 90 % of the inland water area in the region. This difference between the north and the south is mainly explained by the last glaciation.

In contrast to the northern mountains and forests, we find large plains in the south. Arable lands, which account for one-fifth of the drainage area, dominate here. Poland has 41 % of all the arable land in the basin. The south also has the highest population density. Poland alone, with its 40 million inhabitants, has close to half of the population of the drainage basin.

Source for maps: http://www.baltic-region.net/prog/norbal/ballerin/index.htm

PRECIPITATION, RUNOFF AND TEMPERATURE

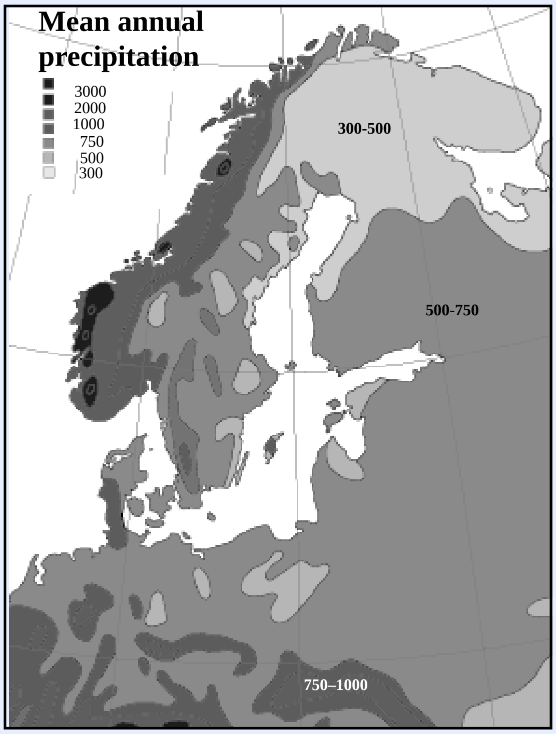

Figure 1.8. Mean annual precipitation.

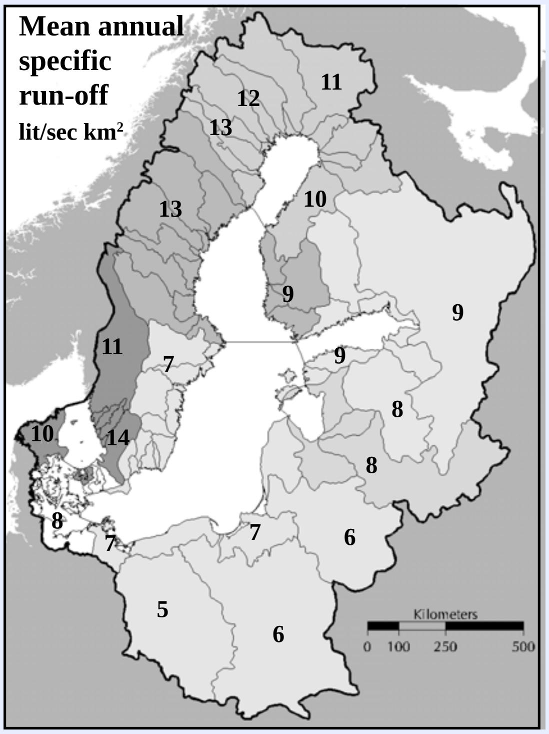

Figure 1.9. Mean annual specific runoff.

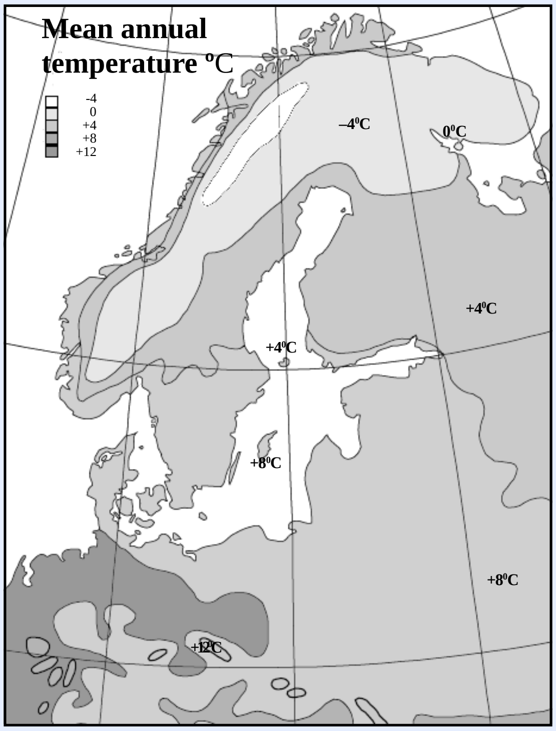

Figure 1.10. Mean annual temperature.

Annual precipitation (top left), annual mean temperature (bottom left) and annual specific runoff (top right) for the Baltic basin are shown on the right panel. The specific runoff is the runoff generated on a unit area, e.g. per square kilometre. On the left panel the seasonal variation of air temperature (left) and precipitation (right) at 30 stations in the Baltic basin for the period of 1931-1960 are shown.

Note the regional variability and the strong precipitation gradient with high precipitation in the western part, decreasing eastwards, and an influence of continental Russia on the climate in the eastern part of the region. The seasonal variability, shown in the left panel, is an important aspect in the design of water management plans.

Data from Landsberg (1985), official Finnish and Swedish climatological yearbooks, and Bergström & Carlsson (1994).

annual volume of fresh water runoff from the land areas of the entire Baltic basin amounts to approximately 450 km^3, Danish Sounds and Kattegat excluded. This corresponds to a flow of 14 150 m^3/s which means that the runoff from the land area of the Baltic basin is only slightly less than that of the Mississippi River and greater than in any river in Europe. The average discharge of the biggest rivers in the drainage basin is presented in Table 1.1.

Table 1.1. The largest rivers in the Baltic drainage basin (Bergström & Carlsson, 1994)

River	Mean annual flow for the period 1950-1990 (m^3/s)
Neva	2 460
Vistula	1 065
Daugava	659
Neman	632
Odra	573
Kemijoki	562
Ångermanälven	489
Luleälven	486

Table 1.2. The largest lakes in the Baltic drainage basin (data from MSSL-WCMC-UNEP, 1989; Raab & Vedin, 1995)

Lake	Area (km^2)
Ladoga, Russia	17 800
Onega, Russia	9 900
Vänern, Sweden	5 650
Peipsi, Estonia	3 100
Vättern, Sweden	1 900
Saimaa, Finland	1 500
Mälaren, Sweden	1 120
Päijänne, Finland	1 100
Oulojärvi, Finland	890
Pielisjärvi, Finland	870
Ilmen, Russia	550

The distribution of lakes in the Baltic catchment is quite uneven. Sweden and Finland are literally covered with small, and some large, lakes. In Sweden there are presently (1999) 95 745 lakes larger than 1 ha, all registered in a central database at SMHI (K. Ehlert, personal communication). Continuous revision changes the number somewhat from year to year. Finland has 35 000 lakes on the lake plateau only. The retreating ice formed a considerable number of lakes in Fennoscandia. In the plains of the three Baltic states and Poland, lakes are not as common. There are eight lakes that have an area of 1 000 km^2 or more (Table 1.2).

There is considerable interannual variability in the runoff to the Baltic Sea as shown in Figure 1.6. The wet year of 1924 had a mean annual runoff of 19 500 m^3/s while the corresponding figure for the dry year of 1976 was as low as 11 100 m^3/s.

The annual inflow of 450 km^3 is a tremendous volume of water, which, in theory, is available to the population in the basin. Evenly spread out over the surface of the Baltic Sea it corresponds to a depth of 1.2 metres of water. Unfortunately the geographical distribution of this water is converse to the population density. Due to the high precipitation and low evapotranspiration of the north the available water resources are much greater there than in the south and particularly great in the northwest. This is in strong contrast to the population density, which is greatest in the south and very low in the northern parts of the area.

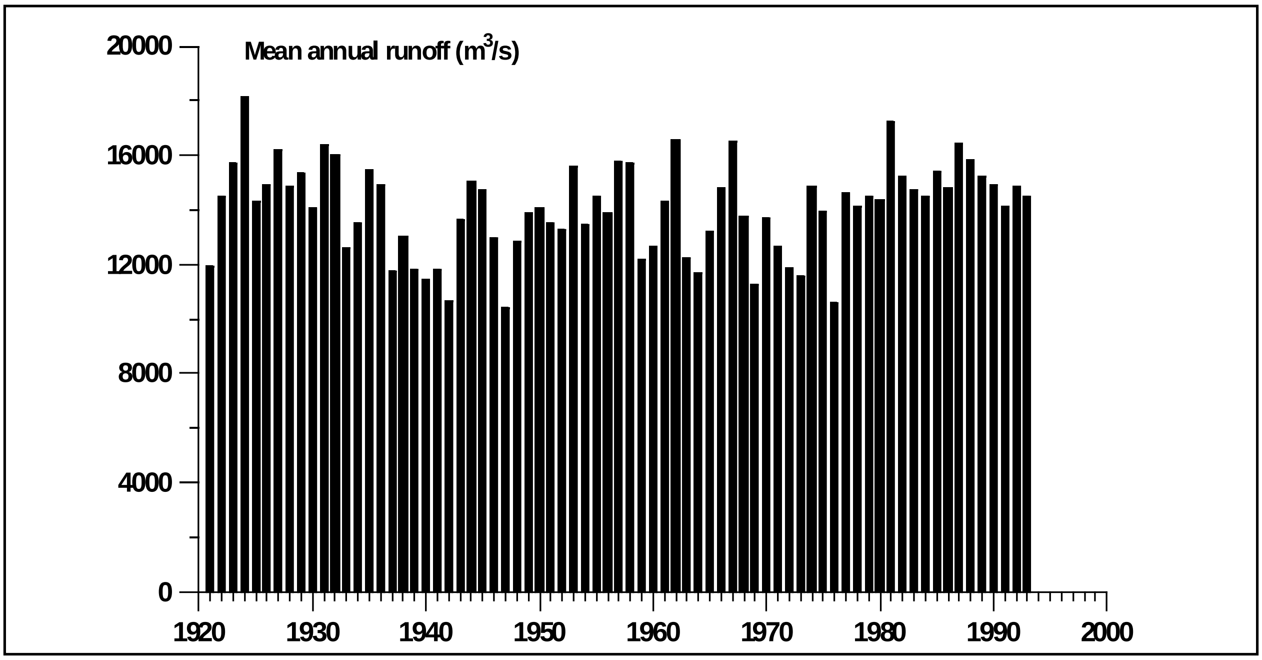

Figure 1.6. Time series of mean annual river flow to the Baltic Sea (data from Bergström & Carlsson, 1994 ; Mikulski,1982).

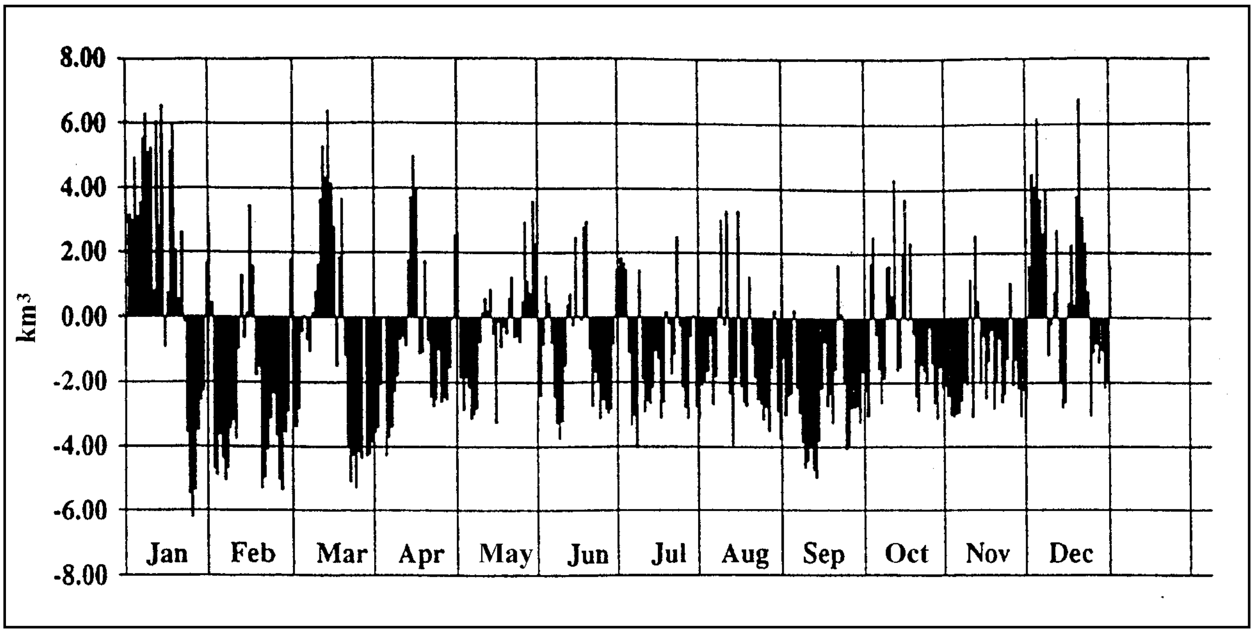

Figure 1.7. Exchange with the oceans. Estimated daily flow of water through the Öresund Sound, between Denmark and Sweden, in 1993. Inflows are indicated by positive signs and outflows by negative signs (prepared by Barry Broman, SMHI).

The water cycle of the Baltic basin ends with an exchange of water with the seas that pass through the Danish Sounds. This is a critical factor for the concentration of oxygen and salinity and thus for the whole ecological system of the Baltic Sea. This exchange is a much more irregular process than inflow via rivers. The flow goes back and forth under the influence of climatological and oceanographic conditions. Typical flow rates may be in the order of ten times the average annual fresh-water inflow. This is illustrated by Figure 1.7, which shows an estimation of daily flows through one of the two main outlets, the Öresund Sound, in 1993. The estimation is based on sea level observations.

In Figure 1.7 one major inflow event in January 1993 can be identified. This type of episodic event is relatively rare. It may occur roughly once every ten years and is of utmost importance for the salinity and oxygen conditions of the Baltic Sea. This is, however, normally only a temporary improvement due to the increased pollution load on the water body. Major inflows of highly saline water to the Baltic Sea have an episodic character and may occur about every ten years (Schinke & Matthäus, 1998).

Basic data on the Baltic Sea

Table 1.3 gives a compilation of morphometric data for the Baltic Sea and some major sub-areas. From this table we may note that the mean depth of the Sound and the Belts is only 14.3 m, which is a most important obstacle for a free water exchange across the Danish straits. The deepest sub-basin of the Baltic Sea is the Baltic proper with a mean depth of 62 m. In the northwestern part of the Baltic proper we find the deepest part of the Baltic, the Landsort deep (459 m).

Table 1.3. Morphometrical data for the Baltic Sea and its seven sub-basins. (from Mikulski, 1985)

	Drainage area (km^2)	**Water area** (km^2)	**Volume** (km^3)	**Max. depth** (m)	**Mean depth** (m)
1. Bothnian Bay	269 950	36 260	1 481	156	40.8
2. Bothnian Sea	229 700	79 257	4 448	294	61.7
Sum of 1 & 2	499 650	115 517	6 370	294	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 of 1 to 5	1 615 223	372 858	20 919	459	56.1
6. The Sound & Belts	27 360	20 121	287	38	14.3
7. Kattegat	78 650	22 287	515	109	23.1
Sum of 1 to 7	1 721 233	415 266	21 721	459	52.3

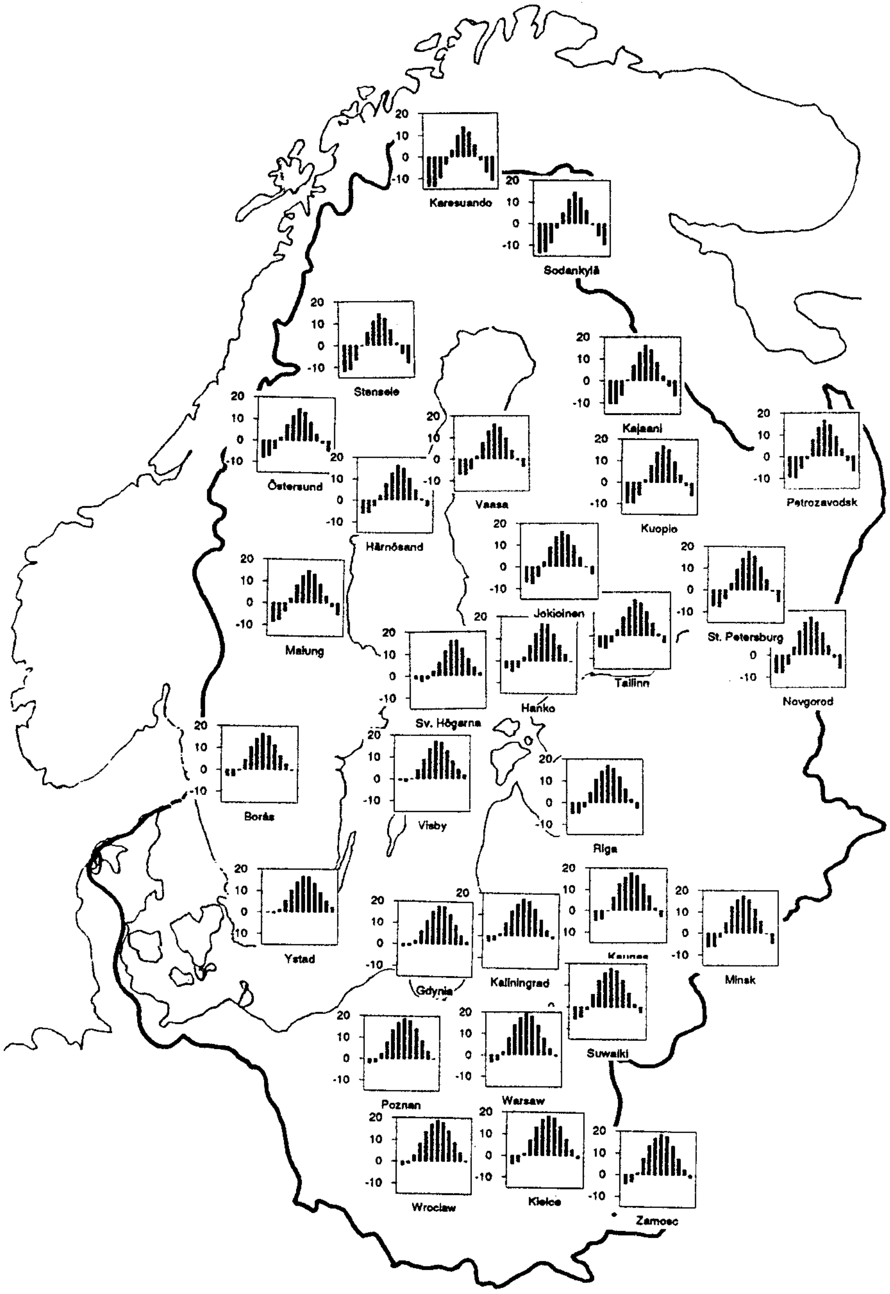

Figure 1.11. Monthly mean temperature.

IN THE BALTIC SEA REGION

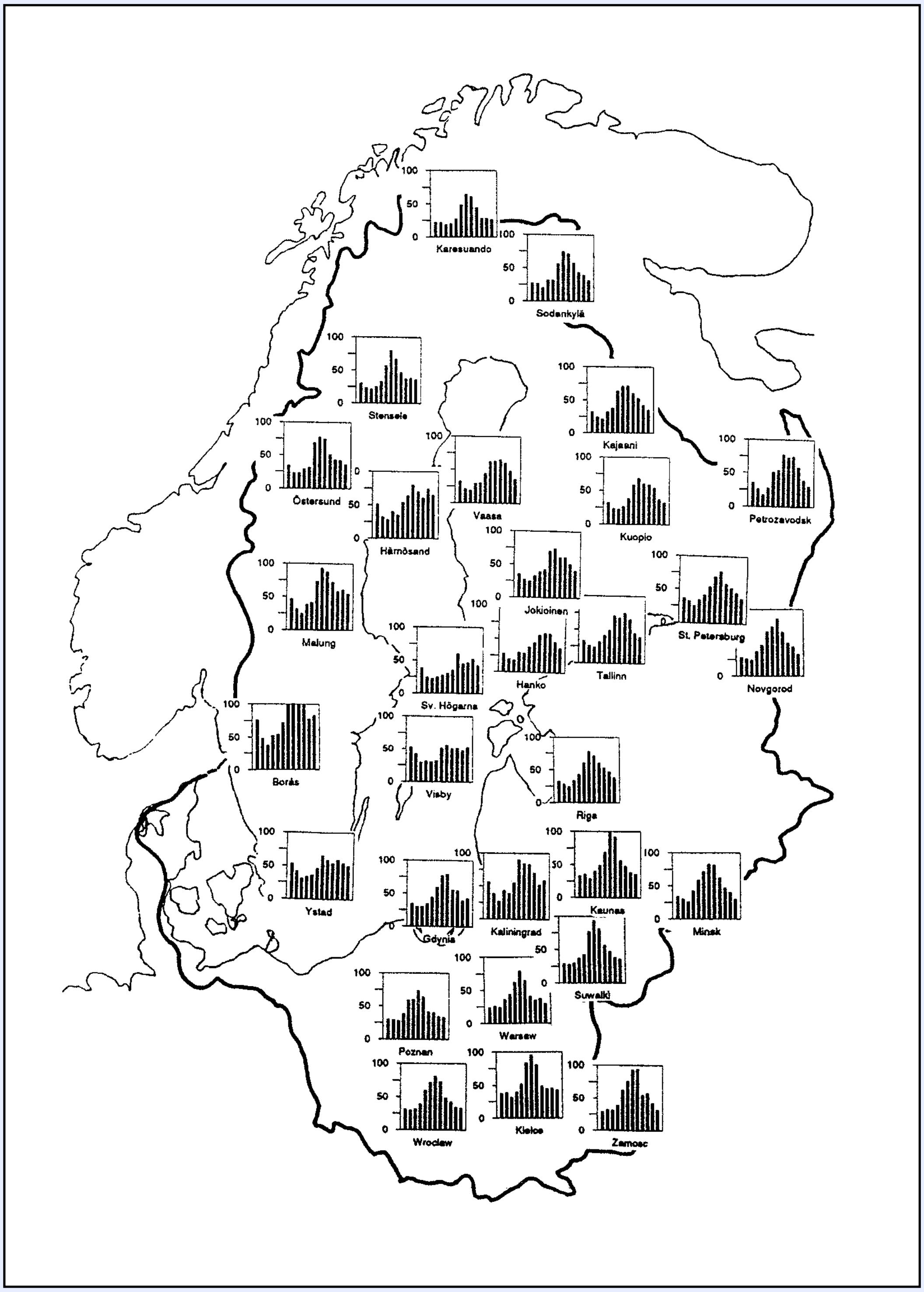

Figure 1.12. Monthly mean precipitation.

Table 1.4. Size of the drainage area (A), mean water discharge (Q) and specific runoff (q) for the largest rivers entering the Baltic. (from Voipio, 1981)

River	**A** (km²)	**Q** (m³/s)	**q** (l/s·km²)
Neva	281 100	2 600	9.25
Vistula	193 910	954	4.92
Daugava	87 900	688	7.83
Nemunas	98 200	674	6.86
Kemijoki	51 400	581	11.30
Luleälv	25 250	477	18.90

Most of the freshwater entering the Baltic emanates from river input (Table 1.4). The precipitation is generally much smaller than the river input and largely of the same magnitude as the evaporation. Surplus freshwater passes through the Danish straits. From Table 1.4, we note that the specific runoff is generally larger in the northern parts of the drainage area than in the southern.

Table 1.5 gives a rough estimate of the Swedish inland water resources. The total volume of the lakes is 700 km^3. Note that the numbers given for the areal classes have been revised since the survey by SNV (1986) was made. Especially the number of small lakes was underestimated in the presented dataset. Generally, the Swedish and Finnish parts of the drainage area are characterised by large numbers of lakes as compared to the southernmost parts.

European climate

Air-mass circulation determines Europe's climate. The relief of the continent makes it possible for air masses originating in the Atlantic Ocean to pass freely through the lowlands, except in the case of the mountains of Scandinavia. Polar air masses from areas close to Iceland and tropical air masses from the Azores can both reach the continent, bringing very different conditions of temperature and humidity. Continental air masses from Eastern Europe have equally easy access westward. The almost continuous belt of high mountains separates southern Europe, and limits the interchange of tropical and polar air masses. Of the various climatic conditions, five air pressure belts can be distinguished: the Icelandic low, the Azores high, the Mediterranean low; the Siberian high, and the Asiatic low. Driven by these pressure patterns, westerly winds prevail in north-western Europe. Winters get sharply colder eastward, while summer temperature increase southward. North-western Europe, including Iceland, enjoys somewhat milder winters because of warm Gulf Stream waters. Four regional European climatic types can be distinguished:

Table 1.5. Number of lakes in Sweden in different size classes (> 1 ha). (from SNV, 1986)

Area (km²)	**Mean area** (km²)	**Mean depth** (m)	**Number**	**Water volume** (km³)
>1 000	2 500	50	3	375
1 000-100	250	25	19	119
100-10	25	12	362	109
10-1	2.5	7.5	3 987	75
1-0.1	0.25	5	19 374	24
0.1-0.01			59 500	
		Sum:	83 242	702

- *Maritime climate* (Svalbard, Iceland, the Faeroes, Great Britain and Ireland, Norway, southern Sweden, western France, the Low Countries, northern Germany, and north-western Spain);
- *Central European (transitional) climate* (central Sweden, southern Finland, the Oslo Basin of Norway, eastern France, south-western Germany, and much of central and south-eastern Europe);
- *Continental climate* (northern Ukraine, eastern Belarus, Russia, most of Finland, and northern Sweden);
- *Mediterranean climate.*

Climate in the Baltic basin

The climate in the Baltic region is that of the Atlantic-Arctic Temperate Zone and can be described as relatively mild. Winters are fairly mild in the south-western parts, getting colder towards the north and north-east, but, although long, they are not very severe, especially in Eastern Fennoscandia, where spring is late and summer is short. Frequent cold sessions during spring affect the climate in the whole region. Throughout the year the relative humidity levels are high and precipitation is abundant. These features are due to the geographical vicinity of the Baltic Sea, the Atlantic Ocean, the White and Barents Seas, as well as the dominance of intensive cyclonic activity during all four seasons.

Eastern Fennoscandia is notable for a peculiar climate resulting both from some specific features of the atmospheric processes in the Atlantic Ocean, Arctic Ocean and Siberia, as well as from the Great European Lakes' and White Sea effects on the drainage basins. The climate formation here is influenced by the high percentage of coverage of the territory by surface waters (lakes occupy 12 % of the territory), forests and wetlands.

Changes in the general atmospheric circulation in the Northern Hemisphere in recent years proved to be conducive to a considerable increase in the number of days with eastward air transport in the eastern part of the region (Eastern Fennoscandia). This is one reason for the increase in mean annual temperature in the area, mainly due to an increase in the air temperature in the spring and autumn periods. In the western region an increase in the occurrence of westerly winds in recent years has also further increased the winter mean temperatures of the last decade.

The duration and stability of the eastern circulation in this area is usually lower than that of the western circulation. It manifests itself mostly during the winter period through low air temperatures, a smaller number of cloudy days and lower precipitation. This type of circulation loses much of its vigour by April when the meridional type replaces it. By the beginning of the summer period, the western air transport takes a dominant role. The dominant form of atmospheric circulation over the territory throughout the year is the western transport (151 days), while the eastern circulation lasts less (94 days) and 120 days are governed by meridional circulation. For the western part of the region western and eastern transport is less (120 and 85 days, respectively) while meridional transport is more frequent (160 days).

Instrumental observations extending over 100 years were used to calculate mean global air temperature changes and the temperature changes in the Great European Lakes area, around Lakes Ladoga and Onega. Data analysis showed a growing deviation from the global mean air temperature, evidenced by a statistically reliable trend (Watson et al., 1996), the mean global air temperature being 15 ºC and the rate of change 0.5 ºC in 100 yearsAn analysis of the data on the surface air temperature in the Northern Hemisphere in the last 100 years showed that intensive warming which had started at the end of the last century actually ended by the 1940s. This warming was interrupted by a temperature reduction, which lasted until the 1960s and was followed in its turn by a new warming starting in the mid 60s. The mean annual air temperature in the Great European Lakes area was as low as 1.6 ºC. The warmest years throughout the whole history of the instrumental observations (i.e. 1881-1993) were the 1930s and the year of 1990 with the mean annual temperature 4.5 ºC. Starting with the late 1970s, rather high amounts of precipitation and raised water levels in lakes were recorded in the Great European Lakes area and in the north-west of Russia. Considerable climate changes in the region in those years are manifested also through a shorter period of snow cover of the catchment areas and a longer ice-free period on the lakes.

When comparing the values of mean annual deviations in the global and regional air temperatures for the Great European Lakes area, certain common features can be seen. Above all, this means a statistically significant positive trend.

Because of the low precision and low resolution of modern global climate models (GCM) applied to indi-

MAPPING OF WATER RESOURCES

In order to manage water resources in a specific community, region or country it is imperative to produce a good description of the available water resources: the rivers, lakes and wetland, major groundwater aquifers and the coastal areas. It is also important to try to regionalise the resources, taking into account the division of responsibility between various water districts, authorities and other jurisdictional bodies. Having mapped the quantitative aspects, preferably grouped into regional classes, the next step will be to map the qualitative aspects, e.g. the load of various fertilisers and pollutants and inherent water quality. As a further step, the societal needs can be mapped in order to get a brief idea of the balance between demand and availability for various regions.

Further steps, including e.g. the creation of a database with GIS (geographical information system) functionality for easy retrieval and presentation of the gathered data, would require an effort compatible with a thesis project or the work that would be performed in a professional situation. Normally, considerable amounts of data are already available from various authorities and the problem is to aggregate the data found in the archives. The effort of putting the data into digital form should not be underestimated. In order to cover the full regional extent or a specific aspect, additional data may need to be gathered. For data with a temporal variation, e.g. runoff or water stage, periodical updates of the database are needed. If no authority is able to provide these data, a specially designed monitoring programme needs to be developed.

The country of Finland was chosen as a case study to be presented in the following boxes, since various information, not only on water resources, was easily available from the Atlas of Finland (National Board of Survey & Geographical Society of Finland, 1986).

Lars-Christer Lundin

Morphology of Finland

The coastline of Finland borders the northern part of the Baltic Sea, the Gulf of Bothnia and the Gulf of Finland. The northern part of the Gulf of Bothnia is called the Bothnian Bay and the southern part the Bothnian Sea. In between these parts, there is a relatively shallow and narrow body called the Quark. The southern part of the Bothnian Sea is the Åland Sea, situated between the Åland Isles and the Swedish coast.

To the west of the Gulf of Finland, south and south-east of the Åland Isles, the area contains numerous small isles and is consequently called the Archipelago Sea.

The land area of Finland can be divided into three distinct subareas:

The coastal plain is a 100 to 200 km-wide belt from the coastline, at an elevation from 0 to 100 m. It covers about one third of the total area. The soils are mainly postglacial sedimentary deposits and form the fertile agricultural land. The lake percentage is relatively low.

The lake plateau is the interior of South Finland at elevations between 100 and 200 m, and covers another third of the area. The area is bounded by the Salpausällkä terminal moraine system in the south. It contains about 35 000 lakes, the largest being the Saimaa, Päijänne, Näsijärvi, Oulujärvi and Pielisjärvi Lakes. Lake Saimaa drains into Lake Ladoga in Russia.

The highland area is the northern part of Finland at elevations between 200 and 400 m except for a few mountains, with one, called Haltiatunturi, being situated on the Norwegian border in the northwest. The lake percentage of the area is rather low but there is one large lake in the northeast part, Lake Inarejärvi, that drains into Barents Sea through River Paatsijoki. In the centre there are two large manmade lakes, Lakes Lokka and Portipahta, which are reservoirs for power production on the Kemijoki River. The area of Lake Lokka is about 400 km^2. The western border to Sweden of the highland area is Tornio River together with the tributary, the Muonijoki River. In the far northwest the Tana River (Tenojoki) forms a part of the Norwegian border. This river drains into the Arctic Ocean.

About a third of the total area of Finland is covered by *wetlands*, mostly peat. In the south about 85 % of the wetlands are drained and thus reclaimed for agriculture and forest production. In the highland area about 40 % is drained, mainly for forest production.

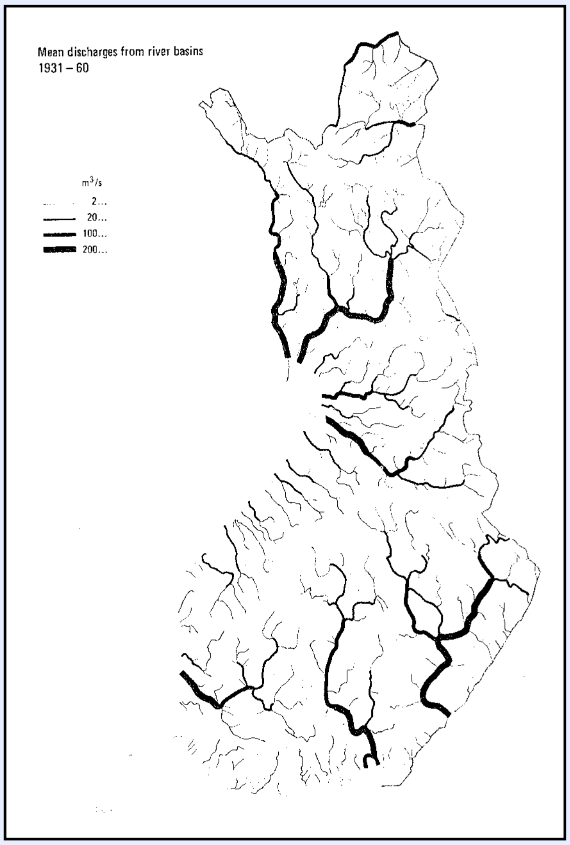

Figure 1.13. Average discharge from main river basins or from subareas of the first partition (from the National Board of Survey & Geographical Society of Finland, 1986, Atlas of Finland, Folio 132, Figure 13i, published by permission no. 420/MAR/98).

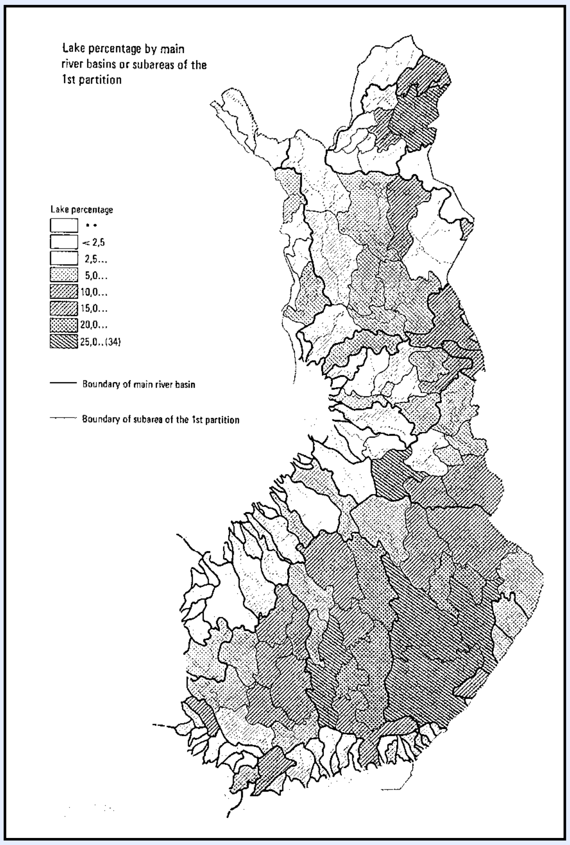

Figure 1.14. Percentage of lakes in main river basins or in subareas of the first partition (from the National Board of Survey & Geographical Society of Finland, 1986; Atlas of Finland, Folio 132, Figure 13g, published by permission no. 420/MAR/98).

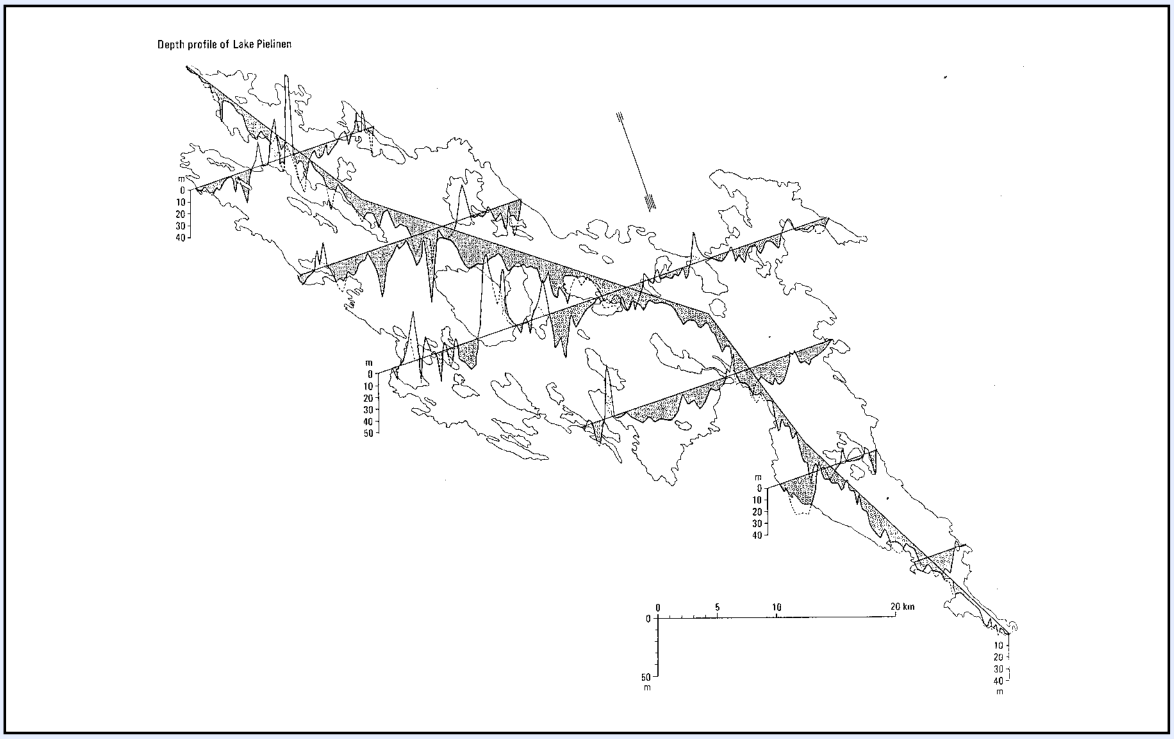

Figure 1.15. Depth profiles for Lake Pielinen (from the National Board of Survey & Geographical Society of Finland, 1986; Atlas of Finland, Folio 132, Figure 17b, published by permission no 420/MAR/98).

Drainage pattern

The major rivers are River Vuoksi in the south-east, River Kymi in the south, River Kokemäenjoki in the south-west, River Oulu in the centre, Rivers Kemijoki and Tornio in the north. A quantitative picture of the drainage is seen in Figure 1.13. The mean discharge for these major rivers exceed 200 m^3/s. Figure 1.14 shows the main river basins and subareas of the first partition. The lake percentage classification is also given in the figure. In three of the subbasins of river Vuoksi in the south-east more than 25 % of the area is occupied by lakes and another similar area is the upper part of the River Kymijoki basin.

The lakes vary greatly in morphology as seen from the depth contour of Lake Päijänne in Figure 1.16. The pattern reveals structures of the underlying eroded old granitic peneplain with a mixture of erosion patterns. On this surface the last ice age left a criss-cross pattern of eskers and terminal moraines within which the numerous lakes were formed after the uplift above sea level. The complexity of this pattern is seen in Figure 1.15 that shows depth profiles along and transverse to the Lake Pielisjärvi's main direction. The deep portions are pockets or trenches in the basement rock. The high protruding features are eskers and morainic ridges.

Erik Eriksson

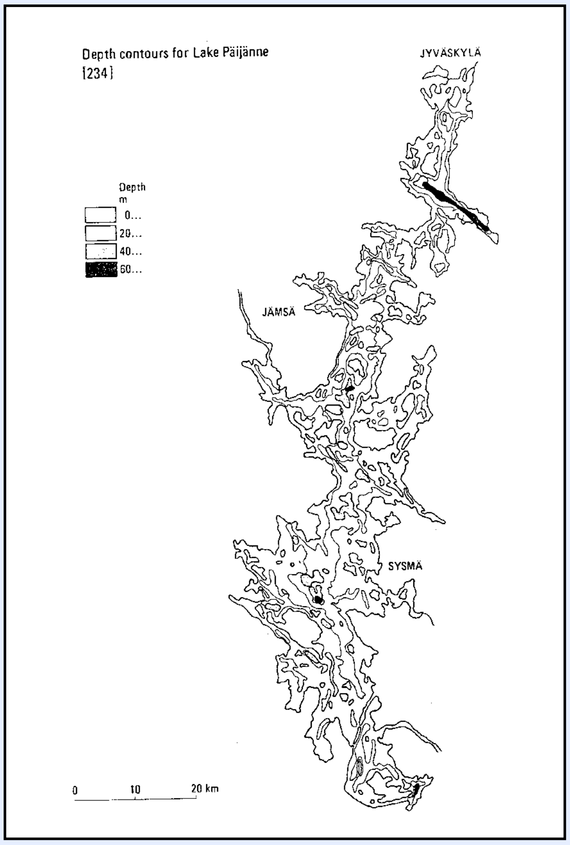

Figure 1.16. Depth contours for Lake Päijänne (from National Board of Survey & Geographical Society of Finland, 1986; Atlas of Finland, folio 132, figure 17d, published under permission no 420/MAR/98).

vidual regions, hydrogeological consequences for regions and drainage areas can as yet only be roughly estimated, and the models are hardly suitable for forecasting. The confidence in temperature projections however is higher than in hydrological changes (IPCC, 1995). Common features for all scenarios include greater surface warming in winter over land than over sea and an enhanced global mean hydrological cycle, caused by warmer temperatures and increased precipitation and soil moisture in high latitudes, such as the Baltic region, in winter. The impact on the hydrological cycle is expected to show up as more severe droughts and/or floods in some regions, but less severe in others. A reduction in the North Atlantic circulation and in the diurnal temperature is included in most scenarios. According to the forecasts given earlier by Shiclomanov (1988) a 12 % decrease of the annual total runoff in north-western Russia is to be expected by the end of the century. Our data from the Great European Lakes area indicate that this forecast might not be entirely accurate. Shiclomanov (1988) also maintained that a dramatic increase in precipitation might occur in southern regions by 2020-2050 with the total runoff of northern rivers growing by that time. This conclusion has already received some corroborating evidence from the changes in the Caspian Sea water level. Several forecasts of climate changes based on linear models, including that of the Caspian Sea (Privalsky, 1985), proved erroneous. It is, therefore, very important to revise the theory and methods of forecasting the climate in order to provide for proper decision-making in the control and management of water resources.

Investigations have shown that the 116-year series of the annual air temperature mean for the Great European Lakes area from 1880 to1995 contains a positive linear trend equal to 0.4 ºC/100 years. Particularly interesting in this context is the analysis of the spatial distribution of the trend value and the sign of annual and seasonal air temperature indices in the Great European Lakes area to estimate the potential effect of large water bodies (Lakes Onega and Ladoga) on the climatic characteristics of the region.

CASE: WATER LEVELS IN LAKES LADOGA AND ONEGA

A comparison of the Great European Lakes' ice-cover dynamics data and the appropriate data of other lakes of the world shows that considerable changes are to be expected in the boreal zone lakes due to a definite tendency towards warming. Observations in the North American lakes (WMO, 1995) demonstrated that the ice cover is getting about 20 cm thinner. The ice on Lake Hoara in the Antarctic has been getting 20 cm thinner each year for the last two decades. At the same time, the Great European Lakes are characterised by an increasing number of ice-free days. Ice cover on the lakes located at high latitudes is a good indicator of climate changes.

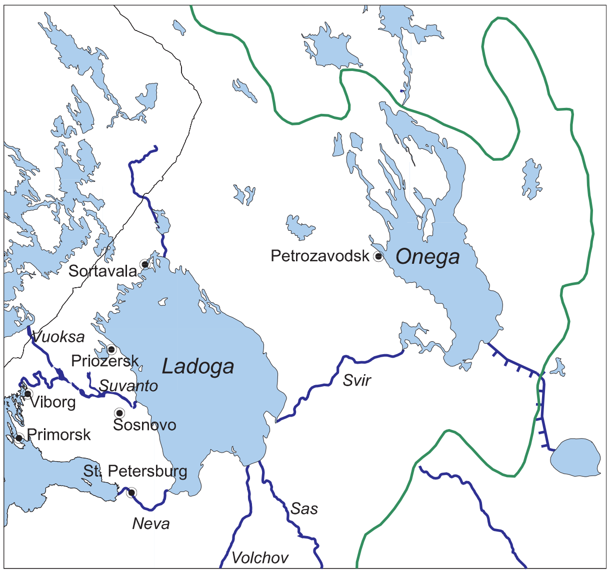

Figure 1.17. Map of the Lakes Ladoga and Onega region. The grey line denotes the Baltic basin water divide (compiled by Patrik Steen).

At the same time, the data presently available are not quite sufficient for identifying the climate-induced changes in lake ecosystems. Nonetheless, they are indicative of the fact (Petrova & Torzhevik, 1987; Filatov, 1997) that the main cause of lacustrine ecosystem changes is manmade factors. Climatic effects, climate change and their impact on large lakes can be determined using the data on the changes in the water balance elements and lake level. It can be stated generally that the largest lakes produce a very significant effect on the features of the spatial-temporal distribution of the local climate characteristics. Lake Ladoga renders the climate milder in the south-western region, as does Lake Onega – in the south-eastern region, the White Sea – in the north-eastern part of the ambient area.

In order to forecast the lake water level, it is important to relate it to the factors governing its variability. These factors for Lakes Ladoga and Onega, just like for other running-water bodies in the boreal zone, are surface inflow, outflow from the water body and, to a lesser degree, atmospheric precipitation and evaporation from the water surface.

Chronological disagreement between atmospheric circulation cycles and water content phases is due to some inertia in the processes occurring in the drainage basin. Beginning with the 1940s, against the background of the increase in winter precipitation and augmentation of the temperature during the cold period, a reduction is observed during the spring flood (the last phase). This situation can be explained by moisture losses from the snow surface at the end of winter under the dominance of cellular circulation.

When assessing climatic effect on water bodies, it is important to analyse fluctuations in the water level as an integral index of the system changes. Various models based on the analysis of the water balance linear equation were widely used to study the water level variations. These models were applied to water bodies without outflow (Caspian and Aral Seas, Lakes Balkhash and Issyk-Kul), to exorheic water bodies.

The application of the linear equation of water balance for forecasting the fluctuations of the Caspian Sea level resulted in an error as large as 1.67 m. It is therefore evident that this linear type of models cannot be applied to the processes. To estimate the water level variations, Hublarjan et al. (1996) studied non-linear physical mechanisms in the system that considered the effect of random external forces on the behaviour of non-linear dynamic systems. As a result, a fundamentally important conclusion was made that because of the multiplicity of equilibrium levels of transition, water bodies may not be appropriate indicators of climate changes at all, but reflect their own non-linear water balance dynamics. The conclusions based on this model seem rather novel and may explain the long-lived "mystery of nature" and determine the mechanisms responsible for the intensive fluctuations of water levels occurring against the background of weak and slow climate changes. According to this theory, the water level in water bodies differing in size and depth, but subjected to similar climatic conditions, e.g. Lakes Ladoga and Saimaa or Lakes Huron and Erie, should demonstrate non-synchronous fluctuations.

Nicolai Filatov & Dmitry Pozdnjakov

Photo, Inga-May Lehman Nådin.

2.

THE BALTIC SEA AND ITS COASTS

Stanislaw Musielak, Kazimierz Furmanczyk, Lars Håkanson, Per Jonsson & Johan Persson[1]

The coastal zone

The archipelago areas in the Baltic Sea, like those of other coasts, show great variety in regard to bottom topography, currents, vegetation, fauna, salinity, etc. Accordingly, coastal areas have different environmental conditions and different sensitivities to human impact. Many coastal areas have higher primary production, richer vegetation and animal life and a larger sedimentation of organic material than the open sea. Shallow coastal areas are often important for spawning and growths of many fish species.

Different coastal areas respond differently to one and the same load of nutrients or pollutants, regardless of whether the load is natural or anthropogenic. In some areas the environmental effect may be negligible, i.e. the areas are not sensitive to high loads, whereas in other areas the effect may be severe due to higher sensitivity. The sensitivity of the coastal area may be expressed as a function of several factors (see Wallin & Håkanson, 1991), e.g. *water turnover, bottom dynamic conditions* and *morphometry*. All of these factors influence the dispersal, sedimentation and recirculation of different substances, e.g. nutrients in the coastal zone.

Water turnover is a very important factor since it regulates how effectively a discharge is diluted by exchange with surrounding waters, thereby affecting the concentration of a certain substance that often is decisive for the environmental effect. Furthermore, the ecological character of coastal areas, with their rapid water turnover, is generally different from areas with slow water turnover. Areas with slow water turnover are often enclosed and generally have a high biological production capacity (see Håkanson & Rosenberg, 1985). Moreover, the deep-water turnover is of great importance to the oxygen consumption/oxygen status of the deeper regions of a coastal area. The quicker the deep-water renewal, the smaller the risk for problems with low oxygen concentrations will be.

Bottoms of coastal areas

Another important factor is dynamic conditions at the sea bottom. The bottoms of a coastal area can be classified according to functional criteria, like erosion, transportation and accumulation of coarse sediments (friction material) or fine sediments (cohesive material). In contexts of coastal ecology it is important to focus on finer materials (< 0.06 mm grain size) since pollutants generally show high affinity with fine materials (Förstner & Wittman, 1981).

Håkanson & Jansson (1983) have defined the bottom dynamic conditions as follows: Coarse materials dominate *erosion bottoms*. These are generally only found in near-shore areas, where water movements and currents are strong enough to remove bottom materials. No deposition of fine materials occurs on the erosion bottoms and the sediment consists of sand or larger particles, with a water-content of less than 50 %. *Transportation bottoms* are characterised by discontinuous deposition of fine matter. Periods of accumulation are interrupted by periods of resuspension and transportation. The water content of these sediments varies in the vicinity of 50 to 80 %. *Accumulation bottoms* are characterised by continuous deposition of fine matter (silty to muddy particle fractions). These sediments have high water content (> 75 %) and also a high content of organic material. A presence of large areas of accumulation implies that much of the settling matter is accumulating within the area whereas an area characterised by erosion and transportation processes will usually function as a transportation route, which means that material will settle outside the area. Areas with large proportions of accumulation areas are usually found in the innermost parts of the coastal zone, in sheltered positions. Exposed areas close to the open sea are usually characterised by significant wave energy processes and thus areas of accumulation are more rare in such areas, leading to a dominating proportion of erosion and transportation bottoms.

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[1] Stanislaw Musielak and Kazimierz Furmanczyk contributed with Baltic coast types and Coastal water management and Lars Håkanson, Per Jonsson and Johan Persson contributed with the introductory text.

Sediments in a coastal area originate from point and non-point sources, rivers, the open sea and surrounding coastal areas, autochthonous production and mineralization of settling material. The dispersal and/or sedimentation of fine matter depend(s) on a number of area-characteristic factors, like the morphometry. The wind/wave action also has an influence, e.g. resuspension of fine matter. In addition, coastal currents and tides have an impact on the transport of fine matter.

Figure 2.1. Cliff coast. In front of the cliff there is a narrow shore consisting of sand, pebbles and gravel. Jastrzebia Gora, Poland.

The energy input into the archipelago coastal areas is controlled mainly by wind/wave impact. The coastal morphometry then determines how the energy is processed within the areas. State variables like wind/fetch and coastal morphometry influence turbidity, water exchange and bottom dynamic conditions which in turn influence nutrient recycling, primary production and eutrophication effects (Wallin 1991; Wallin & Håkanson, 1992).

Functions of the coastal zone

The coastal zone is one of the most important parts of the Baltic Sea ecosystems for a number of reasons, e.g.:

- The coastal zone acts as a filter and purification plant for nutrient discharges.
- There is high biological production in the coastal zone and it acts as a nursery and spawning area for many fish species.
- The coastal zone constitutes a large potential for different forms of aquaculture, e.g. fish-farming in cages. This implies increased release of organic matter and nutrients, which have different environmental effects on different coastal areas.

Due to the lack of sampled data in the beginning of the 20th century, an important question is how much internal (inherited) properties, morphometry, water turnover and bottom dynamics can explain the variation in effect parameters, e.g. near-bottom oxygen concentration or water clarity. Wallin & Håkanson (1991) state that:

The sensitivity of coastal areas, linked to inherent properties like morphometry, water turnover and bottom dynamics can explain a large part of the variation (50-70 %) of the effect parameters. For instance, bottom dynamic conditions give a first rough measure on the trophic level. In other words, the bottoms 'reflect and affect' the trophic state of the coastal areas.

Another important result is that many coastal areas can have natural low oxygen concentrations in the deep water because of the inherent properties of the areas.

The nutrient dose from fish-farms can maximally explain 18-49 % of the variation in the effect parameters. It may, thus, be concluded that inherent properties of coastal areas, linked to e.g. morphometry and water/bottom dynamic conditions, have a major impact on eutrophication effects such as Secchi depth, chlorophyll-a and near-bottom oxygen concentration in Baltic coastal areas. This demonstrates that their basic hypothesis that "different coastal areas have different sensitivities to one and the same dose of nutrients" is correct and that such relationships may be quantified. When choosing suitable/unsuitable coastal areas for nutrient emissions from, e.g. fish farms or other nutrient point sources, at least in the coastal zone of the Baltic Sea, it is therefore, on the whole, the sensitivity of the area that is decisive regarding the eutrophication effects.

Baltic coast types

There are exceptionally many kinds of the coasts on the Baltic Sea. One type was created as a result of wave action and other hydrodynamics factors. Other types were created under great influence from tectonic movement (uplifting or submerging) river mouth impact (riverine coast) or intensive development of biota.

Present Baltic coasts were developed in a primary landscape connected with the latest deglaciation of this region and Holocene transgression of the sea.

The Baltic sea level rose very fast and reached a level about 2-3 metres lower than the present level at about 7 000 BP. During the last 7 000 years the coast zone was created under the influence of much slower sea-level rising, with many oscillations.

In the Baltic region we can find three main types of coasts developed in the primary landscape near the sea level:

- Long, narrow, and deeply U-shaped mountain valleys that made the basis for *fjords.*
- Hilly areas that were the basis for *skerries* (in the archipelago).
- Areas of moraines and fluvioglacial material deposits that were the basis for *sandy coasts*.

The primary coastline shape was changed depending on geological construction, erosion resistance of the coast, slope of the coast above and below the sea level, sea level changing, neo-tectonic movement river mouth location and exposure to wave action.

Sandy coast

The South Baltic sandy coasts were developed mainly on postglacial materials, i.e. moraines and fluvioglacial material. A rapid development was possible because of soft, erosion-prone material that was broadly exposed to wave attack and impact from the rising of the sea level (Furmanczyk & Musielak, 1996).

Depending on the coastal profile slope and amount of sandy material available for the coastal processes, four main categories of sandy coast were created:

- cliff coast
- boddens
- dune coast
- lagoons

The present shape of the sandy coast depends on the following factors:

- geomorphology,
- average level of forms compared to sea level,
- slope of the primary coast,
- sea level change with variations including neo-tectonic movement,
- exposure to wave action.

Cliff coasts

Cliff coasts (Figure 2.1) are abundant when postglacial material (clay and fluvioglacial sands) is present as a highland well over the present sea level. The cliff forms on the steep side of this formation.

We find cliffs in many places along the south Baltic coast. About 30 % of the coast of Germany consists of cliffs, with the most famous areas being the Usedom Islands and the Mecklenburg Bay, where the rate of erosion is very intensive. There are also very high (over 100 m) chalk cliffs on Rugia Island. About 20 % of the Polish coast consists of cliffs. The most famous cliffs in that country are situated on Wolin Island, with a height of about 90 m. Mid-way along the Polish coast there are several cliffs of about 10-35 m. There are also some cliffs in the western part of the Gdansk Bay (40-50 m).

The highest cliffs on the Russian Baltic coast reach a height of some 30-40 m. In Lithuania, stretches of cliff coasts (a total of 10 %) are found north of Kleipeda continuing into Latvia, where 20 % of the coast consists of cliffs no more than 20 m high. In Estonia finally, cliffs are found on some western peninsulas and on the islands.

The profile of the cliff coast depends on its geological formations:

- Vertical walls are created when cliffs are formed by body clay consisting mainly of small grains, i.e. silt and clay.
- Steep slopes are created when mainly fluvioglacial sands form cliffs.
- Combined, multi-step slopes are created when cliffs are formed by clay, sand and silt layers.

Eroded material from the cliff gets segregated when it reaches the coastal water. The small-size fractions are transported by water as suspended matter to the deep basin. Larger fractions, including sand, are located in the coastal zone. Part of this material is used when small sandy beaches are formed in front of the

Figure 2.2. Cliff coast protected by Gabion's seawall. Material has fallen from the cliff and reached the sea over the seawall construction. Groundwater impact is intensified by inadequate water management of the developed area located on the cliff which consists of many sand and clay layers. Jastrzebia Gora, Poland.

Figure 2.3. Bodden area. The coast is mainly low, flat and covered by vegetation. The north-eastern part of Szczecin Lagoon (Poland) appears to be a bodden area.

cliff and for the formation of underwater bars along the shore. Other parts of this material are transported along the shore to the next section of the coast.

On cliff slopes consisting of many clay and sandy layers, intensive processes are going on. The main role in the activity of this kind of cliffs is played by groundwater, especially at the point of contact between sand and clay layers. This is very clearly visible in Figure 2.2, where material falling from the cliff has reached the sea, passing over the seawall construction. It means that for the erosion of this kind of cliff, groundwater and cliff construction have more influence than sea action.

Inadequate water management in developed areas located on the cliff intensifies the groundwater impact. Jastrzebia Gora and Rewal on the Polish coast are typical examples of this.

Boddens

Bodden areas (Figure 2.3) were created in places where the postglacial plain lowland was covered due to a fast rising of the sea level in Holocene transgression. The lowland plains are now a shallow area with a depth of 1-2 metres below sea level. Some parts of the plain lowland (usually front moraines) are situated as islands, a bit above present sea level.

The past and present coastal processes act on the moraine islands, modifying them strongly. In boddens, these islands protect the lowland coast from wave action. This is the reason why coasts inside boddens are mainly low, flat and covered by vegetation. Boddens are usually very large and can reach up to a few tens of kilometres, with depths of 1-2 metres. We can find bodden areas on most of the eastern German coast, the most famous being the Greifswald bodden. On the Polish coast, part of the Szczecin Lagoon (Figure 2.3) and some parts of the Puck Bay appear to be bodden areas.

Dune coasts

Dune coasts (Figure 2.4) are found in places where postglacial material was located as a lowland plain or wide valley a bit higher than or at about sea level.

If exposure to the wave action is adequate and sources of sand can be supplied from surrounding areas (neighbouring coasts or shallow bottom areas), the coastal processes create sandy beaches. Aeolian processes collect some of the sandy material and fore dunes are created at the border between shore and lowland plain. Dune coasts of different sizes are created depending on exposure time to and speed of the sea action process and the volume of sandy material supplied to the coastal zone:

- Short-time exposure to the process or a small volume of available sandy material in the coastal zone usually causes the creation of one dune bar with a height of 2-6 m and width of about 50-60 m.

Figure 2.4. Dune coast. There are visible dunes covered by vegetation. Partly eroded. Wide sandy beach. Lubiatowo (Poland).

- When the process continues for a longer time and more sandy material can be supplied to the coastal zone, a 2-3 dune bar system may be created, with a height of 10-20 m and width of about 200-500 m.
- In exceptionally good conditions a multi-dune-bar system may be created with a height of even more than 40 m and a width of about two kilometres.

On most of the German open seacoast and on about 80 % of the Polish and the Lithuanian coasts there are dunes. The Darss Spit in Germany, with a high rate of accumulation, and the Swina Gate on the Wolin and Usedom Islands, with 1-2 m/year of accumulation speed, as well as the Leba Spit, over 40 m high, the Vistula Spit in Poland and the Kuronian Spit in Lithuania are all good examples of exceptional conditions that have created dune coasts. Another famous accumulation form in Poland is the Hel peninsula.

In the case of the Leba Spit, the balance between open (active) and vegetation-covered (stabilised) surfaces has been destroyed a few times in history. The latest occasion was in 16th century when forest management was inappropriate. This is the reason behind the huge areas of active dunes in the Leba Spit.

Most of the Latvian and Estonian coasts are dune coasts, with famous areas at the southern part of the Riga Bay and in the Narva Bay.

Lagoons

Lagoon coasts (Figure 2.5) are related to dune coasts. Dune coasts were created as a barrier between the sea and a lowland plain or wide postglacial valley. At the same time the sea level was rising slowly and freshwater entering by streams and rivers created wetlands, lakes or river mouths at the border between the lowland and the barrier.

- If the process of creating dune coasts as a barrier was weak (small amount of sandy material), the barrier could be overwashed or broken, episodically or constantly, by the sea because of storm surges and sea level rising or by freshwater during times of flood.
- If the process of creating dune coasts as a barrier was strong, the condition of the barrier was good. The barrier was high and wide, and seawater could not break it.

Groundwater, streams or rivers usually create shallow lakes. If the river carries large volumes of water (at spring or fall), the barrier can be broken at its weakest point by freshwater and a river mouth will appear. This will happen if the river activity is more intensive than the shore and dune-creating activity.

There are two typical examples of this process: the Vistula Lagoon on the Polish-Russian border and the Kuronian Lagoon on the Lithuanian-Russian border, where the barrier is constantly open.

Almost all lagoon lakes now have a connection to the sea, some of which are natural and some of which are artificial channels. There are many examples of this along the Polish coast.

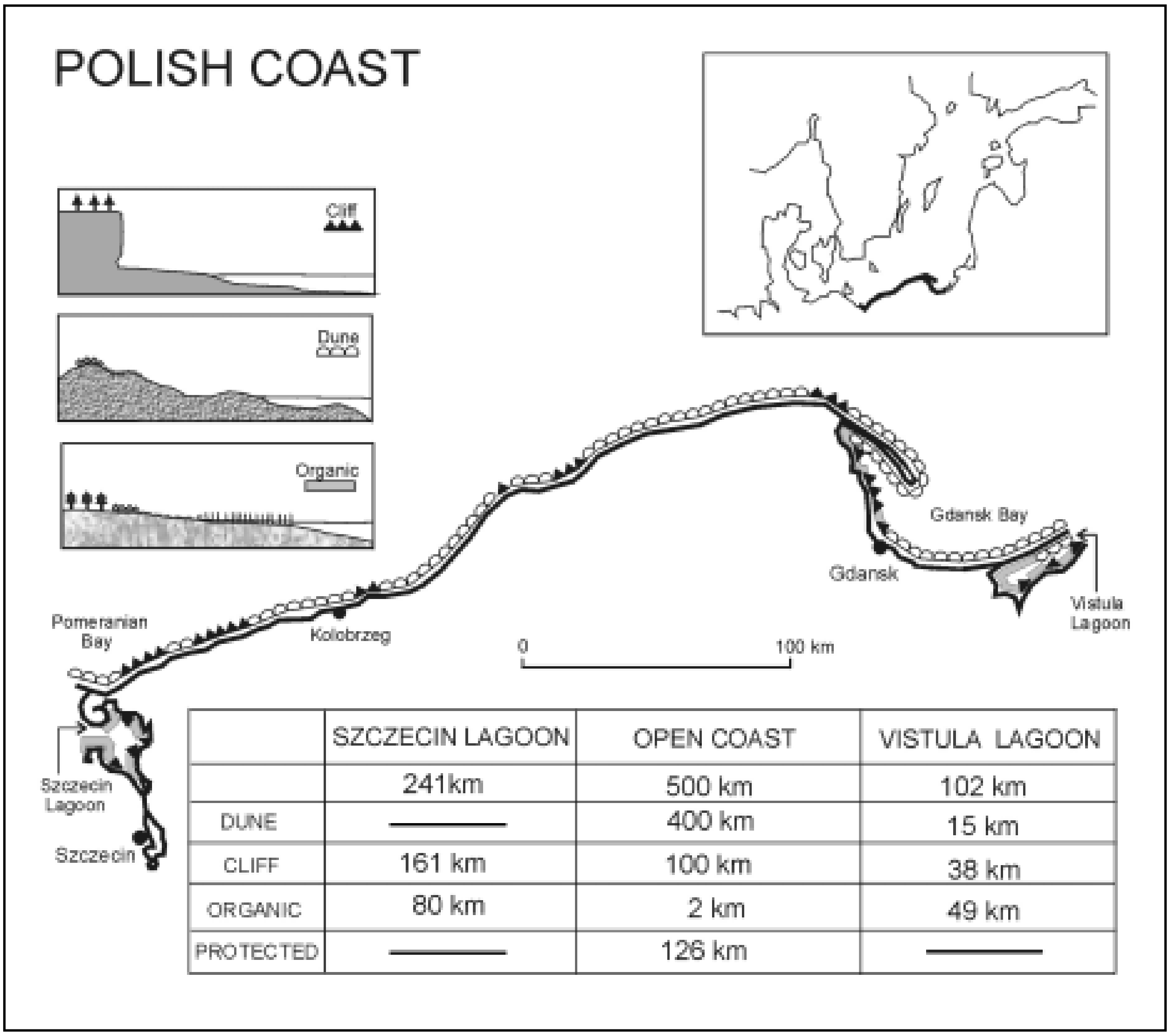
General remarks

Results of recent investigations on the development of the South Baltic coast show that during recent times there has been an acceleration of coastal processes connected to a faster sea level rise. A more intense erosion of the coast has been observed. An average speed of erosion on the Polish coast of about 0,5 m/year was noted, but some parts of the coast are still accumulating. It is difficult to say if this is a constant trend or if it is a part of an oscillation of only a small number or decades of years.

The balance of the sandy sediments on the shore and bottom of the shallow coastal zone decides the position of the coastline. If there is a lack of sediments, a higher rate of coastal erosion is observed. There are two sources supplying sediments in the coastal zone area: coastal erosion (mainly cliffs) and river input.

Human impact on the sediment balance is observed in the coastal zone and is mainly reflected in the followed activities:

Figure 2.5. Lagoon coast. The dune coast functions as a barrier between sea and lowland plain where a shallow freshwater lake was created (right). Pogorzelica (Poland) and Lake Liwia Luza.



	SZCZECIN LAGOON	OPEN COAST	VISTULA LAGOON
	241km	500 km	102 km
DUNE	———	400 km	15 km
CLIFF	161 km	100 km	38 km
ORGANIC	80 km	2 km	49 km
PROTECTED	———	126 km	———

Figure 2.6. Polish coast. Location of different types of coasts.

- Protection of the cliff coast against erosion. Sources of sediments are strongly limited in this case.
- Regulating rivers carry less sediment.
- Jetty construction at the mouth of the river causes sediment to go straight to the deep part and not to the coastal zone.
- Any hydroengineering construction in the coastal zone disturbs coastal processes, especially in extreme cases. In a long-term perspective this causes an increase of sandy sediments coming into the deep basin as compared to the circulation system of an undisturbed coast.

All these activities contribute to a decrease of sediment in the coastal zone.

Usually we want to keep our coasts and to prevent erosion. An ironic outcome of this is that the best protection of the coast is no protection. We should strive to protect as limited a section of the coast as possible, e.g. the harbours and big cities along the coast. Other than that, we should adjust our lives to the action of the sea in the same way that we adjust to volcanoes and hurricanes. It is much less expensive in the long run to move a building or two away from the coast, if possible, than to build heavy hydroengineering constructions to protect them and keep them in good condition for hundreds of years.

The disturbance of natural processes caused by hydroengineering constructions in the sandy coastal zone accelerates coastal erosion. Limitation of human activity significantly decreases coastal erosion.

Polish coast

The Polish coast is located between two bays, the Pomeranian Bay and Gdansk Bay, and is 500 km long. Inside both bays there are lagoons: the Szczecin Lagoon (partly Polish, partly German) and the Vistula Lagoon (partly Polish, partly Russian). Along the Polish coast (including lagoons) we find three kinds of coast: cliff coast, dune coast and flat, organic coast. Organic coast is located mainly inside lagoons where the activity of waves and currents is so small that plants are able to colonise there. A detailed representation of different kinds of coasts in Poland is presented in Figure 2.6.

Coastal water systems

For all kinds of coasts it is very important to know the regularity of the circulation of water and sediments in the coastal zone. In addition, various up-welling phenomena, prevalent along the southern coast of the Baltic Sea, influence coastal water circulation.

These two aspects influence the migration of polluted water, whether it is discharged into the sea from large and small rivers, pipelines, harbours or shipyards and ships.

In the open coast (cliff and dune) in developed areas there are serious problems connected to proper wastewater management. There are three reasons for this:

- Leaking wastewater systems pollute groundwater. This water pollutes the shore when it arrives there.
- Polluted groundwater causes cliff erosion processes and erosion on concrete constructions (foundations of buildings, seawalls etc.) to accelerate.
- Polluted water coming by pipeline from storm sewage systems or wastewater treatment plants (if there are any) is distributed into the coastal water according to its specific circulation system and affects coastal zone ecosystems and people lying at the beach.

The surroundings of river mouths are under influence from river water. Large rivers coming straight to the sea or the bay affect water and beach ecosystems considerably. The direction and range of this influence depends on:

- the purification level of the river water,
- existing circulation systems in the coastal zone,
- the hydrological regime of the sea area, and
- seawall constructions at the mouth of the river.

Boddens and lagoon areas play a key role in water management at the sea and land border. These are mainly shallow areas (a few metres deep), usually with flat, organic coasts, naturally protected against wave attacks. The river mouths in these areas make them much less salt than common Baltic Sea water.

All these features create good conditions for specific lagoon and bodden ecosystems having a high biological production and being a nursery and spawning area for many fish species. These areas also work as major purification plants for polluted river water.

There are many wetlands in surrounding areas that act as bird sanctuaries with nesting areas. Lagoon and bodden ecosystems are very sensitive to pollutants. They play a significant purification role, but too much pollution can destroy them. At the same time shallow calm water is very attractive for water tourism and sports. It is also very important place for fishing and water transport. Both small and large harbours and tourism and sports facilities are often located within lagoons.

All of these natural features and human activities make lagoons and boddens an area of many conflicts. These conflicts must be resolved in agreement with sustainable development legislation. Below, the Szczecin Lagoon is presented as an example of these problems.

CASE : THE SZCZECIN LAGOON

The Szczecin Lagoon is located in the southern-most part of the Baltic Sea, at the Polish–German border (Figure 2.7). It is about 700 km^2 in area with three connections to the Baltic Sea: through the Swina (60-75 %), the Dziwna and the Peene (Majewski, 1980).

It is a very shallow area with a mean depth of about 4 m and a maximum of about 8 m. An artificial navigation channel through the Szczecin Lagoon was dug for ships going into the Szczecin harbour. This channel is about 10-11 m deep and plays an important role in the water exchange between the sea, the lagoon and the Odra River. Because of the channel, the influence of salt water is observed as far as 160 km behind the River Odra mouth.

Water circulation in the Szczecin Lagoon depends strongly on wind direction and bottom shape and it is modified by the channel impact.

In the water balance of the lagoon about 65 % of the water comes from rivers (with the Odra River accounting for about 97 %), 32.7 % of the water comes from the sea and 2.3 % from rain. The sea receives 96.7 % of the lagoon water and about 3.3 % evaporates. The average salinity is about 0.6–0.9 ‰ with a minimum of 0.2–0.5 ‰ in May and June and a maximum of 0.8–1.3 ‰ in November. At the bottom of the channel, salinity may even reach 6–7 ‰ periodically. The Odra River has a dominating impact on the conditions of the Szczecin Lagoon; about 97 % of the river input is from the Odra River. The catchment of the Odra River is about 119 000 km^2, encompassing heavily industrialised regions and a population of about 15 million.

The Odra River is rich in nutrients and pollutants. Annually it carries 5.7–17 kilotons of phosphorus, 38.5–40 kilotons of nitrogen and 12.3–60.2 tons of silicate to the Szczecin Lagoon. Szczecin as a city produces some 300 000 m^3/day of polluted water. About half of this is cleaned mechanically and 10 % biologically.

Mussels (*Dreissena polymorpha*) play a significant role in the natural purification system of the lagoon, involving some 87 % of the benthic biomass, covering about 10 % of the bottom surface. This population can filtrate the whole volume of the lagoon water in 36 days.

About 0.7 million people live around the Szczecin Lagoon. Szczecin is the largest city in this area, with about 0.5 million people. Other cities are Swinoujscie, Police, Kamien Pomorski, Miedzyzdroje, Wolin and Nowe Warpno on the Polish side, and Anklam, Ueckermuende, Wolgast, Usedom and Lassan on the German side. Chemical industry is located mainly in Szczecin and Police. There are sizeable harbours in Szczecin and Swinoujscie. In addition, many small harbours for fishing boats and yachts are located around the lagoon. The conditions for water sports and tourism around the lagoon are good. There are also intensive agriculture areas on both the Polish and the German sides.

Many forests are located around the lagoon, with many protected areas, including national parks, landscape parks, nature reserves and nature landscape complexes. There are over 200 species of birds and sanctuary areas along the coastal areas of the lagoon, which makes the area very attractive for ecological tourism. About one million people annually come here (mainly to the open seacoast) on holiday.

Cross-border tourism, on foot (to Swinoujscie) or by bicycle, ship, car or train, is very popular.

The condition of the lagoon was very bad in the past, but has been improving since the beginning of the 90s. This can be seen in the table (Table 2.1) from the Szczecin voivodship.

There are several reasons for this.

- Many new wastewater treatment plants have been built in the area.
- There is now less production from heavy industry and more advanced and environment-friendly technology has been applied.
- Less fertiliser has been used in agriculture and fewer cattle are kept.

Table 2.1. Development of the use of fertilisers and the level of wastewater treatment in the Szczecin area

Szczecin voivodship	1975	1980	1985	1990	1994
Mineral fertilisers (phosphorus), kilotons	340	320	360	210	290
Paper, kilotons	100	90	110	70	50
Cattle, thousand heads	360	350	280	240	120
Cereals, kilotons	570	570	720	900	600
use of fertilisers kg/ha	280	280	250	240	70
No. of mechanical wastewater treatment plants with biological level	6	5	9	11	41/77*

* 41/77 – 1995/1996

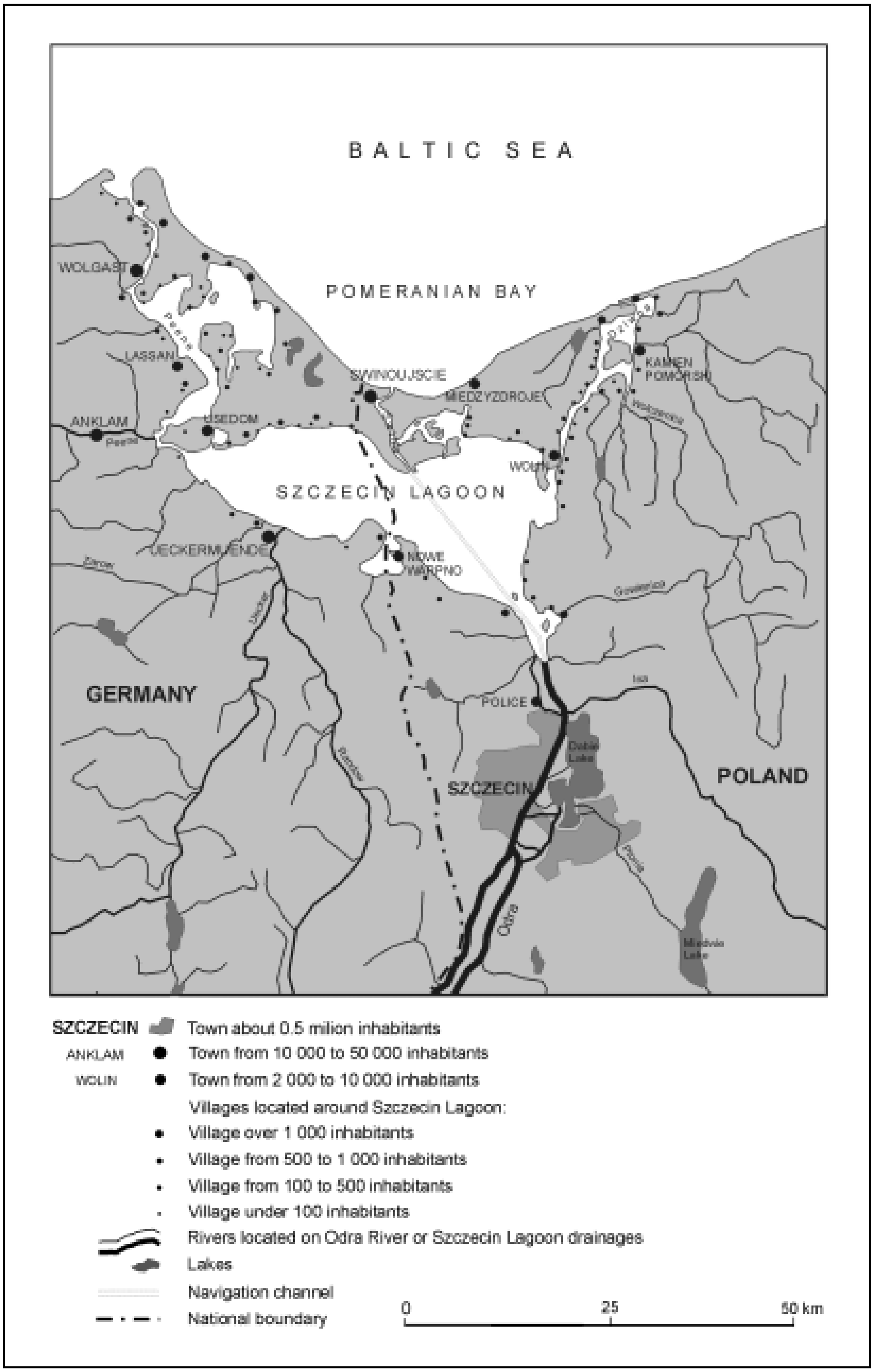


Figure 2.7. Map of the Szczecin Lagoon in the mouth of the Odra River.

BEDROCK AND QUATERNARY DEPOSITS

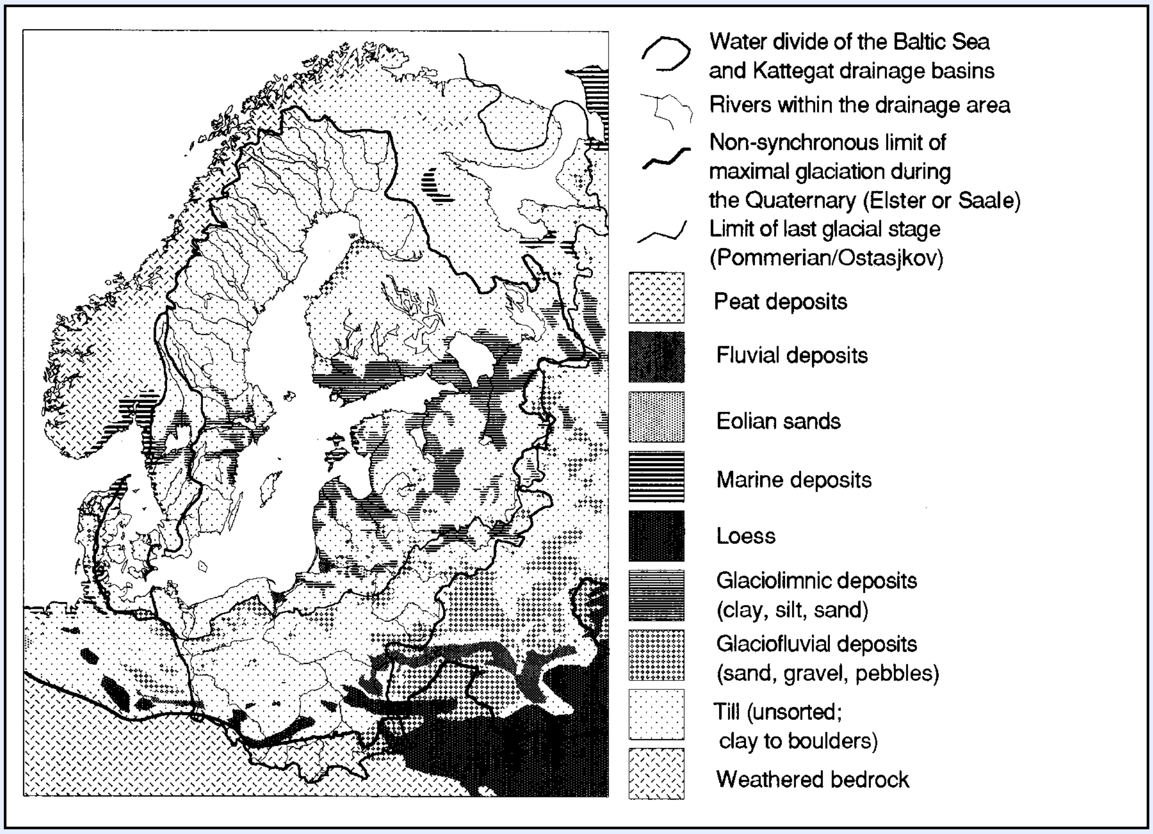


Figure 3.1. Major features of bedrocks in the Baltic drainage area (compiled by Ulf Erlingsson. From Håkanson, 1991).

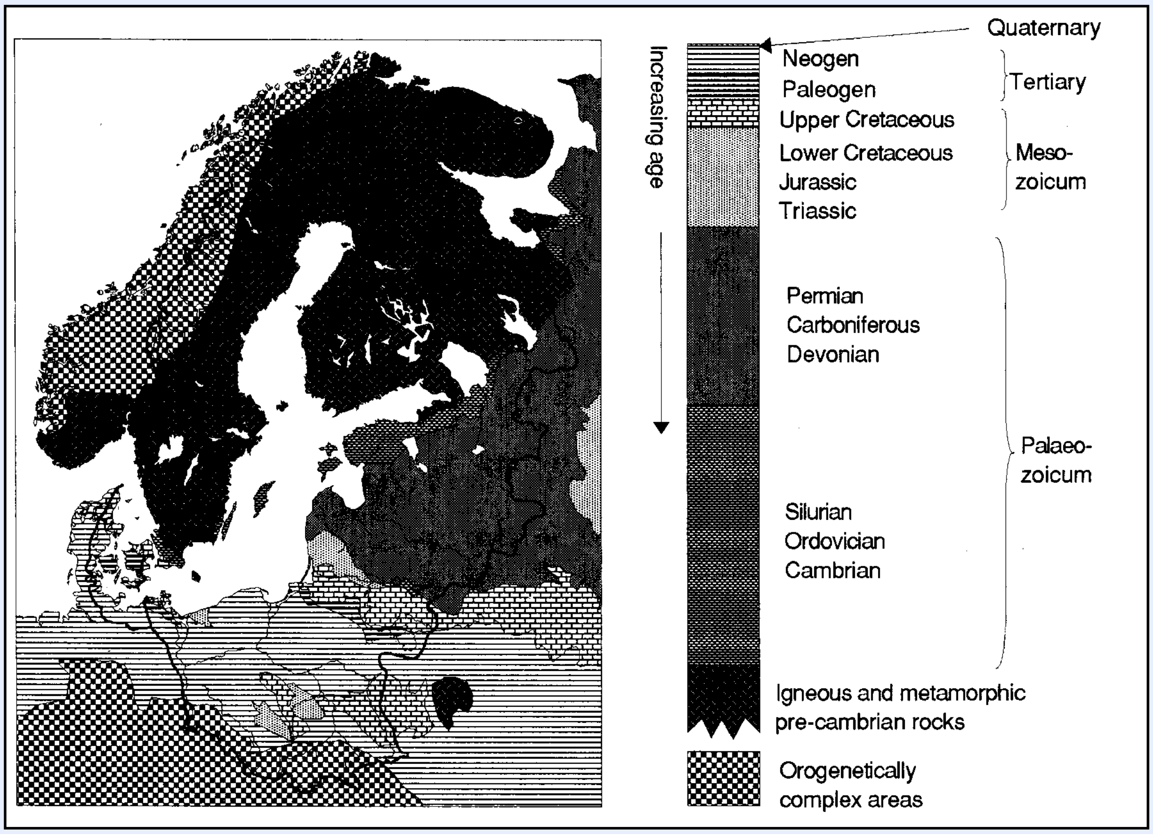


Figure 3.2. Major features of Quaternary deposits in the Baltic drainage area (compiled by Ulf Erlingsson. From Håkanson, 1991).

3

GROUNDWATER IN THE BALTIC BASIN

Erik Eriksson & Sivert Johansson

The Baltic basin hydrology

Groundwater exploration, exploitation and management are ongoing processes for securing water requirements in the future and for correcting mistakes of the past. The accumulation of knowledge and experience is indispensable to this and is fortunately often well documented. The hydrogeology of the Baltic region is displayed in the International Hydrogeologic Map of Europe, amply supplied with sets of Explanatory Notes on each map sheet (Persson & Norberg, 1982).

To describe the loose deposits the following concepts, terms and definitions are used. Overburden, usually unconsolidated mineral matter on a rock, is defined as pre-Quaternary. It consists of material from rock weathering or glacial deposits or both. In the Baltic region weathered rock is rare since most of it has been removed from its original site and mixed into glacial till. Glacial deposits are usually somewhat sorted by flowing water and will therefore contain less clay than the weathering product, since the clay accumulates in lacustrine and marine deposits. Glacial deposits also contain coarse material obtained during the physical force of the moving ice. The distribution of quaternary deposits in the Baltic drainage basin is shown in Figure 3.1.

In the Baltic region the overburden consists mainly of glacial deposits in:

- *boulder clay*, a deposit rich in clay
- *till*, a broad assortment of particle sizes displaying a considerable heterogeneity in structure and texture, with sand and silt as the major components
- *terminal moraines*, a formation of glacial till accumulated in front of a moving ice sheet when the melting rate is balanced by the ice flow rate
- *valley fill*, an accumulation of glacial deposits in old deep river valleys
- *eskers*, deposits from melt-water rivers in tunnels at the bottom of ice sheets. Contain a core of boulders surrounded by gravel and sand, widened by wave action during the postglacial land rise, at elevations above the highest coastline.
- *river sediments*, deposits of sand and gravel along meandering rivers and deltas. The areal extent and depth of these formations are variable. Most of them are phreatic, i.e. in contact with soil water, and, consequently, prone to pollution.

Basement rocks

Crystalline rocks

Crystalline rocks are usually fractured and fissured, forming a particular pore space for water. Part of the fracturing is considered to take place when the rocks are unloaded by erosion and land ice, releasing stresses due to the load. Drilled-well records indicate that this fracturing extends to depths of about 100 m at most. The unloading process should favour formation of sub-horizontal fractures while vertical fractures are the result of the release of shear stresses during faulting, which is regarded as an endogenic process.

Fracture zones result from plate movements and are often associated with dykes of basic rock. The productivity of wells drilled in such fracture zones may be appreciable.

Sub-horizontal fractures in the Baltic shield also occur at depths greater than 100 m. These are also believed to be due to the plate pressure from the NW. Fractures of this type have been observed even at a depth of 800 m. Their hydrogeologic importance has not been determined.

Metamorphic rocks

Metamorphic rocks are made up of either crystalline or sedimentary rocks. Sandstone is converted into quartzite, shales into schist and carbonate rocks into marble. Metamorphic rocks are usually less fractured than crystalline rocks.

Sedimentary rocks

These are consolidated marine deposits containing fossils, i.e. shells of the marine organisms that existed at the time of deposition. They are normally porous and can store fair amounts of water and are therefore highly valued as aquifers. Fracturing increases the productivity of these rocks, too. In the Baltic region the deeper parts of the sedimentary rocks contain saline water, which limits their usefulness. A great deal of the salinity comes from salt deposits in the Zechstein Sea, which covered large parts of Europe during the Perm period.

The merits of an aquifer for water extraction are described in terms of productivity. This is the rate at which water can be extracted, expressed in l/s, also called yield. Presumably this yield is sustainable in a short-term sense.

Figure 3.2 shows the distribution of various rocks in the Baltic drainage basin.

Groundwater in Baltic region countries

Geologically the Baltic Shield – the area of Sweden, Finland and north-western Russia – is covered with crystalline basement rock and glacial till as overburden. In the rest of the Baltic region the basement rocks are sedimentary with appreciable potential aquifer storage.

Aquifers in glacial deposits

The glacial till is relatively thin, on an average 3 to 5 m. The major part is sandy or silty till. The effective porosity, which is the same as the specific yield, may reach 5% in sandy till whereas silty or clayey till is considerably less. The productivity is highly variable but is considered to be less than 1 l/s. The same is valid for springs. Dug shallow wells are abundant in rural areas.

Water quality in dug wells on till may vary widely. If groundwater temporarily reaches the surface the water will pick up organic substances and bacteria. Surface water may also enter on rainy occasions unless the surrounding of the well is raised to prevent such inflow. Locations of wells near farm buildings or sanitary installations can also make the water unsuitable for domestic use. On farmland high nitrate concentrations from excessive amounts of fertilisers will appear in the groundwater (Gustafson, 1997). Ferrous iron is often a common constituent in these waters when groundwater levels are close to the surface.

Eskers and glaciofluvial river plains are productive with yields varying between 10-100 l/s. They can therefore be the supply for towns and smaller cities. The water quality is usually good. The yields will increase with extraction rate if the recharge area increases or if bank infiltration from rivers increases. However, this may mobilise pockets of iron-rich groundwater in eskers, a minor problem since the iron is easily removed. Of greater significance is inflow of nitrate-rich groundwater from farmland or from sewage systems in communities. The esker in central Stockholm contains groundwater with high nitrate content. The esker was once considered to be an emergency water resource for the city. Its water is now used as a coolant for air conditioning systems in the city centre. The water from the esker discharges into River Strömmen, which is the Lake Mälaren outflow to the Baltic Sea.

Finland has an extensive system of terminal moraines consisting of more or less parallel ridges, 10 to 30 m high and up to 100 km long. The moraine consists of glaciofluvial sand and gravel with inter-bedded layers of silt, till and clay. A number of eskers run perpendicular to the ridges, resulting in very high productivity. The most important aquifer is 55 km^2 in area and has an estimated sustainable yield of 450 l/s.

The Baltic Shield also covers a fair part of the area north of Russia's Lake Ladoga, which drains into the Baltic Sea. This area has features similar to those in Finland, particularly the terminal moraines.

Aquifers in basement rocks

Drilled wells on crystalline rock are common in the Baltic Shield region, often used in farms and private settlements as well as in recreational areas. Although drilled wells are costly they are much less sensitive to dry years than dug wells. Yield data for large ensembles of drilled wells in Sweden are shown as cumulative frequency diagrams for a few selected areas in Figure 3.3. Transmissivity seems to vary between 10^{-5} and 10^{-6} m^2/s and hydraulic conductivity between 10^{-6} and 10^{-7} m/s. Effective porosity is low, 0.1% being a frequent value. The variation in groundwater levels by season during a 5-year period is shown in Figure 3.4 for granite, till, redeposited sand and glaciofluvial gravel.

Finland and Sweden

In Finland the range of yields in crystalline rock is given as 0.03 to 3 l/s, the upper limit being obtained from wells in highly fractured granite, Rapakivi. The highest yield obtained from this granite is 13.8 l/s. Except for the Rapakivi granite the distributions of yields in crystalline rocks within the Baltic Shield is likely to fall within those seen in Figure 3.3. The average depth of Finnish wells in crystalline areas is 65 m. The data show no appreciable increase in yield with increased depth.

Water quality in crystalline rocks follows a similar pattern in Sweden and Finland. The mineral concentration in drilled wells is higher than in dug wells in till and the increase is due to relict marine water in crystalline rock.

In the rest of the Baltic Region, i.e. in Estonia, Latvia, Lithuania, Poland, Germany and Denmark, the crystalline rocks are covered by sedimentary rocks of various ages.

Estonia

The quaternary layer is fairly thin and is not considered important as an aquifer. However, it may serve for dug wells in the same way as on the Baltic Shield.

The most important aquifer is the Ordovician-Silurian limestone that extends across the entire country. Its northern half is phreatic and 100 to 200 m thick. Devonian deposits cover the southern half. This limestone is a very important aquifer with fresh water down to a 300-m depth. However, mining of Cambrian oil shale in the St Petersburg region necessitated the removal of 200 000 m^3/day from this aquifer which led to a decrease in groundwater level of between 30 and 50 m. Since 1992 groundwater loss has been reduced, which has brought about a partial restoration of the groundwater level. Despite intensive agriculture the nitrate levels in the water is not on the rise; in some places it is even decreasing.

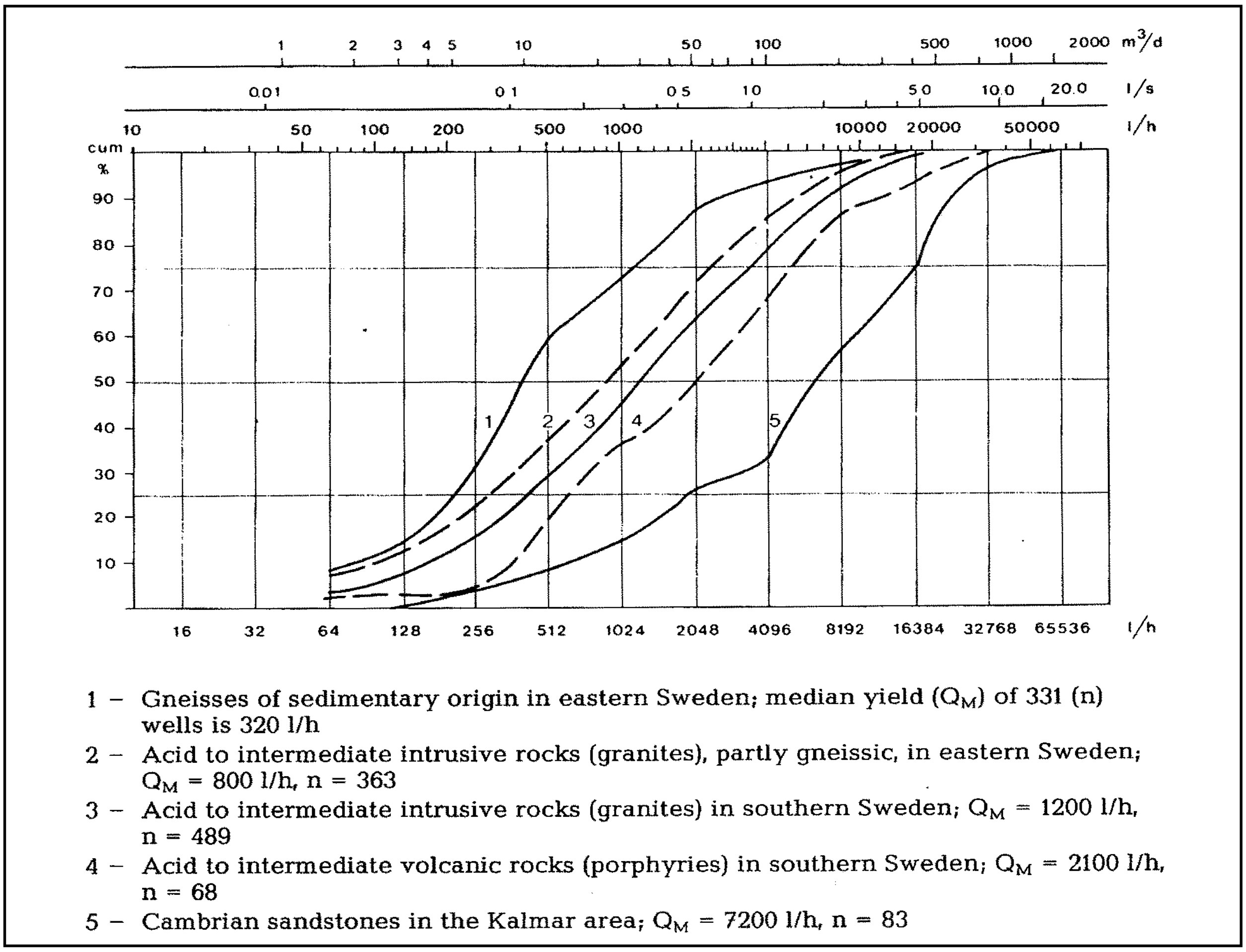
Latvia

Quaternary deposits are 150 to 300 m thick. Interlayering of the till by sand creates fairly productive wells. There is no information available on their importance.

Regarding sedimentary rocks a productive aquifer in the eastern part of the country consists of upper Devonian carbonate, which is about 150 m thick and contains fresh water. The 1% salinity isoline is fairly close to the surface in western Riga but dips below -300 m and then climbs up near the surface at the Velikaja River in the east. In the N-S direction it climbs from -300 to -100 at the Lithuanian border.

Lithuania

The northern part of Lithuania can be regarded as a continuation of southern Latvia with upper Devonian as the productive aquifer. However, in the south this particular aquifer disappears leav-



1 – Gneisses of sedimentary origin in eastern Sweden; median yield (Q_M) of 331 (n) wells is 320 l/h

2 – Acid to intermediate intrusive rocks (granites), partly gneissic, in eastern Sweden; Q_M = 800 l/h, n = 363

3 – Acid to intermediate intrusive rocks (granites) in southern Sweden; Q_M = 1200 l/h, n = 489

4 – Acid to intermediate volcanic rocks (porphyries) in southern Sweden; Q_M = 2100 l/h, n = 68

5 – Cambrian sandstones in the Kalmar area; Q_M = 7200 l/h, n = 83

Figure 3.3. Distribution of well capacities in Scandinavian bedrock (Persson & Norberg, 1982).

ing the Quaternary aquifers as the most important source of water. It is of varying thickness from 10 to 200 m with well yields of 0.5 to 10 l/s. The Quaternary aquifer is heterogeneous, with the water being extracted from inter-bedded sands, gravels and silts.

Since the crystalline basement at the 500-m depth begins to dip strongly westwards and reaches depths of several km, the Devonian system thickens and becomes heterogeneous in water-bearing strata, losing its importance as an aquifer. The Quaternary system takes over.

Western Russia and Belarus

Groundwater conditions in the area that drains into the Baltic Sea are geological and closely related to those at the eastern border of the neighbouring countries. Sedimentary rocks appear to be the major water sources.

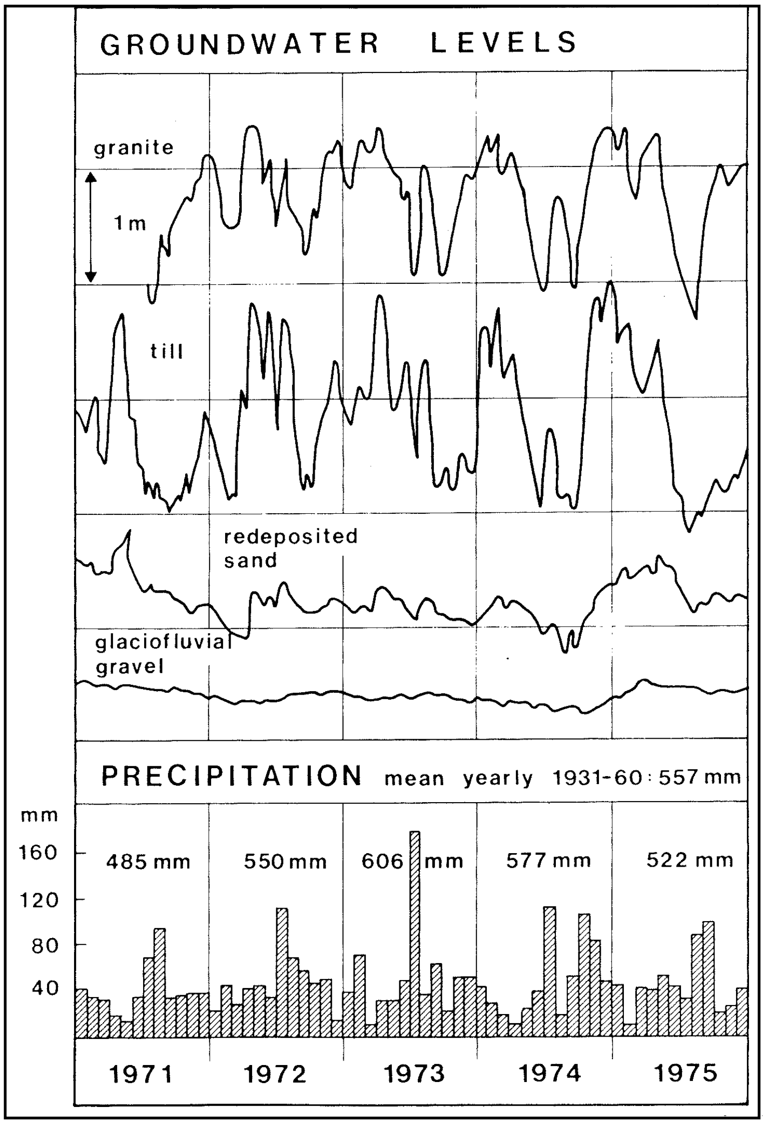


Figure 3.4. Variations of groundwater levels by season in granite, till and redeposited sand and glaciofluvial gravel during a 5-year period (Persson & Norberg, 1982).

Poland

The hydrogeology of Poland is well known, forming an intricate pattern of regions, particularly in the southwest. The major aquifers are Cretaceous limestone deposits as well as younger rocks – sandstones and limestones. Quaternary deposits of importance as regional aquifers are found in terminal moraines, e.g., the Torun-Eberswalde in the north, the Warsaw-Berlin in the middle and the Barycz River Valley in the south. These aquifers are phreatic and require strict management regulations to prevent undue contamination. Their specific capacities do not exceed 10 ls^{-1}m^{-1}. The fourth aquifer is the Great Poland Buried Valley, a deep aquifer covered by boulder clay and therefore less prone to contamination than phreatic aquifers. This aquifer feeds 17 municipal water supply systems and 418 systems for villages and industries.

Important Quaternary aquifers are also found along the river valleys, which form wide plains and are, in places, connected to underlying cretaceous aquifers. Along the Baltic Sea coast sand dunes also provide good aquifers. The freshwater layer is often fairly thin underlain by saline water, mostly from the Permian Zechstein Sea, which has deposited large quantities of rock salt and gypsum. Phreatic aquifers, being recharged from the surface, will keep the water fresh to a certain depth. Confined aquifers recharged by horizontal flow can pick up salinity particularly from salt diapers which are moving, albeit slowly, towards the surface.

Groundwater pollution from sites lacking in waste management resources has created high nitrate concentrations locally near landfills for waste disposal or industrial plant and wastewater utilisation systems. A more serious problem is the contamination of former Russian Army sites due to waste and oil spill. This spill was dumped at 59 locations covering an area of 70 000 km^2. The uppermost water-bearing layer is severely contaminated in a total area of 6 500 ha. The pollutants are primarily petrochemicals, polyaromatic hydrocarbons, phtalanes, halogen derivatives of aromatic hydrocarbons, organosilic compounds, detergents and cresols. Similar problems exist in Estonia, Latvia and Lithuania.

The state of groundwater pollution in Poland is to be monitored by a regional water quality network. Their findings will guide future groundwater management work.

Germany

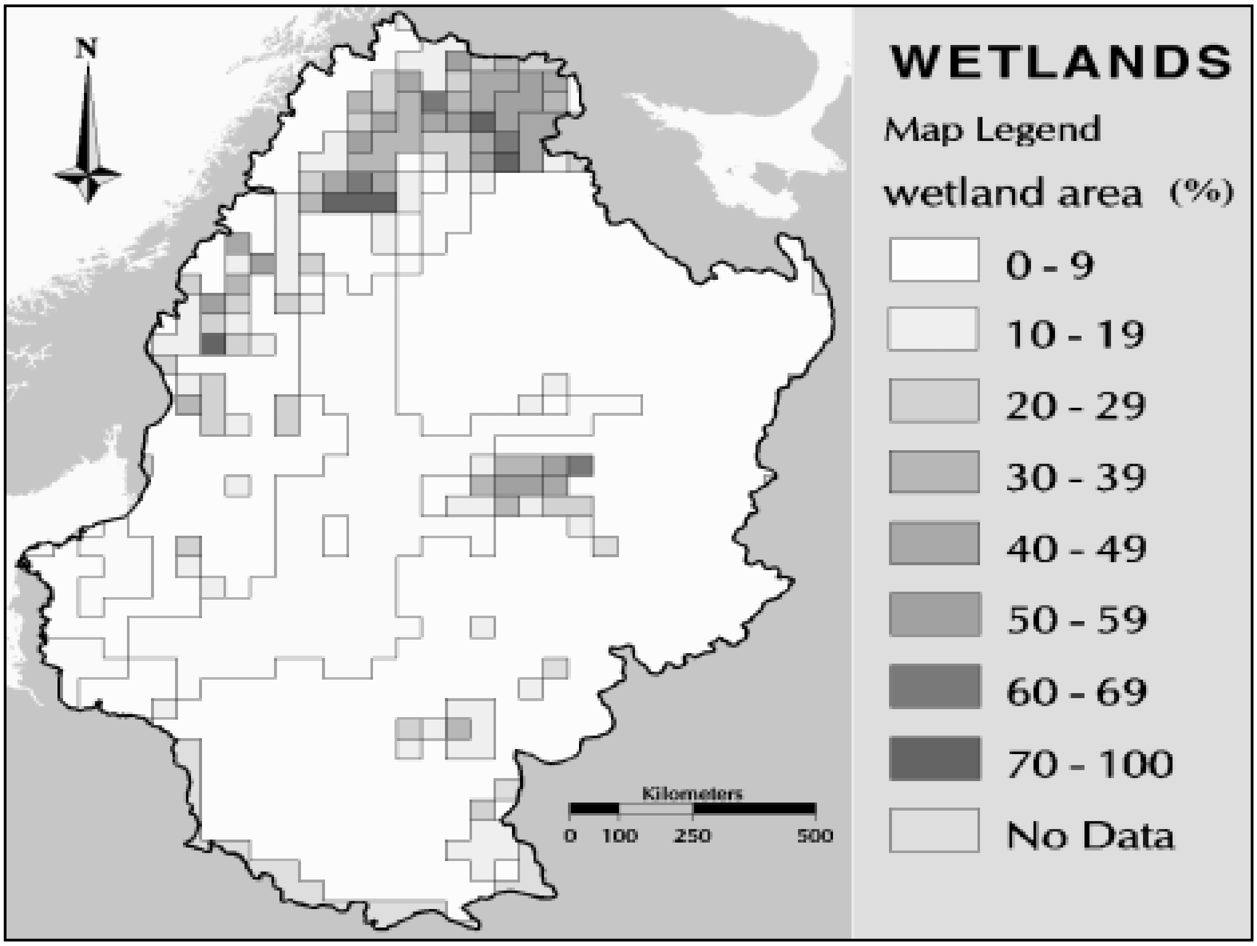
Groundwater conditions in the strip of land draining to the Baltic Sea can be regarded as a continuation of the geology of North Poland. Quaternary deposits exist up to a depth of 200 m and consist of boulder clay, sand and gravel of Scandinavian origin. Terminal moraines are abundant. Cretaceous rocks may also be of value provided salinity is reasonable.

Denmark

For the Baltic, the most important part of Denmark is Zealand, which has a deep Cretaceous aquifer that supplies all the water needed by Copenhagen, obtained through an abundant network of pumping wells. Despite intensive agriculture in Zealand, the nitrate concentration in the groundwater is low.

The drainage from Eastern Jutland into the Baltic takes place along a fairly narrow strip.

Wetland in Belarus (photo, Lars Rydén).



Source: http://jerken.grida.no/baltic/htmls/maps1.htm#wetl

4.

WETLANDS IN THE BALTIC SEA REGION

Lars Lundin

Introduction

In the Baltic Sea region, all the countries – Finland, Estonia, Latvia, Lithuania, Poland, Germany, Denmark, Russia and Sweden – originally enclosed large natural wetland areas. These wetlands developed during the Holocene period and have been considerably affected at later stages by human exploitation. Wetlands now constitute only small areas of Denmark and Germany, where considerable regions are now dependent on land utilisation. Other countries exposed to this wetland degradation are Latvia, Lithuania and Poland, where most of the wetlands have been drained for agricultural purposes. In Europe on the whole, 60 % of the original 53 Mha of mires have been lost due to agriculture (50 %), forestry (10 %) and peat extraction (10 %) (Joosten, 1998). In Estonia and Finland, too, drainage has altered large areas of the territory. Both countries still host considerable natural wetlands, but Finland has lost c. 2 Mha, which has turned into drier mineral soils. In Sweden, exploitation varied greatly, with large differences in regional wetland utilisation. In the north, there has been a relatively small impact, while utilisation was much more comprehensive farther south, especially in the present-day agricultural regions.

Wetlands are not wastelands, even if this policy has been prevalent for centuries. Basically, however, man has realised that in regulating water, wetlands become transformed so as to make possible alternatives uses, of high quality and considerable yield. Wetlands have great value in their natural condition but these can often easily be changed into new values. This explains why wetlands are controversial and of great interest. We all love wetlands but for different purposes. In their natural states, wetlands – like marshes, swamps, bogs and fens – are a challenge, while these essential life-providing systems are recognised in the national sphere as coastal lands, lakes, ponds, rice fields and peatlands. About two-thirds of the world's population are dependent on wetlands for their existence.

Functions

Wetland functions depend on energy supply, which is furnished mainly by sunlight and stored in connection with photosynthetic processes. Involved in

FUNCTIONS OF WETLANDS

Physical functions	Sediment storage
	Erosion protection, especially of river banks,
Hydrological functions	Reduce flood flows
	Take care of urban runoff
	Recharge aquifers
Hydrochemical functions	Natural storage for many elements and substances
	Reduce rural nutrient leaching
	Clean wastewater
	Storage of metals and contaminants
Biological functions	Provide high diversity
	Important to wildlife
	Providing grassing etc.,
Economical functions	Enhancement of water quality
	Providing yields of agricultural, forestry and peat products
	High fish potentials
Societal functions	Recreation
	Scenic views
	Scientific and education
	Culture

Figure 4.1. The well-developed, pool-rich bog, Männikjärve, Endla, Estonia – a unique raised bog with 50 years of monitoring (photo, Elve Lode).

the process, of course, is water supplied from such sources as precipitation, surface water inflow, groundwater discharge and inundation from rivers and the sea. Energy also enters into the wetland ecosystem via additions of organic substances from surrounding terrestrial or water areas (Moore, 1990). Hydrology governs the importance of the processes through hydrochemical flows and influences on autochthonous energy production and allochthonous organic matter input.

Wetlands constitute the ecotone between terrestrial and aquatic environments. They have even been described as "the kidneys of the landscape" (Mitsch & Gosselink, 1993). Some influence comes from the surroundings but they are in turn affected by the wetlands. These influences can be hydrologically categorised, such as immobilisation of contaminants, nutrient sinks, sources of chemical substances and turnover of gases. Wetland functions can also be divided on a subject base (see box, page 43). Obviously, there is a form of competition between nature's long-lasting, sustainable conditions and man-made values that are of significance to large parts of the world's population.

Wetland hydrology

Wetlands are comprised of water-saturated bodies connected mainly to groundwater aquifers. Most wetlands are found in landscape depressions or other relatively low lands. Often, soils underlying wetlands are almost impermeable, i.e. the hydraulic conductivity is low. In systems with permeable soils, outflowing groundwater is able to maintain water saturation. At such locations there can be wetland development succession on permeable soils, such as sand, with the possibility of infiltration clogged by organic material, causing low conductivity. In such cases wetland often turns into peatlands.

Peatlands are composed of low-conductivity organic material with high porosity, often > 90 %. However, the low conductivity and the often flat extension, with low hydraulic gradients, mitigate large and fast water turnover. Thus, such peatlands are often flooded at high water input and gradually turn into shallow-water lakes. Water flows on top of the peat either as surface water or as upper soil water in the acrotelm. This latter is the uppermost layer of peatlands, with a low decomposition (humification) degree. Eventually, after surface runoff, water levels in the peat are lowered to deeper horizons. There, in the catotelm, hydraulic conductivity is low and, together with the almost flat groundwater piezometric gradient, the water flows turn small. Altogether, during high water access, peatlands are mainly transition zones providing water in already wet and high-discharge situations. Nonetheless, peatlands do not furnish additional water during drought. When there is need for water, peatlands keep it to themselves

Sloping landscapes with soligenous peatlands act primarily as transition areas for water flow from uplands to the watercourses. Other wetlands along streams and rivers may be supplied by these surface waters and extend over large flatlands, recharging groundwater on permeable soils and supporting groundwater flows in deeper layers.

However, many wetlands are not peatlands but open water areas. The hydrology of such wetlands is likely to resemble that of lakes, with storage capacities dependent on outflow crests (sill) and thereby able to mitigate both peak flows, by temporary storage, and drought, by slow outflow of stored water.

Wetland types

The scope of wetlands covers a large number of water-related habitats. According to the Ramsar convention of 1971 (Matthews, 1993) wetlands range from oceanic types, such as coastal sea areas with a water depth of six metres at low tide, to limnic types, such as shallow lakes, watercourses, swamps and marshes, and over to the terrestrial wet meadows, mires and peatlands. Coastal areas have been subjected to isostatic and eustatic processes and varying conditions during different period of the entire Holocene era. In the northern part of the Baltic region, such as in Finland and northern Sweden, land lift is still considerable, while in the southern Baltic Sea countries, subsidence prevails. The development of wetlands has been going on since the last ice age.

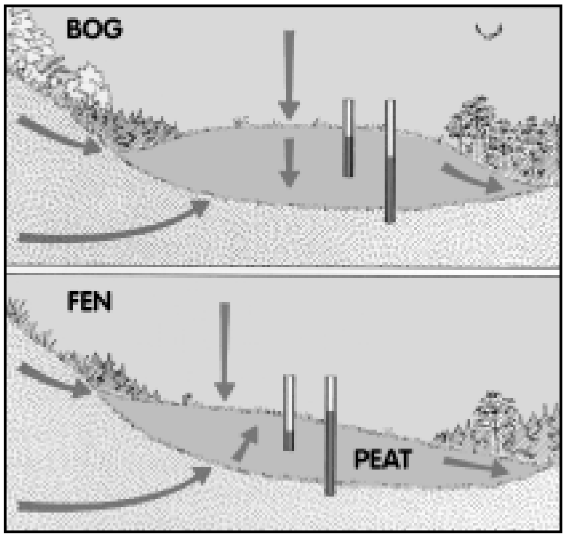


Figure 4.2. The two types of peatlands classified according to hydrology. In the bog, a downward direction; in the fen, an upward (NFR, 1995).

In the early stages of land lift, depressions in coastal areas either first turned into lakes and then started to terrestrialise, or more directly formed terrestrial wetlands from sea conditions. Consecutive changes turned the wetland into peatland, passing through stages of marsh and fen and finally ending up in the bog.

During these processes, the wetland experiences stages of very rich conditions, often as shore ecotones with a variation between inundation and drier conditions, often providing nutrient supply. As wet meadows become more terrestrialised, the habitat changes. The impact of inundation processes depends on water quality, with effects on formed wetland areas. As these turn to fens, groundwater flows become more important, with a number of fen types. Inflow of water to fens gives the types their characteristic features (Dembek & Oswit, 1996):

- Fluviatile mires formed by inundation from surface water bodies
- Soligenous mires receiving discharging groundwater entering the fen on the upland surface
- Water head peatlands with groundwater under piezometric pressure
- Oozing water peatlands with a more diffuse groundwater inflow
- Topogenous peatlands with water entering as groundwater or overland flow to partly isolated depressions

At suitable climatic conditions during a terrestrialisation process, the peat-forming vegetation changes from vascular plants to *Sphagnum* mosses, and the peatland turns into a bog. At this phase, the peatland starts to rise, with the elevated surface becoming domed-shaped, the so-called raised bog. Later, after a considerable amount of time, pools begin to develop on the bog (Figure 4.1).

Bogs and fens are peatlands with a substantial layer of peat. When this layer is very thin, the wetland is called a mire, nonetheless still colonised by hydrophilic vegetation. The type of plants, and consequently the type of peat that is formed, is linked to the supplied water quality. Fens in mineral soils with a high nutrient content will be rich while those in poor environments, poor fens, are even poorer than bogs. Bogs are by hydrological definition furnished with precipitation water only, which is low in nutrients. In mineral-rich environments, nutrient content can be high with a pH of 6-8, such as in calcareous fens. Fens in environments with ordinary soils and bedrock, such as granites, are poorer, with a pH below 6. Bogs can go as low as 4 in pH, carbon-nitrogen (C/N) ratio is often above 30 and carbon-phosphorus (C/P) ratio over 1 000, while C/P in fens can be 100.

Conditions in peatlands depend on the hydrology, with a piezometric pressure in underlying mineral

Figure 4.3. Afforestation with larch on a raised bog in western Sweden (photo, Lars Lundin).

soils that is higher than in the peat water body creating an upward flow. In bogs, the gradients are the opposite, resulting in downward flow from the bog surface (Figure 4.2).

Values and significance

The significance of wetlands in landscape ecology is recognised as crucial to biological diversity, turnover of water and chemical elements such as metals. They are also considered important in the storage of carbon and thereby of relevance to climatic change. From this follows that peatlands and peat growth also have a vital impact on the environment.

Other wetlands, as shown above, hold large value for aquaculture, fish and other food production. There is also value for wildlife and game, recreation, berry picking, mushrooms and special vegetation.

Wetland habitats are home to a large number of plants and soil-living fauna. Often these areas act as refuges for individuals and as pathways in spreading to other areas. In some cases, often involving bogs, certain specialised types find a niche where there is little competition. In other rich habitats, very demanding species manage to survive. In case of forest fire, wetlands can also provide protection.

Regarding water turnover, wetlands have a special influence. As has been pointed out, peatlands act mainly as transition areas for water but other wetlands have impacts on the turnover, providing storage and maintaining base flows.

Concerning water quality, wetlands act in both directions, as sinks for some substances but as producers of others. Sedimentation is an important process and under peaceful conditions, the flow of mineral and organic matter is often limited. Inorganic nitrogen and phosphorus are retained in most wetlands. Phosphorus is stored in the sediments while considerable amounts of the nitrogen may be released as gas emissions due to denitrification. Most elements are contained in peatlands, but organic acids and hydrogen may be released, giving rise to acid and coloured waters. Wetlands often act as transition zones between mineral soil uplands and surface waters and thereby exert crucial influence on the water chemical composition. Drainage of peatlands starts the decomposition of the stored organic material, the peat. This causes an increased outflow of most elements and also a higher pH and less coloured waters.

Especially important to peatlands is of course the organic matter, half of which is carbon. During the development of mires and the storage of peat, carbon is also stored. In fact, this storage is important on the global scale as well, with the total content of 400-500 gigatons of carbon (Immirzi & Maltby, 1992) roughly corresponding to the amount of carbon in the atmosphere. Compared to other soils, 20 % of all stored carbon is found in peatlands. Drainage of wetlands results in decomposition and the release of carbon dioxide into the atmosphere, adding to the greenhouse effect. On the other hand, in natural conditions, methane is released instead. This gas has 25 times the efficiency of greenhouse gas. The release of methane is strongly mitigated by drainage. In addition, emissions of nitrous oxide (N_2O) are limited by drainage and are actually more adherent to shallow surface waters. N_2O has a greenhouse effect that is 250 times greater than that of CO_2.

As regards acidification, many peatlands are the source of acidic waters but also mitigate atmospheric acidification through their organic substances. However, the production of organic acids mainly creates a low pH, while an interaction with the atmospheric acid input also takes place, which, due to prevailing hydrology, could easily be discharged as surface water into streams and lakes.

Wetlands, as open waters, are used as drinking water supplies if they are of pure and suitable water quality. Such wetlands are of utmost importance,

Figure 4.4. The peatland Docksmyren in SE Jämtland county, central Sweden, with ongoing peat cutting (photo, Lars Lundin).

especially since drinking water supplies are deteriorating and decreasing.

Use and management

The utilisation of wetlands has a long tradition throughout all of the Baltic Sea countries. In many of these countries, there are now only remnants of the original natural wetland areas. However, interest is increasing and now international opinion to a large extent is directed towards restoration of wetland habitats. In line with an increasing consideration of environmental values and in concordance with a sustainable use of natural resources, restoration, as compared to exploitation, has become more important (Kuntze, 1994; Wheeler & Shaw, 1995). The main utilisations of peatlands are in agriculture, forestry and peat cutting. Restoration of peatlands into new neat-accumulating areas could win back 1-2 mm/year of natural peat growth.

Several hundred years ago, the first thought to enter the mind of a settler or farmer when he saw a suitable wetland was, 'How should this be drained?' In order to regulate the water level, hydrological concern is crucial to most domestic wetland use. Especially in the southern Baltic Sea states and surrounding areas, at least as far up as Estonia and south Finland, agriculture has concerned large wetland areas. Such areas are rare today but still found e.g. in Scania, the southernmost part of Sweden, and in some other regions. Many wetlands were found especially suitable to farming, including cattle grazing and cultivation of grain. Later, in the late 1800s, forestry on wetlands, mainly peatlands, attracted increasing interest in several countries (Figure 4.3). In Finland, Estonia and Sweden, forested peatlands are very productive and cover major areas.

Parallel to farming, the use of peat as fuel, soil improvement and cattle-house litter meant early peat excavation. In the beginning of this century, horticultural use and use as fuel increased, then slowly decreasing during the mid-1900s, only to increase again during the last two decades. Now, industrial peat winning is in progress (Figure 4.4). In Poland and Germany, this phase has partly passed, and utilisation is decreasing and possibly coming to an end in the decades ahead. In Finland, Estonia and Sweden, peat winning should be possible for a while longer. This is, however, mainly a political concern.

Other uses of peatlands could be for growing special peat-adherent berries such as cloudberries and cranberries.

Naturally, wetlands with open water are of considerable importance to fishery in both inland and coastal waters. They are also important to wildlife game.

In modern agriculture with considerable leaching of nutrients, and a current desire to put a limit to

Figure 4.5. A sedge fen in central Sweden, in the Bergslagen region, subjected to new peatland drainage (photo, Lars Lundin).

it, wetlands are being recreated to act as retention areas, especially for nitrogen and phosphorus. Large drained and channelled areas are changed to return to a more diversified landscape with meandering watercourses and a frequency of wetland ponds. This natural cleaning of man-made nutrient runoff is gaining increasing interest.

Wetlands of the Baltic Sea countries

As has been pointed out, wetlands have been exploited for man-made uses and turned from natural production into crop and tree cultivation and even peat extraction. Drainage has been the inevitable prerequisite activity for achieving the necessary hydrological conditions (Figure 4.5). These practices apply to all wetlands, but here the concentration will be on peatlands. The information has been taken from the compilation of global peat resources (Lappalainen, 1996). Aside from peatlands, other wetlands types, such as coastal and lake shores, have been subjected to bounding and water regulation by pumping. The prevailing conditions in the Baltic Sea states are presented below.

Denmark

Denmark, located at the outlet of the Baltic Sea, has had a minor impact on the catchment. Wetlands are scattered fairly evenly over a major part of the country. Originally, mires covered c. 1 Mha, 20-25 % of the land area. Drainage and cultivation reduced this share to 3.3 %. Now, there is 1 000 km^2 of salt-water marshes and coastal meadows and c. 25 km^2 of near-natural bogs. Peat winning involves 12 km^2.

Estonia

Estonia hosts large wetland areas and belongs to the most peat-land rich countries, with over 22 % of the land area covered by mires, or c. 1 Mha. Fens comprise 0.6 Mha and bogs 0.35 Mha. Agriculture, forestry and peat winning make use of peatlands. About 0.2 Mha of peatland has been drained and 16 Tha is used in peat winning, half for horticulture and half for energy production. An area of 565 km^2, including 69 mires, has been preserved.

Finland

Finland, with its low coastal zones and extensive archipelago, is also the country with the largest share of peatlands. Originally, there existed almost 12 Mha, but this has now decreased to c. 9 Mha. The drained area is 7 Mha in total but more than 2 Mha have been lost, i.e. turned into drier mineral soils by organic matter decomposition. The largest part of the drained area is used in forestry, c. 6 Mha, and about 1 Mha was drained for agriculture, of which only 0.3-0.4 Mha is in use today. Peat winning is carried out on c. 0.05 Mha of the peatlands but 0.6 Mha is suitable for this purpose. Peat in Finland makes up 5 % of the total energy consumption. Mires have also been used as artificial lakes, dumping areas, roads, urban areas, etc., a total of about 0.1 Mha.

Finnish peatlands are grouped into three major types: ombrotrophic bogs, minerotrophic aapamires and orohemiarctic and oroarctic mires. Conservation involves 0.75 Mha, or 8.4 % of the total peatland area, a high value compared to other countries.

Germany

Only a small part of Germany is included in the Baltic Sea catchment. However, in this NE part, considerable fen-land areas exist. Most of them are influenced by human activities, e.g. 95 % of the fens are used in agriculture. A large part of the peatlands of Germany is found in the northern part, with approximately 30 % in the Baltic Sea area. Totally, mires cover 1.3 Mha of the country and 14 % of the bogs are in fairly undisturbed condition. Otherwise, most of the undisturbed mires exist along lake and river shores. Peat winning concerns only bogs and 10 Mm^3 out of 325 km^2 is extracted for horticulture use.

Latvia

The wetlands of Latvia extend over 39,000 km^2, and 19,000 km^2, or 60 %, have been drained. Peatlands cover 6 000 km^2, or 10.4 % of the land area. Drainage for agriculture involves c. 14 Tkm^2, for forestry 4 Tkm^2 and for peatlands c. 2 Tkm^2. Of the peatland areas, 15 % are used for agriculture, 8.4 % in forestry, 1.2 % as ponds and 5.7 % in peat cutting, leaving c. 70 % unused. Of the extracted peat, 60 % is used for fuel and 40 % in agriculture, both domestically and for export. In 1973, peat winning was at its peak and has since decreased to about 50 production units.

Lithuania

Wetlands extend over 30 500 km^2, or 46 % of the country's area. The mire area is 0.8 Mha, of which peatlands with an organic cover thicker than 30 cm constitute 0.5 Mha, while 80% consists of fens, 12 % of bogs and 9 % of transitional mires. Drainage has been done on 0.2 Mha, mainly for agricultural purposes. Peat winning has decreased considerably since 1960, or by 75 %, and is performed on c. 30 km^2. A programme called "Production and utilisation of peat for fuel" has recently been prepared for peatland use. However, there is strong opposition and preservation and conservation are also recommended.

Figure 4.6. International Peat Society, IPS, researchers investigating a fen in the Biebrza Valley in Poland in 1994 (photo, Lars Lundin).

Poland

Widespread wetland areas exist in Poland, with 1.2 Mha of peatland. Fens account for 92 % of this area and 86% has been drained and is now used as meadows and pastures (70 %). Bogs constitute 4.7 % and transitional mires 3.2 % of the peatlands. Large and important wetlands areas are the Biebrza and Note valleys. Most of the undrained area is found in these nature reserves, comprising a total of 1.5 Tkm^2, or 14 % of the peatland area. Peatland utilisation occurs primarily in agriculture (0.8 Mha, or 65 %), forestry (12 %) and peat cutting (4.4 %), the latter mainly for balneological purposes. Conservation originally involved 5 Tha, to which should be added a more recent preservation of close to 10 Tha, mostly in the Biebrza Valley (Figure 4.6).

Russia

Russia, which is the largest country in Europe and hosts the largest wetland areas, touches the Baltic Sea in a small area near St. Petersburg, where the Neva River enters the Finnish Bay, and also at Kaliningrad. North-western Russia encompasses 1 Mha and Kaliningrad 286 km^2 of peatlands. Of this territory, 80 % is an exploitable resource and 20 % is non-exploitable.

Sweden

With the exception of Russia, Sweden is the country that encloses the largest peatland area in Europe, 10.4 Mha. Peatlands with thick peat deposits (> 0.4 m) cover 6.4 Mha. Other wetland areas often have thinner organic layers. Bogs extend over c. 15 % of the area, while 85 % are other wetlands, mainly fens. In southern Sweden considerable use of wetlands in agriculture has taken place. For the total area of Sweden, a low estimate is that there is 0.6 Mha, of which an estimated 0.3 Mha might presently be in agricultural use. Forested peatlands cover 3.4 Mha and drainage has been carried out on almost 2 Mha. Peat winning has been on the rise since 1980 and today amounts to c. 15 000 ha, almost equally shared between horticulture and fuel peat.

Conservation involves first and foremost c. 0.4 Mha, to a large extent located in northern Sweden and the high mountains. Another 0.4 Mha has been proposed to be protected based on the national wetland inventory.

Conclusions

Wetlands in the Baltic Sea catchment attract considerable interest and constitute large areas with significant impact on the quality of the sea. Wetlands comprise c. 20 % of the Baltic Sea catchment. In almost all the countries the wetlands have been utilised for human activities, mostly agriculture, forestry and peat winning. It has been important land to exploit, yielding considerable crops and, more recently, high-productive forests. During the last few decades, the focus has changed and conservation and preservation have gained more attention. Also the use of wetlands in water quality issues, such as the retention of nutrient leaching and cleaning of wastewater, has been increasingly recognised. Peat has proved to be outstanding as a growing substrate and provides important material in horticulture. The value of wetlands, including peatlands, is by common consent of great significance.

Part II

The Hydrological Cycle and the Waterscape Elements

THE HYDROLOGICAL CYCLE

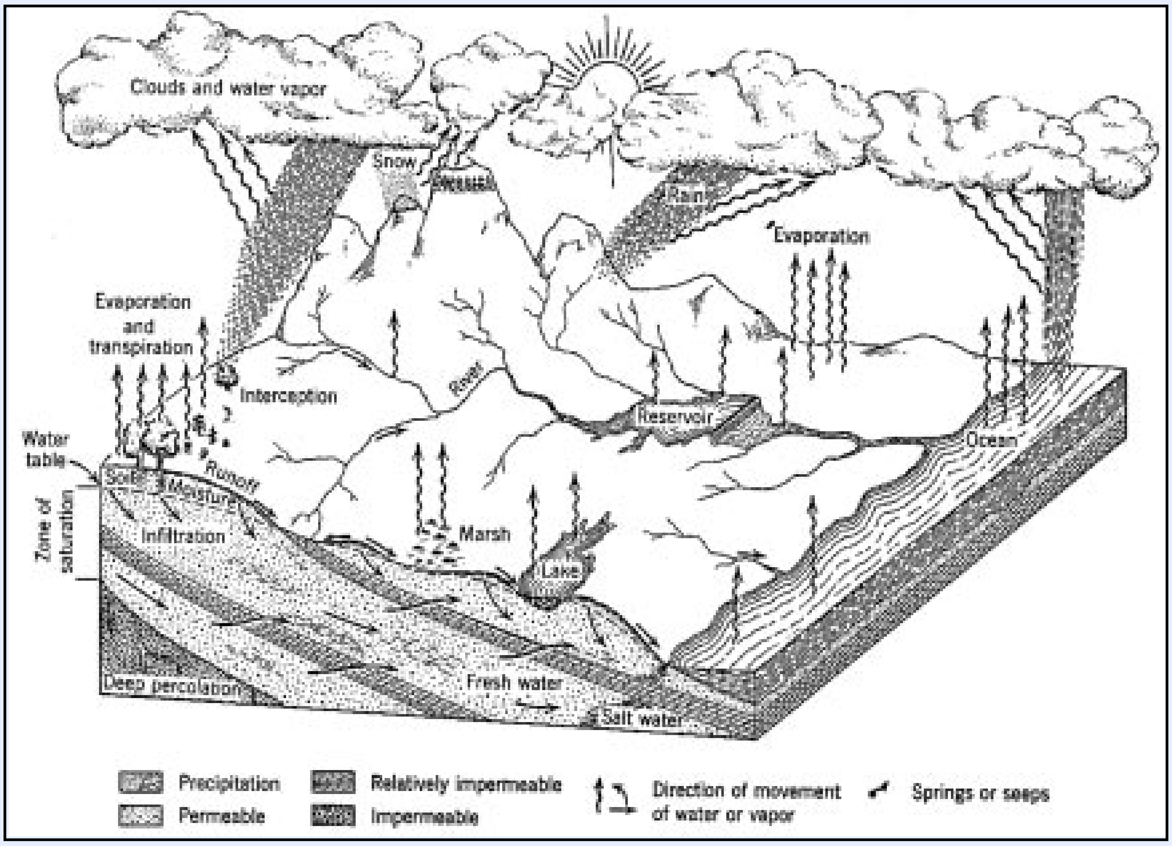


Figure 5.1. The hydrologic cycle (courtesy of the Texas Water Commission).

The concept of the hydrological cycle underlines the fact that water is both renewable and limited. It also lays down what is called a budget for a specific land area or body of water, stating that the income, i.e. the precipitation, will be spent on transpiration from plants, evaporation from the surface or runoff to the ocean. Over shorter periods water can also be stored as soil water and groundwater, or in the water body itself.

The hydrological cycle can be very short, almost like a short circuit, e.g. precipitating water that evaporates back into the atmosphere, or transpiring water from a wheat field that is caught by a thunderstorm and returned as rain after a few hours, only kilometres away. The cycle can also span over hundreds or even thousands of years if water is carried by the large-scale groundwater flow, perhaps even being trapped by deep percolation as relict groundwater or snow that is caught in a glacier.

The driving forces of the hydrological cycle are radiation from the sun – more specifically, the net of long- and short-wave radiation – and the slope of the terrain (gravitation). Net radiation heats the ground (sensible heat) but also supplies energy to the evapotranspiration (latent heat), whereas the slope of the terrain decides the route surface water will take on its way to the sea and how groundwater will flow.

Lars-Christer Lundin

5.

THE HYDROLOGICAL CYCLE AND THE ENERGY BALANCE

Allan Rodhe

As illustrated in the chapters in Part I, the water problems within the Baltic region vary greatly. The important issues are those related to water supply (household, industry, agriculture, energy production etc.), flood protection and a desirable function of the whole ecosystem. The aim of this chapter is to provide basic knowledge of the processes that determine water flow and storage in land areas, as a basis for understanding the natural water conditions of the region and how they are affected by human activities. Our discussion concentrates on physical principles for flow and storage on a general level, with examples from different parts of the region. The general view of the water flow presented in the chapter is useful in an evaluation of the water resources on an extensive level and in identifying problems caused by various human activities. In order to solve specific problems, these principles need to be combined with detailed information on the local conditions such as climate, geology, topography, land use etc.

The catchment

For any point along a watercourse, and for any other point in the landscape, a catchment (or watershed, or drainage basin) can be defined. It is the area within which all water flowing through the point as surface runoff or groundwater flow has been collected by precipitation. The catchment is a fundamental unit in any water management practice. With knowledge of the catchment area of a particular point it is possible to estimate the amount of water flowing through the point. It is also possible to identify chemical changes that may have taken place in the water, e.g. how various geological environments and human activities in the upstream part of the catchment might have influenced the water quality.

The catchment is enclosed by a water divide, which can be determined from a topographic map (Figure 5.2). First a coarse delineation is made based on the connections between the different watercourses and their directions. Then the water divide is drawn as an imagined line from the point, perpendicular to the height contours, while answering the question: is the water flow at a certain location directed towards this stream or towards another (or towards the same stream but downstream of the starting point)? A water divide determined in this way is called the topographic or surface water divide. As will be discussed below, often the greatest portion of the stream runoff is groundwater. Thus the groundwater divide is of more interest than the topographic divide. In areas with a shallow groundwater table, however, the topographic and groundwater divides are normally in close agreement. Such conditions are met in Nordic moraine terrain, with its shallow soil depths and relatively impermeable bedrock. In areas with thick deposits of permeable soil or highly permeable bedrock, and also in areas with very little pronounced topography, the topographic and groundwater divide may differ considerably, making catchment delineation difficult. It is primarily in small catchments (~ 10 km^2 or less) that problems

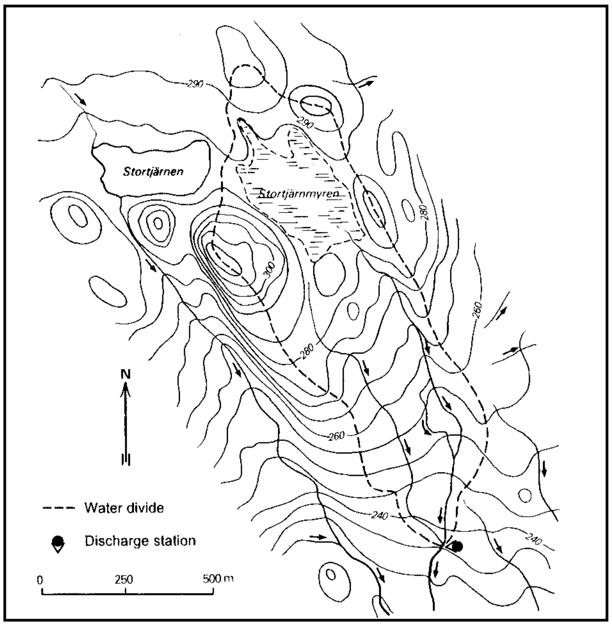


Figure 5.2. A catchment defined by the topographic water-divide (Svartberget, Northern Sweden). The catchment boundary crosses the height contours at right angles and generally coincides with the natural ridgelines (from Grip & Rodhe, 1994).

arise when the topographic and groundwater divides differ. In large catchments the relative error in catchment area based on the difference normally becomes negligible.

Precipitation falling within the water divide can be temporarily stored in the catchment, returned to the atmosphere as evapotranspiration or transported out of the catchment as stream or groundwater runoff. No water can "disappear." This can be expressed by the water balance equation, which in its most general form reads:

$$P = E + R + \Delta S \qquad (1)$$

where

P is precipitation,
E is evaporation,
R is runoff, and
ΔS is change (Δ) in storage (S), ΔS can be either positive or negative.

The terms of the water balance are often expressed as mm/time, where 1 mm water depth = 1 litre/m^2. The term *runoff* is normally used for the water flow from a surface, e.g. a catchment, expressed as volume per unit of time and area, e.g. mm/month or litre/(s km^2). A more precise term for this entity is *specific runoff*. The term *discharge* refers to volume per unit time, e.g. water discharged through a stream or through a certain cross section of the groundwater zone, often expressed as m^3/s or litre/s.

The storage term, ΔS, can conveniently be divided into change in storage in *surface water* (ponds, streams, and lakes), *soil water*, *groundwater* and *snow*. The change in storage alternates between positive and negative, as the storage increases or decreases. Taken for long time periods (several years), ΔS will be small compared to the flow terms, since precipitation is balanced by evaporation and runoff, yielding

$$P = E + R \qquad (2)$$

Over short time periods, the change in storage has a very important role in that it delays the flow and smoothes its temporal fluctuations. Some of the water reaching the catchment during a few hours of rainfall is stored, and after the rainfall declining storage supports evaporation and runoff that may last for several days. (The role of snow storage differs from that of liquid water storages in that the snow pack may accumulate an inflow of several months and release it during a few weeks of intense melting, thus making a concentrated water flow.)

To a great extent human impact on the water flow and water availability in the landscape involves the changes we make in the possibilities for water storage. For the most part human beings make a decrease in these possibilities, resulting in increased fluctuations in the runoff. Urbanisation is an example of such an intervention. The construction of hard surfaces in cities reduces infiltration and thus the possibility for storage in soil water and groundwater, which increases fluctuations in the runoff. Forest clear-cutting, too, results in a decrease in the possibilities for soil water and groundwater storage. When vegetation is taken away evaporation decreases, which increases soil moisture and raises the groundwater level, resulting in fewer opportunities for water storage and faster and greater runoff response to rainfall.

Drainage is an example of an intervention whose effect may act in two opposite directions. Drainage of surface water, such as lowering the level of a lake for agricultural purposes, reduces the possibilities for surface water storage. This will increase the temporal variability in runoff and increase the peak flow in the discharging stream. Drainage of land areas and wetlands lowers the groundwater table, which, on the other hand, may increase the opportunities for temporal soil water and groundwater storage. As long as the groundwater table remains below the ground surface, such an intervention may reduce peak flow.

Long-term mean values of the specific runoff are shown in Figure 1.9. Such a map, although preferably with a better spatial resolution, can be used to estimate the mean discharge in a stream. The mean discharge, Q, is found by

$$Q = R \cdot A \qquad (3)$$

where

R is runoff (litre/(s km^2)) and
A is catchment area (km^2).

A river with a catchment area of 4.5 km^2 in north-eastern Poland (R = 7 litre/(s km^2) according to the map) thus has a mean discharge of approximately 30 l/s. It should be noted that this estimate gives the mean discharge over several years. There are very large temporal variations, within the year as well as between different years. If the runoff instead is given as mm/year, it is practical to use the relationship:

1 litre/(s km^2) = 31.5 mm/year

Equation (3) can also be used to estimate the largest sustainable groundwater withdrawal that can be made from a well or from a group of wells for which the catchment area is known. If all precipitation infiltrates, as is normally the case in the Baltic region, the groundwater recharge equals precipitation minus evaporation, i.e. the specific runoff. Equation (3) thus gives an estimate of the long-term mean groundwater recharge. The maximum withdrawal over short periods, on the other hand, is determined by the storage capacity and hydraulic properties of the soil or bedrock and by the well construction.

Precipitation

As is well known, the water input to land areas is by precipitation. In order to evaluate the water resources and to predict the hydrological behaviour of a catchment, the temporal and spatial variability of precipitation has to be known. In this section the basic processes of precipitation formation will be discussed briefly as a background to an understanding of the precipitation characteristics of the region.

When discussing precipitation formation, some concepts on atmospheric humidity need to be used. The atmosphere always contains more or less water vapour; at the ground level on the order of 10 g/m^3. The vapour content can be expressed as the pressure exerted by the water vapour, called the *vapour pressure*, e. The warmer the air, the larger its capacity to contain water vapour is. The *saturation vapour pressure*, e_s gives the maximum possible vapour content of the air. This entity increases rapidly with increasing temperature according to a known relationship. The degree of saturation is expressed by the *relative humidity*, $RH = e/e_s$, often given as a percent. When a certain air mass is cooled, the vapour pressure remains constant, whereas the saturation vapour pressure decreases, resulting in an increase in the relative humidity. When the relative humidity reaches 100 %, the air becomes saturated and vapour starts to condense to liquid water (or ice). When discussing evaporation-condensation the term *vapour pressure of a liquid (or ice) surface* is used, meaning the saturation vapour pressure at the temperature of the surface, $e_s(T_{su})$, where T_{su} is the surface temperature.

The transformation of atmospheric water vapour into precipitation can be viewed in two steps. As a first step the air has to cool until the relative humidity reaches or passes 100 %, so that condensation can start. The condensation takes place on small particles, so-called condensation nuclei, which are always present, in more or less abundant quantities, in the atmosphere. Now a cloud has been formed, but the droplets that comprise the cloud are very small and their fall velocities are very low. The droplets are kept floating in the air by upwinds and no precipitation occurs. The growth of the droplets through further condensation is too slow to create droplets large enough to fall down from the cloud as precipitation. The second step in the formation of precipitation is therefore various processes by which some of the droplets develop rapidly at the expense of others. Two such processes have been identified. One is based on the fact that if the temperature of a cloud is below the freezing point, ice droplets and supercooled liquid droplets exist simultaneously in the cloud. This is an unstable system. Due to vapour pressure differences between liquid water and ice, vapour will evaporate from the liquid droplets and condense on the ice droplets, which may grow rapidly and fall down as precipitation. But precipitation may also be formed when cloud temperature is above freezing point. Large droplets fall faster than small droplets, resulting in collisions within the cloud whereby the larger droplets grow rapidly by capturing the smaller ones. The intensity of this rain-droplet formation through coalescence increases with the vertical mixing inside the cloud.

From a thermodynamic point of view it can be shown that the decrease in the pressure that occurs in rising air results in a cooling of the air by about 1 °C/100 m as long as no condensation occurs. When the air has been cooled to saturation, the latent heat released by condensation reduces the rate of cooling. The basic prerequisite for precipitation formation is this cooling caused by a rising of the air. The conditions for vertical mixing in the atmosphere are important to the weather forecaster in that they determine the rate of rising and thus the rate of cooling. However, without going into this further, we can look at some typical reasons for the first step in the precipitation formation process, i.e. the reasons for the rising of the air, causing the cooling which may lead to condensation and formation of precipitation. In reality, precipitation is often caused by a combination of the main processes described below and in all cases the stability and moisture conditions of the atmosphere determine whether or not precipitation will be formed (Figure 5.3).

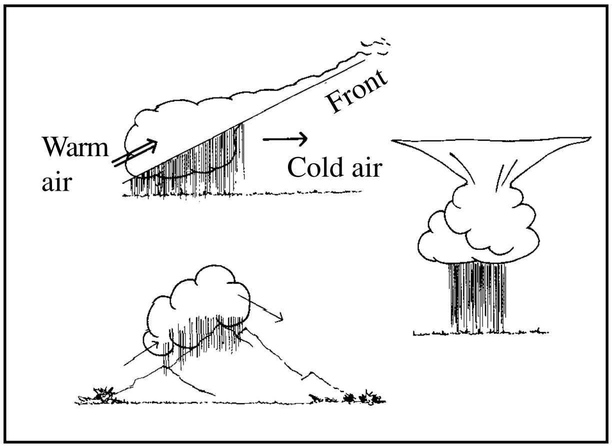


Figure 5.3. Principles for frontal (warm front), convective and orographic precipitation (from Liljequist, 1970).

ATMOSPHERIC WATER

Water in the atmosphere is present both as water vapour and as suspended cloud droplets and, on occasions, as falling rain and snow. The primary source of moisture is evaporation from ocean areas and the major sink is falling precipitation. The total storage in the atmosphere is relatively small in the middle of the Baltic region and depends on temperature. At 60 °N the mean storage is close to 10 kg/m^3 or, measured in the same unit as rain, 10 mm of water. In winter the average is 6 mm and in summer about 14 mm. At the equator the yearly average is well above 40 mm. The total amount of water in the atmosphere (precipitable water) is approximately equal to all the water in freshwater lakes on Earth, $1.25 \cdot 10^{16}$ kg. About half of this is found in 15 % of the air mass (1 000-850 mb) and 90 % in half the air mass (1 000-500 mb).

The horizontal flow of moisture in the atmosphere is proportional to the mean wind. At 60 °N and a zonal wind speed in the lower atmosphere of 20 m/s the flow rate of water will be 200 kg/s per meter width, which looks impressive but bears no direct relation to that which can be removed by rainfall. The rate of precipitation in the same latitude is about 700 mm/year or 2 mm/day. Hence, the atmospheric storage is renewed every 5 days, the residence time of water. As a global average the residence time of water is about 10 days. The water that is returned by evaporation at a latitude of 60 °N is perhaps 40 % of the rainfall. Hence, the residence time of water in the atmosphere in relation to net removal of water is about 10 days.

The meridional distribution of net water flux to or from the ocean surface in the Northern Hemisphere is shown in Table 5.1.

The net flow into the atmosphere in the 10 - 40 °N zone provides the excess rainfall in the tropical strip as well as in the 40 - 80 °N zone. The latent heat transferred from the subtropics and released in the Temperate Zone in this process has a strong influence on the climate in the Temperate Zone.

Erik Eriksson

Table 5.1. Net water flux to or from the ocean surface in the Northern Hemisphere. A minus sign means a net flow from the atmosphere to the ocean surface and a plus sign means a net flow from the ocean surface to the atmosphere. (Peixoto, 1973)

Latitude	**Flow** (cm/year)
0 - 10	-75.0
10 - 20	20.3
20 - 30	48.4
30 - 40	25.5
40 - 50	-26.6
50 - 60	-36.4
60 - 70	-19.2
70 - 80	-10.4

Air may rise due to heating of the ground and the air near the ground, making the air less dense there than the air at higher levels. Under certain stability conditions in the atmosphere such local upwinds may be amplified and a large upward air transport takes place, resulting in cloud formation (cumulus clouds) and possibly precipitation (cumulonimbus clouds). Such *convective precipitation* is typically afternoon showers over land in summer. It can also develop over open sea in winter. Convective precipitation may be of high intensity and, since the convective clouds are of limited size, the showers are local and the precipitation quantities exhibit large areal variability.

Orographic precipitation occurs when the air is forced to rise as it moves in over elevated areas. The orographic effect is clearly seen on a regional precipitation map (Figure 1.8). Moist air masses from the Atlantic are forced upwards along the western coasts of Norway and Sweden, causing precipitation quantities of more than 3 000 mm/year in western Norway and about 1 000 mm/year in south-western Sweden. Precipitation in the Scandinavian mountain chain is generally high, particularly on the western side, which is where the air masses are coming from. High precipitation also occurs in the Carpathians in the southernmost part of the Baltic Sea basin. The air loses some of its vapour through rain as it passes a mountain chain, giving less precipitation (and warmer air) on the leeward side, a so-called rain shadow. The orographic effect is also seen on a smaller scale, as an increase of the precipitation with altitude, also with height differences of only some tens of metres. The rate of increase in the annual precipitation with altitude varies considerably between different locations. In inland areas of Sweden, the annual precipitation has been found to increase by about 30-40 mm per 100 m in the north and by about 50-70 mm per 100 m in the south.

The air can also rise and cool so that condensation occurs when two air masses meet. Such *frontal precipitation* in the Baltic Sea basin is associated with the eastward movement of frontal systems. In a warm front, warm air flows into a region with cold air and the warm air rises slowly over the cold air. The slow rise gives a precipitation of low intensity but of comparatively long duration. In the cold front, the cold air flowing in under the warm air causes the rise. The result can be intense showers of short duration.

Measurement of precipitation is conceptually simple. The precipitation is collected in a gauge with a known horizontal opening area giving the volume of precipitation per unit of area, commonly expressed as mm water depth. There are, however, several practical problems in such measurements, leading to errors that underestimate the precipitation quantities. The main problem is caused by the wind, tending to blow the rain and especially the snow over and around the gauge. Evaporation of the collected water before reading the gauge is another error associated with manually read gauges. For the Swedish standard precipitation gauge, it has been found that the observed annual precipitation quantities have to be corrected by about + 10 to + 20 % (and in some cases more). The degree of the correction depends on the local wind-shielding conditions around the gauge and on the fraction of the annual precipitation falling as snow. The map referred to above in Figure 1.8 shows uncorrected values of annual precipitation.

Precipitation quantities given by meteorological services are normally not corrected for measurement errors. When they are used in hydrological modelling a general correction factor is often applied. In water budget estimates of the actual evaporation, correction is particularly important. In Uppsala, Sweden, for instance, the observed 30-year mean value of precipitation is 520 mm/year. With an observed runoff of 220 mm/year the water budget (Equation 2) gives an evaporation of 300 mm/year. When using corrected precipitation values, estimated at 635 mm/year, the estimated evaporation increases to 415 mm/year.

In many applications, areal mean values of precipitation are needed, such as mean values over a catchment over a certain time period. For such estimates, the representativity of the point measurements has to be addressed. One method of obtaining areal mean values is to use the observed or assumed height dependence of precipitation of the area and transform the observed (corrected) values to values representing different height intervals. If the hypsometric curve of the catchment, i.e. the distribution of the area among different altitude classes, is known, catchment mean value of precipitation can be estimated.

Evaporation

With the exception of the upper north-western half of Sweden and the northern half of Finland, the majority of the precipitation that falls into the Baltic Sea basin returns to the atmosphere from the soil via the vegetation and from other moist or wet surfaces, i.e. evaporation is larger than runoff. In the Baltic Sea, evaporation approximately equals precipitation, implying that the net runoff from the sea into the ocean equals the total runoff from the land areas of the basin.

Of the three main terms in the water budget, evaporation is by far the most difficult to measure or determine. It is an invisible net flow of water vapour from the evaporating surface to the atmosphere that, in contrast to precipitation and stream runoff, is impossible to measure directly. At the same time knowledge of the magnitude of this flow is of great interest since it determines how much of the water input by precipitation is left for groundwater recharge and runoff, i.e. water availability. Evaporation differs from precipitation in that it is far more affected by human activities on both local and larger scales. It is, in fact, by intended change of the evaporation (irrigation) or unintended that we make our greatest interventions in the hydrological cycle. Our land use, such as forestry, agriculture, urbanisation and surface reservoir management affects evaporation either directly by changing the vegetation and the existing wet surfaces or indirectly by changing the possibilities for temporary water storage, which in turn changes the possibilities for evaporation. Starting with the physical process of evaporation, this section discusses the different mechanisms by which water vapour flows from the surface to the atmosphere. Noting that evaporation plays a key role in the energy exchange between land or sea and the atmosphere, the energy budget for a surface is defined and used for analysing conditions of evaporation. The energy budget is later applied to the process of snowmelt.

Within hydrology the term *evaporation* is often used in a general sense for the vapour flow from sea and land, including vegetation, to the atmosphere. This flow is also termed *evapotranspiration*, stressing that it is the sum of *evaporation*, now restricted to the flow directly from water surfaces and soil water, and *transpiration*, which is the vapour flow via the vegetation. If not otherwise stated, the term evaporation is used in this text in its general meaning, i.e. as the total vapour flow to the atmosphere.

Evaporation is the net flux of water molecules between the liquid and vapour phases of water. In nature it is driven by the difference in vapour pressure between the evaporating surface and the atmospheric vapour, and the flow rate is proportional to this difference (Figure 5.4). For a wet surface, the rate of evaporation thus increases with increasing surface temperature and decreasing air humidity above the surface. The conditions for a high rate of evaporation can be systematised, bearing in mind that the evaporation is driven by the vapour pressure difference between the surface and the atmosphere.

Energy supply

High surface temperature gives high saturation vapour pressure at the surface. Energy is needed for the phase shift from liquid water to vapour (latent heat of vaporisation), a process that tends to cool the evaporating surface. In order to maintain a high surface temperature, there must be an energy flux to the surface layer. Otherwise, the surface will cool and the evaporation will decline and eventually cease. In nature the energy is supplied by the sun, directly by solar radiation and indirectly from heat stored in the soil, water or vegetation from earlier heating by the sun (the heat supply for evaporation is observed as a cooling of these bodies). In some situations there may also be a heat flow to the evaporating surface from warm air. However, during periods of high evaporation the surface is normally warmer than the air, generating a heat flow from the surface to the air, a flow that competes with the evaporation for the energy available at the surface.

Air humidity

Dry air and an efficient transport mechanism for the water vapour from the air just above the evaporating surface favours evaporation. The air humidity depends to a large degree on the large-scale origin of the air mass. The transport of vapour from the evaporating surface is caused by turbulence generated by the wind. The wind blows horizontally and generates turbulent eddies, giving a vertical net transport of vapour (and heat) in the direction of decreasing vapour concentration, i.e. from the evaporating surface up through the atmosphere. The stronger the wind and the rougher and the warmer the surface, the more efficient the turbulence will be and the larger the vapour flow for a certain vapour pressure difference. The local climate may also play an important role. Large, open bodies of water tend to increase the air humidity over themselves and in their surroundings, thus reducing evaporation. Conversely, a small wet area in a warm dry surrounding will have a large rate of evaporation, due to dry air and also due to a considerable energy flow from the warm air coming from the surroundings (the so-called oasis effect).

Wet surfaces

The above items mainly express the weather conditions for evaporation. But favourable weather is not enough, for if there is no water available at the surface, there will of course be no evaporation. Water for evaporation may exist as soil water or in wetlands, lakes and open water surfaces. Evaporation takes place directly from such surfaces, but from land areas the main flow takes place via the vegetation, i.e. as transpiration. The rate of transpiration for a particular weather condition depends to a large degree on the total leaf area per unit ground area (the leaf area index, LAI), which in turn depends on the type of vegetation and on its seasonal development. Snow also represents a wet surface for evaporation. Since the temperature of the snow cannot exceed the melting point for water, 0 °C, the vapour pressure difference between the snow surface and the atmosphere is restricted and the rate of evaporation from snow is small.

The conditions for evaporation may be compared with the function of an electrical hair dryer, drying the wet hair by supplying heat (warm air instead of radiation) and effective ventilation.

Potential evaporation

A frequently used concept is the *potential evaporation*, which is the evaporation from a certain surface that has optimal water supply. It is often defined for short green grass growing on a soil with optimal soil moisture conditions for the vegetation (soil moisture content at “field capacity,” see later sections). The potential evaporation is a climatic variable, express-

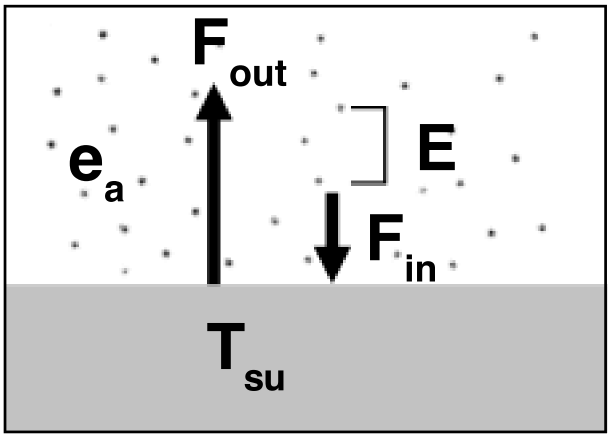


Figure 5.4. Evaporation (E) is a net flow of water molecules between the evaporating liquid and the vapour in the air. The outflow, F_{out}, is proportional to the saturation vapour pressure at the surface, $e_s(T_{su})$, where T_{su} = surface temperature of the water. The inflow, F_{in}, is proportional to the vapour pressure of the air, e_a. $E = F_{out} – F_{in}$ is proportional to $e_s(T_{su}) – e_a$.

ing the ability of the atmosphere to generate evaporation, which can be determined from climatic data. A commonly used method is the Penman equation, giving the potential evaporation from a certain surface as a function of solar radiation or, rather, net radiation (see the definition in connection with Equation (4)), wind speed, air temperature and air humidity. In hydrological modelling of runoff or groundwater recharge, the actual evaporation is often calculated as a fraction of the potential evaporation, with the fraction depending on the soil moisture status. When the soil is wet (at or above the field capacity) the fraction is 1.0, i.e. the actual evaporation equals the potential. As the soil dries out the fraction decreases and, if this drying out continues, it reaches 0, when the soil is so dry that the plants can no longer take up water (soil moisture content at the ”wilting point”).

Transpiration

As mentioned above, the term *transpiration* refers to the vapour flow from vegetation. This vapour flow mainly occurs from the stomata, i.e. microscopic openings in the leaves. When the vegetation opens the stomata to take up CO_2 for photosynthesis and the building of biomass, the vegetation exposes moist surfaces to the atmosphere. The vapour pressure difference between the stomata and the atmosphere generates a vapour flow and the vegetation has to supply this flow by water uptake from the soil. If the soil is too dry, the water uptake will not be sufficient, the water storage in the vegetation water will decline and the vegetation will start to wilt. The transpiration can be seen as the response of the vegetation to an atmospheric demand for water, determined by the weather according to the discussion above. The plants can to some degree regulate the vapour flow by closing and opening the stomata. Figure 5.5 shows an example of water vapour flux (evaporation) and flux of carbon dioxide over a pine forest determined by detailed micrometeorological measurements in a tower over the forest. Also shown is the potential evaporation. The CO_2 flux is directed downwards (negative values) during the summer period, when the forest biomass is being built through photosynthesis (assimilation). During the winter, when respiration (dissimilation) and decomposition dominate, the flux is directed upwards.

Interception

The leaves catch some of the rain falling on the vegetation. This process is called *interception*. About 2 mm of water (2 litre/m^2 ground surface) may be stored in the canopies of coniferous forests and green deciduous forests. The effect of interception can be studied when using a tree as a shelter during a sudden rainfall. Except in extremely dense canopies some rain will reach the ground between the canopies even from the very start of the rainfall. Gradually more rain will reach the ground, and when the interception storage is filled, practically all additional rainfall will have reached the ground as canopy drip, stemflow or as rain between the canopies. During the rainfall there is only slight evaporation from the interception storage, since the air humidity is very high, but after the rainfall vegetation may dry up in a few hours. In coniferous forests in central Sweden it has been found that 20-40 % of the rainfall returns directly to the atmosphere through evaporation in the interception storage. The total interception loss over a certain period depends on the number of drying-up periods, and thus roughly on the number of rainfall occurrences. A certain rainfall quantity distributed among several showers gives less water input to the ground than the same rainfall quantity falling in a few heavy storms. The hydrological role of interception has previously been viewed as small. The available energy was considered to generate a certain vapour flow, regardless of whether the water evaporated from the surfaces of the leaves as interception loss or if it passed through the vegetation as transpiration. This may hold true for grass, but for forests it has been found that the resistance against vapour flow is much greater for flow through stomata than for flow directly from the interception storage. For a certain “atmospheric demand,” the evaporation from a wet forest, i.e. from the interception storage, is much greater than the evaporation from the same forest when it is dry, i.e. the transpiration (also when the soil moisture is optimal). The reduced evaporation and increased runoff that we can observe as a consequence of forest clear-cutting is caused in part by reduced transpiration, but also to a large degree by a reduction in interception loss due to reduction in interception storage capacity.

Energy balance

Evaporation constitutes a large energy flow from the surface. The energy needed for evaporation is transported with the vapour as a so-called latent heat flux. When the vapour condenses and forms clouds in the atmosphere this latent heat is released and contributes to the warming of the air. The water budget, as discussed above, expresses the mass conservation of water within a certain area or volume. In a similar way an energy budget, expressing the conservation of energy, can be established. The energy budget is useful for analysing

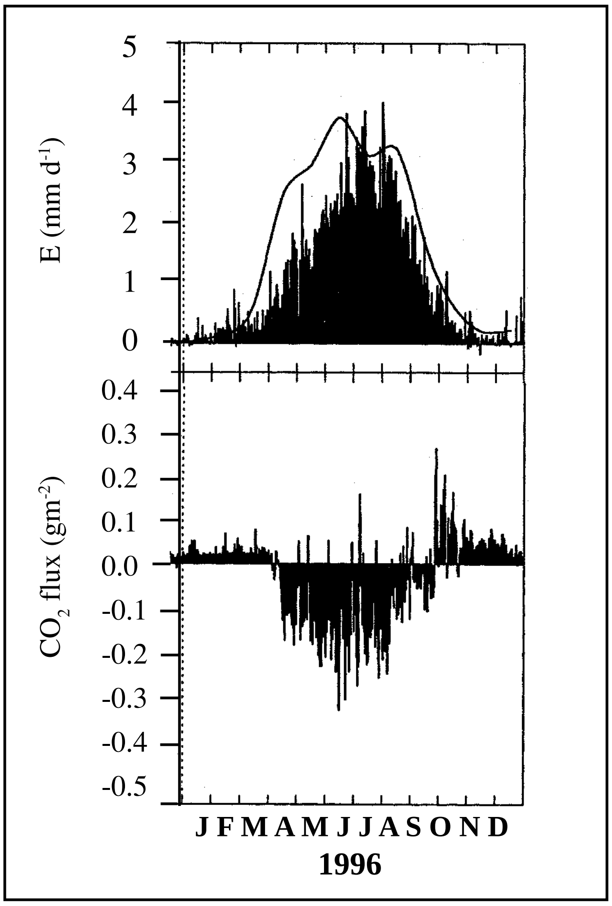


Figure 5.5. Fluxes from a mature coniferous forest in southern Sweden 1996. Upper panel: Evaporation (histogram) and potential evaporation (solid line). Lower panel: Daily sums of CO_2 flux (from Grelle,1997 and Grelle et al,1999).

the interrelationships between radiation, evaporation and heating of the air, soil and water. It is also the basis for commonly used micrometeorological methods of estimating evaporation. The energy balance for a surface can be written:

$$R_n = H + L \cdot E + G \qquad (4)$$

where

R_n is net radiation, i.e. the net supply of radiation, originally from the sun, to the surface and

H is sensible heat flux, caused by a temperature difference between the ground and the air. A positive H implies heating of the atmosphere by the ground, which has been heated by the net radiation.

L·E is latent heat flux due to evaporation, where

E is the rate of evaporation and

L is the latent heat of vapourisation.

G is the heat storage in the substratum, i.e. in the vegetation, ground or lake. A positive G represents a warming of the substratum.

The terms are conveniently expressed as energy per unit time and area, i.e. W/m^2. The net radiation is the sum of the vertical components of direct and diffuse radiation from the sun and long-wave thermal radiation from the atmosphere, minus the sum of reflected short-wave radiation and emitted thermal radiation from the surface. In addition to the terms on the right hand side one should also have, for a vegetated surface, the energy of photosynthesis. This term is small, however, as compared to the other terms and it can usually be neglected.

The energy budget expresses that the energy supply through net radiation as partitioned between the turbulent fluxes of sensible and latent heat from the surface to the atmosphere and the heat flux represented by the heating of the vegetation, ground or lake. As is also the case for the water budget, the storage term becomes comparatively small over longer periods (years), since the ground alternates between heating and cooling, giving positive or negative values of G. At the same time the daily sums of H and L·E almost always are positive. For land surfaces, the storage is less important regarding periods of weeks and months. However, for lakes the storage may result in a characteristic delay of the rate of evaporation as compared to the seasonal variation of net radiation and air temperature, both reaching annual maxima soon after mid-summer. During spring and early summer heat is taken away from evaporation by heating the water body and in late summer and autumn this heat contributes to the energy supply of evaporation. The Baltic Sea, with its large heat storage capacity, thus gives off minimum evaporation in April-May and maximum evaporation in September-October (Figure 5.6).

The partitioning of the available energy between the sensible and latent heat fluxes depends on the surface temperature, air temperature and humidity and water availability at the surface. If the surface is wet and the atmospheric humidity is comparatively low, evaporation and thus the latent heat flux will be high. On a sunny summer day the latent heat flux by evaporation from a green grass surface, not suffering from water deficit, is typically 1-2 times the sensible heat flux. If the soil is dry the sensible heat flux dominates. This is the case on a summer day on a large paved parking place: the radiation heats the ground, which in turn heats the air, with no cooling by evaporation taking place.

Mean values of evaporation over longer periods can be estimated from the water budget. With the catchment as a unit, such estimates provide areal mean values over a well-defined area. For estimates with high temporal resolution, such as hourly or daily values, micrometeorological methods relying on advanced measurement techniques must be used. Such methods can be based on the energy balance and/or direct estimates of the turbulent fluxes from detailed humidity and wind measurements. Climate data collected in the normal observation network are not sufficient for the micrometeorological methods, which require special observations. The potential evaporation, on the other hand, can be calculated from regular climate data. As commented upon above, the actual evaporation can be estimated from the potential using a reduction factor based on the calculated soil moisture content. Such common estimates in hydrological modelling are somewhat crude but they can be useful in that they relate the actual evaporation to water holding properties of the soil, i.e. they can provide evaporation estimates for various soil types within a particular area.

The snow cover – an application of the energy balance

Seasonal snow packs occur over the entire Baltic Sea basin, and in large parts of the basin snow plays a dominant role in the hydrology. Of the annual precipitation, snowfall accounts for up to 50 % in northern Sweden and northern Finland and about 30-35 % in central Sweden and southern Finland. Since large amounts of precipitation may have accumulated in the snow pack during winter, and since evaporation is low during periods of snowmelt (due to low surface temperatures), the snowmelt is very efficient in recharging groundwater and generating stream runoff. The determination of the snow storage at the onset of melting and estimates of snowmelt rates are thus important components of hydrological modelling in the Baltic Sea basin.

The water storage represented by the snow pack is called the *water equivalent.* It is commonly expressed as mm water depth, which is the depth of water that would be obtained by the melting of the snow pack. It can be determined with the help of a snow tube, which collects a vertical snow core through the snow pack. Since the intake area of the tube is known, the water equivalent, equalling the mass of snow per unit area, is obtained by weighing the snow core. (1 kg snow per m^2 = 1 litre water per m^2 = 1 mm). The water equivalent, S (kg/m^2 = mm), of the snow pack is related to the density of the snow by

$$S = \rho \cdot h \qquad (5)$$

where

ρ is the density of the snow (kg/m^3) and

h is the snow depth (m).

The density of newly fallen snow is about 100 kg/m^3. Thus, 10 cm of newly fallen snow represents $0.1 \cdot 100 = 10$ mm of water equivalent, or, stated in the opposite way, 10 mm of snow precipitation yields a snow depth of about 10 cm. During winter the snow pack gradually gets compacted, with the density increasing to about 300 kg/m^3. Melting snow may have a density up to 400 kg/m^3. Besides packing of the deeper layers of the snow, due the weight of the overlaying snow, the snow pack is compacted during the winter by occasional melting with subsequent refreezing and also by evaporation-condensation processes within the snow pack. Evaporation takes place from pointed parts of the snow crystals and the vapour condenses on flat parts of the crystals. This metamorphosis of the snow pack has chemical implications. Salts and other impurities, which do not take part in the evaporation, become concentrated at the evaporating surfaces. The salts will be flushed out with the very first meltwater, which thus may be comparatively rich in salts.

The snow storage varies considerably over an area. Apart from the redistribution of the snow due to wind action, which is an important process in open terrain, the snow storage nor-

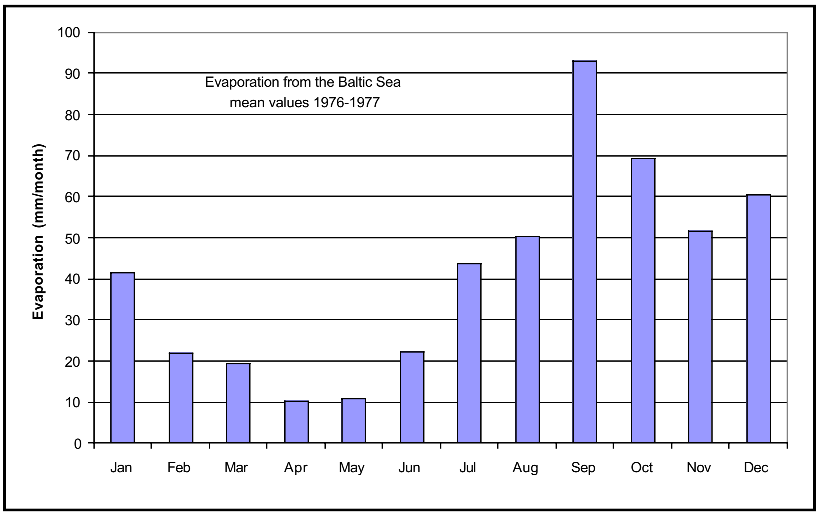


Figure 5.6. Evaporation from the Baltic Sea as estimated according to surface temperature, air humidity and wind speed (aerodynamic method). Mean values of estimates for two years, 1976 and 1977. Annual sums for the two years were 552 and 437 mm, respectively (estimates from HELCOM, 1986).

HISTORY OF HYDROLOGY

THE SCIENCE OF WATER IN NATURE

A history beginning in ancient times

A problem in the geosciences is the strongly varying appearance of nature in space scales. For a generalised description of appearance and dynamics a set of concepts is needed that can serve to illustrate the essential features. This sounds reasonable at first but one must realise that the term "essential" implies an evaluation of something considered important to society. Thus, we must also state the value of these features.

In hydrologic research the ultimate goal is practical, i.e. to find the essential features of water circulation and its fluctuations in time and space that are required for a sustainable development and management of water resources.

A concept is a simplified depiction of nature, considered to be as correct as possible with current knowledge. In practice concepts are models designed with respect to essential features. A concept thus depends on current knowledge and may change with time as more knowledge on and experience of the essential features is accumulated.

Most of the theories on water in nature during the first period (see box) proved later to be wrong. However, at the time of Christ, Marcus Vitruvius gave the first correct conceptual depiction of the circulation of water. A number of hydraulic constructions were also built during this period, including Arabian wells, Persian kanats, Egyptian and Mesopotamian irrigation projects, Roman aqueducts, water supply and drainage projects in the Indus Valley, irrigation systems, canals and flood control works in China, Sri Lanka and Cambodia. They were all constructed well from the viewpoint of today's concept of sustainable water management. The astonishing cultural development of the arts in these societies is well documented and may well be the result of widespread practical hydraulic knowledge of how to master water resources, which required great skill in dam building and canal design.

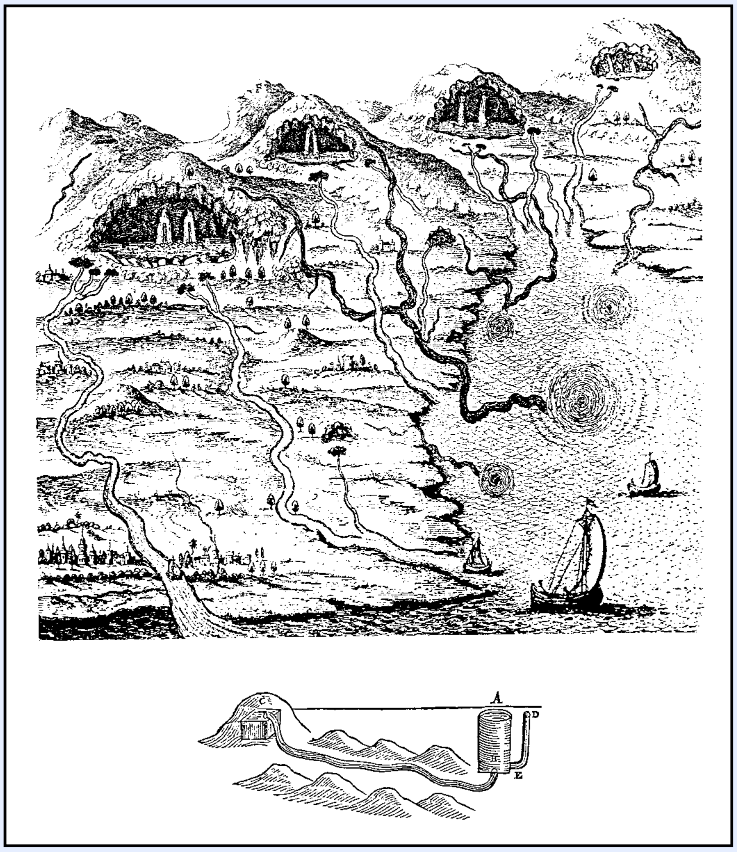


Figure 5.7. In his great work of 1664, Mundus subterraneus the German Jesuit monk and scientist Athanasius Kircher argued that the rivers get their waters from the lakes in the mountains. These cave lakes, Kircher claimed, are filled from the sea through subterranean rivers (shaded in the figure). With the assistance of scientific laboratory experiments Kircher concluded that water would rise up to the mountains influenced by winds and tide.

During the next period, called the observation period, Leonardo da

An excellent history of water science is found in the first chapter of Handbook of Hydrology, edited by Ven Te Chow and published in 1964. This remarkable work presents various parts of water resources research in extensive detail. Ven Te Chow divides the history of water science into the following eight periods:

A.	Period of speculation	(ancient to 1400 AD)
B.	Period of observation	(1400 to 1600)
C.	Period of measurements	(1600 to 1700)
D.	Period of experimentation	(1700 to 1800)
E.	Period of modernisation	(1800 to 1900)
F.	Period of empiricism	(1900 to 1930)
G.	Period of rationalisation	(1930 to 1950)
H.	Period of theorisation	(1950 to date)

Even the titles reflect the historic development very well, which to a considerable extent ran parallel to general scientific advancement.

Vinci and the less well-known Bernhard Pallissy contributed to our knowledge of the details of water circulation. They proposed infiltration of rain to soil as the source of water in springs, returning the water to the sea. During the next period systematic measurements of rainfall and evaporation of water and river discharge were initiated, thereby establishing valuable hydrologic time series.

Modern history

The period of empiricism was something of a prelude to modern modelling technology. This period saw the birth of quantitative empirical formulas based on knowledge gathered at universities and research institutes. There was an obvious need for this in water resource development and management. When numerical computers appeared a more direct physical approach could be taken and the role of empirical formulas faded.

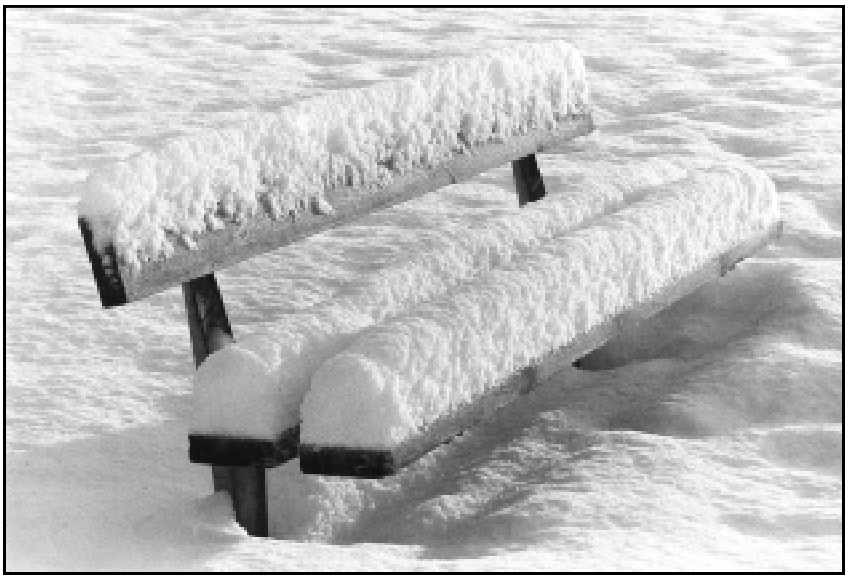
International co-operation in the management of water resources had already taken place during the 19th century, in the form of commissions on international rivers such as the Rhine, the Danube and the Nile, originally with the purpose of promoting flood traffic. More recently, the purpose has shifted towards other uses, primarily waterpower, water supply and water quality. The work of these commissions required reliable hydrologic data and international co-operation in water sciences.

On a national scale international co-operation in research was rarely a government matter. It belonged to the scientific academies, which in most cases operated as non-governmental bodies through national committees. Internationally, water sciences attained an international forum in the International Association of Scientific Hydrology (IAHS), which in turn belongs to the International Union of Geography and Geophysics (IUGG alt. UGGI). The work of the IAHS was mainly to arrange scientific meetings. The first meeting took place in 1924 as the All-Russian Hydrologic Congress held in St. Petersburg. This was followed by the Baltic Hydrologic Conference in Riga in 1928.

An important opportunity for increasing human knowledge about water in continental areas was created during the so-called International Hydrologic Decade, IHD, which ran from about 1965 to 1975. This program was envisioned at a meeting on the UNESCO Arid Zone Research program, which took place in Ankara. All member countries of the UN were invited to participate. Besides improvement of measuring methods and monitoring of hydrological variables, co-ordinated studies of the water balance in representative basins all over the world also inspired development of numerical models for runoff, soil moisture and groundwater storage.

The IHD program was followed by the IHP, the International Hydrologic Program, in which the World Meteorological Organisation, WMO, also participates. This program concentrates on operational hydrology and the use of hydrological information for water resources planning and management.

Erik Eriksson



Photo, Inga-May Lehman Nådin.

mally increases with altitude. This increase is caused both by the increase of precipitation with altitude and by the decrease in temperature with altitude, which in turn causes the fraction of precipitation falling as snow to increase with altitude. Less melting is also a result of the fact that there are fewer warm periods in elevated areas during the winter. In late winter snow storage is greatest in open areas (excluding bare mountain spots) and smallest in dense forest. The difference is partly caused by the warm ground in the forest in the early winter, giving less snow storage at that time, and partly by evaporation and melting of snow intercepted in the forest canopy during the winter.

The snow pack represents a large cold storage (negative heat, i.e. a heat content lower than melting ice), the melting of which requires a large amount of energy. The rate of melting can be estimated from a slightly modified form of the earlier discussed energy (Equation 4).

$$Q_{melt} = L_s \cdot M = R_n - H - L \cdot E + Q_p \qquad (6)$$

where

Q_{melt} is the energy available for melting,
L_s is the latent heat of fusion,
M is the rate of melting, R_n is the net radiation,
$-H$ is the sensible heat flux from the air,
$-L \cdot E$ is the latent heat released by condensation on the snow, and
Q_p is the heat supply through warm rainwater.

There may also be an energy supply from heat stored in the ground, but except in early winter this term is normally small and therefore disregarded here. The energy flow by condensation-evaporation may be directed towards as well as from the snow. When the air is sufficiently moist ($e > e_s(0\ ^{o}C)$) the flow will be directed towards the snow, condensation will take place and there will be a release of latent heat which can be used for melting. From the relationship between the latent heat of vaporisation (L) and the latent heat of fusion (L_s) it follows that condensation of 1 mm water releases energy for melting 7 mm of snow, resulting in 1 + 7 = 8 mm of liquid water. When the vapour pressure of the air is lower than the saturation vapour pressure of the snow surface, $e_s(0\ ^{o}C)$, which is often the case, evaporation will take place. Although the rate of evaporation from the snow is low in terms of vapour flow, the evaporation may considerably reduce the energy available for melting. The energy supply from rain is small even from large rainfalls. The energy from a rainfall of 20 mm, with a temperature of + 4 °C (= assumed air temperature), generates only 1 mm of meltwater. (This is contrary to the common view that snow gets "rained away" during the rainy days of spring. The underlying reasoning is understandable, however, since the air is warm, moist and often windy when it rains, resulting in considerable melting through sensible and latent heat fluxes.)

The rainfall may, on the other hand, be very efficient in generating runoff, since the soil moisture may be high due to earlier melting and the rate of evaporation is then low.

Conditions favourable to melting are thus characterised by intense sun radiation (or actually, large net radiation), warm air (bringing about sensible heat flow from the air), moist air (bringing about condensation and release of latent heat) and strong wind (bringing about efficient turbulent transport of heat and vapour to the snow pack). Due to stronger winds and more intense radiation reaching the ground in open areas, melting is much faster there than in the forest. In late spring it is often found that snow remains only in forest glades with a diameter of about the same magnitude as the surrounding trees. In such areas the favourable snow accumulation conditions of the open areas are combined with the protection against melting provided by trees as a result of shade and windshield.

In hydrological modelling, the full energy balance is commonly reduced to a simple temperature dependence that reads

$$M = C \cdot T_a \tag{7}$$

where

M is the rate of melting (mm/day),
C is a degree-day factor, having values of about 2-5 mm/(day °C), and
T_a is the air temperature (°C).

The melting rate is normally less than 10 mm/day. In extreme cases melting rates up to 30 mm/day have been observed. The water input to the ground is not directly determined by the rate of melting, since the snow pack is a porous medium with an ability to store liquid water through capillary forces (see next section). This capacity, which is equivalent to the field capacity of a soil, is about 4 % of the water equivalent of the snow pack. There will thus be no meltwater drainage from the snow pack until the accumulated melting exceeds approximately 4 % of the snow-pack water equivalent. Before this meltwater amount has accumulated in the snow pack, however, air temperature may drop again, freezing the liquid so that more melting will be required for the drainage to start. Thus, both liquid water storage and the amount of refreezing have to be taken into account when the meltwater production of a snow pack is to be calculated.

CONCEPTS OF HYDROLOGICAL CIRCULATION

Water balance in the accounting sense

The term "balance" can be used in the sense of a static state where everything is immobile if properly balanced. Another way of expressing balance is in the sense of a stationary (or steady) dynamic process when all the states are time invariant. Although such states do not occur in nature, the notion can still be used if we specify "in the stochastic sense." This means that some states are stationary in a long-term sense, and any deviations from them are considered to be random disturbances of time scales well below the "long-term" sense of time. Balance in the accounting sense is a pragmatic term that is aimed to denote the actual state at the end of a selected time period, usually a year. Changes in yearly balances are obviously related to random deviations from the stationary states, which in meteorology and hydrology are represented by averages of fixed time periods, at present 20 years.

Recharge - discharge areas

An inflow area is the surface area of a basin where groundwater is formed or is recharged. Hence, this area can also be called the groundwater recharge area of a basin, or, in short, the recharge area. The outflow area is consequently the remaining area of a basin, also named groundwater discharge area or, for short, the discharge area.

The concept of recharge-discharge areas is fairly recent, from around 1950, and was a result of efforts to simulate groundwater flow in a basin using a numerical model. Previously groundwater discharge was considered to take place only in springs. In the modern concept discharge takes place whenever the flow direction of groundwater has an upward component relative to the slope of the soil surface. During summer the discharge may not be visible because the upward groundwater flow is consumed by transpiring vegetation. Since this water contains more nutrients than rainwater, the vegetation in discharge areas usually displays a greater diversity than in a recharge area.

The importance of the recharge-discharge concept in finding ways to avoid groundwater contamination is obvious.

Soil erosion

Soil erosion was for a long time believed to be caused by overland flow, the frictional forces picking up soil particles and keeping them in suspension, all in analogy to processes in streams on sorted material. Field studies showed, however, that erosion by overland flow contributes less than 10 percent to total erosion. The reason for this is that overland flow is part of a so-called flash flood. During a flash flood water is still infiltrating, with excess water forming overland flow. Infiltration stabilises the surface, limiting erosion except in discharge areas where outflow destabilises the surface. Hence, an important factor is the actual moisture state. Major erosions appear to be gully erosions and small landslides, types that require high pore pressures in the aquifer, built up by excessive rainfall in the recharge areas.

The hydrochemical balance

The role of atmospheric deposition of salts and other substances is now well recognised, particularly in industrially developed regions. Processes in the ground such as chemical weathering, adsorption and ion exchange are also well understood. The circulation of nutrients from the root zone to plants and back to the soil has been studied thoroughly in recent years. A fairly complete picture of the processes taking place during the formation and flow of groundwater to streams can therefore be drawn. Water circulation itself also contributes to the concentration levels in the groundwater because of evapotranspiration.

In many regions the only source of chloride in the groundwater is the deposition of sea salts released particularly from breaking waves. In a steady state the rate of chloride deposition must be balanced by the discharge of groundwater chloride. By assessing the chloride deposition and the chloride concentration in groundwater a simple calculation will tell how much groundwater is accumulated yearly. This is particularly useful in semiarid regions where rainfall minus evapotranspiration is a small fraction of rainfall, so that it almost impossible to estimate it using conventional means.

Erik Eriksson

6.

PATHWAYS OF WATER IN NATURE

Allan Rodhe

Water in the ground

Rainwater or meltwater reaching the ground surface may either *infiltrate* into the soil or be diverted as *overland flow*. In humid forested areas, and also in many agricultural areas, the *infiltration capacity* of the soil is normally larger than the intensity of rainfall or snowmelt, making it possible for all water to infiltrate. The infiltrated water is to a large extent stored in the *soil-water zone* (also called the *unsaturated zone*), which is the soil layer between the ground surface and the groundwater table. The topmost part of the soil-water zone, the *root zone*, plays an important role in the future destiny of the water. Here it is decided whether the water shall *percolate* downwards or return to the atmosphere via the transpiration of the vegetation. Many of the chemical processes that transform precipitation water into groundwater take place in this zone. If the soil-water content is high enough, the pores of the soil will not be able to hold the water against the force of gravitation, and further infiltration will generate percolation towards the *groundwater zone* (also called the *saturated zone*). The groundwater level rises with the water input while the groundwater flow towards low-lying areas and watercourses increases. As a basis for an understanding of the above processes, and for applying them to different local conditions, this section will discuss the physical principles of water flow and storage in the ground (Figure 6.1).

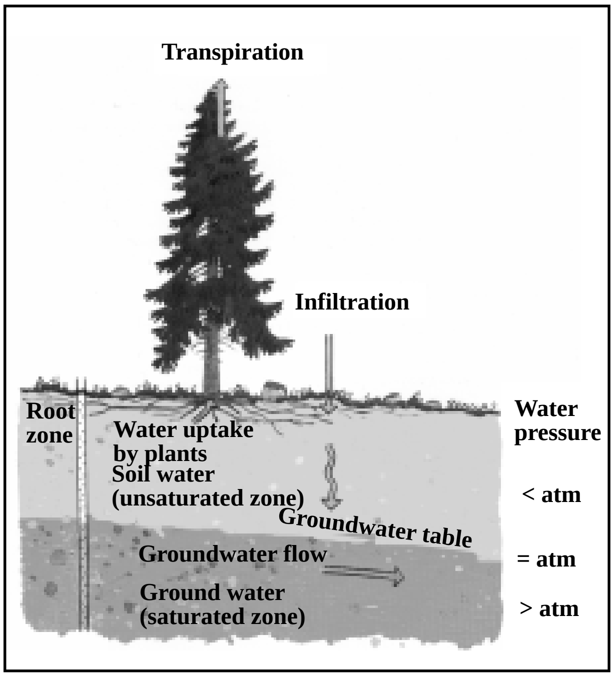


Figure 6.1. The soil-water and groundwater zones and their water flows.

In hydrology the *water content* of a soil sample is usually expressed as a volume fraction, i.e. as the volume fraction of water of the total soil volume, often expressed in percent. The *porosity* is the fraction of voids of the total soil volume. If you dig a hole in the ground, in a place where the loose deposits are sufficiently thick, you will eventually reach the groundwater. Unless the soil is very coarse, the groundwater zone will be reached without a noticeable distinct increase of the soil-water content. It is only when water starts to trickle out from the walls or the bottom of the pit that you know that you have entered the groundwater zone. The height of the groundwater table, on the other hand, is not seen until the water in the hole has been allowed to rise for a few hours or a day. The *groundwater table* can be defined in this way, as the level of the water in a hole or in a perforated tube inserted in the ground. Below the groundwater table, all the pore space of the soil is completely water filled and the water content is equal to the porosity. Above the groundwater table, in the soil-water zone, there is both air and water in the pores. Just above the groundwater table most pores are water filled and the soil-water content is near the porosity, but at higher levels the moisture content is lower and it varies over time depending on the water availability. In the root zone moisture variation during a year is particularly fluctuating, as a result of the combined effect of precipitation, transpiration and percolation.

Water is retained in the soil by adsorption to the soil particles and by capillary forces in the pores (Figure 6.2). Molecular forces between mineral and water cause *adsorption*. This force is strong

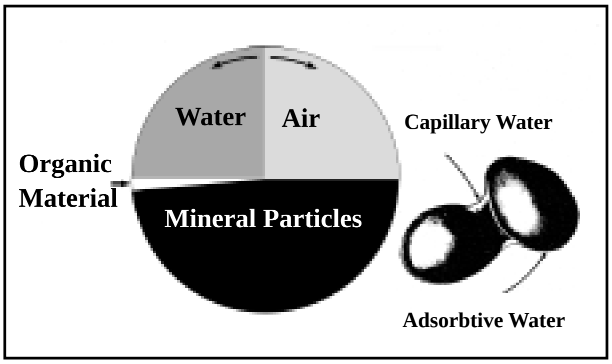


Figure 6.2. In a certain soil, each soil-moisture content corresponds to a certain negative pressure of the water. At a given pressure, all pores below a certain size are water filled. The lower the soil moisture content, i.e. the lower (more negative) the pressure, the smaller the size of the largest water filled pores. The radius of the largest water filled pore is given by $\psi = -0.15/r$ where r is the radius of the pore in cm, and ψ = the water pressure in cm water depth (<0).

but it reaches only over a very small distance, making the water held by adsorption a strongly retained but thin water film around the mineral particles. The very small mineral particles of a clay soil give a large total surface area per unit volume of soil, making a considerable volume fraction of water held by adsorption. In sand, the total surface area of the particles is very small and the water retention by adsorption is negligible.

Surface tension forces in the contact between mineral, air and water cause *capillary retention*. The smaller the pore, the stronger the retention force exerted in the pore. A prerequisite for the development of capillary forces is that there is both air and water in the pores. Capillary retention thus exists only in the soil-water zone but not in the groundwater zone. As a result of the retention, water in the soil-water zone exerts a tension, i.e. a negative pressure as compared to the atmosphere. At the groundwater table the pressure of the water equals that of the atmosphere, and below the groundwater table the pressure is positive. In order to extract water from the soil-water zone, a larger tension (a more negative pressure) than the one exerted by the pores has to be applied; water has to be sucked from the soil. This is the way the plants get their water, by developing a pressure in the roots that is more negative than that of the soil-water.

In a drying soil, the largest pores are the first to be emptied. Thereafter gradually smaller pores are emptied, and the remaining water is gradually more strongly retained. The ability of a soil to retain water can be described by the *soil moisture retention curve*, showing the water content at various negative pressures of the water. At saturation, i.e. when the water pressure is equal to or above that of the atmosphere, the water content equals the porosity. The coarser the soil, the more rapidly the water content decreases as the pressure becomes more negative. In a well-sorted soil, having many pores of the same size, the water content suddenly decreases at a certain pressure. In an unsorted soil, such as a till soil, the decrease takes place more gradually (Figure 6.3).

Two common concepts used in connection with water retention in the root zone are *the field capacity* and *the wilting point*. The field capacity is the water content after free drainage of a saturated soil. It is the highest moisture content the soil can hold against the force of gravity. The wilting point is the water content at which the water is retained so firmly that the plants can no longer take up water from the soil. The difference between the field capacity and the wilting point, constituting the amount of *plant available water*, is the maximum water storage the plants can rely upon during dry periods. During periods of abundant water input to the soil, the water content may exceed the field capacity. Water will then percolate towards the groundwater zone. After a time this flow will cease, as the water content reaches the field capacity. Further emptying of the water in the root zone will be mainly by the transpiration of the plants.

Two main forces, gravity and capillary forces, cause the flow of soil-water. The force of gravity strives to move water vertically downward, whereas the capillary forces strive to move the water towards regions with more negative pressure, i.e. from wet to dry regions of the soil. The water is sucked up

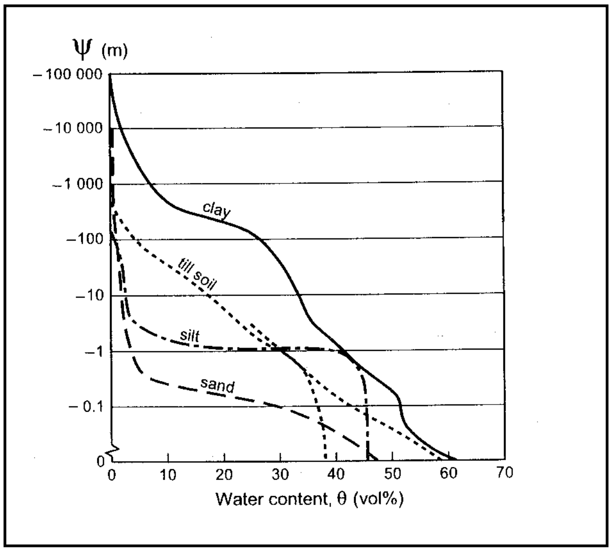


Figure 6.3. Typical soil moisture retention curves for different soil types. The water pressure, y, is given in m along the left y-axis. The shapes of the different curves are closely related to the pore size distribution. In the sand many of the pores are of the same (large) size, and they are drained at a fairly low suction – less than 1 m. Most pores in the silt have the same size and are therefore drained at the same suction. Till and clay have pores of widely varying sizes, so that water content decreases gradually over a large range of suction values (from Grip & Rodhe, 1994).

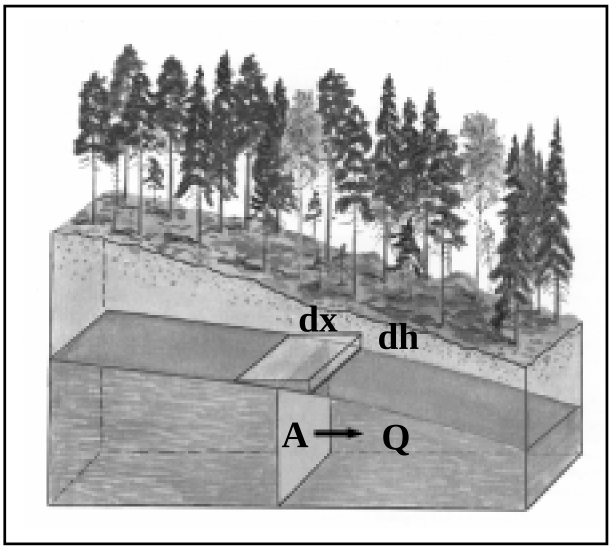


Figure 6.4. Darcy's law. The flow, Q, through a cross-section of the ground, A, is proportional to the cross-section area, A, the hydraulic conductivity, K, and the slope of the groundwater table, dh/dx (from Rodhe, 1997).

from wet to dry regions like the coffee in a lump of sugar partially inserted into one's cup. The capillary forces may act either upwards or downwards, depending on the vertical variation of the soil moisture pressure. If the surface layer of the soil is wetter than the deeper layers, for instance after a large rainfall, the gravitation and capillary forces work in the same direction and the flow is directed downwards. If the surface layer is dryer than the deeper layers, which is commonly the case, the flow may be directed either upwards or downwards, depending on which of the forces is dominant. When there is no vertical flow, the force of gravity is balanced by the capillary forces. Soil-water tension (the negative pressure of the soil water), expressed for instance as metre water height, then equals the height above the groundwater table.

In areas with shallow groundwater, the groundwater level may exert a considerable control over the soil moisture content of the surface layers. If there is no input (infiltration) or output (evaporation) of soil water, the vertical soil-water flow continues until an equilibrium condition is reached, with no flow and with the water tension at any level being equal to the height above the groundwater table. The groundwater level can be said to generate a negative pressure in the soil-water zone, emptying gradually smaller pores at increasing heights above the groundwater level. If drainage is dug so that it lowers the groundwater level, for instance, water is sucked from the soil-water zone. The more fine-grained the soil is, the higher the level above the groundwater table this influence will take place. The influence may reach a few decimetres above the groundwater table in a sandy soil and maybe one or two metres in a more fine-grained till soil. One consequence of this influence is that the water content of the surface layers normally increases downwards along a hillslope, as the groundwater table approaches the ground surface.

While soil-water movement is mainly vertical, upwards or downwards, the groundwater flow is mainly lateral, directed along the slope of the groundwater table. The groundwater flow can be described by Darcy's law, which, after a commonly used simplification (the Dupuit assumption), in one dimension can be written as

$$Q = -KA\frac{dh}{dx} \qquad (8)$$

where

Q is the groundwater flow (m^3/s),
A is the cross sectional area for the flow (m^2),
K is the hydraulic conductivity (m/s),
h is the groundwater level (m),
x is the distance (m), and
$\frac{dh}{dx}$ is the slope of the groundwater table (m/m).

This frequently used relationship states that the groundwater flow through a cross section of the ground is proportional to the slope of the groundwater table (Figure 6.4). The factor of proportionality, K, the (saturated) hydraulic conductivity, is a measure of the ability of the soil to transmit water. This ability increases rapidly with pore size, making the hydraulic conductivity for different soils vary within a wide range, from 10^{-10} m/s for non-cracked clay to 10^{-3} m/s for coarse sand.

It is comparatively easy to determine the direction of the groundwater flow. A first guess is that the flow largely follows the slope of the ground surface. More definite information is obtained from groundwater-level observations from at least three points. The levels can be determined as the water levels in perforated tubes inserted in the ground. When the three levels are known, the slope of the groundwater table can be determined and thus also the flow direction. It is much more difficult to determine the magnitude of the flow, since the variation of the hydraulic conductivity of natural soils is so large, even within a particular soil type. A few large pores, cracks or a thin layer of coarse material can cause a dramatic increase in the hydraulic conductivity and thus of the groundwater flow.

Darcy's law, in a slightly different form than the one above, is also used for soil-water flow. Now the conductivity, the so-called *unsaturated hydraulic conductivity*, is no longer constant but varies with the soil-water content. Since it is the large pores that are the first to be emptied in a drying soil, and since these pores have made the largest contribution to the flow, the conductivity, and thus the flow, decreases rapidly as the water content decreases.

In a structured soil there may be a system of interconnected, relatively large pores that can transmit water much more rapidly than the soil matrix. Such *macropores* may account for a large fraction of the flow through a cross section. Macropores may derive from biological activity (earthworms, burrowing animals, plant roots etc.) or mechanical activity (drying/wetting, freezing/melting), which creates, cracks and fissures in the soil. A prerequisite for a macropore to be able to conduct water is, of course, for the pore to contain water. In the groundwater zone all pores are water-filled. Interconnected macropores will then conduct water very efficiently and to a large extent determine the hydraulic conductivity of the soil. In the unsaturated zone, on the other hand, the contribution to the flow and solute transport by macropores is not that certain. In a dry soil, the large pores are empty and do not contribute to the flow. At a moderate rate of water input to the ground surface, the pores will rapidly be emptied since the water is sucked into the drier surrounding soil. But at large rates of water inflow and/or small saturated hydraulic conductivity of the soil matrix, saturated or near saturated zones may build up around the pores, which then can remain water-filled and make a large contribution to the flow.

So far the water flow in the soil has been discussed in terms of discharge, i.e. volume per time unit (m^3/s). When it comes to the velocity of soil water and groundwater, we need to distinguish between three concepts, all having the dimension of velocity.

The *Darcian velocity*, sometimes misleadingly just called the velocity of groundwater, is not actually a velocity. It is the flow rate per cross-sectional area of the ground (Q/A in Equation 7), i.e. $(m^3/s)/m^2 = m/s$.

The *particle velocity*, on the other hand, refers to the transport velocity along a distance through the soil of an imagined water particle as seen on the macroscale. This velocity determines the time needed for a dissolved chemical compound, not reacting with the soil, to be transported a certain distance. In the soil-water zone the water normally moves slowly, with particle velocities of around a few metres per year. If macropores are contributing to the flow, the movement can, however, be very rapid. In forested till soil the particle velocity of the groundwater is typically on the order of 0.1 m/day at some depth and perhaps 1 m/day close the ground surface. In fractured rock, particle velocities of up to 10 m/day have been observed.

The *pressure propagation velocity* is the velocity, by which a flow change is propagated, determining, for instance, the time lag between infiltration and the rise in groundwater level. The pressure propagation velocity is much larger than the particle velocity (which in turn is larger the Darcian velocity). The groundwater table can start to rise after an hour while it may take months for the infiltrated water molecules to reach the groundwater. When the tap to a filled garden hose is opened, the outflow starts practically immediately (determined by the pressure propagation velocity), while it takes some time before the water molecules that were let into the pipe when the tap was opened begin to flow out (determined by the particle velocity).

Subareas with different functions

The landscape in the northwestern half of the Baltic Sea basin (Sweden, Finland and a part of Russia) is dominated by forested till soil on fractured gneiss or granite. The hydraulic conductivity of the deeper till soil and the bedrock is comparatively low. In order to transmit the groundwater formed by precipitation down to the watercourses, almost the whole soil layer has to be used for the groundwater flow. For this reason, the groundwater zone reaches close to the ground surface. In elevated areas, the depth to the groundwater table may be a few metres and when going downhill, the groundwater table gradually approaches the ground surface. Wetlands and watercourses develop in areas where the groundwater table reaches up to or above the ground surface. Even if the depth to the groundwater table thus varies slightly, it will largely follow the topography of the ground surface, since the height variations of the landscape are much greater than the depth variations of the groundwater table. The undulating groundwater surface results in a characteristic flow pattern for groundwater, with *recharge areas* for groundwater in elevated areas and *discharge areas* in certain low-lying areas (Figure 6.5 and Table 6.1) In recharge areas, where groundwater is formed, the flow is partly directed vertically downwards. In discharge areas the flow is partly directed upwards, towards the ground surface. The discharge areas normally constitute a minor part of the catchment. The areal extent of discharge areas is highly variable, expanding with rising groundwater level. During dry periods the discharge area may be comprised only of the stream itself and some permanently wet areas.

A common finding in Nordic till soils is that the hydraulic conductivity increases drastically towards the ground surface in the top few metres of the soil. Several processes contribute to this increase: biological activity (plant roots and small animals), repeated freezing and thawing of the soil,

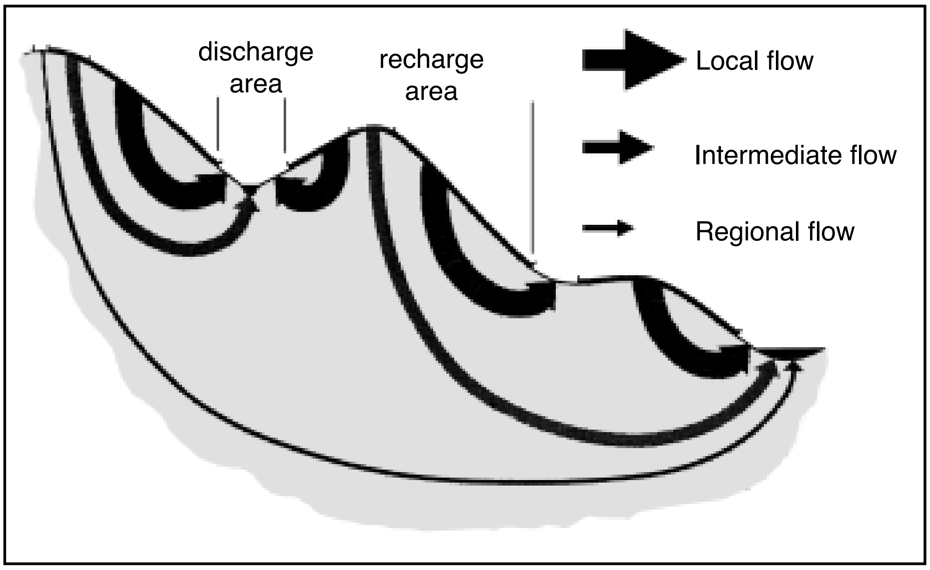


Figure 6.5. Flow systems for groundwater. The greater part of the groundwater flow takes place in the local system, with the water discharging into the nearest downhill discharge area. The deeper below the ground surface and the more downhill the landscape one goes, the older the groundwater may be and the more distant its origin (Grip & Rodhe, 1994).

chemical weathering, and less compaction by overburden than deeper layers. If the surface layers are very conductive, the groundwater table may not reach the ground surface in the discharge area. The discharging groundwater is diverted laterally below the ground surface. A discharge area may thus be saturated or unsaturated to the ground surface.

The subdivision of the landscape into recharge and discharge areas is very useful for an understanding of physical and chemical water conditions in general and for forecasting the effects of various human activities. Forest clear-cutting in a recharge area, for instance, increases the groundwater recharge. The groundwater level rises and the discharge area expands with increased risk of waterlogging in low-lying areas. Polluting substances released into the ground surface in a recharge area, such as leakage water from a waste disposal plant, may on the one hand be able to degrade through microbiological activities in the soil-water zone and become diluted during the subsequent flow with the groundwater to the discharge area. On the other hand, they can pollute the groundwater of a large area. Polluting substances released in a discharge area will affect the groundwater in a small area, but they may be transported to surface water without substantial degradation and dilution.

Information on the wetness conditions can, of course, be obtained directly from measurements of soil moisture or of the groundwater level or by just looking around in the terrain. The water surfaces of wetlands, streams and lakes represent local minimum levels of the surrounding groundwater table. A shallow groundwater surface can also be observed directly as the water level in tractor tracks or in pits under stones or in holes left by trees blown down by the wind. Good information can also be obtained from a topographic map. The wetness at a certain location depends on the relation between the amount of water inflow and the ability of the ground to transmit water downhill. In concave, bowl-formed landscape forms, discharge areas or areas with shallow groundwater and high soil moisture content are often formed. Such areas have a comparatively large local catchment area, furnishing a large groundwater inflow. At the same time the slope decreases when going downhill, reducing the ability of the ground to transmit the water coming from uphill. In a similar way convex hillslopes will be dry, with no or small discharge areas (Figures 6.6 and 6.7).

Naturally geology plays a decisive role in determining the soil wetness and the depth to the groundwater table. Under similar topographical conditions, the groundwater table is normally deeper and the discharge areas smaller the more conductive, i.e. the coarser, the soil. A thin layer of a highly conductive soil may be enough to transmit the groundwater coming from uphill, so the groundwater table does not have to rise to near the ground surface. In coarse and highly conductive soil, the groundwater level is often determined by less conductive thresholds downstream or by the level of the surrounding watercourses. In addition to the difference caused by the comparatively large hydraulic conductivity of the coarse soil, the water retention capacity is smaller in a coarse soil than in a fine-grained soil (less soil moisture content at field capacity), yielding lower soil moisture content and thus drier surface layers.

Table 6.1 Schematic table over the flow systems of groundwater (from Grip & Rodhe, 1994)

Scale	Depth (m)	Length (km)	Transit time (year)
Local	1	0.1	1
Intermediate	10	1	10
Regional	100	10	1 000

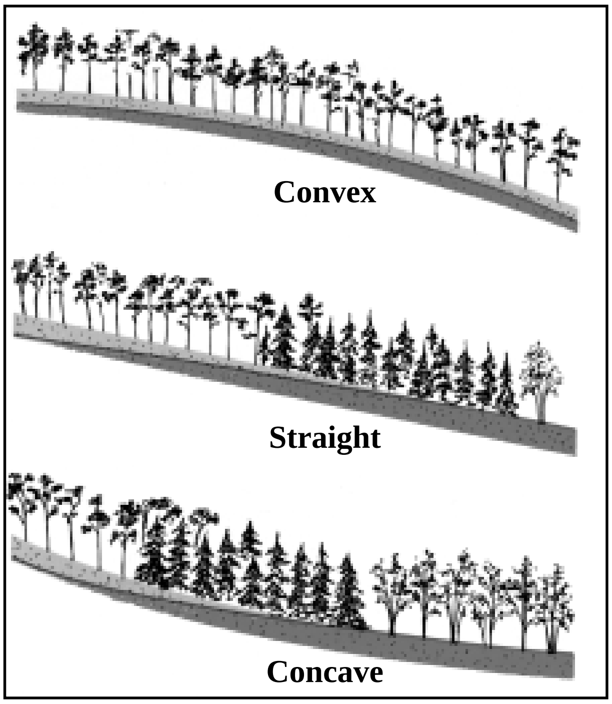


Figure 6.6. The extent of the saturated discharge areas, and of the soil wetness in general, is closely related to the topography. Three idealised situations are illustrated. If the whole soil depth is used for groundwater flow, the slope of the groundwater table cannot exceed that of the ground surface. In the convex slope, the slope of the ground surface increases down slope, increasing the capacity of the soil to transmit the groundwater formed upslope. In the concave slope, where the slope of the ground surface decreases downhill, the point at which the groundwater flow from above equals the maximum possible flow is met shortly. The groundwater zone reaches the ground surface and the saturated discharge area is large (from Grip & Rodhe, 1994).

Streamwater - mostly groundwater

As has long been known, rainfall or snowmelt causes flow events in streams. But the water flowing in the stream may well be dominated by groundwater, i.e. precipitation water that has infiltrated into the soil and remained in the ground as soil water and groundwater for a long or short time. As mentioned earlier, the infiltration capacity of the soil is normally sufficiently large for all rainfall or snowmelt on recharge areas to infiltrate. If the soil is wet and the groundwater table shallow, the groundwater level will rise rapidly (with a delay depending on the pressure propagation velocity), increasing the groundwater outflow to discharge areas and directly to the watercourses. This increase is caused partly by an increased slope of the groundwater table and an increased thickness of the groundwater zone, enlarging the cross-sectional area for the flow. But the main reason for the increase of the groundwater flow is that surface-near soil layers, having very high hydraulic conductivity, start to contribute to the flow. Precipitation on saturated discharge areas cannot infiltrate, but runs off as overland flow together with the out-flowing groundwater. The stream water is thus a mixture of "new" rain or meltwater on saturated discharge areas (including the stream itself) and more or less "old" groundwater that has been pushed out of the ground by the infiltrated new rainwater. The new rainwater may have partly formed this groundwater, but the greater portion is normally water that was stored in the catchment before the rainfall or snowmelt.

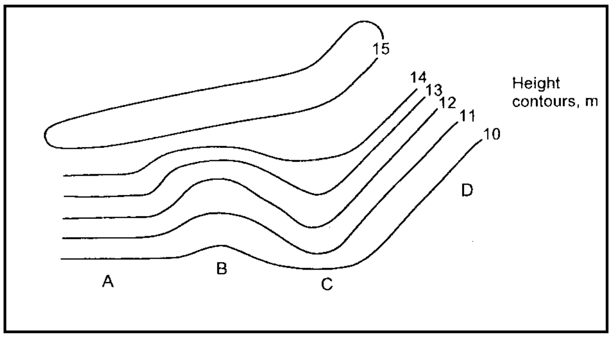


Figure 6.7. A topographic map showing various parts of a hillslope with different wetness conditions at its foot. Part B is the wettest (hollow), followed by part D (concave), part A (straight) and part C (ridge), which is driest.

Overland flow generated on saturated discharge areas is called *saturation overland low*, to be distinguished from so-called *Hortonian overland flow*, which may occur in recharge areas if the infiltration capacity of the soil is exceeded by the intensity of rainfall or snowmelt. Hortonian overland flow, named after the pioneer American hydrologist Robert E. Horton, may be an important part of the runoff process in non-vegetated or sparsely vegetated land, particularly in semiarid areas. In humid temperate areas, such as the Baltic Sea basin, a good number of isotope studies have shown that the stream response to rainfall or snowmelt is indirect, with the runoff events dominated by old (pre-event) water. An example of such a result from a small catchment in southwestern Sweden is shown in Figure 6.8. The dominance of old water shows that the traditional view of stream-flow generation, with runoff events caused by overland flowing rainwater, is not valid. The exact nature of the mechanism by which the groundwater outflow to streams responds to rainfall or snowmelt input, however, is not known. The view sketched in this section, based on the drastic increase of the hydraulic conductivity towards the ground surface, has been developed from observations in Nordic till soils. In areas with other geological conditions other mechanisms may be acting.

Water may also infiltrate in frozen soil

A prerequisite for old water to dominate the storm runoff of streams is that the infiltration capacity of the soil must exceed the intensity of rainfall or

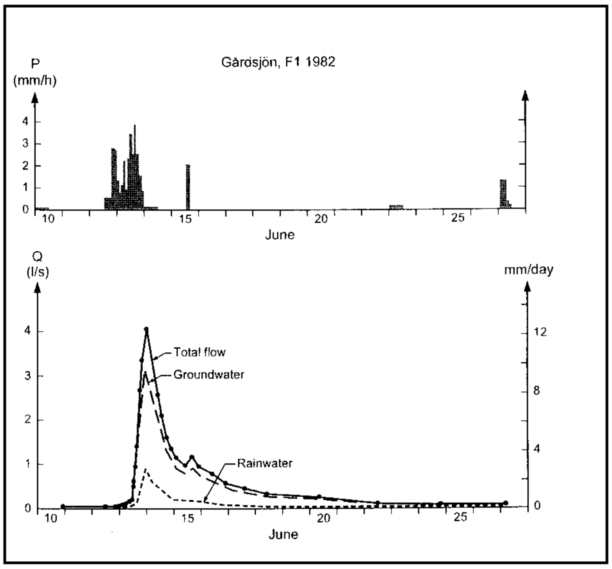


Figure 6.8. Stream hydrograph separated into flows of pre-event water (groundwater) and event water (rainwater) by the stable environmental isotope oxygen-18. Temporal variation in the natural oxygen-18 content of precipitation creates a "signature" of the water precipitating over a catchment at different occasions, making it possible to estimate the fraction of "new" and "old" water in the runoff. The runoff event (Q) is a response to a precipitation event (P), but only a small portion of the streamflow actually comes from the precipitation associated with the event (event water). The largest portion consists of "old" groundwater (pre-event water), released from the catchment during the event (from Rodhe, 1987).

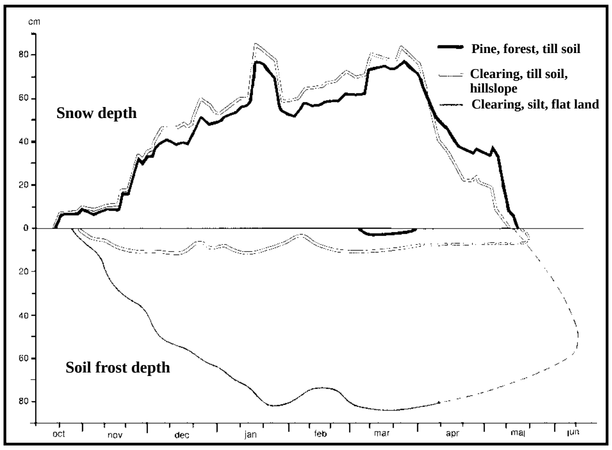


Figure 6.9. Snow depth and soil frost depth at different locations within the Svartberget experimental area in Vindeln, northern Sweden, during the winter of 1982/83. The ground in the forest remains unfrozen during practically the whole winter. Different topographic and soil-water conditions are the reasons for the difference in frost depths between the two open areas. The flat, silty ground clearing is cold due to the collection of cold air from the surrounding area. It also has a comparatively deep groundwater table, yielding low soil moisture content (from Grip & Rodhe, 1994).

snowmelt. But what happens when the soil is frozen during the snowmelt period, which is often the case in a large part of the Baltic Sea basin? The discovery that snowmelt events are also dominated by old water motivates a discussion of soil frost and its effect on the infiltration capacity.

In many places snowmelt occurs on a soil in which the upper layers are temporally frozen. In a frozen soil the water is partly frozen, reducing the pore volume available for liquid water flow. The infiltration capacity of a frozen soil is therefore smaller than if the soil was unfrozen, but the infiltration capacity may still be large enough to allow all meltwater to infiltrate.

The occurrence of seasonal soil frost at a particular site may vary considerably from year to year and there may be large areal variations within a catchment. The heat loss at the ground surface, which is significant when the air temperature is low and the net radiation negative, compels the growth of the frost. Both air temperature and net radiation may vary considerably at the micrometeorological scale. The forest canopy, for instance, reduces the radiation heat loss from the ground surface, so that there may be little or no soil frost in the forest but a considerable frozen layer in a nearby open field or clearing. Snow is a poor heat conductor and effectively reduces the heat loss from the ground surface, thus reducing frost growth. A snowfall of a few decimetres of snow on a bare soil may stop the frost growth or, in some cases, even cause the frost to start melting through the heat flow from the ground below. Apart from meteorological conditions, the frost depth depends on the water content of the soil. The more water in the soils, the more heat that has to be conducted away to freeze a certain layer and the slower the subsequent thickening of the frost. This relationship is reflected by differences in frost depth in soil with different textures. The greatest frost depths are thus found in coarse soils, which, due to their restricted water holding capacity, normally have the lowest water content at freezing. Figure 6.9 shows an example of the development and melting of soil frost in three different locations within an experimental area in northern Sweden.

The process of freezing is in some ways equivalent to the drying of a soil. The water in the largest pores freezes first, decreasing the pressure of the remaining water and thereby lowering its freezing point. In a soil that is saturated at the time of freezing, the hydraulic conductivity falls drastically after freezing. Although some liquid water remains that is able to conduct water, it is the large pores – which would provide the largest contribution to the conductivity – that are frozen. Snowmelt infiltration, on the other hand, normally takes place in soils that were unsaturated at freezing. Depending on the water content at freezing there may or may not be a sufficiently large open pore space to allow the meltwater to infiltrate. If freezing in the autumn starts directly after a heavy rainfall, the infiltration capacity of the frozen soil may be small and Hortonian overland flow may occur the next spring. But if the same soil freezes at lower water content, all meltwater may well infiltrate.

It is thus not the frost depth, but the water content of the upper soil layers at the time of freezing that determines the infiltration capacity. Since the water content of the upper soil layers to a large extent is governed by the topography, we can expect the most permeable frozen soil on ridges and the upper parts of the hillslopes. All meltwater may infiltrate in such areas, whereas Hortonian overland flow may be generated on frozen areas in the lower parts of the hillslopes, where the water content at freezing was high due to a very shallow groundwater table. During snowmelt periods with repeated melting and freezing, particularly in connection with large rainfalls on the melting snow, concrete ice could form on the ground surface. Such ice, often occurring in agricultural land, is impermeable and generates overland flow.

7.

GROUNDWATER HYDROLOGY

Erik Eriksson & Sivert Johansson

Introduction

The circulation of water in a hydrologic basin area can be illustrated in a conceptual box model as in Figure 7.1. Two boxes represent the soil, which is taken to be the so-called root zone below the earth's surface. The left box in the figure represents *groundwater recharge areas* of a catchment, where the groundwater is formed. The rate of formation is simply precipitation minus evapotranspiration. This water then flows through the unsaturated zone, between the root zone and the saturated zone, which constitutes the groundwater proper, i.e., the *aquifer*. From there water flows through soil and rock and finally enters the *groundwater discharge area* through the second root zone. In the field it is often easy to notice where the groundwater discharge begins because of the changes in plant species. In a forest the discharge zones bring lush undervegetation.

The discharge areas, too, receive water from the atmosphere and lose water by evapotranspiration. This water is thus a rather mixed concoction, forming what are commonly called surface waters, i.e., streams, rivers and lakes. Precipitation falling on peat land, particularly bogs, is also surface water, which joins the other categories at the final destination, the ocean or the sea.

As discussed in the previous chapter, the ratio of recharge areas to discharge areas is closely related to the topography and to the geological conditions. A system of medium scale ridges will show large ratios since discharge areas are concentrated to the narrow valleys between the ridges. Figure 6.5 shows a generalised flow pattern in relation to the groundwater level in an undulating topography. Due to seasonal variations in precipitation and evapotranspiration there are large seasonal variations in the rate of groundwater recharge, which has a seasonal variation similar to that of stream runoff. The discharge areas expand and contract during the year following the variation in the rate of groundwater recharge.

An increase in recharge area will be equal to a decrease in discharge area. The change in the discharge area can also have effects on the groundwater quality, as will be discussed later.

Extraction of groundwater will affect the local pattern of recharge/discharge since a cone of depression is formed in the groundwater table. This is important in a discharge area where a lowering of the groundwater table could create a local recharge of surface water that is of less desirable quality.

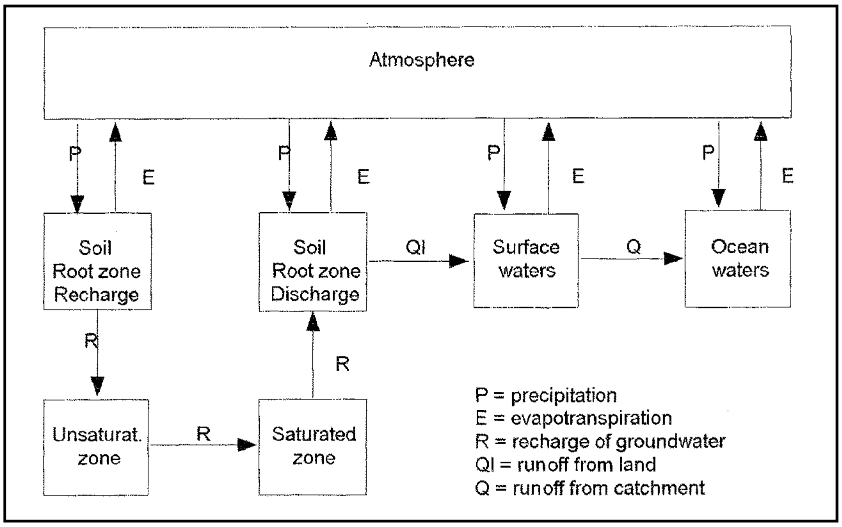


Figure 7.1. Box model representation of the hydrologic cycle. Note the distinction between groundwater recharge and discharge areas.

Groundwater storage

Water in the ground below the soil surface is usually described as soil water in the unsaturated layer, above the groundwater surface below which water can be extracted by lifting. The groundwater domain is usually divided into aquifers separated if necessary by aquitards. An aquifer is a relatively homogeneous part of the groundwater, in particular regarding extraction of groundwater. An aquitard is a low conductivity layer.

There are by definition two types of aquifers. A phreatic

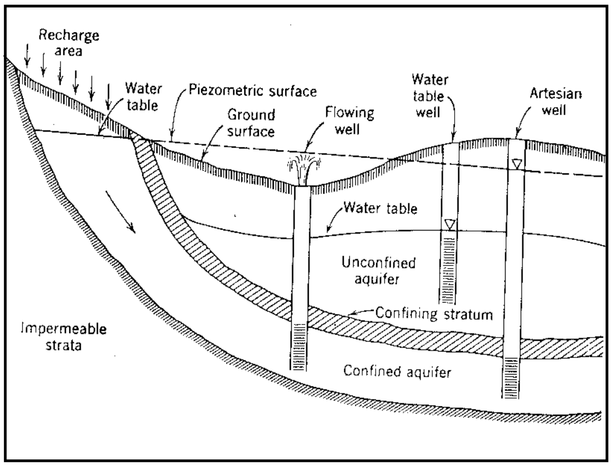


Figure 7.2. Phreatic (unconfined) and confined aquifers separated by aquitard (Todd, 1959).

aquifer is physically in contact with the atmosphere through the groundwater surface, which usually varies in level depending on the inflow rate of water from the unsaturated zone. The second type is the confined aquifer where the upper limit borders a layer that is impermeable to water, such as a clay layer or fine-grained shale. In a confined aquifer the hydrostatic pressure exceeds that of a phreatic aquifer at the same elevation. This excess in pressure is sometimes referred to as an artesian condition. A drilled well will cause a spontaneous outflow of water. Figure 7.2 shows the two different kinds of aquifers. Here, the phreatic aquifer is designated unconfined. The confining stratum is an aquitard.

Extractable groundwater is found at great depths according to Kulikov & Vartanyan (1984). Fractures are found at 4.5 km and groundwater at this depth behaves in the physically expected way. Groundwater below a 4.5-km depth behaves differently. Even though fractures disappear water in boreholes still seeps into the borehole.

The water at great depths becomes very salty and is hardly of any use as freshwater. A practical depth limit for extracting freshwater is probably a few hundred meters.

Aquifers can be categorised by their porosity, by which is meant the fraction of space not filled by solid matter. In phreatic aquifers the effective porosity is the space from which water freely drains during extraction. Effective porosity is lower than porosity.

In confined aquifers the extraction of water is possible through compression of the pore water space. This happens automatically when the hydrostatic pressure is decreased by extraction of water. The amount of water obtained per unit area by lowering the internal hydrostatic pressure one unit constitutes the specific yield, which is comparable to the effective porosity of phreatic aquifers.

A common situation is a phreatic aquifer existing below the unsaturated zone that borders on an aquitard and then, below this, a confined aquifer. Such a situation may occur when two chalk layers are separated by shale. Because the aquitard conducts groundwater, albeit slowly, the whole system – phreatic aquifer, aquitard and confined aquifer – will be in hydrostatic equilibrium. However, if water is then extracted from the confined aquifer the hydrostatic pressure will be decreased. This causes an immediate compression of the pore space in order to maintain the previous steady state. If the extraction stops a slow flow through the aquitard sets in to recreate the original pressure conditions. This recovery is a slow process compared to the compression rate. The confined aquifer therefore appears as leaky, which can be detected by analysing pump test data.

A phreatic aquifer can be operated as a sustainable source for water by adjusting the extraction rate to the recharge rate. A completely confined aquifer cannot be recharged. Thus the extraction of water in such a case is equivalent to mining. A leaking confined aquifer, sometimes referred to as a semi-confined aquifer, will always be recharged naturally and is thus a sustainable source of water. But extraction must be adjusted to the leakage rate of the aquitard, not to the infiltration rate of the upper phreatic aquifer.

Aquifers in Quaternary deposits

These aquifers are common in Scandinavia and Finland and are as a rule shallow. There are two major types: glacial till and glaciofluvial deposits.

Glacial till (moraine)

Glacial till forms to a considerable extent in the old basement rocks granite and gneiss. It is usually sandy/silty and appears as overburden on the basement rock. Glacial till at altitudes below the highest marine limit (HML) at the end of glaciation was eroded to a considerable extent by wave action as the land emerged from the sea. The fine material, clays of various kinds, settled in the system of bays that emerged during the postglacial period.

Glacial till holds a wide assortment of particle sizes, from boulders to clay minerals. When the sand fraction dominates, the till is capable of acting as a fair phreatic aquifer. The thickness of the till layer varies considerably. The effective porosity is usually fairly low, less than 5 percent, so the effective storage capacity may be of the same order as the yearly recharge. The aquifers are therefore very sensitive to the occurrence of dry years. Water in these aquifers is usually obtained from dug wells and may well serve the needs of a family in rural areas.

Glacifluvial deposits

Prominent to this category are the eskers that were formed as tunnels at the end of the last glaciation. A classical esker is a ridge on the basement rock, winding its way, sometimes dipping into postglacial sediments. The centre of the esker is made up of very coarse material – boulders, stones and coarse gravel – surrounded on its sides and top by gravel and sand ending in still finer sediments like silt and clay. Wave erosion during the sea retreat wore down the top, leaving layers of coarse sand on the sides, which sometimes spread some distance from the esker. There is no preferred flow of water along the esker. Frequently groundwater can cross an esker. The storage capacity for water is usually high, which make eskers particularly important as water sources for towns and cities. Groundwater turnover time is a matter of decades. Extraction of groundwater enlarges the recharge area considerably, which has sometimes led to underestimates of their sustainable yield.

Second most important after eskers are the numerous sandy river sediments along flood plains and in coastal areas. When extraction of water takes place near the river it induces recharge flow from riverbanks or, in shallow rivers, from the bottom sediments. The same applies to extraction of groundwater near fresh water lakes.

Aquifers in sedimentary rocks

Sandstone in this category has usually considerable porosity for storage. Some of these aquifers may be semi-confined, i.e., leaky confined aquifers. Chalk deposits and calcareous sandstones have high porosities. Karstic limestone has porosity concentrated in galleries of solution cavities. Highly fractured limestones also make excellent aquifers, partly because the fractured surface allows rapid infiltration with small evapotranspiration losses.

Fractured basement rock

The fracture system in hard rocks often forms a network of fracture zones, which are excellent collection sites for groundwater extraction. Water yield can

ARTIFICIAL RECHARGE OF GROUNDWATER

A common way of increasing the extraction rate of an aquifer is to first increase the infiltration rate by adding water from a surface water source. For an esker the addition may be made by means of a pond on the ridge in such a way that added water is forced to pass through several meters of unsaturated soil before it enters the groundwater body. A biological filter is apparently created containing bacteria that consume the organic matter normally present in surface water. Suspended matter is removed at the bottom of the pond through a sand filter.

Where water extraction takes place from a well near a river, bank infiltration is induced by water extraction and the sandy medium acts as a filter for inflowing water.

Infiltration of water can also be created by adding water to extraction wells for certain periods while extracting it during the rest of the time. This may be practised if the quality of the added water is adequate for its intended use and does not clog the screen of the well. In practice this method has been used for temporary storage of water.

A very special recharge arrangement has been developed called the WYR method. It is quite common that groundwater contains ferrous iron due to reducing conditions during the recharge of groundwater. According to the WYR method theory, injecting well-oxygenated water at points around a circle at some distance from the extraction well will prevent the transport of ferrous iron into the extraction well. This water would mix with the oxygen deficient water on its way to the production well. In practice, mixing the oxygen deficient with the oxygen-rich water caused precipitation of the iron as ferric hydroxide, or oxyhydroxide. The effect was surprisingly high, about twice that expected from the concentrations of ferrous iron and oxygen. It can, however, be explained as the result of additional adsorption of ferrous iron into ferric hydroxide until it is converted into a composition similar to that of magnetite. The method might be practical in cases where ferrous iron concentrations are relatively low but still high enough to be a nuisance. The formation of ferric hydroxide would even be advantageous in cases where heavy metals exceed quality criteria since ferric hydroxide is a very effective adsorbent for various metal ions.

be considerable. Fractured granite is most favourable as an aquifer while quartzite is usually fairly compact with low porosity. Rocks rich in heavy minerals (iron-magnesium minerals) are less brittle and not prone to fractures.

Darcy´s law

Practical groundwater flow modelling and calculations are based on Darcy´s law, discussed in previous chapter (Equation 8). It states that the groundwater flow is proportional to the slope of the groundwater table, with the constant of proportionality being K, the hydraulic conductivity. The hydraulic conductivity expresses the ability of a unit cross section area of the ground to transmit water. It is a key parameter in groundwater flow modelling. Since the hydraulic conductivity normally varies largely over depth an integrated value of the hydraulic conductivity, the transmissivity, is often used. This entity, which can be determined from pumping tests, expresses the ability of a unit width of the aquifer to transmit water. Mathematically it is given by

$$T = mK$$

where T is the transmissivity (m^2/s), m is the thickness of the groundwater zone (m), and K is the vertical mean value of the hydraulic conductivity (m/s).

Groundwater investigation methods

Two groups of methods can be regarded as main approaches to groundwater investigation: surface investigations and subsurface investigations. However, before using any of these methods, a groundwater investigation always starts in collecting and analysing all sources of information. Of course, the first issue that needs to be addressed is the groundwater demand, i.e. the quantity and the quality needed in each case. The primary sources are meteorological, hydrological and geological data. Topographical, geological and hydrogeological, if available, maps and even available maps on evapotranspiration and surface runoff provide valuable information for further investigations.

From the topographical maps it is possible to determine the surface water divide, which often but not always coincides with the groundwater divide. This circumstance might cause problems in groundwater investigations, as the area of infiltration into a planned well can turn out to be smaller or larger than estimated, which will affect the available yield. If the aquifer is bigger than expected some parts with inferior water quality may be activated and drawn to the well during pumping. Small-scale topography in combination with the geology of the area gives an indication of the infiltration for recharging the groundwater.

In some cases aerial and/or satellite photographs can be used for the analyses. Hydro-meteorological maps are usually obtainable from the meteorological offices. What should be stressed concerning such data is that the longer the series of observation, the better is the result that can be obtained. The degree of reliability is much higher with mean values from many years of observations. A source of information of the highest dignity is one of the databases established by the national geological surveys, the Academies of Science or the environmental authorities. These databases often contain information on surface and groundwater.

One type of information that should be given high priority is data on the physical and chemical properties of the water, since these will reveal properties that make it possible to distinguish between surface water and groundwater. Furthermore, hydrochemical data can be used, e.g. estimates of groundwater formation and models of groundwater flow. Taken together this will provide a good basis for the next steps in the groundwater investigation.

Surface investigations

Surface topography

Even when geological and topographical maps are available, it may be necessary to undertake complementary mapping, especially if the scale of the maps is so large that it makes it difficult to gather all the needed geological information or to use the maps as the basis for planning further activities. For example, a rather small (in terms of total area) geological formation can be of interest from both a hydrogeological and geological point of view. In order not to lose this vital information, the formation must be presented on a larger scale map or, due to scale problems, the presented area must be enlarged for printing reasons to be readable at all. In the case of groundwater hydrology the area of infiltration is of utmost importance and any errors in this will lead to miscalculations.

A special type of geological mapping can be used in areas with shallow earth layers and with outcropping crystalline or metamorphic bedrock, a rather common type of geology in Norway, Sweden, Finland, north-western Russia and in some parts of Poland, Czech Republic and Slovenia. The available groundwater in thin earth layers may not be sufficient even for single households and water may need to be supplied from the bedrock. The original porosity of this type of bedrock is very low, often less than 3%, and most of the water emanates from the secondary porosity created by tectonic activity that has

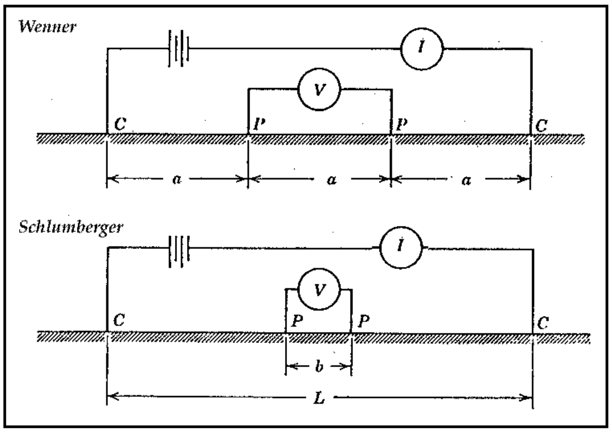


Figure 7.3 Common electrode arrangement for resistivity measurements (Todd, 1959).

formed fracture zones. Even chemical weathering and frost activities can contribute to this porosity. A survey in such a region performed by a bedrock geologist, who analyses the tectonic pattern, can point out fractured zones and the open bigger cracks, which are able to yield sufficient groundwater (I. Larsson, personal communication).

Geophysical measurements

For direct surface investigations there are a number of geophysical methods that can be applied depending on the prevailing geology, the size of the investigation area and the demand on groundwater quantity. Geophysical explorations are scientific measurements of physical properties of the earth's crust and detect differences, or anomalies, in these. The results can then be interpreted in terms of geologic structure, rock type and porosity, water content and water quality (Todd, 1959). Originally most of these methods were developed for locating petroleum and mineral deposits, which then led to further development and refinement of both methods and equipment. Society's increasing demand for water in the last few decades has led to a development where these methods are now in common use in groundwater investigation.

Over large areas and under certain geological conditions airborne geophysical measurements may be used. RAMA measurements (RAdioMAgnetic) use radio signals from a VLF-transmitter (very low frequency, 15-20 kHz). These radio waves penetrate very deeply into the ground and if they hit conductive bodies, secondary waves are emitted by induction. These inducted waves are recorded as anomalies and are presented on a so-called RAMA-map. The anomalies can be power lines, railroads, ore bodies or steeply dipping groundwater-bearing major fracture zones. These latter can supply substantial amounts of water. An interpretation, of course, requires good knowledge of the bedrock geology of the area. The same geophysical method can be used on a smaller scale on the ground by measuring the VLF-resistivity along a profile, where the groundwater level can be detected. The penetration depth depends on the resistivity in the soil layers, which will be changed in the presence of groundwater. This method may also make it possible to determine the interface between fresh and saline water, which can be of great interest in coastal zones, for instance if an overdraft of fresh water has occurred resulting in salt water intrusion (Mullern & Eriksson, 1981).

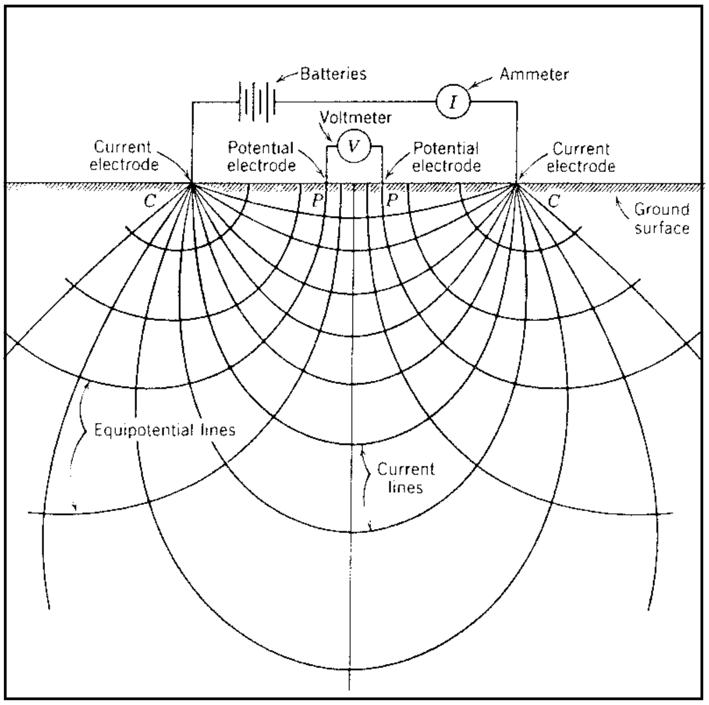


Figure 7.4 The electric field generated and measured by these arrangements (Todd, 1959).

The electrical method

Among the most commonly used surface geophysical investigation methods is the electrical method. It can be carried out by measuring either conductivity or resistivity, with or without an external electricity source. Measurement of the earth resistivity in the ground between two electrodes in an artificially created electrical field is the method most commonly used. The two potential electrodes are placed between two current electrodes on a straight line (Figures 7.3 and 7.4). By changing the spacing between the electrodes a new electrical field will be formed. Increasing the distance will yield a deeper penetration into the ground. The results are affected by, e.g. porosity, water content and water quality, especially salt content. This means that both

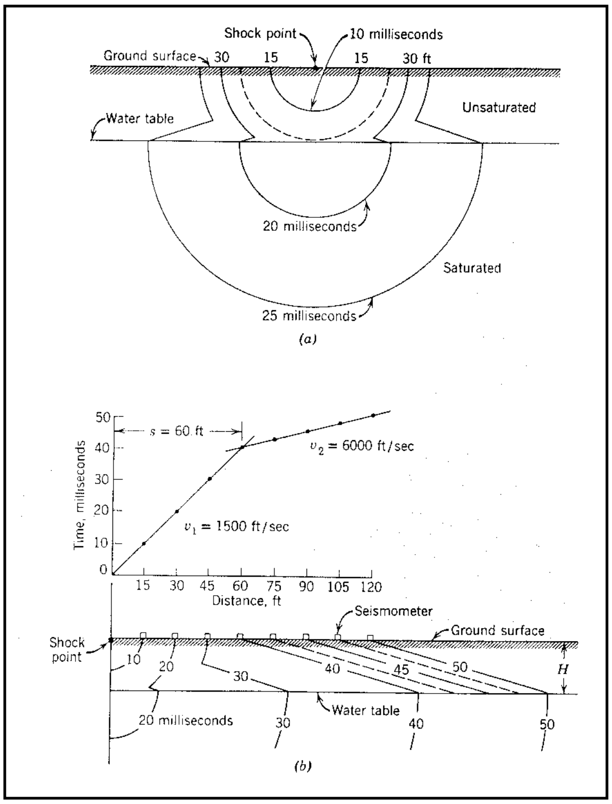


Figure 7.5 Seismic refraction method applied for determination of depth to groundwater surface (Todd, 1959).
(a) Wave front advance (b) time-distance graph.

VLF resistivity and earth resistivity measurements, in addition to groundwater investigation in general, are good tools for detecting saline water or seawater intrusion and for mapping out the interface between fresh and saline water. Another application of this method is to locate seepage loss areas along canals.

Seismic methods

Seismic methods, as with many other geophysical investigations, were developed and refined for use in prospecting after oil or ore bodies. There are two seismic methods, refraction and reflection, both based on the same physical principle. Sometimes refraction seismic can be seen referred to as “shallow seismic.” Seismic waves follow the same laws of propagation as light rays and may be reflected or refracted at any interface where a velocity change occurs. (Todd, 1959).

By creating a small shock on the earth’s surface, either by a heavy mechanical impact or by a controlled explosion, the resulting shock wave can be recorded when it reaches the instruments. With knowledge of distance and time, it is then possible to estimate the velocity in the ground (Figure 7.5).

Wave velocity (which determines the travel time) depends mainly on porosity, especially the elastic properties, of the geological formation. Solid igneous rock can have seismic velocities varying from 5 000 to 7 000 metres/second while unconsolidated material (dry sand and gravel) has a seismic velocity of approximately 300-1 000 metres/second.

The reflection seismic method provides information on geological structures some thousand metres below the surface, while the refraction method penetrates some hundred metres. In groundwater investigation the latter method is the one most commonly used. The physical principle is that the higher the porosity, the lower the seismic velocity, but water-filled pores increase the velocity as compared to dry pores. This makes it possible to determine the depth of the groundwater table in unconsolidated material rather easily (Figure 7.5.).

Interpretation of seismic refraction data can supply information on

- depth of the groundwater level,
- depth of different layers,
- type of formation (clay, gravel, moraine etc.),
- depth of the bedrock,
- changes between rock types,
- weathering on the top of the bedrock,
- the thickness of top of the bedrock zone,
- major fault lines and crushed up zones shaped by tectonic activity, which can yield high amounts of groundwater.

Gravity and magnetism

Two geophysical methods of minor interest for groundwater investigation are gravity and magnetic methods. Gravity measurement can be used to detect thick alluvial deposits bordering a mountain area or intrusive bodies bordering an aquifer. Magnetic measurement can reveal indirect information, such as dikes that form aquifer boundaries or limits of a basaltic flow.

Subsurface investigations

The logical approach to groundwater investigation is one or several of the different steps presented above, where the background information, the demand for groundwater quality and quantity and the general geology determine the choice of method(s) to be used. After using the general sources and a suitable surface investigation method it should be possible to choose the best location for subsurface investigations. These are comparatively expensive, but impossible to avoid if data on quality and quantity of the groundwater are desired.

One or more small diameter holes are drilled at the chosen location to supply information on the groundwater level and the geological substrata. There are several drilling methods that can be used and the choice is determined by the geological conditions.

The results of the drilling and sampling of material make it possible to establish a geological log with information from the different strata for both unconsolidated (loose) and consolidated (bedrock) material. The log can contain e.g. grain size distribution of the loose material, which provides information on the porosity or the frequency and distribution of fissures and cracks in the bedrock. Besides sampling of material, it is also possible to take groundwater samples at specific depths for chemical analysis, which gives a first indication of the groundwater quality in the area.

Any number of geophysical logs can be used, depending on the geological conditions, which are more or less parallel to those determining the choice of surface geophysical investigations. From among these methods can be mentioned the spontaneous potential, which is created by means of an electrochemical potential between the borehole mud, water-bearing and dry bed rock strata. Resistivity logging can also be used. An acoustic log measures the speed of sound in the rock near the borehole and as the travel time of sound is strongly dependent on porosity, the method can be used to assess the variation of porosity in different strata. Another technique is the logging of radioactivity, either natural radiation or radiation from a radioactive marker, which can be used to identify different bed rocks (natural radiation) or radiation from a marker to measure the groundwater flow and velocity. Temperature logs can help in the interpretation of resistivity and potential logs. Calliper logging is a method of continuous measurement of the diameter of the borehole. This diameter can change depending on the hardness of the rock (Davis & DeWiest, 1966).

The drilled testholes make it possible to observe the groundwater level and thus map the gradient and the flow direction. This may in some cases also be traced with dyestuff, e.g. in lime stone areas. The flow velocity can also be determined by other means, such as radioactive markers or dilution methods.

Pumping tests

The last step in an investigation for a groundwater well is a pumping test. This is perhaps the best subsurface method of all, as it will reveal substantial information on both quality and quantity of the groundwater. In order to perform a pumping test not only is a test well required, which makes it possible to measure the water level in the well, but an observation net with several observation wells around the test well is also needed (Figure 7.6). Here, testholes that may have been drilled earlier can be useful as observation wells.

Pumping tests can be carried out in two different ways, using either short time or long time pumping.

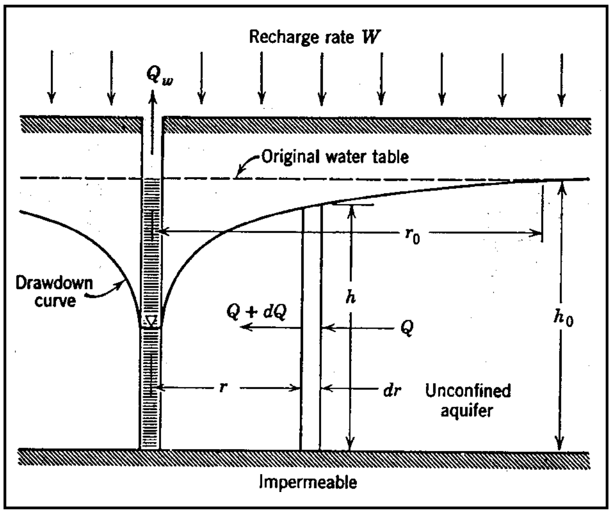


Figure 7.6 Radial flow to a well in a phreatic aquifer (Todd, 1959).

The schedule for a short-time test can be, for instance, pumping at a fairly high rate (constant throughout the pumping time) for 8-10 days, with measurements of the groundwater levels in the test well and all the observation wells taken at the same time, with a logarithmic increase of the measuring time interval. When pumping stops the recovery of the groundwater level is measured in the test well and all the observation wells for the same time length as the pumping time and with the same measuring-time interval. During a long-time test the pumping continues for several months, sometimes with a gradually increasing rate. The measuring program is then the same as for the short pumping test. Water sampling at suitable intervals for chemical analysis are done during the duration of the pumping time.

Analysis of the data received from the pumping test provides information on permeability, transmissivity, yield of the well, and water quality. During a pumping test a steady-state condition may be reached (Figure 7.7), implying that the amount of pumped-out water from the test well is equal to the total recharge of groundwater. This condition

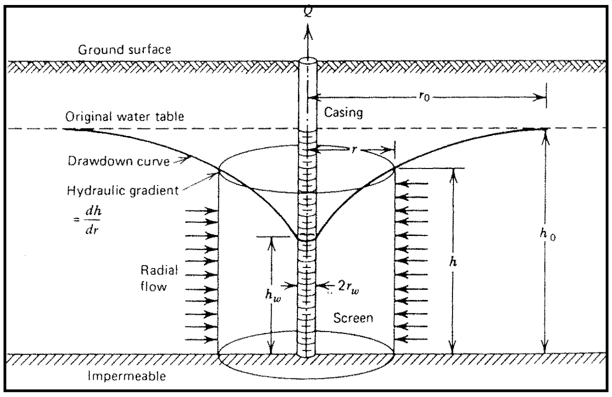
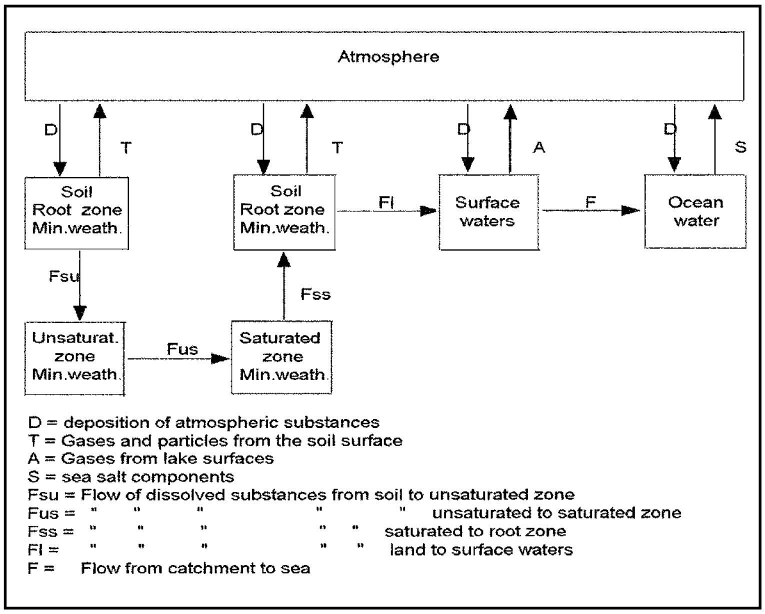


Figure 7.7 Steady state radial flow to a well in a phreatic aquifer (Hammar & MacKichan, 1981).



D = deposition of atmospheric substances
T = Gases and particles from the soil surface
A = Gases from lake surfaces
S = sea salt components
Fsu = Flow of dissolved substances from soil to unsaturated zone
Fus = " " " " " unsaturated to saturated zone
Fss = " " " " " saturated to root zone
Fl = " " " " " land to surface waters
F = Flow from catchment to sea

Figure 7.8 Circulation of water-soluble substances in nature.

marks the limit of groundwater production from the well and all amounts up to this limit can be regarded as a safe yield for this well. Passing the limit will lead to overdraft of groundwater and a gradual emptying of the aquifer. Since pumping tests, too, are rather costly it is important to know the differences between short and long pumping tests. In general it can be said that the short-time test reveals approximately eighty per cent of the information received from the long-time test. In most cases this is enough. What may be lost is information on the steady-state condition (which, however, can be estimated) and the long-term water quality. The latter can namely change during a long-time test as parts of the aquifer, distant from the well, are activated and involved in the groundwater production and may deliver a less good water quality. The costs for the test pumping can be regarded as an investment for the future in terms of knowledge received about quality and quantity of the groundwater resources. Furthermore, the observation wells are needed for the monitoring program of the groundwater pumping well. This is in all essential information for sustainable management of groundwater utilisation.

Groundwater chemistry

Dissolved substances

Groundwater contains a fair number of dissolved substances, of which the major inorganic ones are the cations Ca^{2+}, Mg^{2-}, Na^+ and K^+, followed by the anions HCO_3, Cl, SO_4 and NO_3. This group of ions is often referred to as the major dissolved components. They are present in concentrations ranging from 0.1 to > 10 mg/l. In absence of dissolved oxygen ferrous iron, Fe^{2+}, and divalent manganese, Mn^{2+}, often appear, since the oxidised states have low solubility. At pH-values < 4.2 aluminium, Al^{3+}, will appear and at very low pH-values, less than 3, ferric iron, Fe^{3+}, will also show up. Dissolved silica in the amorphous form is usually present in mg/l concentrations. Very low concentrations of such metal ions as Ba, Sr, Ti, Cu, Zn, and Cd may be noted but require sensitive analytical equipment for detection.

Dissolved organic matter also appears to be common in groundwater but no systematic studies of their nature is yet available. This organic matter forms complexes with the metal ions that occur at low concentrations. Organic matter may be important as carrier substances for heavy metals.

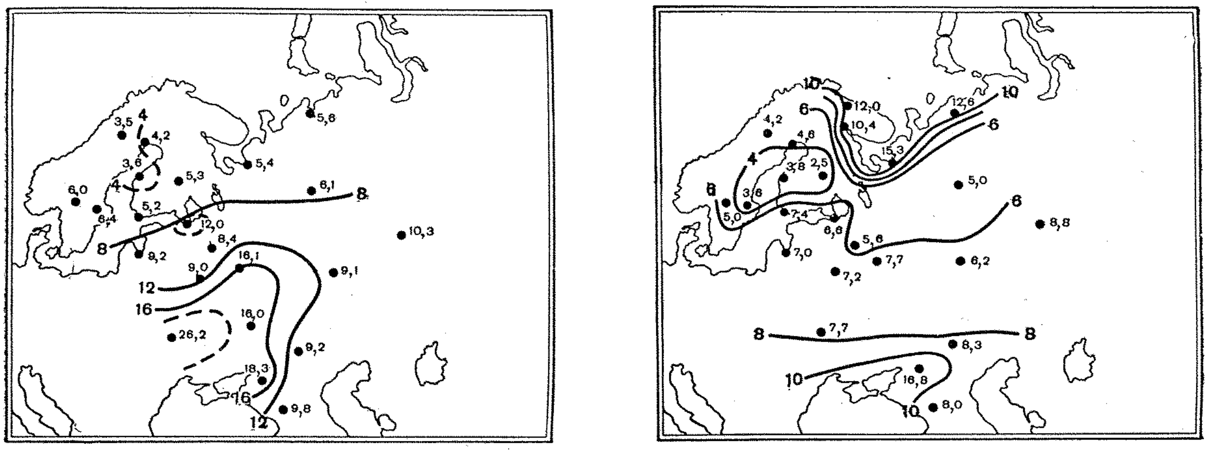
Inorganic minerals, especially clay minerals, will act as adsorbents in the saturated zone because of their large surface area. It is well known that the common cations Ca, Mg, Na, and K are adsorbed as exchangeable base cations and form a strong buffer against changes in concentrations of these ions in the water solution. Adsorption of anions such as sulphate and phosphate also takes place, with the intensity of adsorption being related to the pH of the solution. Chemical weathering in the soil will release base cations from silicates at a practically steady rate along the path of the water.

With this short preview in mind we can now look closer at chemical processes during the flow of water, from the soil surface and through the ground to streams, rivers and lakes and oceans, up into the atmosphere and back down to the soil surface.

Major ions in groundwater

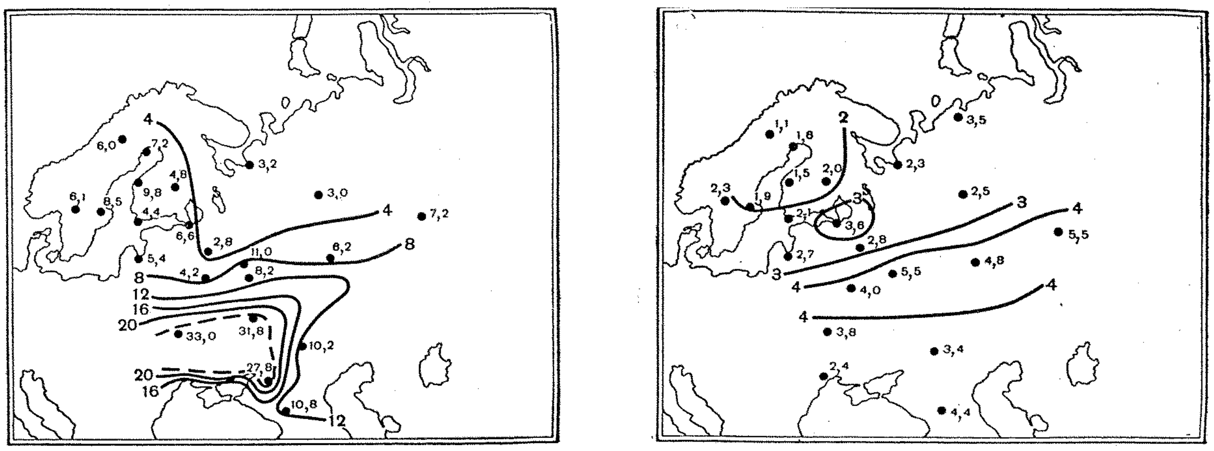
Figure 7.8 shows a box-model representation of the flow of dissolved chemical components. There are three major sources of dissolved substances in groundwater. One is the atmosphere delivering sea salts and biogeochemical components from the ocean areas and the second is soil and rock, which deliver base cations through chemical weathering. The third is the biosphere on land that delivers volatile nitrogen compounds as by-products of complicated and, in a quantitative sense, not fully understood biogeochemical processes. Obviously the source resides in soils in the root zone.

Deposition of atmospheric components onto the ground is well established by atmospheric chemis-



Deposition of Sulphur. (kg/ha and year)

Deposition of Clorine. (kg/ha and year)



Deposition of Calcium. (kg/ha and year)

Deposition of Nitrogen. (kg/ha and year)

Figure 7.9 Atmospheric deposition rates (bulk deposition) of S, Cl, Ca and N in kg/ha and year for Scandinavia and Eastern Europe (Drosdova et al, 1964).

try networks. Figure 7.9 shows the wet deposition of S, Cl, Ca and N as yearly averages in kg/ha. But the soils also supply the atmosphere with "dust," a collective name for mineral and organic particles raised by strong turbulence near the ground. Arid areas like deserts are particularly good sources of calcium in particles but even areas that are seasonally dry are good sources. Agricultural land used intensely for grain production also promotes "dust" during ploughing and preparation for the next crop when the soil is relatively dry. Mineral particles then react in the atmosphere with sulphur trioxide and nitric oxides, which will make base cations water soluble. Gases like ammonia may also escape from the ground to the atmosphere where they may be caught by acidic components. It is estimated that manure applied to soil may lose as much as half of its ammonia nitrogen to air. In recharge areas high groundwater levels will favour denitrification either to dinitrogen oxide, N_2O, or to nitrogen gas, N_2. Surface waters are probably insignificant sources of atmospheric gases. Ocean areas are major sources of sea salts, formed by collapsing air bubbles in breaking waves. These particles will have about the same relative salt composition as seawater. In addition the oceans seems to emit dimethyl sulphide formed in biological processes in the water. The quantitative importance of this source for atmospheric sulphur is not yet established.

Chemical weathering is a practically stationary, slow process in soils and rocks and releases major cations from primary minerals such as granites and from metamorphic rocks such as feldspars, mica and the heavy minerals that contain a mixture of ferrous iron and magnesium. Of the sedimentary rocks those containing calcium carbonate are of great importance for determining the chemical composition of groundwater. Shales often contain fine-grained pyrite, FeS_2, which is oxidised to form sulphuric acid in the presence of oxygen. This sulphuric acid is highly active as a weathering agent.

The influence of mineral weathering

An important agent during weathering of limestone and dolomite is carbon dioxide. In the root zone about half of the assimilated carbon dioxide is released in the processes supplying energy to the plant for nutrient uptake and physical support. Most of the released carbon dioxide has to leave the root zone by diffusion into the atmosphere. This creates a high partial pressure of carbon dioxide in soil air, from 10 to 100 times higher than that in the atmosphere. This high partial pressure is also maintained in the unsaturated zone below the root zone.

Calcite weathering

The reaction between calcite and carbon dioxide is

$$CaCO_3(s) + CO_2(g) + H_2O(l) = Ca^{2+} + 2HCO_3^-$$

and the equilibrium condition is

$$[Ca^{2+}][HCO_3^-]^2 = K \cdot p_{CO_2}$$

Note that [Ca] = 2[HCO_3]. The equilibrium can therefore be written

$$[Ca^{2+}]^3 = K \cdot p_{CO_2}$$

with K being a constant. This means that an 8-fold increase in carbon dioxide partial pressure doubles the calcium concentration. This carbon dioxide partial pressure will be proportional to the release rate of carbon dioxide and inversely proportional to the permeability of the root zone.

Since dissolution of calcite is rapid as compared to the weathering rate of silicate minerals, calcium ions will dominate wherever calcite is present in the ground and be balanced by bicarbonate ions. The water will show appreciable hardness – carbonate hardness to be specific. Absence of calcite in the ground will result in soft water, when calcium no longer dominates the base cations. Dolomite, (Mg, Ca)CO_3, reacts somewhat slower than calcite.

Primary minerals

The rate of weathering of primary silicate minerals in soils may vary between 30 and 100 $meqm^{-3}yr^{-1}$. With a recharge rate of 200 $mmyr^{-1}$ this increases base cations concentrations in water by 0.15 to 0.5 $meql^{-1}yr^{-1}$ or, expressed as Ca, from 3 to 10 $mgl^{-1}yr^{-1}$. If water was to be extracted after 10 years it would contain somewhere between 30 to 100 mgl^{-1} of base cations due to weathering of silicate minerals.

Sulphide

Mineral sulphide is stable under strongly reducing conditions and may be formed from ferric iron and organic matter in water-saturated soils such as pyrite, FeS_2. Sedimentary rocks, particularly shale, usually contain pyrite. On exposure to atmospheric oxygen, i.e. due to drainage, pyrite is oxidised into ferric hydroxide and sulphuric acid. This is a strong weathering agent that dissolves clay minerals as well as primary minerals if present. This increases the pH value but may bring various heavy metals into the solution as long as it is strongly acid.

8.

LAKES

ORIGIN, ONTOGENY AND NATURAL FUNCTIONS

Peter Blomqvist & Anna-Kristina Brunberg[1]

Origin and ontogeny

Standing waters are beautiful elements of the landscape and greatly appreciated and valued when they occur. However, lakes are not given components of all water systems; in fact many catchments lack lakes. In the Baltic catchment, luckily, there are several hundred thousands of small lakes, with an especial concentration in the most northern countries. The definition of the term 'lake' varies, but it is usually related to the turnover time of the water and the depth of the basin. The turnover time is used to distinguish lakes from running waters. According to Wetzel (1975) turnover time of the water is longer than one year in lakes, whereas rivers have a turnover time of less than three weeks. Using these definitions, most of the small lakes in the Baltic watershed are within the transition zone between lakes and running waters. As an example, Brunberg & Blomqvist (1998, p. 890), in a study of the lakes of the lowland county of Uppsala, Sweden, noted that 85 % of the 117 lakes in their survey had a turnover time of less than one year. The second part of the definition of lakes, the depth of the basin, is used to distinguish between wetlands and lakes. The former have a maximum depth of < 2 metres, which is by no means a measure chosen at random but rather to correspond with the greatest depth at which emergent aquatic macrophytes can begin to grow.

Lake basins are formed by some kind of natural catastrophe (in the term's most widely used sense), and there are many different ways in which the formation can occur, thoroughly reviewed by Hutchinson (1975). Immediately following formation, the basin starts to fill out with material that is transported from the drainage area and settles to the bottom due to the decreasing flow of water. Organic material produced within the lake itself also contributes to the sedimenting material. On the basis of physical properties, i.e. erosion and sedimentation, erosion, accumulation and transport bottoms can be identified in lakes in a similar manner as for the sea (Håkansson & Jansson, 1983). Erosion bottoms may also occur at deeper sites, e.g. in cases when strong groundwater currents are entering the lake.

Under natural conditions, and seen on an annual basis, the sedimentation process is slow. The sediments grow at a rate of approximately 0.5-2 millimetres of consolidated sediment per year (e.g. N.J. Anderson et al., 1997; Håkansson & Jansson, 1983). Thus, the life span of a lake basin partly depends on the conditions of the drainage area and partly on the basin morphometry. As lakes age naturally, which is referred to as the *ontogeny* of lake basins (see e.g. Wetzel, 1983), the basin is transformed from a lake into a wetland and successively reaches a climax stadium of terrestrial character (Figure 8.1).

A major share of the numerous lakes in North Temperate areas, such as the Baltic watershed, were formed during the last glaciation period approximately 10 000 years ago. Many lakes were also formed by the activity of the glacial rivers when the ice was melting (Hutchinsson, 1975). Most of the lake basins of glacial origin are relatively shallow and will thus, in a geological perspective, fill out and disappear rather quickly. Another kind of lake basin, which is common in the Baltic waterscape, is the tectonic type, i.e. basins that have been formed by movements in the earth's crust. These lakes are usually very deep and thus have a long life expectancy. Lake basins formed by fluvial action (e.g. meandering of rivers) are also common, especially on easily eroded soils in the lowlands of river basins. Such lakes are often very shallow. Other, less common lake basin types found in Northern Europe are volcanic and meteorite basins.

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[1] This chapter is a short version of a text used for teaching Limnology within the SOCRATES programme 'Environmental protection and management.' Copyright © 1998. Peter Blomqvist & Anna-Kristina Brunberg, Department of Limnology, Uppsala University, Sweden. No part of this chapter may be reproduced or distributed in any form without the prior permission of the authors.

The functioning of lakes from a catchment perspective

Wherever lakes occur, they are an integral part of the hydrological cycle. Their metabolism (i.e. the functioning of the lake ecosystem) is to a large extent governed by their morphometry, by the geology of the drainage area and by the climate of the region. The climate determines the distribution of heat in the water, for example whether the water column becomes thermally stratified or not, and also the balance between precipitation, evaporation and runoff of water. How much water enters a lake basin also depends on the size of the drainage area; the larger the drainage area the more water is transported to the lake basin. This inflowing water is the carrier of most of the constituents needed for production of organisms in the lake ecosystem. The chemical quality of the inflowing water is in turn determined by the geology and vegetation of the drainage basin, e.g. the more easily weathered the soils of the drainage basin, the higher the concentration of inorganic compounds in the water entering the lake. Also, as the vegetation becomes more extensive, the organic matter that is exported from the humus layers to the lake increases in volume.

The turnover time of the water in a lake depends on a) how much water enters the lake from the drainage area and b) the storage capacity of the lake, e.g. the volume of the basin. The turnover time of the water is important when discussing the relative impact of the drainage area on the lake metabolism. We could say in general that the shorter the turnover time of the water, the greater the impact of the drainage area on the system. The influence of organic matter from the drainage area on the lake metabolism is normally very high. It has recently been shown that, in terms of CO_2/O_2 balance, most of the lakes in the world can be regarded as heterotrophic systems, in which organic material from the drainage area is metabolised on its way to the ocean (Cole et al., 1994; del Giorgio et al., 1997). This metabolism demands more oxygen than is produced through photosynthesis by the plants in the lake ecosystem. As a net result, lakes generate CO_2 to and consume O_2 from the atmosphere. This is a major difference from the situation in oceans, where the opposite is true: oceans act as a sink for CO_2 and serve as a source of O_2 in the atmosphere.

Thermal regimes of lakes

In order to understand lake metabolism, it is very important to consider the distribution of heat in the water. The greatest source of heat to lake water is solar radiation, while heat is lost from lakes principally by thermal radiation. Water has its maximum density at a temperature of ca. + 4 °C and as the temperature deviates from this value (in both directions) the density decreases. This decrease is not linear but increases with increasing difference in temperature from + 4 °C. As a result, the density difference between waters of + 24 and + 25 °C is much greater than the density difference between waters of + 4 and + 5 °C. Conversely, the wind energy required to mix the water column is much greater at the higher than at the lower two temperatures. These density properties of water, together with the fact that the main source of heat is solar radiation, often cause lakes to become thermally stratified during some period of the year. In the Baltic watershed, three types of annual patterns of thermal stratification and circulating (mixing) periods are frequently found: cold-monomictic lakes, dimictic lakes, and warm-monomictic lakes.

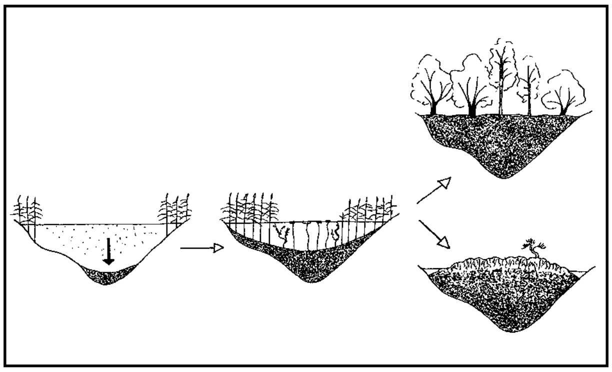

Figure 8.1. The ontogeny of a lake, from (a) a stage in which the open water production dominates, through (b) a wetland stage in which the littoral zone becomes the prime source of carbon to the ecosystem and into (c) a closed system of terrestrial character e.g. a forest dominated by alders and other deciduous trees or a bog (Moore & Bellamy, 1974).

Dimictic lakes (Figure 8.2) are common in North Temperate Zone. These lakes are ice-covered during winter and have an inverse thermal stratification (cold water close to the surface) during this period. The water circulates twice a year, during spring and fall, and is directly stratified (highest temperature at the surface) in summer. During summer stratification, three different strata can be distinguished, referred to as epilimnion, metalimnion and hypolimnion. During winter stagnation there is a more gradual increase of the temperature with depth, and such a division into separate strata is not applicable.

Cold-monomictic lakes seldom reach water temperatures higher than + 4 °C. The lake water circulates once a year, during the ice-free period (Figure 8.2). These lakes are largely restricted to the Arctic and to high elevation mountain areas. However, many shallow lakes in temperate areas can also be considered cold-monomictic, since the low water depth allows them to circulate freely during the whole ice-free period.

Warm-monomictic lakes are common in the southern part of the Temperate Zone and in subtropical areas. They lack ice cover during winter and the water temperature seldom drops below + 4 °C. Like the cold-monomictic lakes, these lakes also circulate once per year but this occurs during the cold season. During the warmer part of the year a direct stratification develops (Figure 8.2).

The pattern of thermal stratification vs. free circulation regulates a number of processes of major importance to the lake metabolism, some of which are presented below:

The concentration of dissolved oxygen is a crucial factor in lake metabolism and tightly coupled to the water temperature and the patterns of circulation and stratification of the water column. Dissolved oxygen (DO) is essential to all aquatic organisms that possess aerobic respiratory organs. There are essentially three sources of DO in a lake ecosystem: the atmosphere, photosynthesis by plants in the lake, and inflow of water from the drainage area. The air contains approximately 21 % O_2 and 79 % N_2. Since oxygen is more soluble than nitrogen in water, the proportion of these two gases when dissolved in water changes to ca. 35 % O_2 and 65 % N_2. Atmospheric oxygen dissolves in the lake water at the surface and is transported downwards by wind-generated currents. The solubility of oxygen in the water is nonlinearly related to the water temperature and decreases as the water temperature increases (Table 8.1).

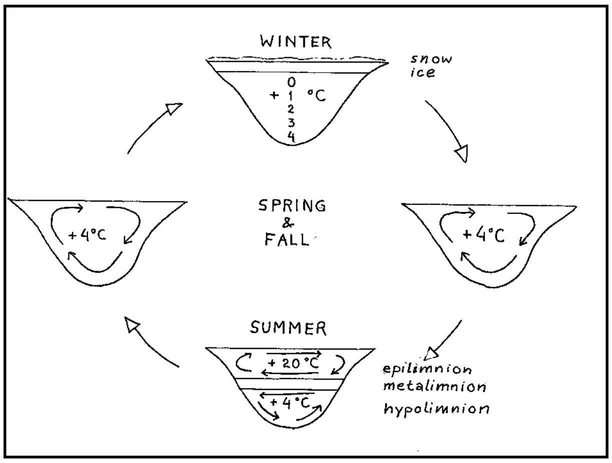

Figure 8.2. Patterns of thermal stratification and free circulation of the water at different seasons in a north temperate dimictic lake covered by ice during winter. The thermocline (metalimnion), formed during summer stagnation, should not be regarded as a static barrier located at a given position during the entire stratified period. Instead the thermocline usually develops in a shallow position and is successively moved downwards during the summer.

Table 8.1. Solubility of oxygen in pure water in relation to temperature, from saturated air at 1013 hPa (Montgomery et al., 1964)

Temperature (°C)	**Oxygen content** (mg O_2/l)
1	14.23
5	12.77
10	11.28
15	10.07
20	9.08
25	8.26
30	7.57

At periods of circulation (e.g. in spring) dissolved oxygen is easily spread downwards and it is not unusual that saturation is reached throughout the water column. When such a system becomes thermally stratified, less DO is found in the upper (warmer) layer and more in the deeper (colder) layer (cf. Table 8.1). Such a depth distribution of DO during stratification is normally only found in low-productive clearwater systems. In most systems, the distribution of dissolved oxygen shows a different pattern (Figure 8.3), with high concentrations of DO in the epilimnion and low concentration of DO in the hypolimnion during summer stratification, and lowered concentrations of DO in the entire water mass during winter stagnation (particularly close to the bottom). The reason for this is that biological processes producing and consuming oxygen occur concomitantly, and that the consumption in deeper strata greatly exceeds production. When exchange of DO between surface layers and deeper strata is restricted, the bottom water normally obtains lower concentrations of DO than the uppermost layer. During winter conditions, ice-covered lakes are almost entirely cut off from the atmospheric source of DO. Production of DO from plants in the lake ecosystem normally occurs close to the surface, where light conditions are good enough to sustain photosynthesis. During free circulation this DO is distributed throughout the water column, but in the case of stratification, and when there is only sufficient light for photosynthesis in the epilimnion, this source of DO is also cut off from deeper strata. During winter conditions in lakes that get covered by ice, this source of DO is cut off from the lake at periods when the ice is covered by snow. The third source of DO to the lake ecosystem, namely the inflowing water from the drainage area, is also unevenly distributed over the year, especially in cold climates where the precipitation is stored on land in the form of snow and ice during winter. In North Temperate latitudes major flow events normally coincide with the inflow of melt water during early spring and with heavy rainfalls during late summer and autumn. During winter and during the dry months of the year (often early summer) inflow of water from the surroundings is minimal. The history of the inflowing water is also important in determining how much DO is brought in via this source. The water that reaches the lake directly in the form of groundwater usually has a very low concentration of DO due to respiratory processes in the soils of the drainage area. In contrast, the water that reaches the lakes via surface water inlets can often be near-saturated with DO due to turbulent conditions and close contact with the air in the tributaries. The inflow of water to a lake normally takes place close to the surface (Eriksson & Holtan, 1974). This is true for the groundwater as well. Sediments in shallow areas are generally courser and allow more water to penetrate through them than the deeper fine sediments, which are sometimes more or less impermeable to groundwater. This density, which is temperature-dependent, determines where the inflowing water eventually ends up in the lake. Surface water entering during summer may often be as warm as, or warmer than, the surface water of the lake and will, during stratification, stay in the epilimnion. However, during summer groundwater is normally colder than lake surface water, as is also water from high altitudes that rapidly passes into lowland areas. Thus there are examples of inflowing surface water sinking into deeper strata due to a higher density. During winter conditions, surface water flowing into the lake may be as cold as the existing surface water (which then is colder than the underlying water in the lake). In such cases the inflowing water will stay just beneath the ice but there are other possibilities as well if the inflowing water is warmer.

Photosynthetic processes

Oxygen in the lake water is consumed at respiration and the concentrations of DO are important in determining the respiration rates of the organisms in the water. Respiration rates are also temperature dependent. Within the temperature range frequently found in nature (0-30 °C) these rates increase with rising temperatures. Availability and amount of substrates are also important in determining the respiration rates; the easier the availability of the substrate, the higher the respiration. Respiration rates are normally higher at the sediments level than in the open waters due to sedimentation and concentration of organic matter to the bottom. The lake metabolism, in terms of formation and consumption of dissolved oxygen or production and respiration of organic material, can be summarised in the following formula:

$$CO_2 + H_2O + \text{about 20 inorganic elements} + \text{energy} \longleftrightarrow \text{organic material} + O_2$$

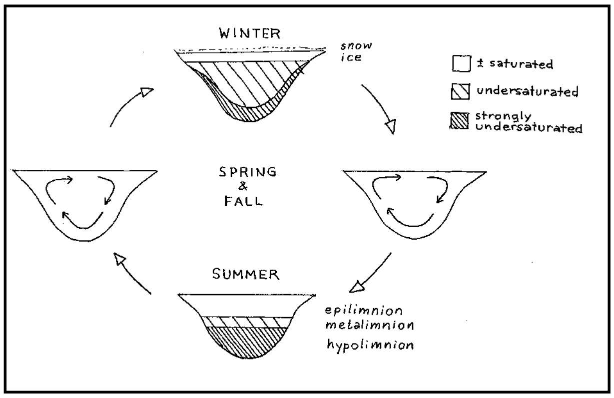

Figure 8.3. The distribution of dissolved oxygen at different depths in a northern temperate dimictic lake covered by ice. In the example, light is assumed not to penetrate into meta- and hypolimnion during summer stratification, thus resulting in a state where no dissolved oxygen is formed through photosynthesis in those strata. The gradually increasing oxygen deficit with increasing depth during winter stagnation is the result of higher concentrations of organic material demanding oxygen for decomposition closer to the bottom.

‘Energy’ refers to solar energy in the case of photosynthesis and chemically released energy in the case of respiration. Note that although this formula describes photosynthesis and respiration by a single cell or plant, it can also be applied to a community of plants and animals. Furthermore, by adding the processes of import and export of all constituents to and from the community (e.g. a lake), the influence by adjacent systems can also easily be included. Thus the equations may be turned into a model, describing processes in a lake at a catchment level.

To understand the process of photosynthesis in a lake ecosystem, it is necessary to look more closely into three of the four major constituents of the process: carbon dioxide, inorganic elements and solar energy. The fourth constituent, water, is always present in aquatic ecosystems and needs no further dissection. The process of photosynthesis is regulated by the availability of the participating compartments. It was discovered very early that a shortage of one single element is enough to halt the entire process, a phenomenon often referred to as Liebig’s ‘Law of the minimum’ (Liebig, 1840).

From the point of view of limiting constituent, carbon dioxide is not particularly interesting, since this gas easily dissolves in water via atmospheric exchange, its solubility in water being some 200 times greater than that of oxygen. Furthermore, it is formed during respiration of organic material in the system (lakes are net heterotrophic systems, see above). Therefore, carbon dioxide is seldom, if ever, limiting to photosynthesis. However, there are other interesting aspects of CO_2, partly coupled to photosynthesis, that deserve mention here. Carbon dioxide can react with water even in the absence of biota and during this chemical process carbonic acid is formed.

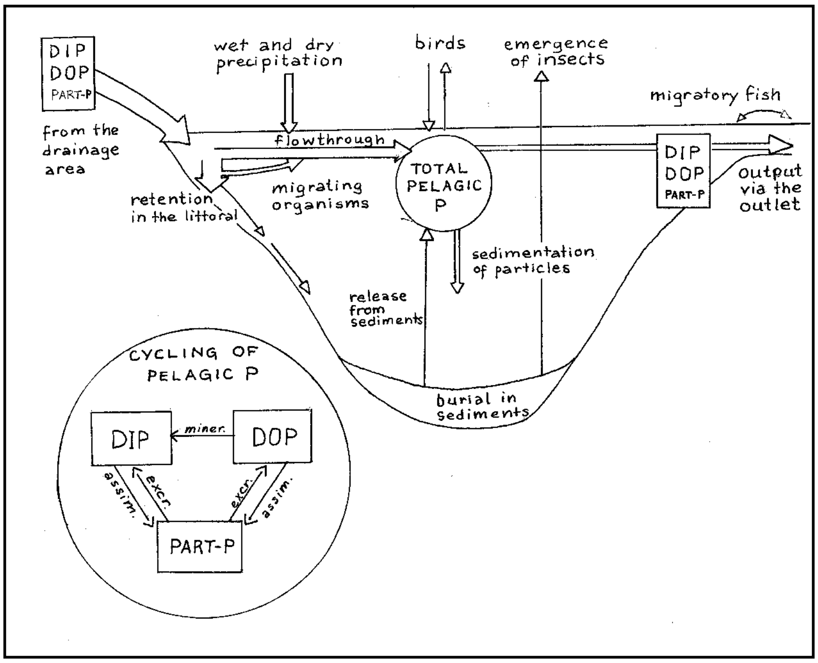

Figure 8.4. Import and export of phosphorus to, and cycling of phosphorus in, a lake ecosystem.

Carbonic acid is a fairly weak acid and dissociates rapidly in the water according to:

$$CO_2 + H_2O \longleftrightarrow H_2CO_3 \longleftrightarrow H^+ + HCO_3^- \longleftrightarrow 2H^+ + CO_3^{2-}$$

Bicarbonate and carbonate ions are also imported to the lake ecosystem from the weathering of carbonaceous minerals in the soils and bedrock of the drainage area. When this happens, hydrogen ions are eliminated by the buffering effect of the carbonic acid system, resulting in the formation of carbon dioxide and water. In non-humic lakes with pH-values > ca. 6, this is the most important buffering system against import of acid. If bicarbonate ions are consumed instead of carbon dioxide by photosynthesising plants, this consumption will affect the pH-value of the water via a series of complicated processes. The easiest way to view all these processes is to say that the net outcome of a process that requires CO_2 but consumes HCO_3^- will be formation of OH^-, a strong base that immediately consumes existing hydrogen ions and thereby causes an increase in the pH value of the water. In conclusion, CO_2 is seldom a limiting element to photosynthesis but photosynthesis may increase the pH value of the water, at least temporarily if bicarbonate ions are assimilated.

About 20 different inorganic elements are required to produce a living organism (Reynolds, 1984). Relative to the chemical composition of the organisms, many of these elements are present in considerable excess in the lake water under natural circumstances. Examples of elements usually present in excess amounts are Ca, Mg, Na, K, S, and Cl, i.e. those elements that are also the most important in determining the salinity of fresh waters. Elements that are less abundant and that frequently, at least for short periods during the year, become limiting to the production of all or certain groups of plants in the lake ecosystem include P, N, and Si. Probably some trace elements, e.g. Se and metals like Fe, should also be included here. Limitation of primary production by trace elements has not been especially well studied, and therefore the following text concentrates on the cycles of P, N, and Si.

The phosphorus budget

Phosphorus in lake water is often divided into three fractions (Figure 8.4): inorganic phosphorus (DIP, mainly PO_4-P), dissolved organic P (DOP) and particulate P (PP). Taken together these three fractions are referred to as total-P. The main sources of P in a lake are:

- inflowing water which brings P from weathering of the bedrock and soils of the drainage area,
- wet precipitation (rain and snow falling directly on the lake surface),
- dry precipitation (fine and course inorganic and organic material brought to the lakes by winds)

In some cases, migratory organisms (e.g. fish, birds) may also contribute substantially to the P budget of a lake. Thus, all the three different fractions of phosphorus – DIP, DOP and PP – enter the lake. Under natural conditions, especially in forested regions, the greater part of the P entering the lake is bound to dissolved organic substances (e.g. humus). Almost regardless of the form in which P enters the system, it can rapidly be transferred into biota (Fenchel & Blackburn, 1979). In the case of inflow of groundwater to near-shore areas of a lake ecosystem, most of the phosphorus is trapped in the vegetation zone (Wetzel, 1996). P entering the lake via major tributaries is transported directly to the open water. A large part of the PP, originating either from the inflowing water or from the production of organic matter within the lake, settles to the bottom. Due to this sedimentation process, almost all natural lakes act as phosphorus traps in the large-scale flow of phosphorus from the continents to the sea. Normally, some of the P entering the sediments via sedimentation is deposited there but under certain circumstances (e.g. oxygen deficiency) a share of this P may be recycled to the water after decomposition of the organic material to which it was bound. The phosphorus that is not recycled is buried in the sediments and lost from the system. P is also lost from the lake ecosystem via the outflow of water, including all three fractions of phosphorus. Since lakes normally act as sinks for phosphorus, the amount of phosphorus in the outgoing water is lower than that of the incoming water, when seen over a longer period of time.

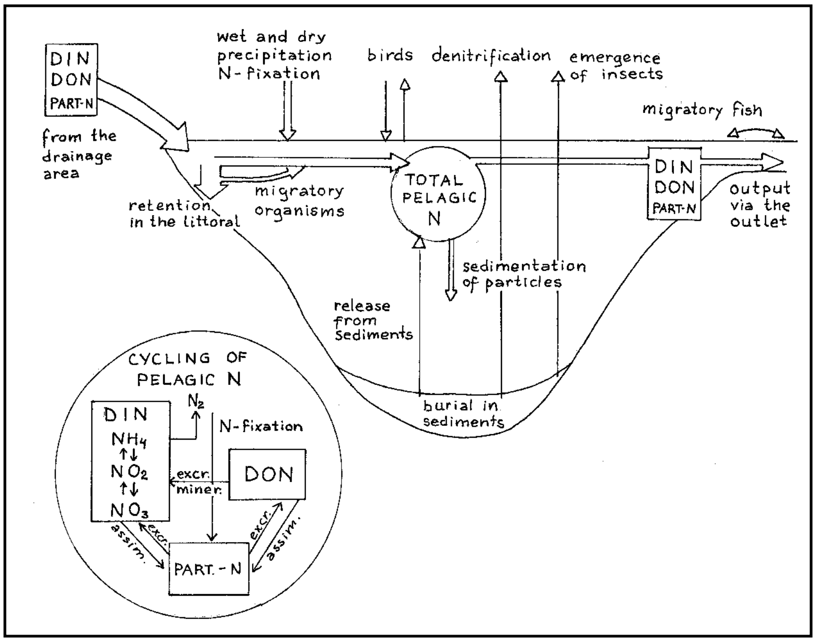

Figure 8.5. Import and export of nitrogen to, and cycling of nitrogen in, a lake ecosystem.

The nitrogen budget

The nitrogen cycle is slightly more complicated than that of phosphorus. Most of the nitrogen inflow from the drainage area is, as for phosphorus, bound to dissolved organic material (Hedin et al., 1996). The total amount of nitrogen present in lake waters can also be divided into three fractions (Figure 8.5): dissolved inorganic-N (DIN), dissolved organic N (DON), and particulate-N (PN). However, instead of being present in one form, as was the case with P, the dissolved inorganic N may be present as ammonium-N, nitrite-N and nitrate-N, referred to collectively as total dissolved inorganic nitrogen. Also as regards the sources of these elements to the lake ecosystem, the nitrogen cycle is more complicated than that of phosphorus. Nitrogen fixing organisms (certain species of cyanobacteria), which are present both in the drainage area and in the lake ecosystem, can fix molecular N (N_2) and turn that compound into organic N. The three inorganic forms of nitrogen can be transformed into each other via bacterial activity. Nitrate-N and nitrite-N can be turned into molecular N (N_2) via denitrification (a process mediated by bacteria) and thereby be lost to the atmosphere. This process requires anoxic conditions and is therefore allocated to deeper strata and particularly to the sediments. Thus, sedimented nitrogen is to a lesser extent than P buried in the sediment and instead partly lost to the atmosphere. In most other respects, the cycling of nitrogen is similar to that of phosphorus, and nitrogen is also lost from the system via outflowing water.

The silicon budget

Silicon (Si), which occurs in lakes principally as silica (SiO_2), is not a limiting nutrient to aquatic plants in general. However, this element is of major significance to the production of diatoms and certain chrysophytes, which are photosynthetic organisms that grow both in open water and on illuminated areas at lake bottoms. These organisms reinforce their cell walls with SiO_2 and require much higher concentrations of Si in the water than other organisms to which Si is more or less a trace element. The major source of silica to the lake is degradation of aluminiosilicate minerals in the drainage area, followed by transport by the water flowing into the system. Silica is taken up by diatoms at photosynthesis and incorporated into their frustule, which makes them heavy and subject to high sedimentation losses. The diatom frustules deposited on the sediments are decomposed very slowly and therefore silica is to a great extent buried in the sediments. Because of this, diatoms are usually excellent paleoindicators and can be used to reconstruct conditions in the system far back in time (e.g. Renberg et al., 1993). Diatoms, as well as silica, are also lost from the lake ecosystem via the outlet.

Limiting factors for primary production

To summarise the section concerning limitation of primary production by inorganic elements it can be said that the two most commonly occurring limiting nutrients are P and N (Blomqvist et al., 1993; Elser et al., 1990), but for diatoms Si might also become limiting (Lund, 1964). Comparisons between TN:TP ratios (Total-N:Total-P) in the lake waters and the proportion of these elements in phytoplankton (generalised to about 7:1 by weight; Redfield, 1958) indicates that P is the most commonly limiting nutrient in unaffected waters. However, tests of the limiting nutrient in enclosures *in situ*, using a factorial design (no addition, only P, only N, and N+P) have revealed that co-limitation by P + N is found commonly in Scandinavian waters located far from the major air-pollution sources of N (Gahnström et al., 1993; Jansson et al., 1996). Thus, regardless of which nutrient becomes limiting first, it is important to remember that there is often only a very small step before the next element becomes limiting, too. Furthermore, in those cases when N becomes limiting to primary production, the plant community can continue to grow if a succession towards nitrogen-fixing cyanobacteria occurs. However, nitrogen fixation is an energy requiring process and development of nitrogen fixing cyanobacteria in the open water is restricted to nutrient rich waters. In other types of lakes, nitrogen fixation is restricted to the illuminated parts of the bottoms.

Finally, in a discussion of photosynthesis-limiting factors, we need to treat solar energy. Light, which is seldom a limiting factor to primary production in terrestrial ecosystems (per surface area seen from above and at low-to-moderate latitudes), is often a limiting factor to aquatic primary production. The reasons for this fundamental difference between systems is to be found in the optical properties of the water molecule and in those of the dissolved and particulate matter suspended in the aquatic system.

The solar energy income

Solar energy reaches the water surface in the form of infrared, visible and ultraviolet radiation, corresponding to wavelengths of ca. 100-3 000 nm. The wavelengths that can be used by photosynthetic plants correspond roughly to the visible part of the spectrum (400-700 nm). In the following, the term ‘light’ will be used to refer to this part of the spectrum. All light reaching the surface of a lake does not penetrate into the water. A portion is always reflected from the surface and, unless backscattered from the atmosphere, becomes lost from the system. How much light is reflected depends partly on the angle of incidence of the incoming light and partly on the surface characteristics of the water (calm or disturbed by waves). The lower the angle and the higher the wave activity, the more light is reflected. Clear smooth ice has approximately the same reflection of light as a calm water surface (Wetzel, 1975) but as soon as the ice becomes covered by snow, the reflectivity of the surface becomes almost total. Thus, there is very little light penetrating into a snow-covered lake. In addition to reflection, backscattering of light out of the water results in almost twice as much light being lost from the system. Both the quantity and quality of the light energy penetrating the water changes with depth due to scattering and absorption of light by the water itself and the solutes and particles present. This attenuation of light differs considerably from lake to lake depending on the amount of dissolved coloured substances and particles present in the water. The total attenuation of light with depth follows an exponential relationship (Wetzel, 1975):

$$I_z = I_o \cdot e^{-kz}$$

where I_z is the light intensity at the depth z and I_o is the light intensity at the surface, e is the base of the natural logarithms and k is the total attenuation coefficient. As mentioned above, the total attenuation coefficient is influenced not only by the water itself but also by absorption by dissolved coloured substances and by particles. Thus, the total attenuation coefficient (k_t) can be divided into three components (Åberg & Rodhe, 1942):

$$k_t = k_w + k_d + k_p$$

The water molecule itself has a rather low attenuation of blue light but changes the quality of the light absorbed on the red side of the spectrum. Thus, in distilled water blue is the most penetrating component.

In contrast to the water molecule, the effects of coloured dissolved substances (in lakes particularly present in the form of humic compounds) on the absorption of light energy are marked, and in this case the blue component is very much absorbed. In brownwater lakes light penetration is very low.

Particles of varying optical properties are suspended in lake water. One such ‘particle’ almost always present in lake ecosystems is chlorophyll-containing phytoplankton. These organisms also alter the quality and quantity of the light by absorption of light energy into the photosynthesis apparatus. Chlorophyll mainly absorbs light in the red-orange and blue parts of the spectrum, whereas the green part is scattered. However, due to the presence of accessory pigments other wavelengths than those absorbed by the chlorophyll are also utilised. The presence of dense phytoplankton blooms in the water can lead to an almost total extinction of light within the visible spectrum even at only a few decimetres below the surface. Clay particles, too, greatly increase backscattering and may substantially reduce the light in lowland lakes and glacier lakes.

To summarise, the penetration of photosynthetically active radiation into lake water is a function of optical properties of the water molecule and of the content of optically active dissolved and particulate matter. This means that for each given lake there is a certain depth below which photosynthetic plants cannot actively photosynthesise and grow. This depth is sometimes referred to as the compensation level for photosynthesis and is defined as the depth where (at a cellular level) the production of carbon equals the respiration. Although this depth varies with season, it can be used to divide the bottom areas into those that can and cannot harbour actively growing photosynthetic organisms (see below).

The light climate

Calculations of the light climate for plants suspended in the water column (i.e. phytoplankton) are considerably more difficult than measurements of the light penetrating to benthic plants. The reason for the difficulty is that phytoplankton cannot choose position in the water column but are transported from surface to bottom, or under stratified conditions, from the surface to the thermocline. In this case the average light intensity (I_{eff}) for an average cell of the phytoplankton population, assumed to circulate randomly within the upper layer, can be used (Blomqvist et al., 1981). It is calculated using the formula:

$$I_{eff} = \frac{1}{V_z}\sum_{i=0}^{n} I_i \frac{1-e^{-k_i \Delta z_i}}{k_i \Delta z_i} V_i$$

where z is the depth of the mixed layer, divided into n intervals, V_z the volume of the mixed layer, z_i the upper depth of the depth interval i, k_i the attenuation coefficient in the interval i, Dz_i the depth of the interval i and Vi the volume of the interval i.

In this manner calculations of the effective light climate reveal very different light conditions in the water compared to those on the surface but can only be used to describe the underwater light climate during the open water periods. The formula cannot be used for the part of the year when the lake is covered by ice, because at that time no currents are moving the phytoplankton around in the water. The plants existing under the ice usually possess a means of buoyancy regulation control (e.g. flagella) and are able to influence their position under the ice. On such occasions direct measurements of the light conditions are more relevant and relatively easy to perform. By combining the measurements of the light conditions under the ice, with calculations of the effective light climate, a picture of the seasonality of the underwater light climate for phytoplankton can be obtained. The differences between the light conditions above and below the surface are striking (Figure 8.6).

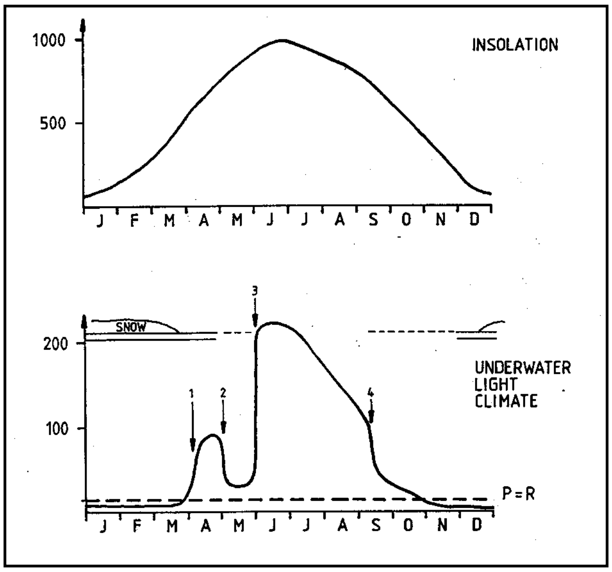

Figure 8.6. A generalised picture of the insolation to the lake surface vs. the underwater light climate for an average cell in the phytoplankton community in a dimictic lake in the northern part of the Temperate Zone. During the end of the winter stagnation period, when snow is gone and light penetrates the ice, the cell is assumed to be able to choose position in the water column and chooses to stay just beneath the ice. During the other seasons the cell is assumed to be circulating at random in the upper, partly illuminated, circulating layer of the pelagic zone.

The ecosystem of lakes

For functional reasons the ecosystem of lakes is often further divided into subunits (e.g. Hutchinson, 1975, Wetzel, 1983). First of all the lake ecosystem can be divided into two parts: the open water and the areas of the bottom and their various flora and fauna, the former having free-floating or swimming organisms and the latter with organisms attached to or moving on the bottom substrate.

The distribution of photosynthetically active radiation in amounts high enough to sustain photosynthesis can then be used to divide the benthic ecosystem into two subunits: the littoral zone which is illuminated and has green plants, and the deeper profundal zone which is the dark area lacking vegetation (Figure 8.7). The pelagic ecosystem can of course also be divided into an illuminated and a dark zone with respect to photosynthesis, but this division has little meaning since the organisms (at least the phytoplankton) are moved around in and out of these two layers with the currents. Instead, the pelagic zone is normally only divided into layers in cases of the presence of a thermocline. The resulting layers are then termed epilimnion, metalimnion (the thermocline), and hypolimnion (Figure 8.2 above). In some lakes on islands or close to the Baltic coast, an additional separation of layers may be done, due to formation of a halocline between water masses of different salinity.

The littoral zone

From a structural point of view, the littoral zone can be further divided (Figure 8.8). Starting from land, which from the littoral point of view is the 'epilittoral zone,' the first area affected by the lake water is the supra-littoral zone. It is located above the true littoral zone and is the part of the shore, which is affected by spraying from waves. The littoral zone then starts with the eulittoral zone, which is the zone between the highest and lowest seasonal water levels. This is the part of the littoral that is wet during high water periods (e.g. in the spring in temperate lakes) and dries out during low-water periods (e.g. mid-summer). Below that follows the infra-littoral zone, which is always wet and often has a characteristic zonation of macrophytes (see below). The area just below the littoral zone, bordering the profundal zone, is characterised by a lack of macrophytes and is termed the littoriprofundal.

In sheltered areas of the shore, a distinct macrophyte zonation often develops in the littoral. From the shoreline and extending to the deepest part of the infralittoral, three different zones can be distinguished. The innermost zone with emergent macrophytes is termed the helophyte zone. This is followed by the floating-leaves zone where the macrophytes have leaves that float on the surface. Finally the submersed zone with underwater plants is reached. In addition to the helophytes, the helophyte zone often also contains lemnids, which are free-floating plants with their roots freely exposed in the underlying water. Lemnids are more or less restricted to nutrient-rich waters, which can provide them with sufficient amounts of nutrients, and they are usually absent in oligotrophic waters. The submersed macrophytes can be further divided into elodeids and isoetids. The elodeids extend into the overlying water and have soft stems that can move with the currents, while isoetids grow close to the sediments. The latter are usually lacking in eutrophic systems and are characteristic of nutrient-poor clear-water lakes.

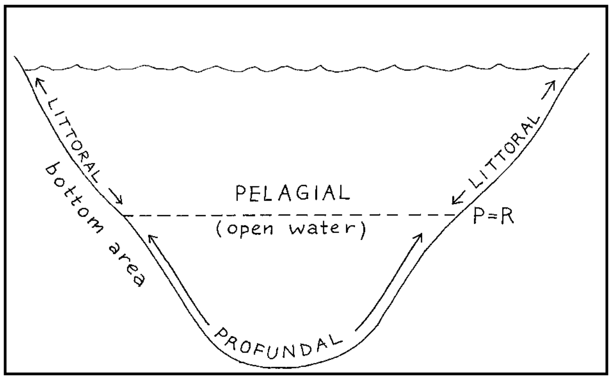

Figure 8.7. A lake ecosystem can be divided into two principal parts, the open water and the bottom area. The latter can then be further divided into the littoral zone (which has green plants) and the profundal zone, which lacks primary producers. Profundal and littoral areas are separated by the compensation level, i.e. where the photosynthetic production (P) equals the respiration of the primary producers.

Due to the shelter given by the macrophytes, the sediments of the littoral zone are soft and sedimentation rates may be considerable. Due to the canopy of macrophyte leaves above the surface, there is also very little light penetrating into this biotope. Hence, there is little room for microscopic plants on the sediment surface. However, the macrophytes provide a three-dimensional structure on which an abundant microflora can develop. This microflora is one part of a tightly linked ecosystem, with the periphyton, containing photosynthetic organisms such as algae and cyanobacteria, heterotrophic bacteria, fungi, protozoa and higher animals such as nematodes. Due to the three-dimensional structure of the biotope, the periphyton community acts as a very efficient filter of the water that passes through the littoral on its way from the groundwater or from smaller tributaries. After the passage through the littoral zone most of the nutrients and easily available dissolved organic compounds have been lost and, when entering the pelagic zone, the water contains mostly refractory organic matter. The functioning of the littoral zone as a sieve for incoming water has slowly been uncovered during the past two decades and relatively little is as yet known about the function of each organism. However, what is relatively clear is that the food for higher trophic levels to a great extent comes from this surface film and not from the macrophytes on which the periphyton community grows. Also the macrophytes may contribute to the production of the periphyton community through the uptake of substances through their roots, transport into the macrophytes and exudation through their stems and leaves. Since the surface film comprises an entire ecosystem with both autotrophic and heterotrophic parts, it is also active during periods of low insolation (e.g. in the winter). However, the net result of production and retention of different substances may vary on diurnal as well as seasonal basis.

The larger animals of the littoral

The littoral zone provides larger animals with an abundance of food of different size classes from large macrophyte parts to very minute bacteria. This wide range of food items promotes a high diversity of larger animals in the biotope. The abundant omnivorous benthic fauna include scrapers such as gastropods (snails) and various insect larvae that feed on the surface film, shredders that feed on larger organic material, and filtrators that feed on the fine particles in the biotope. With this high diversity of primary consumers also follows a high diversity of invertebrate predators such as leeches, the water spider and diving beetles. Many vertebrate predators (e.g. fish) spend most of their life in the littoral zone and the zone is also very important as a spawning ground for most fish in a lake. Dominant littoral fishes in northern Europe are adult roach (*Rutilius rutilus*), which are omnivores, medium-sized perch (*Perca fluviatilis*), which are more or less obligate benthic fauna feeders, and bleak (*Alburnus alburnus*), which feeds on plankton and surface fauna. The dominant piscivore, at least in lowland systems, is pike (*Esox lucius*). To avoid being preyed upon by visual predators (e.g. predatory fishes and birds), most fishes migrate in and out of the littoral zone on a daily basis.

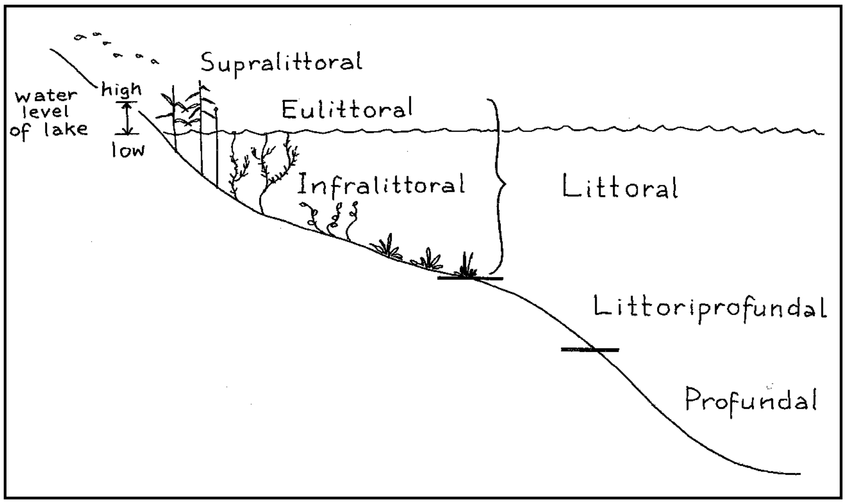

Figure 8.8. The shore and the littoral zone can be divided into different sections with respect to the influence of lake water. The supralittoral section is the part affected only by wave-induced spray. Below that follows the littoral zone, which can be divided into the eulittoral section (the area between the highest and lowest annual water level of the lake) and the infralittoral section (which is always under water). The outermost zone, which lacks vascular plants and constitutes the border to the profundal zone, is termed the littoriprofundal. In this zone primary production is principally carried out by microflora (e.g. algae and cyanobacteria). In the infralittoral zone of sheltered areas of the littoral, there is often a pronounced zonation of aquatic macrophytes.

Special types of littorals

In large lakes, where wave-action is considerable, a special type of littoral zone develops, often referred to as the wind-exposed littoral zone. This zone is characterised by a lack of macrophytes and the dominance of attached photosynthetic organisms, mostly larger algae and cyanobacteria. There is often a pronounced zonation of these larger photosynthetic organisms in the biotope, the upper part of which has to be recolonised each year during periods of high water levels in the lake. The coarse substrate in the biotope is caused by the wave's activity, which prevents finer material to settle. In northern latitudes, the ice-out also often causes major disturbance in the system on those sides of the lake where the ice is forced onto the shore. This is a highly productive system, in open contact with the nutrient rich groundwater, which easily enters the lake through the coarse bottom substrate dominating close to the shore. As in the case of the sheltered littoral, the existing organisms act as a filter to the incoming water and sieve off much of the nutrients. Since there are no macrophytes shading the system, there is plenty of light entering the water, which promotes a high primary production. Another reason for the high productivity of the system is that the waves continuously bring in new nutrients to the system and remove waste products. On the larger photosynthetic organisms and on all other substrates in the ecosystem, a surface film like that in the sheltered littoral develops, containing microscopic plants, bacteria, fungi and microfauna. The surface film is an important source of food for larger benthic fauna animals, and scrapers (e.g. gastropods and insect larvae) often dominate the biotope. This is also the main biotope for the largest benthic fauna in North Temperate lakes, the crayfish. Crayfish use the cavities between the stones to hide from fish predators and they are omnivores that feed on the attached plants and animals during the night. The benthic fauna in turn provides food for invertebrate predators, such as leeches, and for fish. The dominant fishes in this system are the same as in the sheltered littoral, i.e. roach and perch. Most of the fishes migrate in and out of the biotope on a daily basis in order to avoid predation by e.g. piscivorous birds. In contrast to the situation in the wind-sheltered littoral, there is very little room to hide from predators in the exposed littoral zone.

However, there are at least two stationary species of fish that are characteristic of this biotope, miller's thumb (*Cottus gobio*) and small individuals of burbot (*Lota lota*), which hide under the stones. Piscivorous fish (in this biotope mainly pike) also perform daily migrations in and out of the biotope in order to escape predators. Through this migration, the fish bring nutrients harvested in the biotope out to deeper strata, thereby acting as a pump for nutrients and organic matter between the littoral zone and the open water.

Brown-water lakes surrounded by *Sphagnum* mosses may often have a special kind of littoral zone, with a different function from the one described above. The mosses, which lack true roots, often lose their attachment to the bottom where the entire littoral zone floats at the outer edge. In the case of dominance by *Sphagnum*, the three-dimensional structure is more or less closed by the dense growth of the moss, and few larger animals are able to penetrate into the vegetation. Although poorly studied, it seems to be a general characteristic that these lakes have very little littoral macrofauna, concentrated to the vertical outer part of the edge of the vegetation. In such systems, the populations of littoral fish are also often limited.

The littoral sieve

The main functional characteristics of the littoral zone are summarised in Figure 8.9. In contrast to the situation in other lake biotopes, relatively little is known about the quantitative importance of different processes connected to energy and material cycling in the littoral. Wetzel (1996) championed the function of the littoral as a sieve, filtering off most of the valuable substances from the inflowing water before it reaches the pelagic zone. However, there are also other, less studied processes that may act in the opposite direction; i.e. the dramatic event of ice-out in North Temperate lakes and the effects of fish and other organisms migrating in and out of the system.

The pelagic zone

The pelagic ecosystem contains two basic groups of organisms: *plankton*, which cannot resist wind-generated currents and therefore are transported around in the water column, and *nekton*, which can swim and thereby choose their position relative to the currents. As in most other cases there are no distinct borders between these two major groups. Larger zooplankton (e.g. copepods and cladocerans) can migrate up and down in the water on a daily basis and most flagellated organisms can also choose position if conditions are calm.

Plankton consists of at least four functionally different groups of organisms: phytoplankton, bacterioplankton, protozooplankton and metazooplankton.

Phytoplankton

Phytoplankton is always pigmented and can photosynthesise when light is available. However, most phytoplankton is not obligate autotrophs but can also utilise dissolved and particulate organic carbon to supplement their growth (heterotrophy). This ability to be both a plant and an animal is most pronounced among motile forms (flagellates) and is

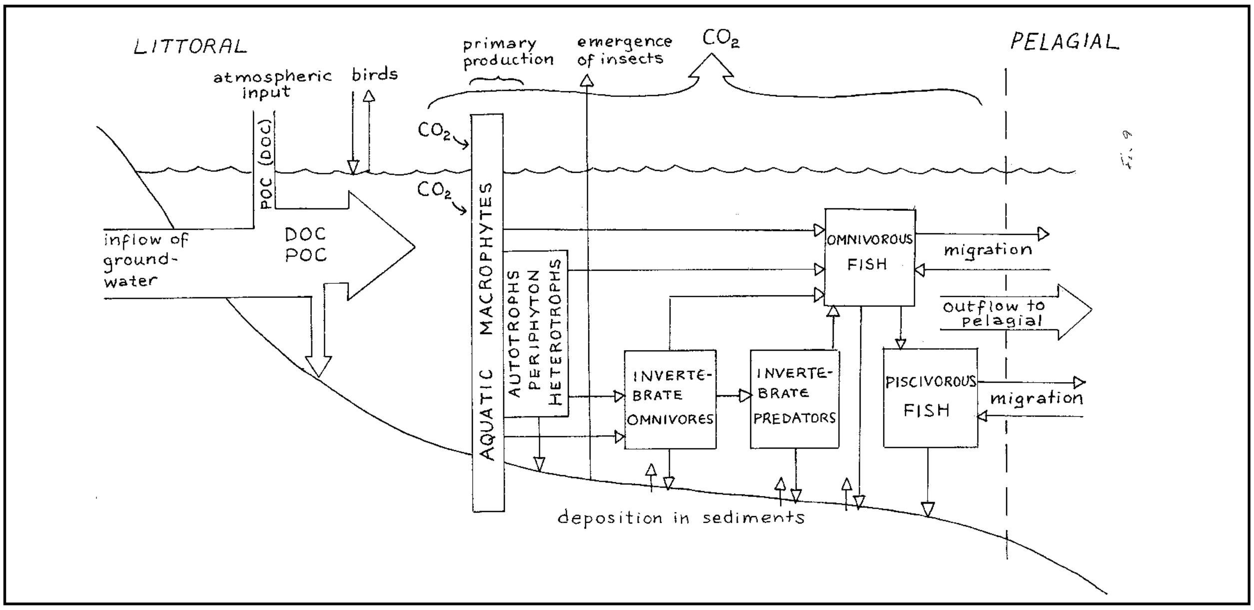

Figure 8.9. Generalised picture of the flow of energy and material through the littoral zone of a lake.

termed mixotrophy. During periods of low light or low availability of dissolved inorganic substances, phytoplankton can grow directly on organic carbon or supplement themselves with nutrients from the digestion of organic compounds and use it in the formation of organic carbon via photosynthesis. Several different taxonomic groups are found in the phytoplankton, the most important in lakes being the following:

Cyanobacteria (formerly termed blue-green algae) are among the oldest organisms on earth and consists of many species. Cyanobacteria are mostly autotrophs, although ability to utilise dissolved organic carbon has been shown. One important characteristic found among the cyanobacteria that carry a specialised type of cell, termed heterocyte, is the ability to fix molecular N. In situations where N is limiting to primary production but other nutrients are still available, nitrogen-fixing cyanobacteria often become dominant in the phytoplankton community. However, nitrogen fixation is an energy-demanding process and pelagic nitrogen-fixing cyanobacteria are therefore only present in nutrient-rich waters. Cyanobacteria's major importance to plankton comes during the warm part of the year (late summer). They are usually of little value to grazers due both to their size, which make them difficult to ingest, and to the gelatinous envelopes which surround them, making them difficult to digest, and/or due to their ability to produce strong toxins, causing grazers to avoid them. This group also includes many very small (< 2 µm, mostly < 1 µm) unicellular organisms collectively termed autotrophic picoplankton (see also green algae below).

Chrysophyceae contain mostly flagellates, many of which are small and unicellular. These are the dominant organisms in nutrient-poor waters, particularly brown-waters, and have their maximum importance in spring and early summer. In early summer they are also very important in more nutrient-rich systems. They benefit from their ability to utilise bacterioplankton as a source of carbon and nutrients at times when the concentrations of inorganic nutrients are low (i.e. always in nutrient-poor waters and, during the early part of the stratified period, in more nutrient-rich waters as well). In the same functional group of phytoplankton there are also two other taxonomic groups: *Haptophyceae* and *Cryptophyceae*, both exclusively composed of flagellates. Altogether, these small flagellates constitute the best available food for herbivorous zooplankton. Considerable losses due to grazing occur in all three groups.

Bacillariophyceae (diatoms) are not found in low-alkalinity or acidic oligotrophic waters. Instead their main importance is in more nutrient-rich lakes and they are most successful during periods of full circulation (i.e. in dimictic lakes during spring and fall circulation). They are mostly autotrophic plants, which impregnate their cell walls with silica. The silicified cell walls make them heavy and during calm conditions they settle quickly out of the water column. Many diatoms are too big to be ingested by herbivorous zooplankton, but after sedimentation they constitute one of the most important sources of energy for herbivorous benthic organisms in the profundal zone.

Dinophyceae (dinoflagellates) have their most important period in late winter under the ice and during the later part of the summer stratification (during the same period when cyanobacteria are favoured). The group consists almost exclusively of relatively large flagellates, which benefit from their ability to migrate vertically and obtain nutrients from deeper strata and/or from their ability to ingest large prey (e.g. other phytoplankton). Both of these abilities are very useful at times of low turbulence and scarcity of inorganic nutrients, e.g. the stratified periods.

Chlorophyceae (green algae) are of most importance in highly eutrophicated lakes and in ponds. In natural lakes they are often found to dominate in early summer, just after the small flagellates. They benefit from their ability to pass undigested through the gut of herbivorous zooplankton in which they can also utilise the nutrients released from digested phytoplankton. This group also includes many picoplanktonic forms, which, however, are usually slightly larger than the picoplanktonic cyanobacteria. Picoplanktonic green algae are usually within the size range of 1-2 µm.

Bacterioplankton

Bacterioplankton are small organisms, usually picoplanktonic by size (< 2 µm). The best-studied bacterioplankton are the heterotrophic forms, which utilise organic carbon as an energy source. In lakes with little input of allochtonous carbon (from the drainage area), these organisms are dependent on phytoplankton for a carbon supply. In such systems (e.g. clear-water lakes) they are usually of less importance to the total production at the base of the food web. In systems with a high input of organic carbon (e.g. brown-water lakes) the importance of heterotrophic bacterioplankton is much greater and there they often compete directly with the autotrophs for inorganic nutrients which they need to metabolise the organic material. Since bacterioplankton are smaller, and thereby have a larger surface to volume ratio, promoting rapid uptake of nutrients, they often out compete the larger autotrophs and become the dominant producers of biomass for higher trophic levels. Another factor contributing to the imbalance between bacterioplankton and phytoplankton in brown-water lakes is the coloured dissolved organic substances, which bring about the poor light climate. In brown-water lakes, autotrophic phytoplankton is scarce but the presence of bacterioplankton instead promotes mixotrophic flagellates, which obtain nutrients and energy from ingestion of bacteria.

Protozooplankton

Protozooplankton consists of unicellular organisms. They are mostly heterotrophic and feed on smaller particles such as bacterioplankton and phytoplankton. However, some protozooplankton have symbiotic green algae inside their cells, providing organic carbon to their hosts. Protozooplankton can be divided into at least three sub-groups: heterotrophic nannoflagellates (HNF), *Ciliata*, and *Heliozoa*. The heterotrophic nanoflagellates are a heterogeneous group, many of which are related to mixotrophic phytoflagellates (especially *Chrysophyceae* and *Cryptophyceae*). All three groups of protozooplankton have representatives that feed on bacteria as well as on phytoplankton and many species also feed on their own relatives. Protozooplankton are also fed upon by metazooplankton and usually have their period of maximum abundance in early summer, before metazooplankton have developed. All three groups also contain species that attach to larger planktonic organisms (phytoplankton and metazooplankton).

Metazooplankton

Metazooplankton consists principally of three taxonomic groups of organisms: *Rotatoria*, *Cladocera* and *Copepoda*. They are all heterotrophic and feed on other organisms such as bacterioplankton, phytoplankton and their own relatives. Many metazooplankton are filter feeders, and filtrate the water from particles within a given size range. The best-studied group in this respect is *Cladocera*, in which the size range of harvested particles has been determined for a large number of organisms (e.g. Bern, 1990). Regarded as a group, *Cladocera* have a size preference of prey ranging from about 1-60 µm in diameter, with considerable variation among different species. Within this size range are bacterioplankton, small phytoplankton and many protozooplankton, which thus suffer losses to predation by these animals. The filter feeders are often non-selective, i.e. they do not usually select certain particles within the size range of their feed. Also many copepods can filter-feed, but these organisms usually select relatively large (20-60 µm) particles and they can also switch to a grasping mode of feeding. Rotifer feeding is the least studied but it is known that many species feed on small particles (e.g. picoplankton). However, there are also ‘graspers’ within that group and they select considerably larger food items, including other rotifers as well.

Nekton

Nekton are comprised of invertebrate and vertebrate organisms, in temperate areas the latter almost exclusively being fish.

The invertebrate nekton are principally composed of insect larvae such as *Chaoborus* larvae and larger crustaceans e.g. the opossum shrimp *Mysis relicta*. In northern Europe, unless deliberately introduced, *Mysis* and other large crustaceans of marine origin are restricted to lakes in land-rise areas, which at some time after the last glaciation have been the bottom of the sea (so called marine-glacial relicts). These invertebrate nekton are usually zooplanktivores and feed on metazooplankton such as cladocerans and copepods. To avoid predation by fish, *Mysis* and *Chaoborus* larva perform diurnal vertical migrations to the surface during night for feeding and to the bottom during daytime to hide from visual predators.

Few fish spend their entire life in the pelagic zone and most species undergo ontogenic diet shifts (i.e. they change their main diet and thereby also usually their habitat as they grow). Fish fry usually spend a period of their lives in the open water feeding on zooplankton. Most species then return to the littoral zone to feed on the organisms produced there, but in northern Europe at least 4-5 species stay pelagic for the rest of their lives. Most of these pelagic fish form schools with many thousands of individuals that systematically clear the water from crustacean zooplankton as they move around in the lake. Examples of fishes that stay planktivoruos during most of their lives are smelt (*Osmerus eperlanus*), vendace (*Coregonus albula*), arctic charr (*Salvelinus alpinus*), zope (*Abramis ballerus*) and certain forms of whitefish (*Coregonus sp.*). The presence of schools of planktivorous fish also attracts predators (piscivores) and examples of fishes that typically prey on the planktivores are pikeperch (*Stizostedion lucioperca*), trout (*Salmo trutta*), large perch *(Perca fluviatilis*), burbot (*Lota lota*) and asp (*Aspius aspius*).

The function of the pelagic zone

From a functional point of view, the basic production in the pelagic zone is carried out by phytoplankton and bacterioplankton (Figure 8.10). The balance between these two groups of organisms is to a great extent determined by the presence or absence of an allochtonous carbon source (e.g. humus and other organic compounds from the drainage area). In clear-water lakes the organic material for bacterioplankton growth is provided by phytoplankton, which then control the system. In brown-water systems, bacterioplankton principally utilise allochtonous substances for their growth and can thereby compete with phytoplankton for inorganic nutrients – a competition often won by bacterioplankton. In such systems, bacterioplankton can dominate the production of biomass at the base of the pelagic food-web. However, mixotrophic flagellates can then feed upon bacterioplankton and thereby phytoplankton biomass is sometimes significant in brown-water systems as well. Protozooplankton and metazooplankton also feed on bacterioplankton, as well as on small phytoplankton. Protozooplankton are fed upon by metazooplankton, which in turn are fed upon by invertebrate nekton, and planktivorous fish feed upon both these latter groups. Piscivorous fish, finally, feed upon planktivorous fish. Altogether, the interactions among pelagic biota give rise to a very complicated flow of energy through the pelagic food-web, with numerous loops and feed-back mechanisms. Organisms from the pelagic ecosystem are lost through the outlet of the lake and via sedimentation to the bottom. The sediments are also used by many of the pelagic organisms (e.g. phytoplankton and zooplankton) for rest during periods of unfavourable conditions in the water (e.g. winter).

The profundal zone

An important structural characteristic of the profundal zone is the lack of photosynthesising organisms. Due to the poor light conditions, the organisms here are dependent on import of organic carbon, which has been produced in other biotopes of the lake and in the drainage area. The profundal zone thus is fuelled by organic carbon from the surroundings, especially from the pelagic zone (Figure 8.11). Organic carbon from the water column, especially in the form of living and dead phytoplankton, is settled and concentrated on the sediments. The true accumulation bottoms are final stations for the sedimenting material. However, profundal lake bottoms may also be transport bottoms, where the sediment particles occasionally are resuspended and further transported to other, often deeper, areas of the lake. This is especially pronounced in shallow lakes, where transport bottoms often dominate the profundal zone, and resuspension is of major importance for the exchange of material and nutrients between sediment and lake water.

The settling organic material is initially utilised by various heterotrophic organisms, e.g. bacteria, fungi etc., a process that may already start in the lake water. The depth of the lake and the resistance of the organic material to decay thus determines how much of the microbial utilisation takes place in the water and how much in the sediments. It is not uncommon that the microbial activity in settling particles results in high bacterial growth rates and even net uptake of inorganic nutrients from the water on its way down to the sediments. The various microbial organisms have different sources of carbon supply, but the availability of easily degraded carbon forms may regulate the profundal production, even in sediments with high organic content. The various types of organic matter are successively exhausted in the order of their biodegradability, which results in a bulk of organic compounds with very long turnover time in the sediments. As a consequence, sedimentation events after spring and autumn blooms of phytoplankton, which bring in new substrates, are coupled to periods of high bacterial activity. Other factors that regulate the bacterial activity are temperature and availability of electron acceptors. During aerobic conditions, molecular oxygen (O_2) is the main electron acceptor, but anoxic conditions prevail even within a few millimetres depth of the sediment, and may also extend into the overlaying lake water during periods of stratification. During these reduced con-

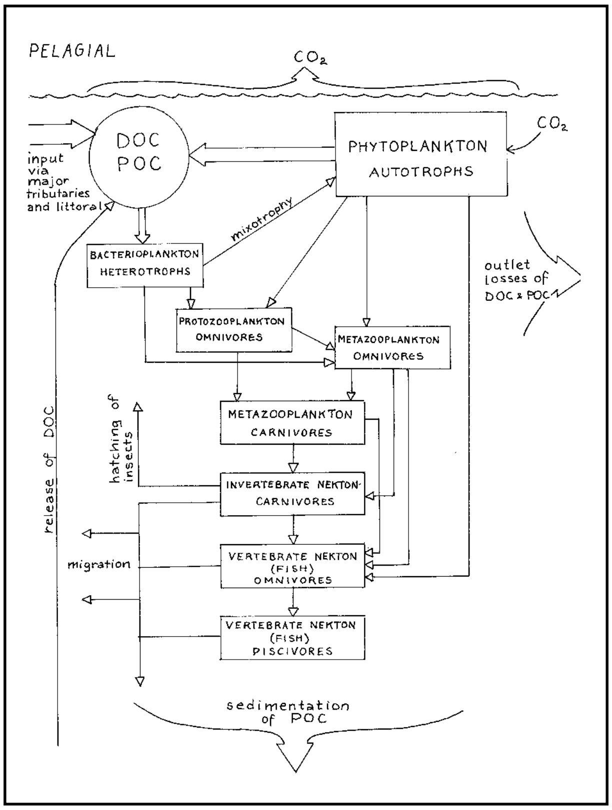

Figure 8.10. Generalised picture of the flow of energy and material through the pelagic ecosystem of a lake.

ditions, fermentation of organic compounds occurs. Different functional groups of bacteria will then utilise NO_3^-, MnO_2, $Fe(OH)_3$, SO_4^{2-} and CO_2 in a gradient of more reduced conditions with increasing sediment depth. However, the composition of profundal sediments is complex and processes like bioturbation and resuspension alter the environmental conditions, thereby creating a heterogeneous and constantly fluctuating pattern of microhabitats in a three-dimensional structure. This enables all kinds of microbial processes to occur simultaneously, with their varying extents determined by the more large-scale fluctuations of sedimentation, stratification etc.

When sulphate is reduced in the sediments to elemental S and further to sulphide, hydrogen sulphide is formed, a strong poison to most oxygen demanding organisms. Thus, despite organic material (i.e. food resources) in abundance, the animals living in the profundal zone may have to face harsh environmental conditions at least temporarily. Dead phytoplankton, and bacteria colonising these and other sediment particles, are the prime sources of food for the benthic fauna. The benthic fauna can be divided into three size classes, termed micro-, meio-, and macrofauna. The ecology of the microfauna (animals < 200 μm) is poorly known but protozoans (ciliates, heliozoans and heterotrophic nanoflagellates) and rotifers are important constituents of that size class. Little is known about the meiofauna (size between 200 μm and 2 mm) but motile crustaceans (e.g. *Ostracoda* and *Copepoda*) are abundant in the profundal zone and feed on particles at the sediment surface. The macrofauna has been better studied and is usually dominated by one or a combination of organisms from either *Oligochaeta* or *Chironomidae* (larvae of a *Diptera*; *Insecta*). Aquatic oligochaetes, like their relatives on land, ingest sediment when digging through the system. Chironomid larvae are often filter feeders and take the settling particles as they arrive to the sediment surface. Among the chironomids there are also many taxa that act as predators on the other benthic fauna present in the biotope. Micro- and meiofauna as well as the oligochaets usually spend their entire life cycle in the sediments, while the chironomids at certain occasions during the year swim to the surface, develop into pupae, hatch and leave the lake for adulthood in the terrestrial ecosystem surrounding the lake. On such occasions many chironomids become victims to the fish in the open water that feed on these organisms, which at the same time can be termed 'benthic fauna' and 'nekton.' As the chironomids leave the biotope to turn into fully developed air insects, so does part of the organic carbon and nutrients from the sediments. This is one of the processes by which living organic carbon is exported from this 'import-dominated' system. Few fish spend their life in the profundal zone but a typical example of a bottom dwelling fish frequently found in the dark deeper parts of the lake is ruffe (*Gymnocephalus cernuus*). The adult stages of this small fish are bottom-fauna feeders and the ruffe can also hunt in very limited light conditions thanks to its eye pigmentation, which reflects and thereby concentrates light. Most other fishes found in the profundal zone stay there only occasionally to rest (e.g. planktivores and piscivores from the pelagic zone).

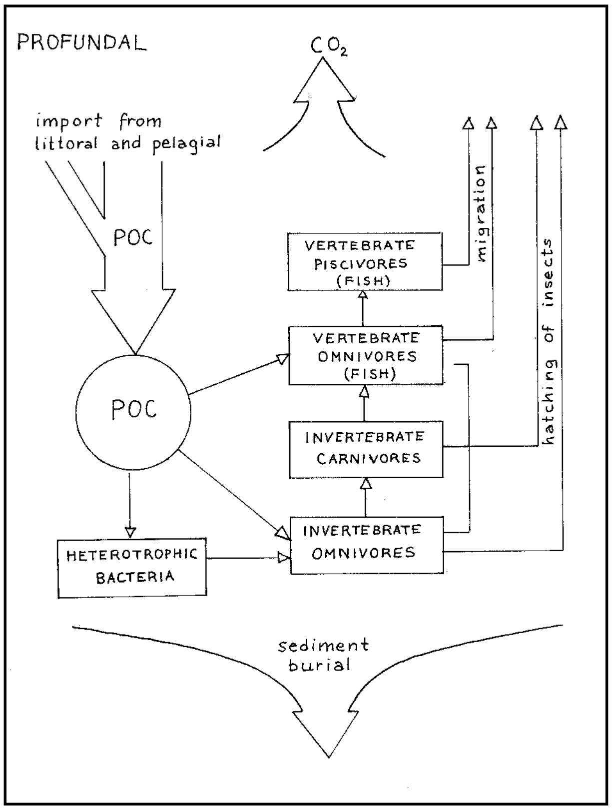

Figure 8.11. Generalised picture of the flow of energy and material to and from the profundal zone of a lake.

An integrated view of the functioning of the lake ecosystem

Putting the three subunits of the lake ecosystem together, a picture of the functioning of lake ecosystems emerges (Figure 8.14). The basic function of the lake in the drainage area is as a sink for particles and nutrients from the aquatic and terrestrial ecosystems upstream. This means that fewer nutrients and particles leave the lake systems than enter through the tributaries. The retention of material occurs in several steps. In a first step, the littoral zone acts as a sieve for particles and nutrients entering with the groundwater and through small tributaries. The caught material is stored in this part of the lake but later released and transported further into the sys-

Water quality in lakes

Table 8.2. The three most important independent variables for the quality of fresh water (From Laaksonen, 1970)

Independent variable	Dependent variable						
	Suspended Solids	Conductivity	Colour	BOD$_5$	Tot-N	Tot-P	Tot-S
Percent lake area	II		III	II	II	II	
Mean discharge							
Percent peat land							
Percent cultivated land	III	III			III		I
Fraction waste water		I		III		I	II
Fraction Litorina area	I	II	I				III
Percent drained peat			II	I			
Percent clay soils						III	
Percent alkaline minerals					I		

The water authorities in Finland have published two reports (Laaksonen, 1970;1972) of general interest to the area of lake water composition. The results are presented as areal averages of the 26 variables listed in Table 8.4. A more advanced statistical analysis has been made on ten of the variables, considered as dependent on another set of independent variables representing environmental conditions such as temperature, percentages of lakes, mineral soils, peat, etc. The geographical variation in average concentrations of the subareas, though not unexpected, is a valuable contribution in assessing the effect of geology, past history and present human activities.

The data analysis of the ten selected variables has been performed in two ways. The first was a type of factor analysis and the other was a multivariable regression analysis seeking to find the most important of the independent variables for each dependent variable. This analysis is presented in summary in Table 8.2, listing and ranking the three most important independent variables, limited here to eight variables. The independent variable named Litorina is the percentage of land within a subarea that inundated the present land area at the time of the Litorina Sea. During this time saline water soaked the rocks and soil and the clay, and silt washed out of the glacial debris settled to form the present clay soils. The average concentrations for the country as a whole are also given and are found in Table 8.4.

The second paper is a study of the stratification which takes place in ice covered lakes. The stratification observed in the chemical properties is a result of the biological processes in the water. Some heat flow from the bottom sediments will induce a circulation pattern and strong winds on the ice surface may induce some internal

Table 8.3. Average water quality in March for 155 stations (Laaksonen, 1972)

Variable	Sampling depth			
	1 m	5 m	Mid depth	Bottom-1 m
Sampling depth in m	1	5	19	35
Temperature, °C	0.5	1.2	2.2	3.2
Oxygen, percent of saturation	83	81	70	37
Carbon dioxide, mg/l	5	5	7	14
Suspended solids, mg/l	1.6	1.3	1.8	6.0
Conductivity at 18 °C, mS/m	4.6	4.5	5.0	6.0
Alkalinity, me/l	0.17	0.16	0.18	0.29
pH	6.6	6.6	6.5	6.4
Colour, mg/l Pt	49	45	48	89
$KMnO_4$ consumption, mg/l	42	41	48	55
Total nitrogen, mg/l N	0.5	0.5	0.5	0.8
Total phosphorous, mmg/l P	19	16	28	75
Total sulphur, mg/l S	3.1	3.2	3.6	3.6
Potassium, mg/l	1.2	1.2	1.2	1.3
Calcium, mg/l	4.2	4.2	4.7	5.2
Sodium, mg/l	2.7	2.7	3.1	3.4
Magnesium, mg/l	1.5	1.4	1.5	1.7
Iron, mg/l	0.3	0.2	0.3	1.8
Silica, mg SiO_2 /l	2.9	2.7	3.0	4.0

Table 8.4. Composition of lake water in Finland. Analysis of chemical and physical data based on water samples collected four times a year at 160 research stations during 1962–1968. Computed from the data by Laaksonen (1970)

Variable	Unit	Amount
Oxygen	Percent of saturation	85
Turbidity	Abs.units times 1 000	14
Suspended solids	mg/l	13.3
Total residue	mg/l	90
Fixed residue	mg/l	51
Conductivity at 18C	mS/m	6.9
Alkalinity	me/l	0.24
Total hardness	°dH	1.5
pH		6.6
Colour	mg/l Pt	91
$KMnO_4$	mg/l $KMnO_4$	56
BOD_5	mg/l O_2	1.9
Coliforms	colonies/100 ml	2 500
Enterococci	colonies/100 ml	700
Total nitrogen	mg/l N	0.8
Total phosphorous	mmg/l P	58
Total sulphur	mg/l S	4.9
Potassium	mg/l	1.7
Sodium	mg/l	4.6
Calcium	mg/l	5.9
Magnesium	mg/l	2.1
Chloride	mg/l	6.1
Iron	mg/l	1.1
Manganese	mg/l	0.1

seiches, presumably weak ones. The vertical mixing below an ice cover is thus rather weak. Assimilation will go on and the phytoplankton will sink towards the bottom. Decomposition of organic matter continues, however, releasing carbon dioxide, nitrate and phosphate along the vertical path, creating the chemical stratification.

Water samples were collected from large and fairly large lakes at 155 stations, most of them on the so-called lake plateau. The sampling took place in the later part of March at four depths, 1 m, 5 m, mid depth and 1 m above the bottom, selecting the deepest portion of the lakes. This sampling program started in 1965 and ended in 1970. The presentation of results is similar to that of the previous investigation, listing the area averages on the subareas of the map. Table 8.3 shows the averaged concentrations of all subareas averages and demonstrates very well the biological enrichment mechanism of stable stratification.

Temperature regime

The temperature regime in four of the large lakes is shown in Figure 8.13 and displays differences in the local climates in the north and the south. On the lake plateau the disappearance in spring of temperature stratification occurs in the second half of May whereas in Lake Inarijärvi in the north it take place in early June. The same event in the fall occurs at the end of November in Lake Päijänne while it takes place one month earlier in Lake Inarijärvi. The depth of the lakes influences these processes, greater depth delaying the adjustment of temperature.

Erik Eriksson

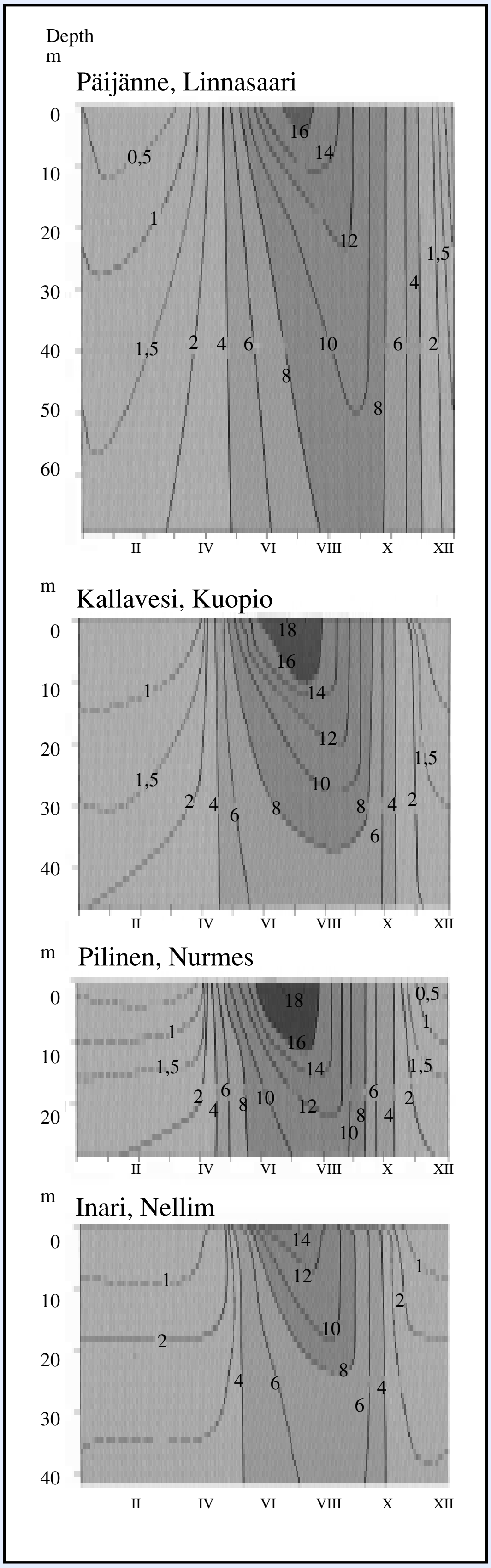

Figure 8.13. Annual course of water temperature in representative lakes in 1961-1975 (from National Board of Survey & Geographical Society of Finland, 1986; Atlas of Finland, folio 132, figure 18a, published according to permission no 420/MAR/98).

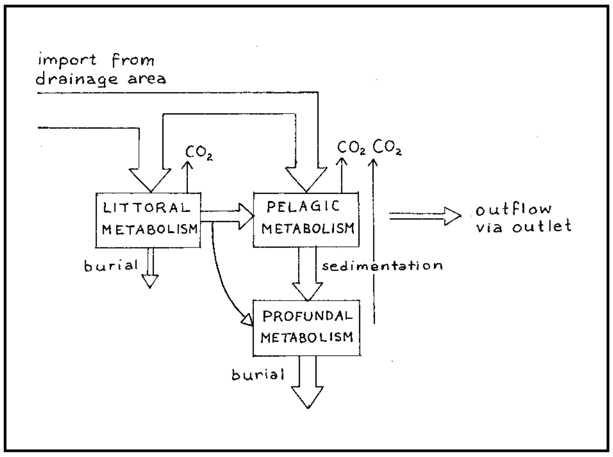

Figure 8.14. The functioning of a lake ecosystem, and its different biotopes, as a trap of particulate matter and nutrients from the water flowing through the system.

tem, either along the bottom or passing by the pelagic zone. Secondly, particles and dissolved material entering the lake through major tributaries are processed within the pelagic zone and leave for deeper strata and finally the fine sediments of the profundal zone via sedimentation. Organic material and nitrogen is lost from the sediments in the form of CO_2 and N_2, respectively, due to respiration of the organic material settling there. Phosphorus, and also nitrogen and organic carbon in dissolved form, is lost from the sediments through diffusion and resuspension processes and is transported back to the pelagic zone by water currents during the circulation periods. However, as a net outcome over the year in most natural lakes, the sediments act as a final sink for a considerable part of the material entering the lake ecosystem.

Finally, to complete the picture of the lake as part of the hydrological cycle, it must be emphasised that although lakes act as a trap for material entering the system, this does not mean that nothing is transported through the lake and lost through the outlet. During periods of flow, most of the non-motile components (i.e. plankton) of the pelagic ecosystem and all forms of dissolved substances (inorganic as well as organic) are lost through the outlet. The export of newly produced organic substances through the outlet provides the running water fauna just downstream with excellent food and the richest bottom fauna found in running waters often occurs just downstream a lake. Thus, the connections between the ecosystems within a catchment indeed are tight and what is lost from one system is usually utilised in the next.

9.

THE RIVER CHANNEL

Wojciech Puchalski

River channel processes, the traditional approach

Water quality is one of the major issues in river management. Management depends mostly on the quality and quantity of substances that are dissolved or suspended in the water. If a river is not polluted by point sources (industrial or municipal sewage, which should be treated in appropriate sewage treatment plants), special consideration is paid to nutrients, i.e. nitrogen and phosphorus compounds, which are the most common factors limiting primary production of algae and macrophytes. Excessive nutrient availability results in extensive growth of submerged macrophytes and filamentous algae in river channels (undesirable from the point of view of flood control and drainage management). However, the most important effect is the development of phytoplankton bloom in the recipients of river water – lakes, reservoirs and the sea, as well as in large lowland river channels. There are three main sources of nutrients: atmospheric precipitation, leaching of bedrock minerals, and anthropogenic sources (sewage, fertilisers, emissions to air, intensified soil erosion).

The river has always been considered an open ecosystem, i.e. its functions depend on the external load of matter. Groundwater discharge (subsurface flow) through springs and seepage (bottom and lateral) is a main and relatively stable source of water in most river channels. Surface flows become important during extensive rain and snowmelt events, resulting in floods. Subsurface flows also provide loads of dissolved matter, both inorganic (as dissolved ions) and organic (DOM). Waters from surface flows contain dissolved matter (often different in its composition and concentrations than that in groundwater), but also carry loads of particular inorganic (e.g. silt, sand) and organic matter (POM), such as fine (FPOM) and coarse (CPOM) detritus, plant debris, or even tree branches and trunks during large floods. For forest streams, tree litter is an important source of POM. Dissolved gases (O_2, N_2, and CO_2) come from groundwater and atmosphere and are, under turbulent conditions, relatively freely exchangeable with the atmospheric pools.

Channel processes may be divided into three groups as described below.

Physical (erosion/sedimentation) processes

The variability of these processes depends mainly on current velocities, which are different in space and time depending on channel morphology, slope, bottom roughness and water discharge. A gradual increase of current-velocity leads to bottom and/or bank erosion, evolving from light, small particles to heavier ones, which are transported downstream. These particles sediment in stream segments with lower flow velocities. Thus, particular matter is not only moved, but also sorted according to particle dimensions. A bottom of riffles is built of stones or boulders and runs of sand and gravel or of organic detritus. Pool bottoms may be covered by silt, thus becoming impermeable for groundwater discharge. Differential lateral erosion of lowland river channels causes their meandering and later the formation of backwaters and oxbow lakes. Large structures in river channels, such as boulders or fallen tree trunks, produce local differences in current-velocities, further increasing the structural diversity of the channel. Microhabitat diversity, resulting from physical processes, is a key factor for the intensity of chemical and biological processes.

Chemical processes

These are mainly adsorption/desorption processes, as binding phosphate or metal ions to clay particles, co-precipitation of phosphate with $CaCO_3$ (precipitating as a result of CO_2 depletion by photosynthesis), precipitation of humic substances with calcium ions, formation of organic complexes by binding metal or phosphate ions to dissolved humic substances. These processes reduce the biological availability of phosphorus and heavy metal toxicity; however, they are reversible and in a changing environment, carbonate sediments may dissolve when CO_2 or hydronium ion concentrations increase, and when humic complexes become destroyed by photooxidation.

Precipitated particles are light enough to be transported relatively long distances with water currents. Then they settle down with detritus or silt particles, forming calcium- or phosphorus-rich fine sediments, important for biological processes.

Special attention should be paid to chemical processes in poorly buffered (i.e. with low bicarbonate concentrations) streams undergoing acidification, where aluminium and heavy metal ions become soluble (and toxic); solubility and availability of phosphorus also increases.

Biological uptake/release processes

If sunlight access is sufficient, algae and higher plants assimilate carbon dioxide (as dissolved gas or bicarbonate) in photosynthesis, whereby oxygen is released to the water. In the production of more complex plants, organic matter (primary production) and elements such as nitrogen, phosphorus (in the approximate ratio C:N:P = 100:16:1), and microelements (K, Ca, Mg, S, Si, and some others) are assimilated from water, mostly in soluble ionic forms. Nitrogen is assimilated as NH_4^+ or NO_3^-, or rarely as urea or free amino acids. Some cyanobacteria are able to fix elemental nitrogen, but this process is of minor importance. On the other hand, non-heterocystous cyanobacteria are dependent on ammonia as a nitrogen source; nitrate may be even toxic to them. Phosphorus is fixed as dissolved PO_4^{3-}, but some algae are able to produce exoenzymes (phosphatases), hydrolysing organic phosphate esters.

Nutrients, assimilated by rooted plants and attached algae, may be considered as temporarily retained. Also, a high productivity by dense vegetation (as a result of high nutrient availability) may lead to the precipitation of $CaCO_3$, connected to a partial immobilisation of phosphorus. The plant organic matter produced may be consumed (in temperate rivers mostly by invertebrates; diatoms are preferred as a food source over red algae or green algae with thick cell walls and vascular plants) or decomposed by bacteria after the vegetation period. Plants also excrete some amounts of dissolved organic matter, also easily assimilated by bacteria.

Plant debris, both of autochthonous (grown in the river) and allochthonous (transported from external land ecosystems, such as tree leaves) origins, undergoing decomposition by bacteria and fungi, with considerable participation of some invertebrates (shredders) that fragment large plant material into smaller particles. The decomposed particulate and dissolved organic matter finally ends up as mineral element species. However, leaf packs and allochthonous organic sediments in stream channels may play an important role in the retention of dissolved nitrogen and phosphorus. In that case it is a result of very high ratios of C to N and P in leaf litter (as high as 760:20:1; Bretschko & Moser, 1993) due to nutrient retranslocation from leaves to timber tissues before fallout. Therefore it is necessary for decomposing organisms – bacteria and fungi – to assimilate dissolved N and P compounds from water to synthesise the organic matter of their cells. Thus heterotrophic nutrient uptake by sediment particles is considered an important mechanism for reducing available nutrient concentrations in river water.

Photo, Inga-May Lehman Nådin.

Inorganic or organic allochthonous matter and light-energy availability determine the auto- or heterotrophic character of stream ecosystems. Agricultural streams, with high nutrient loads and light access, are autotrophic, whereas forest streams, loaded with organic matter under closed tree canopies, are heterotrophic. Autotrophic food chains are more effective in terms of final consumer yield (i.e., fish production) than heterotrophic food chains, which is a rule of obvious economic importance. The rule applies especially when primarily-produced biomass (edible algae) is assimilated by those that consume it, without being decomposed by bacteria in a microbial loop.

The next level of both auto- and heterotrophic food chains is composed of invertebrates, which consume epilithic or periphytic algae and bacteria (scrapers), drifting detached or planktonic algae or suspended detritus (collectors-filtrators), bottom detritus (collectors-gatherers) or coarse live or dead plant tissues (shredders). Many of these are insect larvae, which later – as adult forms – will leave their water habitats. Emerging insects may remove as much as 40 % of the catchment phosphorus load originating from precipitation (Dabrowska-Prot & Hillbricht-Ilkowska, 1992) from water bodies. Invertebrates may, however, during their life in water, release considerable amounts of nutrients in available form as excrement.

The next important element of riverine food chains is fish communities. For non-predatory fish species invertebrates are the main food source whereas predators feed on benthivorous species. Appropriate fishery management may also remove some of the nutrients from the river system as caught fish. Fish excrements, as in the case of invertebrates, return a part of nutrients previously consumed in their food to the water.

As can be seen from the above short review of biological river channel processes, a nutrient atom may pass through repeating sequences going from uptake (immobilisation) to release (mobilisation) to downstream transport. This is the basis for the concept of nutrient spiralling (Newbold et al., 1981). The length of such a spiral turn is the average downstream distance that a nutrient atom passes in an uptake/release sequence. The shorter the distance (and the tighter the spiral), the higher the retentive properties of the stream channel. The nutrient retention capabilities, important for water management, are enhanced by long flow time, channel structural diversity and biotic diversity, abundance of biotic components active in nutrient transformations, and retentive properties of sediments (connected to intensive land/water interactions).

River channel ecology

Traditional river channel ecology is based on mostly uni-directional matter flow: from the land ecosystems of a drainage basin through streams and rivers to the sea. Such a view of river ecosystem functions would lead to the conclusion (in fact, a bit simplified) that almost all catchment nutrient loads flushed to the river may be processed and temporarily retained in its channel. Eventually the nutrients then reach the final recipient – a lake or sea, affecting the structures and functions of the benthic ecosystems by their eutrophication. Therefore, the only method to protect the sea and lakes from diffuse nutrient loads should be measures to prevent land erosion and nutrient leaching from agricultural areas, which are usually the most important nutrient sources in the catchment. Models of nutrient control effects show us that even if we did this with the best available methods, it would still be difficult to maintain nutrient loads within permissible limits (O'Sullivan, 1993). However, there is another powerful tool: introduction and appropriate management of buffer strips, or riparian ecotones.

The novel concept of ecotones

Clements (1905) introduced the idea of transitional zones, or ecotones, between ecological units. He defined the term as a "junction between two [plant] communities where processes of competition or exchange might readily be observed." Later, the ecotone concept has been widely adapted to interfaces, edges, transitional zones, or boundaries between adjacent ecosystems. Increased knowledge of ecological processes has changed the focus of understanding ecotone processes and their importance in landscape ecology. Ideas from other natural sciences, paying special attention to processes observed at interfaces of various kinds, as well as a change of the social perception of borders (not as frontiers producing stress and competition, but more as interfaces enabling exchange, diversity and stability), have influenced the concept. Ecotones between land and water ecosystems became the most interesting, both from scientific and practical (landscape management) points of view. A special UNESCO/MAB programme called "Land/inland water ecotones," which has significantly increased the knowledge and appreciation of ecotone functions in landscape ecology (e.g. Naiman & Decamps, 1990; Hillbricht-Ilkowska & Pieczyñska, 1993; Gibert et al., 1997; Lachavanne & Juge, 1997) has been established for 1989-1996 (Naiman et al., 1989).

This programme adopted as its working definition of an ecotone: "Zone of transition between adjacent ecological systems, having a set of characteristics uniquely defined by space and time scales and by the strength of the interactions between adjacent ecological systems."

This definition has some important implications, viz. that an ecotone:

- develops as a distinct contact zone between more homogenous adjacent patches in a landscape,
- maintains its own characteristic and recognisable structure,
- may be determined as a linear structure (but also characterised by its width),
- may change its dimensions, structure and functions in time, and
- differs from adjacent patches by characteristics and intensity of ecological processes; at least some of them should be more intense than in neighbouring ecosystems.

Vertical extension of a river

Groundwater seepage through the stream bottom or banks in most cases remains the main source of water in stream channels. Therefore, considering the effect of filtration through sediments, one might ex-

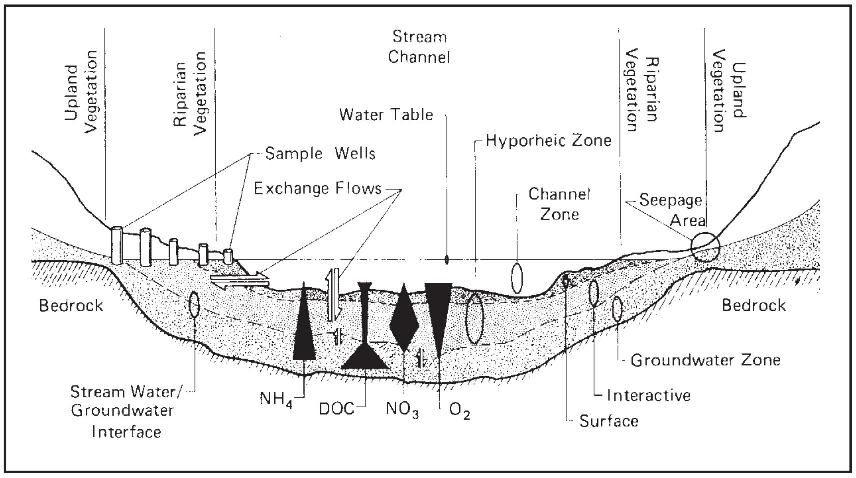

Figure 9.1. Conceptual model of the groundwater-surface water linkage. Waters are divided into three zones: a channel zone containing surface water, a hyporheic zone, and a groundwater zone. The hyporheic zone has been divided into a surface hyporheos with virtually identical chemistry to channel waters, and containing $>98\%$ advected channel water, and an interactive hyporheos, containing $<98\%$ but $>10\%$ advected channel water, characterised by physical-chemical gradients (e.g. NH_4, O_2, DOC, NO_3, and temperature). The shape of the concentration profile theoretically represents the overall solute concentration. Transport of solutes across the groundwater-stream water interface (the stream boundary) is a function of the relative hydraulic heads of groundwater and stream water tables and the permeability of the interface, a response to concentration gradients, or dominated by advective processes (from Triska et al., 1989).

pect that the chemical composition of water below the sediment surface should be intermediate between those of upland groundwater and river water. But taking water samples in such a contact zone we may observe very strong chemical gradients – both vertical and horizontal. Unexpectedly high concentrations of dissolved organic matter, low concentrations or even lack of dissolved oxygen (and this associated with the presence of dissolved reduced iron or manganese ions or hydrogen sulphide) and steep gradients of nitrogen compounds (Figure 9.1) may be found. Many of these characteristics are considered undesirable from a water-quality point of view – therefore a question arises: Why are river ecologists so devoted to protection and enhancement of this zone's features?

The hyporheic zone is an example of an ecotone. It is defined as a zone of mixed groundwater and surface water of a river. But, as we already know, for ecotones, some characteristics and processes should be different from those observed in adjacent systems. The flow rates are determined by the porosity of the sediments and the hydraulic gradient. The lack of direct contact with the atmosphere and high rates of biochemical processes involving gases also reduces the exchange of gases. Darkness makes photosynthesis (and oxygen production) impossible. High DOM concentrations originate from partial decomposition of particulate organic matter coming from both land and water ecosystems. Decaying plant debris, compounds excreted by plant roots, and detritus particles, buried in the unstable river bottom, are the main sources of DOM.

The hyporheic zone is therefore totally heterotrophic. Bacteria and fungi, creating biofilms on sediment particles, are abundant and trigger off processes of organic matter transformations. They open hyporheic food chains with numerous invertebrate species as consumers (with total densities often higher than on the bottom surface), whose occurrence is restricted to this zone only. They take advantage of higher habitat stability than that of the stream channels and more abundant food base than in groundwater. Many of these bacteria and fungi are endemic and have great biodiversity value. Others, typically groundwater or stream species, may penetrate the hyporheic zone to some extent. Ecologists use the distribution of particular species as an indicator of ranges of mixing zones, and in environmental monitoring. These animals are also considered to be "ecosystem engineers," by influencing the availability of resources and modifying habitat conditions and nutrient dynamics (Ward et al., 1998).

So let us return to biogeochemistry. Live organisms gain energy from metabolic, electron-accepting processes. Decomposition of organic matter, as well as respiration, is an oxygen-consuming process. It is now clear why oxygen may be depleted. The redox potential drops to a level enabling nitrate reduction, performed by denitrifying bacteria, also using organic matter as the energy source. Nitrate is reduced to nitrogen, which is released to the atmosphere through water. This is a particularly important process of reduction of anthropogenic nitrate loads, creating a nuisance to the environment. As the next step, when the redox potential is decreased, oxidised manganese and iron, which form insoluble compounds under normal environmental conditions, become reduced to Mn^{2+} and Fe^{2+}, respectively, which are soluble in water. Finally, sulphate, or even CO_2, may become oxidisers of organic matter, being reduced to H_2S or methane, respectively (Dahm et al., 1998).

All of the above processes are reversible: when oxygen becomes available, chemoautotrophic bacteria transform reduced forms into oxidised ones, gaining energy in the process. Spatial differentiation of the hyporheic zone enables connectivity between sites of opposite reactions. Usually, lower hyporheic

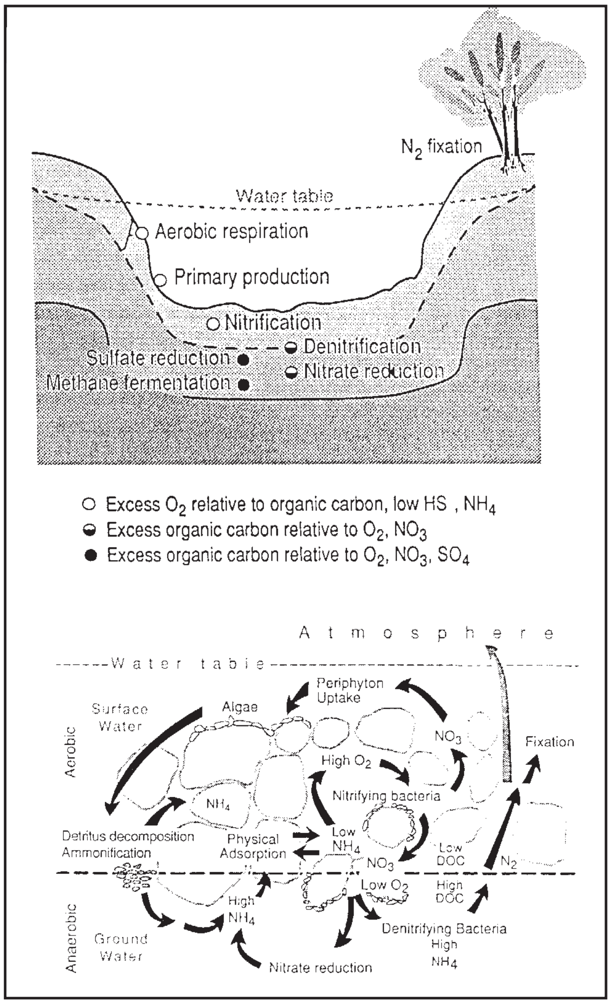

Figure 9.2. A: Major biological processes in reduced groundwater in the riparian ecotone (dark grey), oxidised waters of the hyporheic zone (medium grey), and surface water (unshaded). B: Conceptual model of nitrogen cycling in the hyporheic zone as groundwater crosses the terrestrial-aquatic interface (from Triska et al., 1993).

strata contain processes of reduction, while upper ones contain oxidation. This is important in eliminating loads of various nitrogen compounds (Figure 9.2): denitrification is the only process for reducing NO_3^- to non-reactive N_2. But to transform ammonia (NH_4^+) to particular nitrogen, it is necessary to oxidise it to NO_3^- as the first step (nitrification), and then to reduce it to N_2 in an oxygen-depleted environment.

Reduced iron and manganese ions may play an important role during their oxidation in phosphate removal from water: during the oxidation of these ions, co-precipitation of phosphorus occurs, making it unavailable for primary producers. The above processes explain the importance of the hyporheic zone in withdrawal of the most dangerous nutrient loads.

The main difference in the biogeochemistry of river channels and their hyporheic zones is that the most important processes in rivers are based on nutrient and light availability, whereas in hyporheic zones this depends on organic matter availability and redox potential. In both cases these processes may be modified by flow patterns.

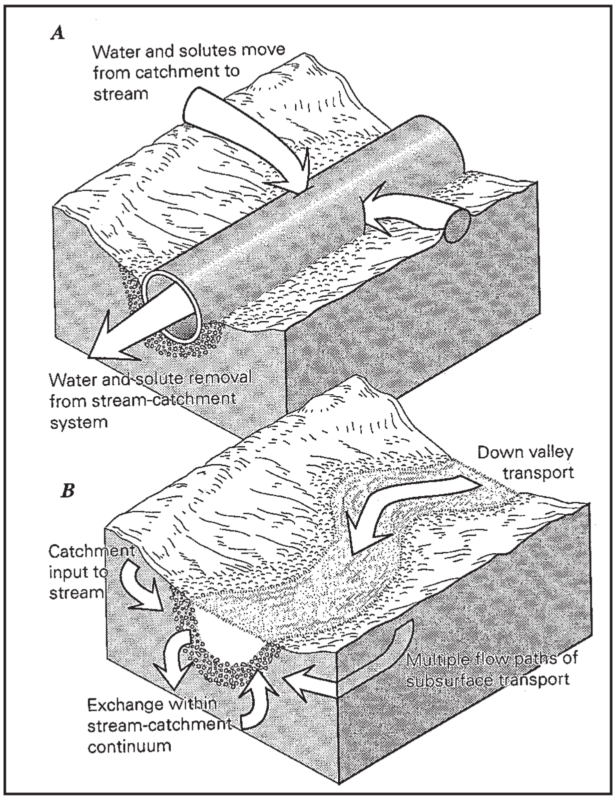

Figure 9.3. A: The stream's function in its catchment is viewed simply as that of a pipe. B: A contrasting view of the stream's function places the stream as an integral part of the catchment system (from Bencala, 1993).

Hyporheic flow patterns are more complex than those based on the traditional river channel concept, where a river might be considered to be like a drainage pipe collecting water with solutes from its catchment and removing it from the whole system (Figure 9.3a). In fact (if only the river has not been transformed to such a pipe by old-fashioned drainage engineers), the exchange of water between the channel and its hyporheic zone is bi-directional (Figure 9.3b). There are distinct longitudinal differences in this exchange (Figure 9.4): in headwater streams the direction from groundwater to the channel prevails. In middle reaches, differences in channel morphology (riffle-pool sequences, meanders and lateral channels) create down- and up-welling sites at the channel bottom and its banks. In large rivers, we observe mostly down welling of water from river channels to groundwater. The direction of flow also depends on the relation of the actual groundwater level to the stream water level, which is subject to change according to climatic conditions. The magnitude of the flow depends on the permeability of the bottom sediments (permeable sand or impermeable clay), clogging (collation) of bottom surfaces (e.g. by siltation or development of algal/bacterial mats). In addition, as is the case e.g. in low-order streams in Northern

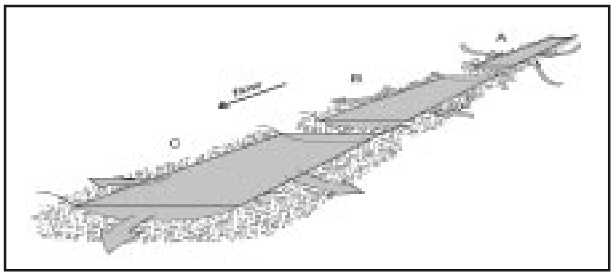

Figure 9.4. A: Hypothetical representation of the primary directions of water movements within streambeds: a headwater stream (A), a mid-reach stream with a pool-riffle-pool sequence (B), and a larger river with a well-developed floodplain (C). B: Conceptual longitudinal model of down-welling and up-welling sequences within the bed of a mid-reach stream: channel water (A), hyporheic zones (B), and groundwater zones (C) (from D.S. White, 1993).

Poland, it depends on bottom seepage in up-welling zones, often exceeding 40 lm^{-2}h^{-1}.

The complex patterns of water flow not only process upland groundwater, discharging into a river within its hyporheic zone, but also absorption of nutrient, organic matter and sediment loads, already existing in the river water. This is why "natural," morphologically diversified channels are characterised by the highest self-purification and load reduction abilities. Groundwater/surface water exchange is therefore an important feature of healthy riverine ecosystems.

Horizontal extension of a river

The riparian zone is defined as a floodplain bottom, extending laterally from the river channel to slopes or terraces of the river valley, usually covered by vegetation of distinct structure. Various plant communities may occur: riparian forests or wood lots, perennial floodplain wetlands or meadows. The riparian zone with its rich vegetation may start from riverbanks, or may be separated from them by a parafluvial zone. This is a region of an active channel, without surface water during times of lower discharge, not overgrown by plants or with only ephemeral plant communities. This zone occurs mostly in sub-mountain river reaches, or in regions with large amplitudes of the river water table. Gravel bars in meandering rivers constitute another, discontinuous example of parafluvial biotopes.

Riparian communities, as a rule, are characterised by relatively high plant biomass and productivity, stimulated by high nutrient availability. The uptake of nutrients to plant tissues is one of the processes of their retention in riparian ecotones. Harvesting riparian herbaceous communities may remove 20-30 % of the nutrient input (Mander et al., 1995). However, a major part of the nutrient load (up to 75 %) becomes retained, not in plants, but in soil, involving microbial processes. Organic matter, produced by riparian plants, is accumulated and decomposed in the soil, or may fall into river channels. Decomposition of organic matter results in oxygen depletion of the soil, which starts the chain of reductive processes, described above, with denitrification as the most important. Denitrification often appears to be more intensive in winter periods (but not in a frozen soil), when direct nitrogen uptake by plants ceases (Vought et al., 1995; Figure 9.5).

Some wetland plants are able to translocate oxygen to their roots and then release it to the soil. This helps maintain the performance of the oxidative processes, which are active in phosphorus retention. Particular plant species create habitats for specific microflora, active in different biogeochemical processes.

The abundance of water in riparian zones enables high transpiration intensity. During sunny summer days a 10-m wide forest or meadow belt completely reduces groundwater fluxes with a 1 % water table slope (Ryszkowski & Kêdziora, 1993). This is another mechanism of groundwater and nutrient retention within a riparian zone, where concentrations of solutes increase. However, low temperature or high air humidity reduces transpiration rates substantially.

Riparian zones are the source of both fine and coarse organic matter entering river channels and later being processed there as described above. Large woody debris, also originating from riparian zones, is an important element that increases river channel diversity.

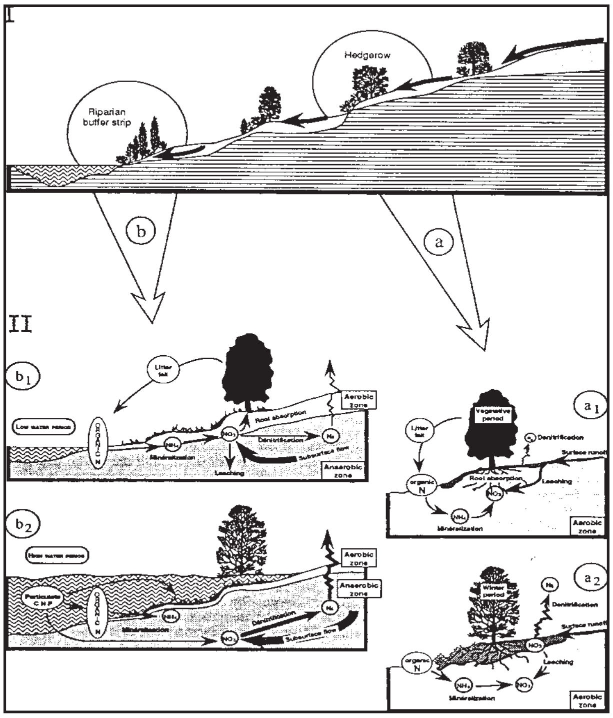

Figure 9.5. Conceptual model of nitrogen cycling in (a) upland buffers, i.e. hedgerow and (b) riparian forests, during (1) vegetative and (2) winter periods (from Vought et al., 1995).

Riparian zones act as mechanical filters, retaining suspended matter from surface runoff to river channels and also from river water during floods. Another function of riparian forests is to reduce light access to the stream channel, which determines the auto- or heterotrophic nature of these forests' food chains and other light- or oxygen-dependent processes (such as nitrification). Reduced light access, as well as evapotranspiration, leads to lower water temperatures (with higher oxygen solubility) in stream channels.

Riparian zones, however, do not always act only as nutrient sinks. Sometimes decomposition rates in their soils are so intensive that in critical periods (summer), riparian forests may release phosphates or ammonia to the river water (Mulholland, 1992). Some plant species (like *Lythrum salicaria*) may effectively accelerate eutrophication of downstream water bodies by decaying their leaves (Emery & Perry, 1996). Others, like black alder (*Alnus glutinosa*), with symbiotic bacteria on their roots, are able to fix atmospheric nitrogen and then increase ammonia loads to waters. Retentive abilities may change in different succession stages of riparian communities: the primary increase often becomes replaced by a decrease of nutrient retention in mature or senescent communities. Also, overloading with excess sewage or fertilisers may lead to failure of the riparian retentive functions.

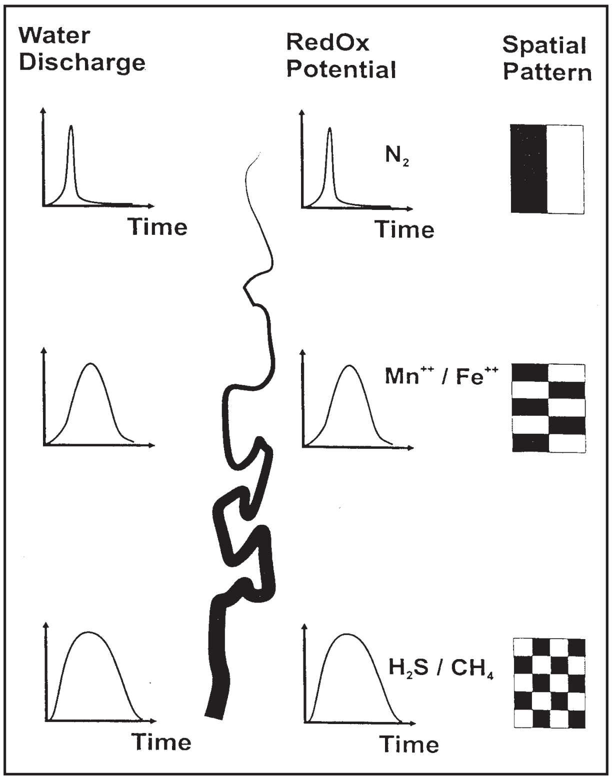

Figure 9.6. Changes in redox potential along a temperate stream. Redox dynamics parallel water inputs, which become more uniform downstream. The spatial pattern is symbolised by reduced zones in black and oxidised zones in white. This pattern becomes more heterogeneous and patchy downstream (from Tabacchi et al., 1998).

The modern approach: the floodplain as an ecological system

The above review shows how there are continuous exchange processes within a river floodplain rather than a uni-directional matter flow, which is the traditional model of a riverine ecosystem. In fact, the three zones – channel, hyporheic and riparian – are closely interconnected and function under influences from each another. For each river, scales, diversity and spatial and time patterns change with its length. The erosion (upper), transition (mid-reach) and deposition zones can be distinguished along a river basin system (Tabacchi et al., 1998). These zones are characterised by the relative intensity (decreasing downstream) and stability (increasing downstream) of their external input into the river channel, as well as by their role in exchange processes related to input within a river floodplain, which also increases downstream. This produces a higher stability of lower river courses, connected to their increased spatial diversity (patchiness, Figure 9.6).

Ecological processes on a local (river reach) scale depend not only on the relative position of a given reach in the longitudinal river continuum. Local settings, such as geomorphology, catchment geology and climate, determine the characteristics, scales, distribution and amplitudes of floodplain processes. Therefore, on a scale of the whole Baltic drainage basin, we should expect distinct differences between floodplain functions. Compare, e.g., the humic and acidified, soft-water forest-rivers on granite bedrock in the cold climate of northern Sweden, and the clear-water, calcareous rivers in the agricultural, karstic catchments of southern Poland and the wide, large swamp floodplains of north-eastern Poland and Belarus. Mountain, upland and lowland rivers are characterised by their own geomorphological settings, determining the functions of the whole floodplain.

The functioning of a whole floodplain system is driven by opposite, compensating processes, maintaining relative stability of the whole system (Puchalski et al., 1996). The nutrient removal properties increase with increasing external loads (Faafeng & Roseth, 1993). Zones of nitrification and denitrification are separated in space and time, optimising nitrogen processing. Sediments overgrown by *Berula erecta* are characterised by their ability to buffer phosphate concentration in stream water: when it is low, phosphate is released, and when it is high, phosphate is retained (Puchalski, 1999). Intensive input of nutrient-rich hyporheic waters to a channel affects the growth of algal mats on sediment surfaces, which in turn increases the nutrient uptake rates and decreases the hyporheic flow by decreasing the sediment permeability. The nutrient retention maxima of reaches based on autotrophic primary production and on processing of imported tree litter are seasonally separated. The low riparian retentive properties are accompanied by high uptake rates within a stream channel and vice versa.

External perturbations, however, make the whole floodplain system unstable. The most important perturbations within floodplains are floods. They produce intensive erosion, may change the channel morphology and destroy structures of the biotic communities, both riparian and channel ones. Large amounts of solutes and particular matter are eroded, transported and accumulated in other systems and places. However, as long as a flood is not totally destructive, new sediment or juvenalised riparian communities often gain increased retentive properties, which, at least partially, eliminates the excess of solutes (among others, available nutrients) introduced to the system. This is a typical feature of e.g. submountain streams (Dorioz et al., 1986), where floods occur relatively often. A lack of perturbations in a longer time perspective would undoubtedly reduce retentive properties and decrease internal compensating processes. Such river systems should be considered perturbation-dependent. On the other hand, in the broad floodplains of swamps, where the flood maxima are normally flattened by interception, an intensive perturbation will remove and transport previously retained nutrients and the destruction of the floodplain structure will be more evident. The floodplain structure will also be more difficult to regenerate. Such systems are perturbation-independent and it is important in management to reduce causes of potential perturbations.

Please compare your local river monitoring data of a typical summer to those of the summer of 1997, when a catastrophic flood in the southern part of the Baltic catchment and a drought (which is also a perturbation!) in its northern part occurred. What was the major difference in water quality? Is your river system perturbation-dependent or independent and why? What are the consequences in terms of management options?

10.

HYDROLOGY AND WATER QUALITY OF EUROPEAN RIVERS

Artur Magnuszewski

Introduction

Europe as a continent shows large variability in climate, geological structure and relief. These elements determine the look of the landscape but also the water circulation and behaviour of the rivers. Human activity adds a new dimension to the availability and quality of water resources. Looking only at rivers of the Baltic catchment the difference in the hydrology of the southern and the northern rivers of the region is easily seen. It is also interesting to take a more general look at the rivers of Europe as a whole, since this context aids understanding of the problems of the Baltic region. The problem of water resources' quantities and quality can be better evaluated by comparison with other European regions. The regional patterns of biological oxygen demand and nutrient concentration (phosphorus and nitrogen) will be discussed.

A river is a system comprised of the main channel with all its tributaries and the area that the river system drains – called the catchment. The climatic conditions influence the water input to the catchment, while characteristics such as topography, bedrock geology, soil type and land use determine the catchment response to rainfall. Human activity affects river systems in numerous ways, for example, through urbanisation, agricultural development, land drainage, pollutant discharge and flow regulation (dams, canalisation, etc.). The lakes, reservoirs and wetlands in a river system act as storage elements, attenuate the natural fluctuation in discharge and serve as settling tanks for material transported by the rivers.

The land

The peninsular pattern and close proximity of the sea are characteristics of Western Europe. Eastern Europe has a much larger area and is continental in its character. A traditional division is along the line linking the base of the Jutland Peninsula with the coast of the Adriatic Sea. Fortunately, Europe has no continuous mountain obstacle aligned north-south, that would limit access of the maritime air masses from the ocean. The prevailing part of Europe has both low altitude and low relief. The North European Plain, common to much of Poland, northern Germany and Denmark, broadens in western France and continues, across the narrow seas, in south-eastern Great Britain and Ireland. The major peninsula of Scandinavia is mostly upland and highland, with a high edge in the Norwegian coast, while seas to the east and south are approached more gently. The highest altitudes and the young mountain-relief of the European continent is located farther south, in the structures of the Cenozoic orogeny. These are: the Alps, the Pyrenees and the Sierra Nevada of Spain, the Apennines, the Dinaric Alps and the Balkan Mountains, as well as the Carpathian Mountains.

Generally, four broad topographic units can be distinguished in the continent of Europe:

- The coastal and interior lowlands
- The central uplands and plateaux
- The north-western highlands
- Southern Europe

Drainage

The drainage basins of most European rivers stretch to the areas uplifted by the Caledonian, Hercynian and Alpine orogeny periods. They receive heavy precipitation, including snow. Drainage is direct (or via the Baltic and the Mediterranean Seas), to the Atlantic and the Arctic Oceans and to the enclosed Caspian Sea. In a geological sense, Europe is a relatively young and structured continent. River catchments are numerous but relatively small and rivers are short. The present courses and valley forms of the major rivers result from late and recent geological history involving such processes as erosion by the head stream, down-cutting, capture of other rivers, faulting and isostatic changes of land and sea levels. The Rhine, for example, once drained to the Mediterranean before being diverted to its present course. The rivers of Scandinavia and the North European Plain have been shaped since the Pleistocene epoch. While ridges of the Alps, Apennines and Carpathians form watershed boundaries, rivers (for example the Danube) have cut through other mountain ranges. On the

East European Plain, catchments are relatively large and rivers are long. In western, central and eastern Europe, rivers are largely 'mature,' i.e. their valleys are graded and their streams are navigable. Northern and southern Europe's rivers are still 'youthful,' with ill-graded profiles and are thus more useful for hydroelectricity than for waterways. The mouths of the Atlantic rivers have tidal estuaries widening seaward, while in the Baltic, Mediterranean and Black seas, with minimum tidal influences, deltas (Neva River) and spits (Vistula River) have been created.

About 70 European rivers have a catchment area exceeding 10 000 km^2. The three largest rivers in Europe, the Volga, the Danube and the Dnieper Rivers, drain one quarter of the continent, but are rather small in comparison to other rivers of the world (Figure 10.1). The major European rivers flowing north into the Barents Sea and the White Sea are the Severnaya (Northern) Dvina and the Pechora Rivers. The Volga and the Ural Rivers which flow south and the Kura River that flows east, drain into the Caspian Sea while the Dnieper and the Don Rivers drain south into the Black Sea. The largest river to discharge into the Black Sea is the Danube, which has its catchments in 16 countries of central Europe and the Balkans. The main rivers to discharge into the Baltic Sea are the Neva, the Vistula, the Oder and the Neman Rivers. Ten rivers with catchments larger than 50 000 km^2 drain into the Atlantic and the North Seas, with the Rhine, the Elbe, the Loire and the Douro Rivers being the largest. The rivers that drain into the Mediterranean Sea are relatively small, the Rhone, Ebro and Po Rivers being the largest.

Countries whose coastline is long in relation to their area, for example Iceland, the UK, Ireland, Norway, Sweden, Denmark, Italy and Greece, are usually characterised by a large number of relatively small river catchments and short rivers. Many European countries are drained by only a few river catchments; thus the Vistula and Oder Rivers drain more than 95 % of Poland and the Danube River drains most of Hungary, Romania and Slovenia. In the small catchments the population tends to congregate in towns along the coastline and wastewater is discharged directly into coastal areas rather than into the river systems. Large catchments have a more uniform distribution of the settlements, sometimes concentrated in the upstream area (for example the Vistula catchment and Silesia district).

Because Europe has a temperate humid climate and a high percentage of limestone in the surface rock, the weathering rate is the highest of all the con-

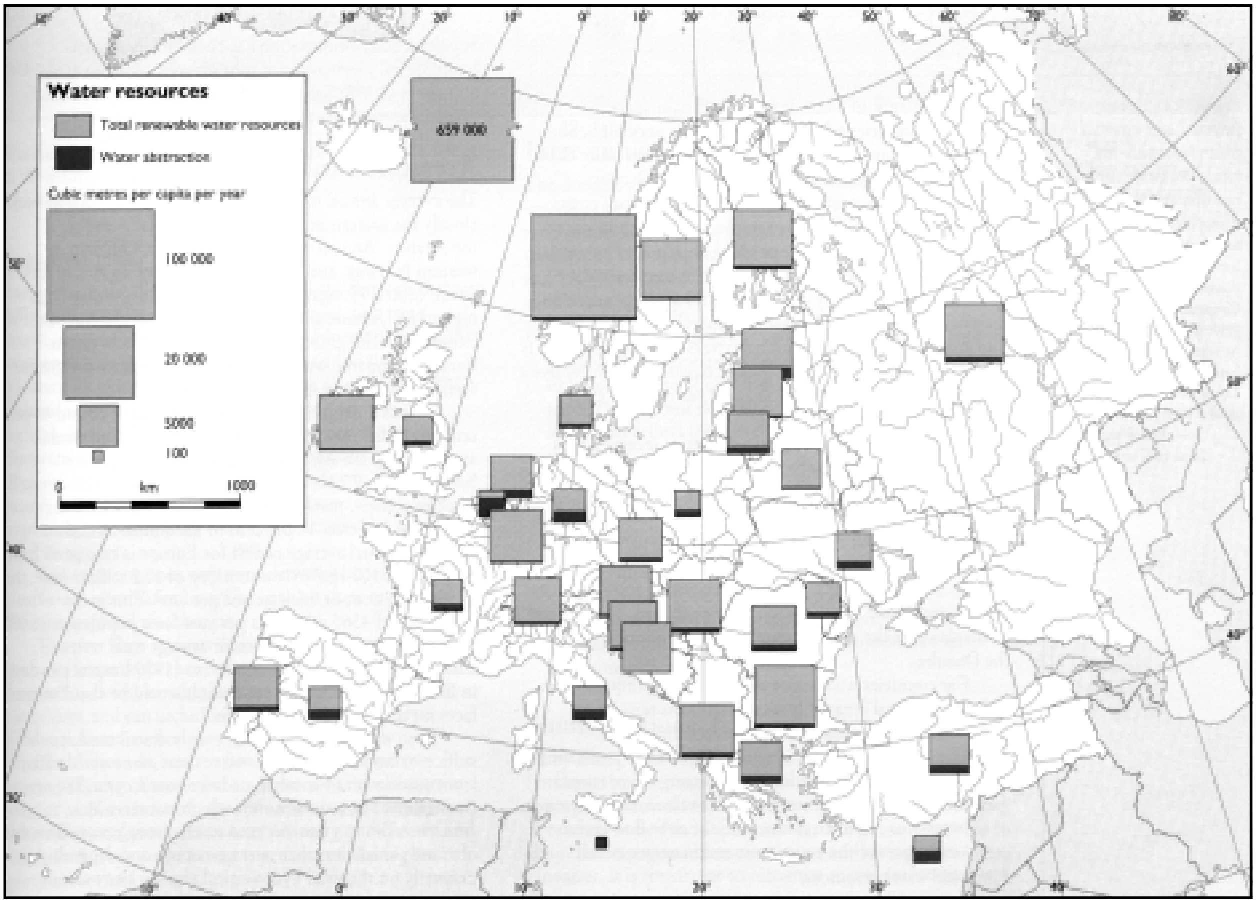

Figure 10.1. Water resources per capita in Europe. All the graphs show specific discharge in l/second per km^2 (after Stanners & Bourdeau, 1995).

tinents; as a result, 12.6 % of all dissolved solids discharged to the oceans are derived from Europe. Europe is relatively densely populated and has a high proportion of agricultural areas, which affects the concentration of dissolved substances in river water.

There are more than 500 000 natural lakes larger than 0.01 km^2 (1 ha) in Europe; of these about 80 to 90 % are small, with a surface area between 0.01 and 0.1 km^2, with only roughly 16 000 having a surface area exceeding 1 km^2. Three quarters of the lakes are located in Norway, Sweden, Finland and the Karelo-Kola area of the Russian Federation.

Hydrology

The river runoff volume and temporal discharge distribution from the rivers of Europe are governed by factors that include local conditions of rainfall, snowmelt and retention capacity. The river flow regimes of large catchments can be different from those of small catchments. Large rivers are much less variable because they integrate runoff over a large area, with different climate and physiographic conditions.

The average annual runoff in Europe follows very closely the pattern of average annual rainfall and topography. Annual runoff is greater than 4 500 mm in western Norway decreasing to less than 250 mm in parts of Spain, central Hungary and eastern Romania, in large regions of Ukraine and the southern part of the Russian Federation. The greater variation of runoff in western Europe, compared with eastern Europe, reflects the greater variability in topography, and hence rainfall. Across most of lowland Europe, between 25 and 45 % of the rainfall runs off into water bodies. In high rainfall areas, such as the Alps, western Norway and western Scotland, over 70 % of the rainfall may become runoff. In drier regions, particularly southern Spain, runoff may amount to less than 10 % of the annual rainfall.

The rivers in the western area have higher discharges in the winter season and lower in the summer. The rivers of mountainous and continental climates are fed by snowmelt, being highest in the spring and early summer. The longer rivers of the continent, notably the Rhine and the Danube Rivers, have complex regimes, since their basins extend into areas of contrasting climates. Some rivers that are fed by glaciers show a more even distribution of the discharge during the year.

Although embanking measures have reduced the problem, flooding is a continued threat to many large European rivers. Thus the rivers of central and eastern Europe are liable to flood with the spring thaw because water rise is often caused by the ice jams. Oceanic rivers may flood after heavy or prolonged rain covering the whole basin; Alpine rivers when the warm foehn wind rapidly melts the snow. The Rhone River achieves a steady flow throughout the year, due to heavy winter rain and spring and summer snowmelt from the Alps via Lake Geneva. The winter supplies from the Alps that are reaching the rivers in spring and summer feed the Rhine and Danube Rivers. The Vistula, Oder and Volga Rivers have their highest water levels in the spring and early summer due to snowmelt, and then fall to a summer low.

Water resources and management

The annual average runoff for Europe is estimated at 3 100 km^3 (about 8 % of total world discharge) over a territory of 10.2 million km^2; that is, 304 mm/year, or 9.6 l/s km^2. This is the equivalent of 4 560 m^3/per capita, per year, for a population of 680 million. The renewable water resources per capita show very large variations between different geographical regions (Figure 10.2). The populations of the Nordic countries have generally six to eight times as much water available for consumption per capita as the population of the other three geographical regions: eastern, southern and western Europe. Low water availabilities are found in 36 % of the European countries, in particular in the southern countries. Densely populated western countries with moderate precipitation (e.g. Belgium, Germany, Denmark and the UK) also fall in these categories. Water availability is also low in some eastern countries (Poland, Ukraine), mainly due to low precipitation. Above average, high or very high water availabilities are found in another 32 % of the European countries. Water is plentiful both in sparsely populated countries where precipitation is very high, like the Nordic countries and in countries with large transboundary rivers running through them. Countries like Hungary, Moldova, Romania, Luxembourg and the Netherlands receive more than 75 % as external contributions; Latvia, Ukraine and the Czech Republic receive between 50 and 75 % of their renewable water resources from abroad. Bulgaria and Romania share the water resources of their boundary river, the Danube. For countries with major rivers running through them, estimates of total renewable water resources tend to overestimate sustainable water resources.

Rivers and other surface bodies provide 70 % of the water for all utilisation sectors in Europe. Groundwater is the next most important source. Countries like Spain, Belgium, the Netherlands, Finland and Moldova, with insufficient groundwater supplies, abstract more than 90 % from surface water sources. However, in Cyprus, Switzerland, Slovenia, Iceland and Denmark, which are countries

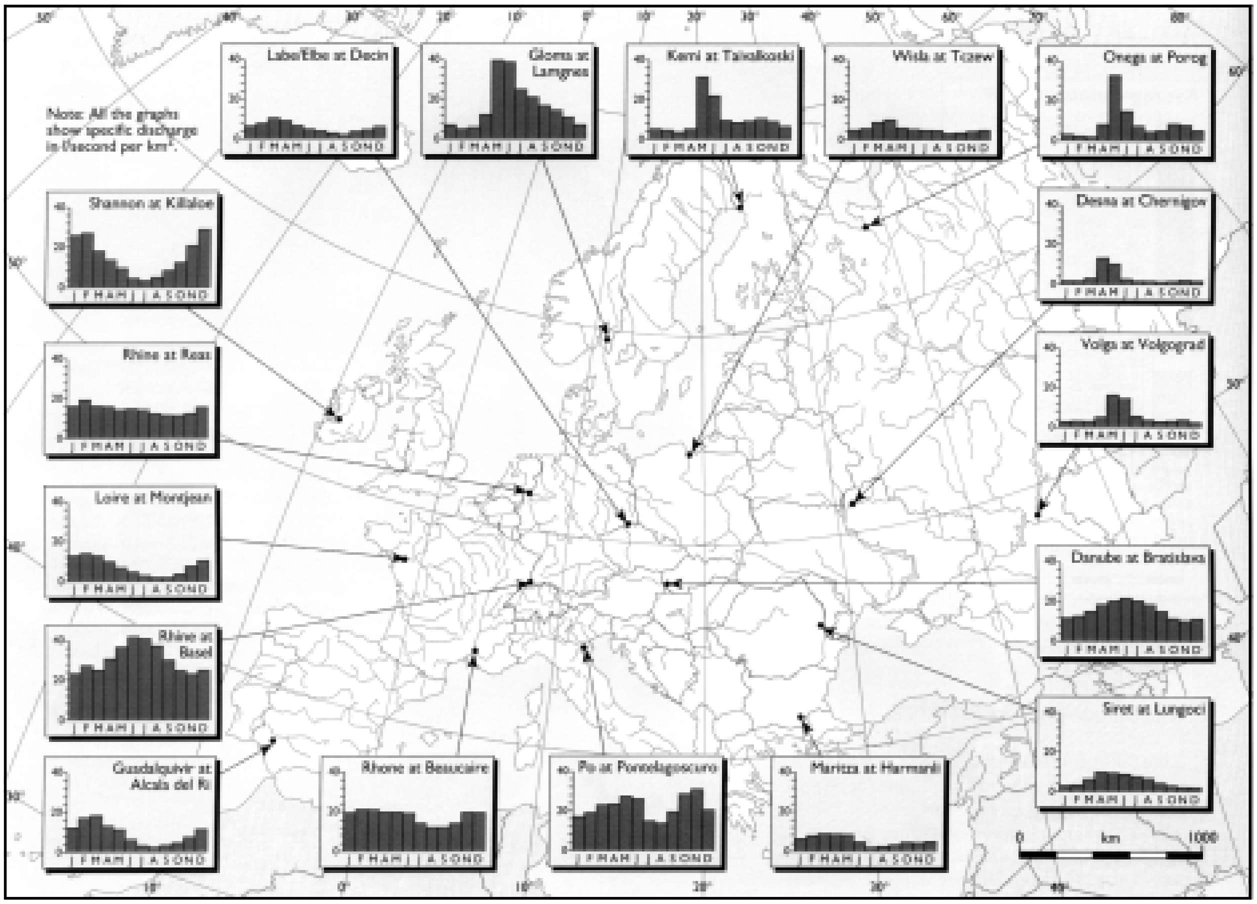

Figure 10.2. Specific discharge in selected river catchments of Europe (after Stanners & Bourdeau, 1995).

with extensive groundwater reservoirs, more than 75 % is drawn from groundwater. For Europe as a whole, about 65 % of the public supply is provided from groundwater which normally is of a better quality than surface water. In general, 53 % of the abstracted water (surface and groundwater) is used for industrial purposes, 26 % in agriculture and only 19 % for domestic purposes.

Reservoirs are the most important structures in the water management schemes in Europe. There are more than 10 000 major reservoirs covering a total surface area of more than 100 000 km^2. The numbers of relatively large reservoirs are greatest in the Russian Federation (ca 1 250), Spain (ca 1 000), Norway (ca 810) and the UK (ca 570). Other countries with a large number of reservoirs are Hungary (ca 300), Italy (ca 270), France (ca 240) and Sweden (ca 225). Many European countries have numerous smaller man-made lakes, for example Latvia, Bulgaria and Estonia, which have about 800, 500 and 60, respectively. The six largest reservoirs are located in the Volga River system in the Russian Federation, the largest being the Kuybyshevskoye (6 450 km^2) and the Rybinskoye (4 450 km^2) reservoirs. Of the 13 European reservoirs with an area exceeding 1 000 km^2, only the Dutch reservoir Ijsselmeer lies outside the Russian Federation and Ukraine. Reservoirs usually have a relatively short water residence time – sometimes just a few days – so they can be regarded as a hybrid between a river and a lake. Reservoir construction in Europe seems to be stagnant, mainly due to the lack of suitable sites and growing public opinion against the construction of dams and reservoirs.

River regulation has been undertaken in many catchments of western and southern Europe. In countries such as Belgium, England, Wales and Denmark, the percentage of river reaches that are still in a natural state is low, typically 0 to 20 %. In contrast, in countries such as Poland, Estonia and Norway, many rivers still have 70 to 100 % of their reaches in a natural state. In many countries where there is intensive agricultural production, many of the rivers have been regulated. In Denmark, for example, 85 to 98 % of the total river network has been straightened. River regulation often causes major changes in river processes, primarily the flow regime and the transport of dissolved and particulate matter. The effects are seen not just locally, but may be extensive with downstream reaches.

In 1990, in 24 countries for which data were available, about 60 % of the European population was served by sewage treatment of some nature. Sewage treatment facilities are poorly developed (with less than 50 % of population served) in many countries (e.g. Iceland, Ireland, Poland, Portugal, Belgium and

Greece). On the other hand, in the Netherlands, Luxembourg, Switzerland and the Scandinavian countries, some sort of wastewater treatment plants serve more than 90 % of the population, with Denmark topping with 98 %.

Water quality

The most important sources of river pollution are organic waste fed from domestic and industrial sewage. The decomposition and breakdown of organic matter is carried out by microorganisms and takes place mainly at the surface of the sediment and vegetation in smaller rivers and in the water column in larger rivers. Immediately downstream of a sewage effluent, organic matter decomposition reduces the oxygen content of the water and results in the release of ammonium. Further downstream, the concentration of organic matter decreases as a result of dilution and continuing decomposition. As the distance from the effluent increases, bacteria oxidise the ammonium to nitrate, and oxygen enters the water via the water surface, thereby increasing its oxygen content. Eventually the levels of organic matter, oxygen and ammonium reach those present immediately upstream of the sewage effluent; this process of recovery is called self-purification. Organic pollution is still a serious problem in many European rivers and will continue to be so for as long as large amounts of sewage water are discharged into the rivers without being treated.

Human settlement and associated clearance of forest, agricultural development and urbanisation greatly accelerate the runoff of materials and nutrients into rivers and lakes. This stimulates the growth of phytoplankton and other aquatic plants and in turn the growth of organisms higher up the aquatic food chain. The process is usually known as 'cultural eutrophication.' Enhanced biological production and other associated effects of eutrophication are generally more apparent in lakes, reservoirs, coastal areas, semi closed seas, and large, slowly flowing rivers, than in small rivers.

Organic matter decomposition requires oxygen, so the amount of organic matter in a river can be measured in terms of the biochemical oxygen demand (BOD) or the chemical oxygen demand (COD), the units of which are mg O_2/l. River reaches little affected by human activities generally have a BOD below 2 mg O_2/l whereas a BOD exceeding 5 mg O_2/l generally indicates pollution.

For Europe the median BOD, COD and dissolved oxygen content are 2.8, 14.5 and 9.7 mg O_2/l, respectively. Extremely high BOD concentration exceeding 500 mg O_2/l can be found generally only in smaller rivers polluted with raw sewage. As population density in the catchments increases, the level of organic matter in the rivers generally increases and the oxygen content decreases. For example BOD concentration is usually lower than 2 mg O_2/l in catchments with less than 15 inhabitants/km^2, it generally exceeds 5 mg O_2/l in catchments with more than 100 inhabitants/km^2. The great variation found in extensively populated areas is attributable mainly to variation in the extent of wastewater treatment; well-functioning treatment plants can decompose up to 90 % of the organic matter in the wastewater.

In terms of BOD, rivers in Ireland, Georgia, Estonia, Latvia, Austria, Switzerland, the Netherlands, the UK, Denmark and Croatia are least affected, with less than 25 % of the rivers having a BOD exceeding 3.5 mg O_2/l. In Hungary, Lithuania, Portugal, France, Ukraine, Germany, Slovenia and Italy the rivers are moderately affected, with less than 25 % having a BOD exceeding 5 mg O_2/l. More affected rivers are found in Albania, Poland, the Czech Republic, Moldavia, the Russian Federation and Spain, where more than 25 % of the rivers have a BOD exceeding 5 mg O_2/l. BOD is highest in Bulgaria, Belgian Flanders and Romania, exceeding 5 mg O_2/l in 60, 69, 80 % of the rivers, respectively. In Iceland, Norway, Sweden and Finland organic matter content is measured only as COD. In these countries discharge into rivers of organic waste derived from human activity is negligible and COD levels therefore are generally low.

Phosphorus is measured both as total phosphorus and soluble reactive phosphate (dissolved orthophosphate). In 321 European rivers dissolved orthophosphate was found to average 59 % of total phosphorus. In some countries total phosphorus is not measured and data are available only for dissolved orthophosphate. Median annual mean total phosphorus and dissolved phosphate were found to be 173 and 126 mg P/l, respectively, annual mean phosphorus levels being below 50 mg P/l at only 25 % of the stations. In catchments with limited or no human activity phosphorus levels in rivers are generally lower than 25 mg P/l. Phosphorus levels exceeding 50 mg P/l indicate an anthropogenic influence, for example sewage effluent and agricultural runoff. In rivers heavily polluted by sewage effluent, phosphorus levels may exceed 500 to 1 000 mg P/l. The lowest phosphorus levels are found in the rivers in Norway and Iceland, although many rivers in Sweden, Finland, Ireland, Austria, France, the Russian Federation, Slovenia, Albania, Georgia and Bulgaria also have a low annual mean phosphorus concentration. The concentration exceeds 50 mg P/l in 10 to 40 % of the rivers in Sweden, Finland and Ireland, and exceeds 125 mg P/l in 10 to 50 % of the rivers in France, the

River Dvina at Polotsk, Belarus (photo, Lars Rydén).

Russian Federation, Slovenia and Bulgaria. In many other countries only 10 to 20 % of the rivers have a phosphorus concentration below 50 mg P/l. These relatively unpolluted rivers are generally situated in catchments in mountainous and forested regions where the population density is low. In Estonia, Latvia, Lithuania, Switzerland, Austria, Croatia, Italy and Portugal, more than 40 % of the rivers have a phosphorus level below 125 mg P/l; however, many of the rivers in these countries have a high phosphorus level. The highest phosphorus levels are found in a band stretching from southern England, across the central part of Europe through Romania and Moldavia to Ukraine; in these countries more than 80 % of the rivers usually have a phosphorus concentration exceeding 125 mg P/l. In Poland, Belgium (Flanders), Luxembourg and the UK, about 50 % or more of the rivers have a phosphorus level exceeding 500 mg P/l. With the exception of large rivers in the Russian Federation and the Nordic countries, the phosphorus levels generally exceed 100 mg P/l in the downstream reaches in all of the largest rivers in Europe.

Bearing in mind the regional differences described above, Europe can be divided into four main regions according to phosphorus levels. The phosphorus levels are lowest in the Nordic countries, average in both southern and eastern European countries (although slightly lower in southern European rivers) and highest in western European countries.

Dissolved inorganic nitrogen, particularly nitrate and ammonium, constitutes most of the total nitrogen in river water; thus inorganic nitrogen was found to constitute 88 % (nitrate 78 % and ammonium 4 %) of the total nitrogen in 240 to 420 European rivers. In some countries data are available only for nitrate and occasionally ammonium. The results presented are therefore total nitrogen, inorganic nitrogen, or only nitrate nitrogen. Whereas ammonium levels are generally below 0.5 mg N/1, nitrate and total nitrogen concentrations exceed 1 mg N/l in most of the rivers. The average levels of ammonium and nitrate in pristine rivers are reported to be 0.015 mg N/l and 0.1 mg N/l, respectively. Although rivers in a strictly pristine state are rarely found in Europe because of high atmospheric nitrogen deposition, the levels of nitrogen in relatively unpolluted streams ranged from 0.1 to 0.5 mg N/l. Nitrogen levels exceeding 1 mg N/1 indicate an anthropogenic influence, for example agricultural runoff and sewage effluent. The ammonium level normally rises and the oxygen level falls when rivers receive sewage effluent or effluent from animal husbandry farms. In heavily polluted rivers the ammonium level may rise to as much as 1 to 5 mg N/1, which, when converted to ammonia, may be toxic to fish and other river fauna. The nitrogen concentration is generally lowest in rivers in Iceland, Norway, Sweden, Finland and Albania, being below 0.75 mg N/l in 60 to 100 % of the rivers.

In southern Sweden and Finland, and in Latvia, Lithuania, the Russian Federation, Ireland, Austria, Switzerland, Slovenia, France, Portugal and Spain, nitrogen concentrations are higher, ranging from 1 to 3 mg N/1 in the majority of the rivers. The highest nitrogen levels are found in eastern and western European rivers, particularly in the Czech Republic, Denmark, Estonia, Germany, Luxembourg, Moldavia, the Netherlands and Romania, the concentration exceeding 2.5 mg N/1 in more than two-thirds of the rivers. Whereas the median nitrate concentration is only 0.18 mg N/l in Nordic rivers, it is 3.5 mg N/l in western European countries, where rivers with nitrogen levels below 1 mg N/l are rare. The nitrate levels in the rivers of southern and eastern European countries are basically the same, although nitrate levels in southern European countries are rather homogeneous whereas there are large regional differences in Eastern Europe. Thus, the concentration is high in central European countries like Romania, the Czech Republic and Poland, but low in the new Baltic states and large parts of the Russian Federation.

Conclusion

Looking again at the Baltic region rivers and comparing them to other European rivers, Sweden's special position is noticeable. Sweden is a sparsely populated country, where heavy rainfall feeds the rivers, catchments are small, and many major towns are located along the coast. The country also has one of the highest levels of sewage water treatment in Europe.

Elevated nitrate concentrations in European surface waters have been strongly connected with modern agricultural practices, particularly the usage of nitrogen fertiliser. In rivers located in catchments with less than 10 % agricultural land, nitrogen levels are generally below 0.3 mg N/l. Nitrogen levels lie between 0.5 and 2.5 mg N/l in rivers where agricultural land constitutes 10 to 50 % of the catchment. In rivers with the highest proportion of cultivated land in the catchment area, the nitrate and total nitrogen levels are generally above 1.5 and 2 mg N/l, respectively. In countries like Denmark, Latvia and Poland, most of the nitrogen discharge to inland waters is a consequence of agricultural activities. It is very difficult to considerably lower the load of nutrients from such agriculture-dominated catchments. However, point sources of water pollution can be mitigated by proper sewage treatment technology. In Eastern Europe this approach can bring a visible effects, because the current percentage of population served by sewage treatment plants is still very low in this region.

Water quality is directly linked to available water resources. Poland has one of the smallest resources of fresh water per capita among the countries of Europe. This is mostly due to the small rainfall amount and rather high evaporation compared to the size of the population. One approach to solving this shortage is a program for water conservation, which should include all sectors of the economy. The target amount of water used for household purposes per capita per day is 100 l. This level should be reached in many countries in Eastern Europe in the nearest future. To increase the usable existing water resources the quality must also be improved, but the process of river restoration can take a few decades. Programs for wetland and natural floodplain conservation should also enhance the natural river self-purification potential.

The natural state of many rivers in Eastern Europe, a result of the political and economical past, turns out to be a very fortunate situation. Instead of spending money on the naturalisation of rivers, the resources can be redirected to other environmentally sound projects.

River input of suspended matter to the Baltic Sea

The glacial processes have influenced large parts of the Baltic basin in the Quaternary period. It is now recognised that the global Pleistocene-Holocene material fluxes are qualitatively distinct from the earlier Cainozoic and Mesozoic (Hay, 1994). The mass of Quaternary sediments is significantly larger than the masses of older stratigraphic units. The apparent increased mass is a result of erosion of older sedimentary rocks, the effect of ice age climate, land cover and general increase in erosion rates as a result of tectonic activity. Glaciers are efficient in removing, pulverising and transporting clastic sediments and low-grade metamorphic rocks, but less effective in eroding crystalline rock. The fact that shallow seas now mark sites of the centres of the Laurentian and Scandinavian ice caps, suggests that they have removed large masses of sedimentary rock from the Canadian and Fennoscandian Shields (W.A. White, 1972). Large volumes of sediments redeposited in the Baltic Sea basin by glaciers are the result of erosion. The weathering and erosion products are transported by the rivers, which are major pathways in the global geochemical and hydrological cycles. River load can be divided into dissolved, suspended and bed loads. Here, the suspended sediment load to the Baltic Sea is discussed. The estimation of the suspended sediment flow gives information on erosion rate and is important not only for civil engineering, but also environment protection studies. Recently, special attention has been paid to the fact that dissolved, colloidal and solid matter from industrial and urban effluents often contaminates the suspended material. This implies a serious environmental problem, as the river-transported sediments often contain heavy metals, toxic substances and other undesired contaminants, which affect the water quality, especially within the coastal depositional areas.

There are a number of factors controlling the rate of the erosion in the river basins and sediments supply to the river channel. Past geologic history in a river basin should be considered, since the post glacial features affect chemical and physical weathering. Glacial deposits in the mountain previously glaciated are one of the major sources of particulate material.

On the other hand, the former glacial abrasion may have left only bare rock (like in the Scandinavian Shield), resulting in limited sediment supply. Some of the Quaternary sediments may be very easily erodable, the eolian loess is a peculiar case. Meybeck (1994) has proposed a tentative scale of the rock sensitivity to mechanical erosion (in order of increasing erodability): pure limestone < granite and gneiss < mica schist < consolidated volcanic rocks < shale << volcanic ash, sands, glacial deposits < clay < loess. Geomorphic features control erosion rate. Especially important is relief pattern and slope steepness, as well as proportion of wetlands in the river basins. Lake retention may greatly affect the suspended sediments load. The settling of the suspended sediments in the natural lakes varies between 90-99 % and in artificial lakes (reservoirs) 40-60 %. The size of the basin is also an important factor since the amount of particulate matter transported downstream by a river is only a small part of the material produced by the upland erosion. The larger the basin is the more effective is the temporary storage of sediments on the river floodplain, foot slopes and other surfaces.

In the case of the Baltic Sea, the suspended material is transported by rivers and usually deposited in the estuary area or redeposited by the sea currents to the deeper parts of the sea. The first complete evaluation of the suspended sediment flow to the Baltic Sea has been done within the international project ‘Water Balance of the Baltic Sea’ – IHP UNESCO. The results of this study are used for this paper together with some new materials from ‘Atlas Morza Bałtyckiego’ (Majewski & Lauer, 1994).

Sediment load characteristics

The main function of the river channel is to convey the runoff, but together with water the products of weathering (solutes and sediments) are transported. The characteristic feature of the sediment transport is the discontinuous movements of the particles. A given particle can be transported on the bottom of the channel as a bed load, entrained by the flow as suspended sediment and deposited for varying time intervals in the channel form or on the floodplain. The average vertical distribution of the sediments has a maximum concentration near the bed where there is a continuous exchange of bed load with suspended sediments (Figure 10.3). The amount of suspended-sediment flow across the measuring section of the river channel can be obtained by integration of the water velocity and the sediment concentration fields where

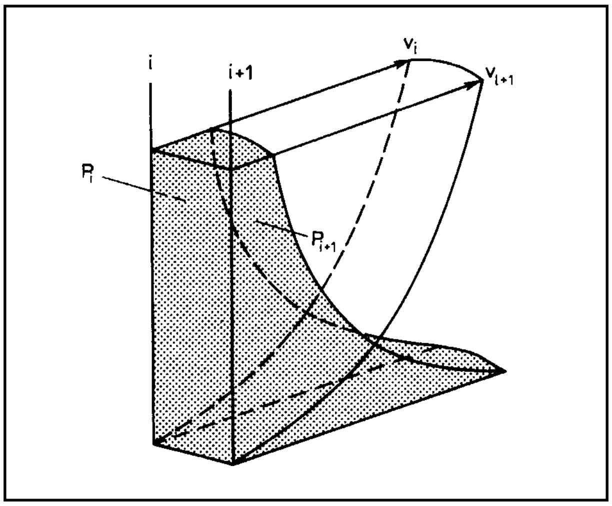

Figure 10.3. Example of the vertical velocity and suspended sediments distribution (Bajkiewicz-Grabowska et al., 1993).

$$T = \int_0^B \int_0^h v \, C \, dx \, dy$$

T is sediment flow in kg/s,
v water velocity in m/s,
C is sediment concentration in g/m^3 or mg/l,
h is depth of the water, and
B is width of the channel in the measuring section.

The vertical distribution and cross-section of the sediment concentration and the velocity are not even, so the values of these entities must be integrated or averaged. The concentration of sediments in a point is obtained by taking samples of the water and suspended material mixture. By filtering the sample and weighting the filter before and after filtration the mass of the solid material is evaluated in a given volume of the sample.

The changes of sediment flow in time are very significant and not always well correlated with the water discharge fluctuations. For the calculation of the sediment load it would be ideal to have continuous measurements of water discharge and sediment concentration. This is of course very difficult to arrange, so for practical reasons other approximate methods of discrete sampling have to be applied.

Having the average daily values of suspended sediment load, the total mass (usually during one year) of the transported material through the given river cross-section can be calculated. To normalise the sediment transport values between basins of a different area, the measure of mass per unit area per unit time is used, commonly in t/km^2/year. This value is commonly called a river basin denudation rate.

Suspended sediment flow measurements

In the Baltic Sea basin there is an evident difference in river network density and catchment size. In the north, Finland and Sweden have a large number of medium size rivers (with a discharge of 100-500 m^3/s), while in the south and south-eastern part of the drainage basin the rivers are few with very large drainage areas. From 200 rivers which drain to the Baltic Sea only 32 have a discharge of 50 m^3/s. Figure 11.4 shows the rivers that drain into the Baltic Sea. Only those with a mean annual discharge of more than 10 m^3/s are identified in the figure.

In the IHP UNESCO project on the suspended sediment load, the comparison of the methods of measurements and data processing has shown that the time series have rather poor spatial and temporal coverage. In some countries the measurements have been initiated occasionally because of reservoir construction, river channel regulations or dredging, in others the measurements program has been a standard element of the activities of the national hydrological services. The measurement methods of suspended sediment load are not standardised, as in the case of discharge measurements. There is a great variety of samplers used for taking samples of the suspended sediment and many methods of evaluation of the sediment concentration and load. When comparing the sediment load from various rivers of the Baltic Sea catchment, measuring methods and calculation procedures have to be considered.

Observation network density and measurements frequency

The difference in river network density in the Baltic Sea catchment makes it difficult to design and maintain an observation network. In some countries the measurements are very sparse, as in Denmark, where measurements are taken only on selected rivers.

In Finland the observation network was not focused on suspended sediments but on studying chemical composition of river water. Twenty-one stations, located near the river mouths, cover 85 % of the area drained along the Finnish coast. The sampling frequency is 12 samples a year.

In Sweden a network particularly designed for sediment transport studies was started by the national IHD-Committee 1966-67 (B. Nilsson, 1972). From mid-1975, the Swedish Meteorological and Hydrological Institute have carried out the observations. Before 1966, only irregular investigations were undertaken in some rivers (Arnborg, 1958: 1967; 1969; G. Nilsson & Martvall, 1972; Sundborg & Norrman, 1963). The IHD network covered 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 made it possible to analyse about 10 % of the total water discharge from Sweden, with one sample representing the conditions during one day.

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

In Poland the network covered almost the entire catchment of Oder and Vistula Rivers and the coastal area from which the water was discharged to the Baltic. The sampling frequency in Poland varied from daily samples at some stations, for instance in the Vistula River, to every fifth day at other stations.

Water sampling instruments

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-integrating sampler was used within the IHD network (B. 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 where the mean transport was largest. 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 and 0.8 l. The lower limit of the sample volume is stated because of analysing accuracy and the higher volume because it prevents through flow of water in the sampler.

In Poland and in the former USSR the government hydrological services did the measurements of suspended load in selected cross-sections. In these measurements, in addition to the water sampling with a bathometer (at 0.2, 0.4 and at 0.8 of the verticals depth), water discharge and daily observations or continuous water stage recording is performed. In the majority of

RIVER RUNOFF

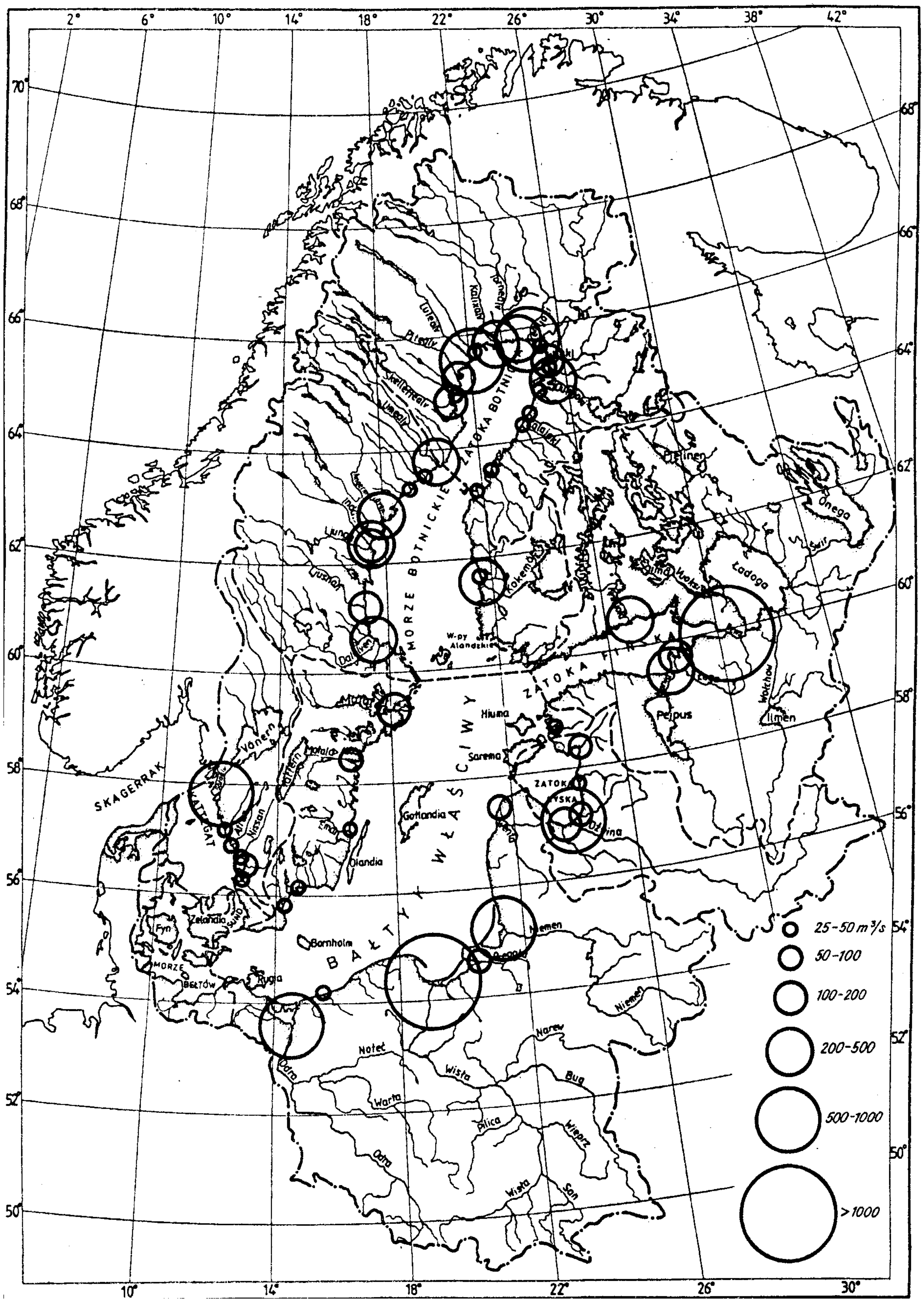

Figure 10.4. River network of the Baltic Sea catchment (Majewski & Lauer, 1994).

SEDIMENT TRANSPORT

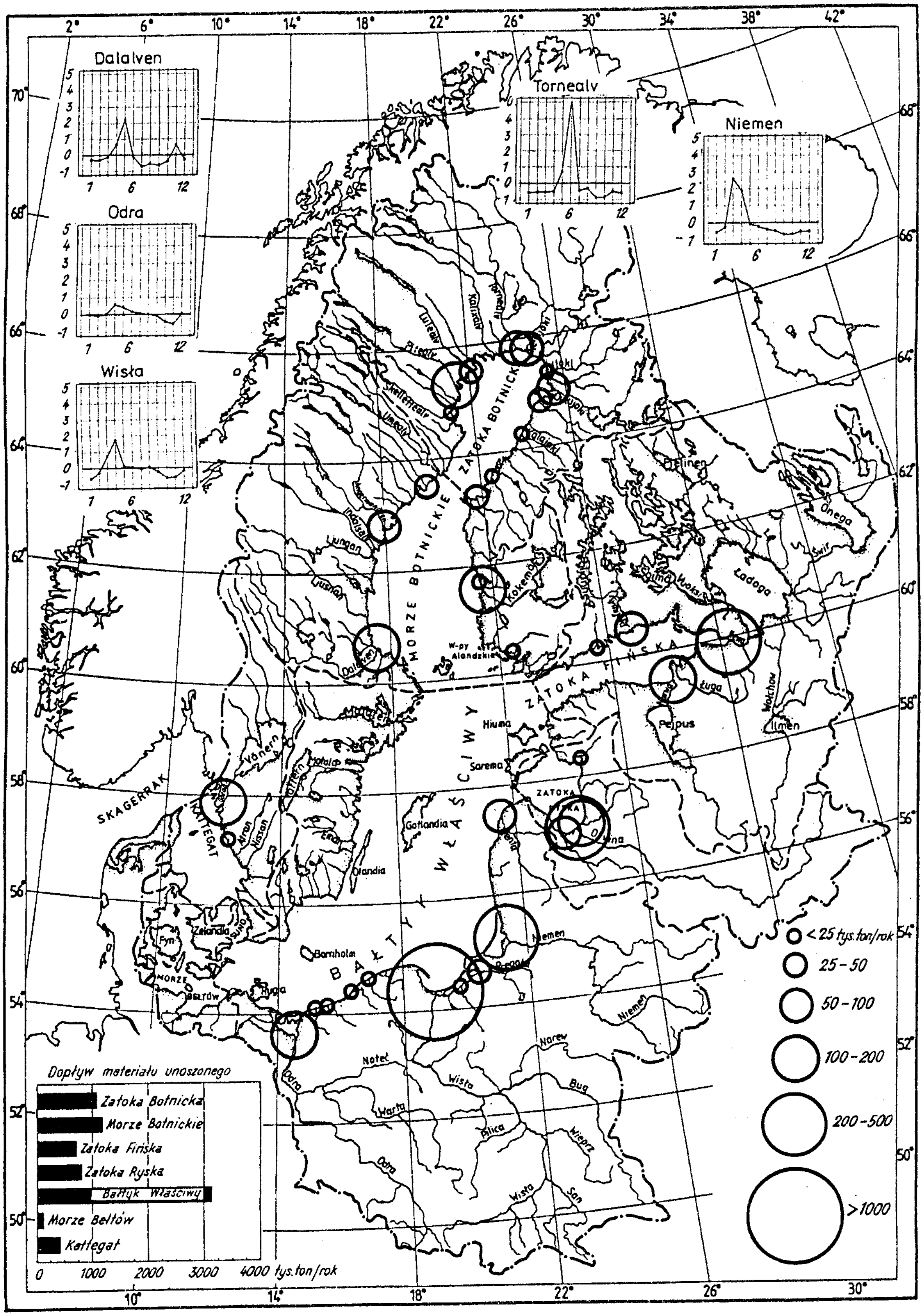

Figure 10.5. Suspended sediment transport to the Baltic Sea (Majewski & Lauer, 1994).

stations, water reference samples were taken every day (at some of the stations sampling is done 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. As the load measurements were completed, a single reference sample was collected at the site of constant sampling.

Methods of sediments concentration analysing

In Finland a water sample of 50-100 ml was filtrated through a 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 (B. Nilsson, 1971). The material was washed down to a vessel and dried at 105 °C. After cooling in a dessiccator for 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 former USSR the 2 l water samples were filtrated through paper filters 185 mm in diameter, having 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.

Calculation of input of suspended matters into the Baltic Sea

As mentioned before, the calculation techniques differ between Finland, Sweden and Poland. Using interpolation techniques based on similarities of the denudation ratio, the measured values were extended to the unmeasured basins and the suspended sediment transport to the Baltic Sea could be evaluated. Because of uneven distribution of the gauging network, unequal sampling frequency and 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, coastal regions of Sweden and, especially, of Finland, could certainly be more accurate by having better knowledge of the physical conditions of the areas.

Input of material during the period 1961-1970 has been based on literature data. There were very few data published on sediment transport in Finnish rivers during the period 1961-1970. By using the data published for the years 1970-1972 and 1974-1976 (Wartiovaara, 1975; 1978), an attempt was made to estimate the transport. The sediment transport of different rivers displays quite varying dependence on stream-flow 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 1961-1970, calculated by Mikulski (1975), was then used to estimate the denudation.

The same technique was applied to the Swedish data. The temporal extrapolations extended however only between the years 1961-1966. The transport values from the Ångermanälven River were available for the whole period (B. Nilsson, 1974).

The highest annual denudation rates, exceeding 50 t/km^2, have been found in the Carpathian Mountains, especially in the Carpathian Foothills, which produce an average of 380 t/km^2 (Łajczak & Jansson, 1993). A large part of the sediment load is deposited in the Vistula River catchment, in the place where the river gradient decreases between the Carpathian Mountain and Lowland areas. Sediment deposition along other rivers is 78 % in River Oder, 70 % in River Nemunas and 70 % in River Daugava.

The transport from the Danish islands and from Jutland to the Baltic Sea and to Kattegat was difficult to estimate. Irregular measurements in nine small rivers on Zealand gave transport values ranging between 5-20 kg/day/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 numbers an annual transport of about 6 t/km^2, seems to be a reasonable value for the mass transport condition on Zealand. 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 Jutland 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 & Edens, 1974). Using the Swedish River Viskan as an analogy, the annual transport from Jutland during the years 1967-71 has been assumed to be 12 t/km^2.

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 (Brański, 1974; 1975; IAHS, 1974; Lisitsina & Aleksandrova, 1972; Lvovic, 1971; Mikulski, 1975). This refers to the rivers on which the transport is

Table 10.1. Annual mean input of suspended material to the Baltic Sea and its seven subbasins (HELCOM, 1986)

Subbasin	**Contribution from countries** (10^3 tonnes/year)							
	Denmark	**Sweden**	**Finland**	**USSR**	**Poland**	**GDR**	**FRG**	**Total**
1	-	625	455	-	-	-	-	1 080
2	-	890	290	-	-	-	-	1 180
3	-	-	170	545	-	-	-	715
4	-	-	-	810	-	-	-	810
5	6	225	-	800	2 100	-	-	3 131
6	78	-	-	-	-	35	-	113
7	84	335	-	-	-	-	-	419
Total	168	2 075	915	2 155	2 100	35		7 448

measured. The data are rather inconsistent and collected during different periods. Most of the data come from the years 1950-1970. In collecting the supplementary data for the areas for which no information was available, various spatial interpolation techniques were applied (B. Nilsson, 1986).

The results of all the calculations of the input of suspended matters to the Baltic Sea during the decade 1961-1970 are summarised in the Table 10.1.

The results

Due to very unevenly distributed measurements, geographically as well as over time, an estimation of the total suspended transport to the Baltic must have 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 in length. Besides the poor network and data series for different periods of time, the fact that many power plants were constructed during the 60s, implying a complete change of transport conditions, contributed to making the estimation of mass transport mere guesswork. Furthermore, the techniques of sampling, of analysing and of data evaluation often varied from one investigation to another. Certainly some intercalibrations of methods were carried out in Denmark, Finland and Sweden. Still a lot of work remains to be done for methods of sampling and calculating standardisation.

According to the estimates given, the total input of suspended matters to the Baltic is in the order of 7.5 million tons a year. Recent studies give values of 4.5-6 million tons a year for the whole Baltic (HELCOM, 1986; Łajczak & Jansson, 1993; Cyberski, 1994). No more than 20-30 % of the total annual amount of suspended sediment produced in the upstream parts of the catchments reaches the Baltic Sea. Sediment is deposited on the alluvial terraces, in the river channels and is trapped in the reservoirs. Though slightly disturbed by the large lake areas of central Sweden, central Finland and of the River Neva drainage basin, the geographical pattern of the denudation in the individual river basins shows an increase from the north to the south (Figure 10.5). The input 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 former USSR 3.6 t/km^2. The main mass of the sediments reach the Baltic Proper (about 40 %), around 30 % reach Bothnian Bay and less reach the Gulf of Finland and the Gulf of Riga.

The Vistula River is the main source of suspended sediment supplied to the Baltic; it carries 866 000 t annually, which comprise 52 % of the Baltic Proper and 20 % of the Baltic Sea loads. The River Neva discharges 506 000 t, or 12 % of the input to the Baltic Sea and 64 % of the input to the Gulf of Finland. The input of sediment to the Bothnian Bay and the Bothnian Sea is more uniform, because the rivers of their catchments are rather small and similar in size.

The sediment flow shows higher variability than runoff. The maximum load of sediments is transported in the period March to July; the rest of the year provides only 10 % of the total load. The construction of many artificial reservoirs after the energy crisis in the 70s plus use of the lakes for water storage has changed the retention capability of many catchments. This has lowered the sediments flow to the Baltic by at least a few dozen percent (Cyberski, 1998). Calculated sediments inflow does not include the bed load, which can be quite significant in geologically young rivers. For example, in the middle reach of the Vistula River the total load causing sedimentation of Włocławek Reservoir is 1.30 million t in which bed load comprise 0.470 million t (Dziurzyński & Magnuszewski, 1998).

DISCHARGE OF DISSOLVED MATTER TO THE BALTIC SEA

There are three components of special interest being discharged by runoff to the Baltic basin. One is organic matter that will consume dissolved oxygen in seawater, another is phosphorous which together with nitrogen will produce organic matter in phytoplankton, admittedly under the release of an equivalent amount of oxygen gas. Oxygen may escape into the atmosphere but can also be added from the atmosphere, all depending on the temperature at the surface and the vertical mixing of seawater. The organic matter, appearing to a large extent as particulate matter, will slowly sink towards the bottom, being gradually converted into carbon dioxide, dissolved phosphate and nitrate by a chain of predators, consuming dissolved oxygen. A trickle may reach the sea floor, in which case the bentonic fauna eats it, provided that there is oxygen left. If this is not the case, sulphate ions will supply the oxygen needed for further decomposition, being converted to hydrogen sulphide, a gas poisonous to all kinds of animal life in the sea.

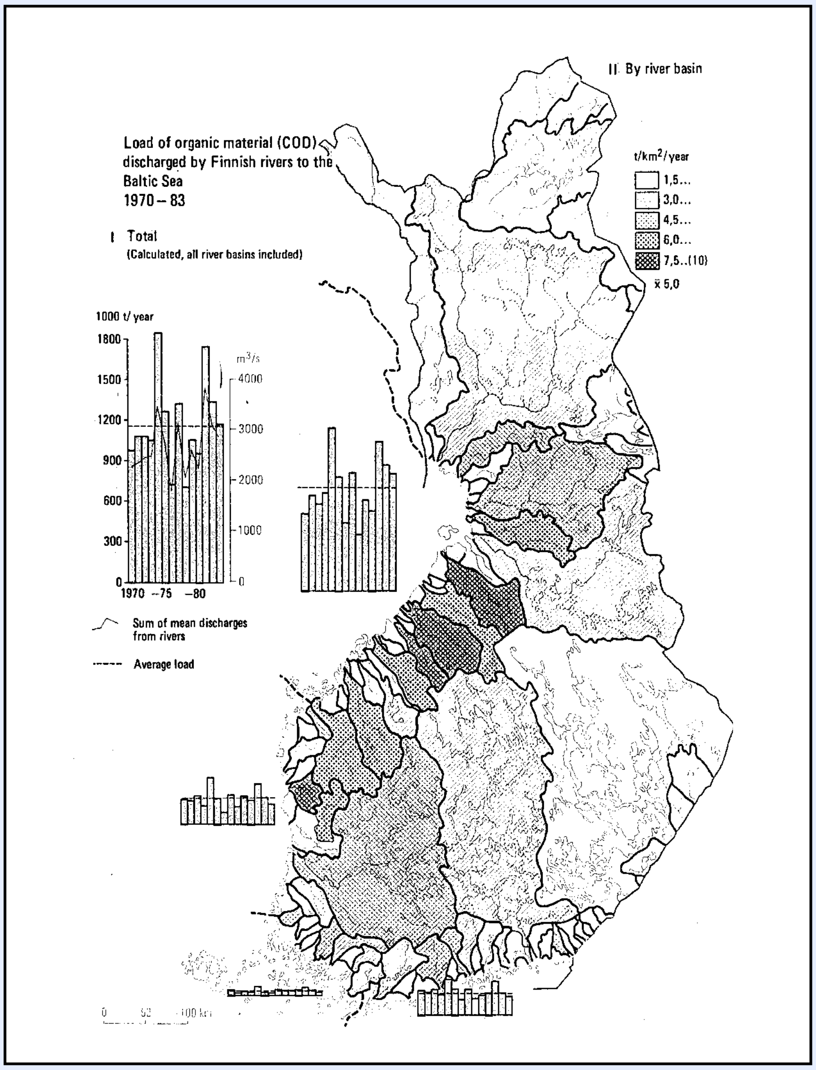

Figure 10.6. Load of organic matter (COD) discharged by Finnish rivers to the Baltic Sea 1970–1983 (from the National Board of Survey & Geographical Society of Finland, 1986; Atlas of Finland, Folio 132, Figure 25d, published under permission no. 420/MAR/98).

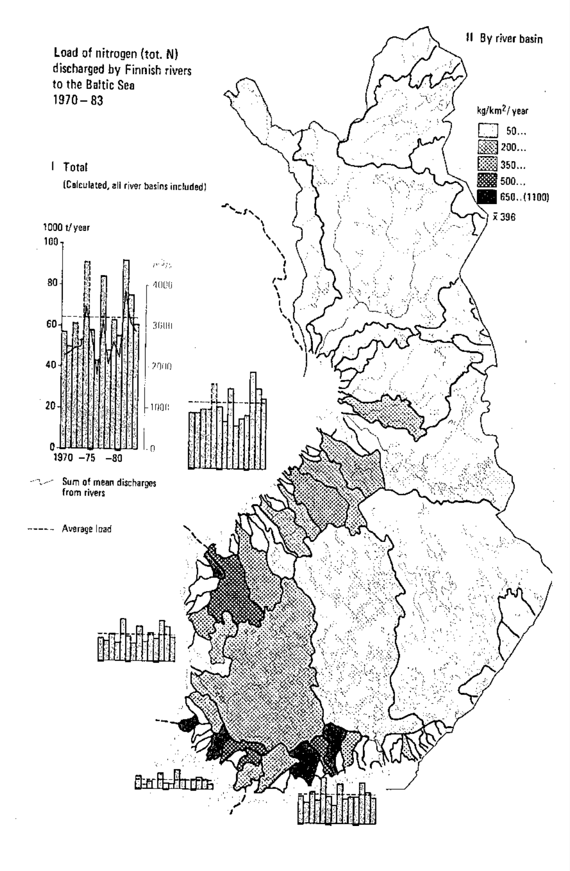

Figure 10.7. Load of phosphorus (tot-P) discharged by Finnish rivers to the Baltic Sea 1970–1983 (from the National Board of Survey & Geographical Society of Finland, 1986; Atlas of Finland, Folio 132, Figure 25e, published under permission no. 420/MAR/98).

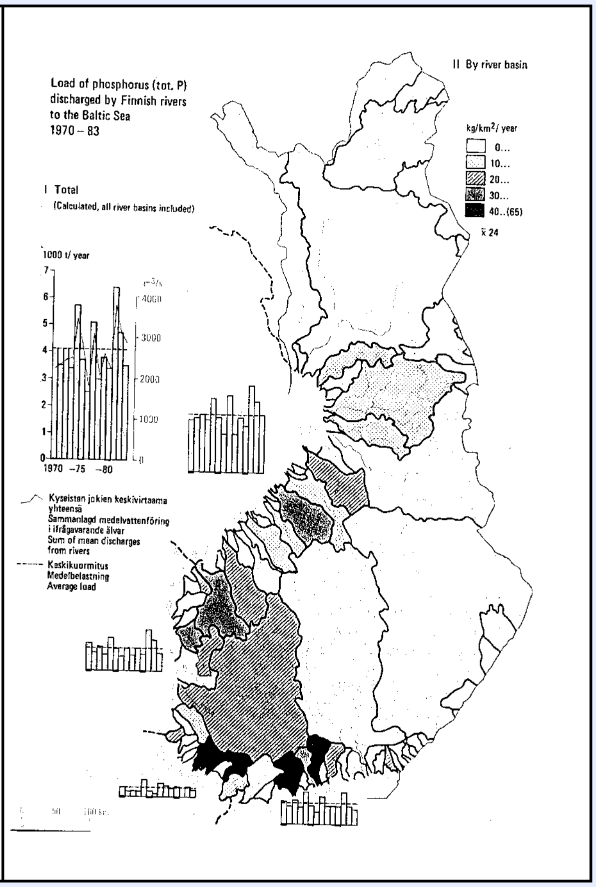

Figure 10.8. Load of nitrogen (tot-N) by Finnish rivers to the Baltic Sea 1970–1983 (from the National Board of Survey & Geographical Society of Finland, 1986; Atlas of Finland, Folio 132, Figure 25f, published under permission no. 420/MAR/98).

Figure 10.6 is based on records of the chemistry of river water and discharge by rivers. It gives a rather detailed picture of the geographic distribution of sources of organic matter carried to the sea. The coastal plain seems to supply most of it, particularly to the Bothnian Bay. The discharge of organic matter to the Bothnian Sea is much less, comparable to the discharge to the Gulf of Finland. The total discharge to the Baltic is as seen nearly 1.2 million tons per year.

Figure 10.7 summarises the transport of phosphorous by the rivers, about 4 000 tons per year. Half of this goes to the Bothnian Bay, the rest being divided between the Bothnian Sea, the Archipelago Sea and the Gulf of Finland. Most of the phosphorous seems to originate in agricultural areas.

Figure 10.8 shows the transport of nitrogen, in organic matter and in nitrate to the Baltic Sea. The total discharge rate is slightly more than 60 000 tons per year. Half of it goes to the Bothnian Bay. The transport pattern is similar to that of phosphorous. The ratio of nitrogen to phosphorous in the discharge is close to 15. This is about twice as high as the ratio in seawater.

Erik Eriksson

11.

HYDROLOGICAL MODELS AND MODELLING

L-C Lundin, Sten Bergström, Erik Eriksson & Jan Seibert[1]

Models – a synthesis

Although the hydrological cycle is a system that is fairly easy to grasp and understand, it is far from easy to quantify the processes in the system. In order to do this various types of hydrological models are used. The term "hydrological models" is here used in wide sense, meaning all models describing the hydrological cycle or its major parts. Variations in climate, topography, land types and land-use as well as various man-made interferences with the system make it very difficult to construct general models that treat the whole hydrological cycle in any given catchment in the world. Most models only treat a part of the cycle, e.g., runoff or groundwater-flow. Models developed in a certain climatic or geologic region often have difficulties when used in a different setting.

Models are simplified systems that represent real systems. In the case of hydrological models the real system may be an entire river basin or parts of it (e.g., only the river itself, a small headwater catchment, or a soil column). Hydrological models can range from sand-filled boxes to complicated computer program. The first type is called scale models. In these the real system is reproduced on a reduced scale. The second type, where a number of equations stand for the real system, is termed mathematical (or symbolic) model. Hydrological models can also be classified into conceptual models and physically based models. The conceptual models are rough simplifications of reality, conceptualising the ideas of important processes and simulating internal variables, such as soil moisture, by various types of response functions. In physically based models the processes are described by detailed physical equations. In practise, even physically based models often have elements of empirical or conceptual equations.

Although hydrological models basically aim at giving figures to various flows in the hydrological system they also have an important role as pedagogical and research tools. In a model, all parameters have to be quantified and specified, preferable so that their value can be deduced from actual field measurements. Their relative importance can then also be assessed. Research models are focused on process studies and the development of new knowledge and tend to be very complex and not always user friendly, whereas operational models are more focused on producing background data for decisions and planning.

The terminology in the modelling community can sometimes be somewhat of a barrier for non-modellers. In the following, the ambition is to use a simple language, not going in to details. A few central concepts are however used and will be briefly described: A *parameter* is a control device in the model, much like the volume knob on a radio. Most models use a number of parameters to control soil, land, climate and river properties. *Input data*, or driving data, are the data sets that are processed by the model and results or *output data* are the results of the processing. It is a well-known truth that the quality of the results will not be any better than the quality of the input data. *State variables* and *flow variables* are the also central, being the value or level in a model box and the flow of a property between boxes. State variables often are expressed in units of height (mm) or energy content (J) whereas flows would then have the unit mm/s or W.

Use of hydrological models

Hydrological models have become increasingly important tools for the management of the water resources of the Baltic basin. They are used for flow forecasting to support reservoir operation, for flood protection, in spillway design studies and for many other purposes. Recently hydrological models have found a new role in studies of climate change impacts on water resources (Saelthun et al., 1998).

Hydrological models are used for several practical purposes. Imagine a flood disaster: during the flood event a model may help to predict when and where

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[1] L-C Lundin is responsible for the introduction to the area and the compilation of model examples, Sten Bergström contributed with the water balance modelling, Erik Eriksson is responsible for the description of the various model types, and Jan Seibert wrote the part on model application.

there is a risk of flooding (e.g., which areas should be evacuated). After the flood, models may be used to quantify the risk that a flood of similar or larger magnitude will occur during the coming years and to decide what measures of flood protection may be needed for the future. Furthermore, models may help to understand the reasons for the magnitude of flood (e.g., if the flood was enlarged by human activities in the catchment).

Other types of hydrological models are used in planning of groundwater management. These models are often referred to as groundwater models or hydrogeological models. The Soil-Vegetation-Atmosphere Transfer (SVAT) models concentrate on the evaporation and heat exchange at the Earth's surface and have a wide use in plant production studies and also in climate modelling.

Hydrological models focus on the pathways and the actual fluxes of the water, but since water also is the main transport media in nature attention to the transported substances is becoming more and more important. Groundwater models, e.g., are often able to quantify the transport of dissolved substances as well, making them important tools in pollution studies. Runoff models are used as a basis for calculation of sediment transport and substances dissolved in the river water. Soil water flows calculated by SVAT models are used as the basis for transport of nutrients and pesticides.

Model application

The typical steps in a model application can be summarised as shown in Table 11.1. The steps are illustrated by an example where a design flood is needed for the planning of a hydropower plant. Note, however, that calculation of design flows is a complex task and different procedures are used in different parts of the Baltic region. Variations from this simplified presentation can thus occur. First, the problem to be solved has to be identified and a list of available data has to be compiled. Based on this information one has to choose a suitable model. The parameter values have to be determined on the basis of measurements. Usually, this is possible only for some of the parameters and the others have to be estimated by calibration. In this case, their values are changed (manually or by some automatic calibration algorithm) until a satisfactory agreement between observed and simulated runoff is achieved. Before the model with its calibrated or measured parameter values is used to solve the problem, its capability to simulate an independent period should be tested. This test usually is called validation.

Hydrological models

Water balance simulation and prediction

Runoff models are probably what most hydrologists spontaneously refer to when discussing hydrological models. This was also the first branch in which models were used when computers became easily available in the 1970s. The basic principle in hydrological modelling is that the model is used to calculate river flow based on meteorological data, which are available in a basin or in its vicinity. Hydrological models include subroutines for the most significant hydrological processes, such as snow accumulation and melt at different

Table 11.1. The different steps in hydrological modelling

Step in model application - Example
Identify problem Determine the probable maximum flood
Available data 15-year series of runoff, precipitation and temperature, sequence of probable maximum precipitation
Choice of model HBV model (it fits the needs and there is a lot of experience from previous applications in Sweden)
Determination of parameter values by measurements and/or calibration All parameters of the HBV model have to be calibrated (the first 10 years are used for calibration), an acceptable agreement between observed and simulated runoff is obtained
Validation The model is run (without changing parameter values) for the 5-year period which was not used for calibration, the simulations agree acceptable with the observations
Solve the problem The probable maximum precipitation sequence is inserted at different times (seasons, years) and the model is run to simulate the flood caused by this sequence

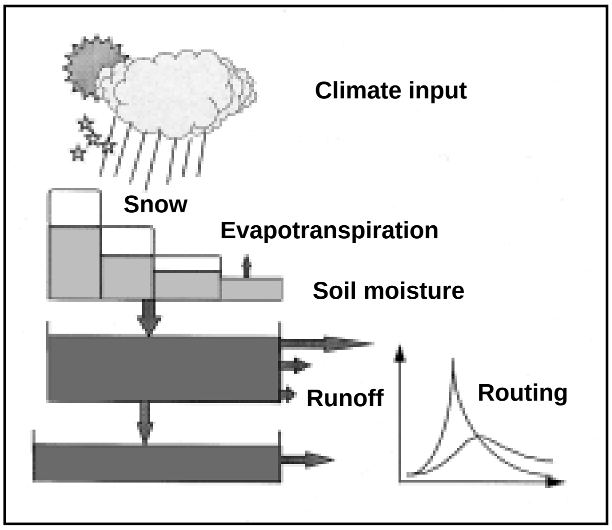

Figure 11.1. Schematic figure of the HBV hydrological model showing its main computational components.

elevations, soil moisture dynamics, evapotranspiration, recharge of groundwater, runoff generation and routing in lakes and rivers. Most runoff models are based on the water balance, using precipitation as a driving variable and calculating the quantities directed as runoff, R, from the water balance equation,

$$R = P - E - DS,$$

where P is precipitation, E evapotranspiration, and DS represents various storage terms.

In general, the different driving forces for development, refining and application of models can be grouped into three classes. At first, models can be used instead of expensive or time demanding measurements. Often, climatic data (e.g., precipitation and temperature) are much easier available than runoff data. In the case of extending runoff series with historical climatic data, the alternative of direct measurements becomes impossible. Secondly, models are used for short- and long-term forecasts and to serve as a basis for management decisions. Long-term forecasts, with a time scale of months or more, are, for instance, needed to operate hydropower reservoirs in an optimal way. Models can also contribute to answering 'what if' questions, e.g., what will be the effect of a changed land use or what are the hydrological implications of a climatic change. The third point is the use of models to compile and impart knowledge of real systems and their functioning.

Water balance models are often divided into three categories; lumped models, distributed models, and stochastic models.

Lumped models are often used for planning of water management programs in river systems with power stations. The term lumped implies that the entire catchment is made into a few boxes of water reservoirs, usually the root zone, the unsaturated zone and the groundwater storage. These models are most often conceptual and are also referred to as empirical or black-box models. Only the output (runoff) generated by a certain input (precipitation, temperature, etc.) is of interest and an input is transformed into an output by simple equations, which have no association with the real processes. The natural flow rates between boxes are set by parameters, which must be assessed by optimisation procedures, considering observed data with computed. The output is discharge to the river system.

The weakness of lumped models is the way parameters are selected which makes them inter-correlated. The way boxes are interconnected is immaterial since optimisation always finds parameter sets for best fit. Inter-correlated parameters indicate that there are too many parameters or too many boxes. An improvement should entail assessment of parameters independent of the model but for a lumped model this is difficult since a lumped model is, conceptually, a poor substitute for a real river basin.

The spatial resolution of a model varies; lumped models represent the entire catchment by a few boxes and no spatial differentiations are considered, and distributed models divide the catchment into a large number of cells (e.g., 100 by 100 metres). In between there are semi-distributed models where the catchment area is grouped into different classes (e.g., elevation or vegetation zones) but only the proportion and not the spatial distribution of each class is considered. Event-based models concentrate on single floods whereas continuous models allow simulating runoff series.

An example of a widely used lumped model is the HBV[1] (after the Hydrological Bureau Water-balance section) model presented in more detail below. The model developments have gone in the direction of discretisation of the drainage basin in sub-basins and elevation zones and the model is therefore sometimes also referred to as a distributed model. In the Nordic countries the HBV model, with roots in the early 1970s, is the most commonly used hydrological model (Bergström, 1995; Lindström et al., 1997). Its configuration is shown schematically in Figure 11.1.

There are many different versions of HBV-model software besides the original SMHI version. One recent version is HBV light, which has been developed at Uppsala University (Seibert, 1997). One motivation to develop this version of the HBV model

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[1] http://www.smhi.se/sgn0106/if/hydrologi/hbv.htm

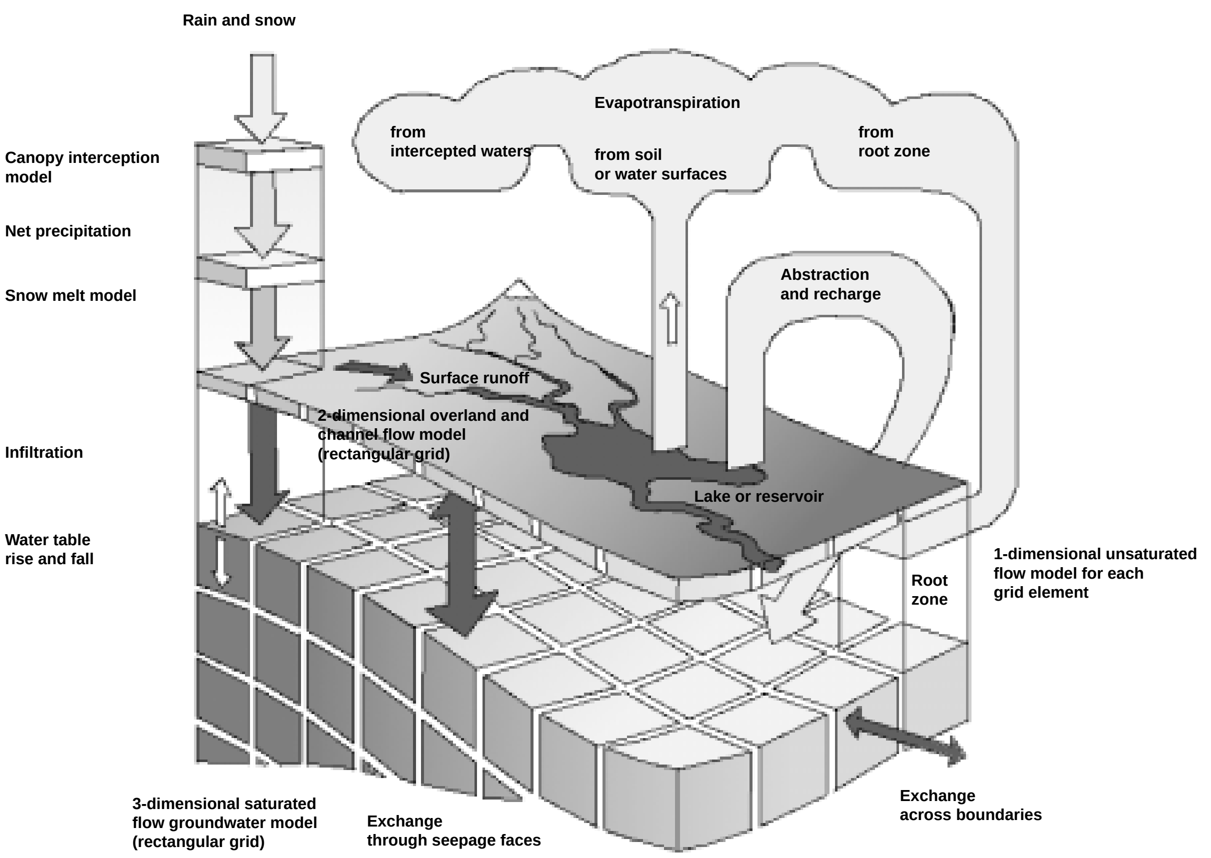

Figure 11.2. The MIKE SHE model from Danish Hydraulic Institute (DHI).

was to improve the user-friendliness, especially considering the use in education. During the last years the new version has been used successfully in several courses. HBV light corresponds in principle to the version described by Bergström (1992; 1995) with only slight changes. In order to keep the software as simple as possible several functions available in the SMHI version have not been implemented into HBV light. It is, for instance, not possible to divide the catchment into subbasins.

Distributed models are laborious to construct since they normally require a detailed hydrologic description of the area, to be used for delineating homogeneous sub-areas. Once this is accomplished field data are collected to assess parameters for the sub-areas. The variation of the recharge part within sub-areas should also be made and related functionally to the groundwater level by a parameter. Evapotranspiration also need observed parameters in order to function properly. The ground within a sub-area can be divided into root zone and groundwater storage. Hydraulic conductivity, groundwater surface slope and direction of slope computed from adjacent sub-areas govern groundwater flow. Most of the parameters will thus be obtained independent of the model. The development cost of the model would be high but this is an investment cost for a reliable and solid construction. The effect of forest management is easy to include.

Examples of this type of model are TOPMODEL, which can be downloaded as freeware for educational and research use[2], the commercial model Systeme Hydrologique Europeen (MIKE SHE)[3], developed and promoted by Danish Hydraulic Institute (DHI) and the research-oriented model ECOMAG (ECOlogical Model for Applied Geophysics), developed in Russia.

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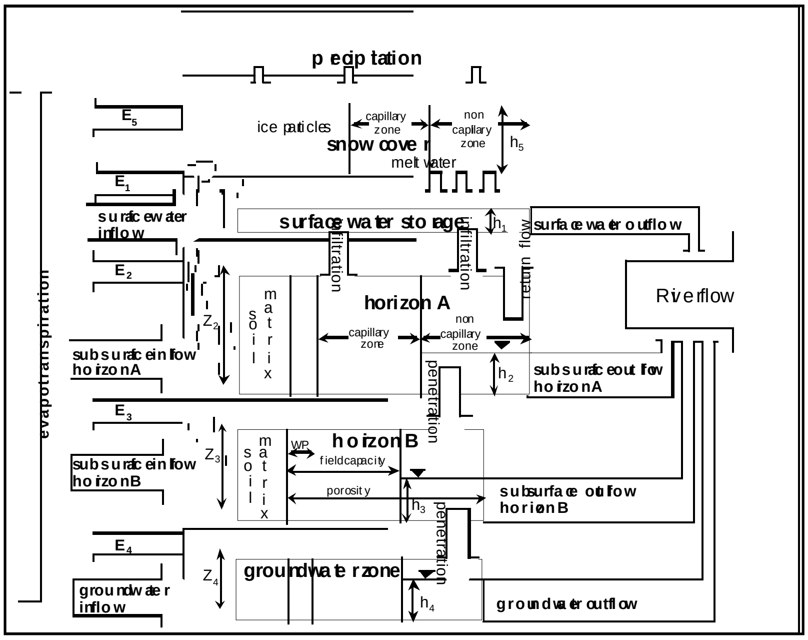
[2] http://www.es.lancs.ac.uk/hfgd/topmodel.html

[3] http://www.dhi.dk/gishydro/mikeshe/Mshemain.htm



Figur 11.3. Vertical structur for a model element in the ECOMAG model (Motovilov et al., 1999).

TOPMODEL (Beven, 1997) is a rainfall-runoff model using an analysis of catchment topography as its bases for distributed predictions. The idea is that the model should be simple enough to be modified by the user. Developments of the TOPMODEL are thus widespread in research applications.

MIKE SHE is an advanced integrated hydrological modelling system (Figure 11.2). It simulates water flow in the hydrological cycle from rainfall to river flow, via various flow processes such as, overland flow, infiltration into soils, evapotranspiration from vegetation, and groundwater flow. It is normally used in regional studies covering entire river basins, often carried out by consultant companies as well as in local studies focusing on specific problems on small scale often being research applications.

ECOMAG (Motovilov et al., 1999) is a physically based distributed model, much of the same type as SHE. However, it leans less heavily on support from extensive data sets on catchment properties and also has a module treating transport and reactions of chemical substances in the catchment. The basic input data are topographical and geomorphological properties of the catchment. The model also applies stochastic approaches using distributions functions in order to describe parameter variation within model elements. A guiding principle is to keep parameters and state variables interpretable in a physical sense.

Since the concepts of the ECOMAG model structure are fairly representative of the different distributed models they will be presented in some detail below (Figure 11.3).

The catchment is divided into a number of elements that are treated as homogeneous areas. Each element is described by its inclination and is made a member of a specific soil class, groundwater-zone class, vegetation class and land-use class. For each class a specific parameter set is used. Some of these parameters are, as mentioned above, given values as stochastic distribution functions rather than absolute values. The vertical fluxes and distribution of properties are described by dividing each element into three layers, A-horizon, B-horizon, and ground-water zone, treated as linear and non-linear storages. Horizontal flow of soil water is described by the Darcy equation and the equation of continuity whereas overland flow and river flow is described by Manning's formula.

Stochastic models for river basins are constructed on the basis of river discharge history describing river discharge by a long term mean, possibly a long term trend, seasonal variation, and a random component treated as a stochastic process with e.g. autoregression parameters or, alternatively as conditional distributions. The seasonal variation in stochastic parameters is usually very large, at least in the northern part of the region. These models are generally used for dimensioning purposes and have little forecasting use.

Hydraulic models

The hydraulic models are used to calculate water stage, or water-surface profiles along a river or channel. They can also be used to determine areas inundated by flood discharges and to study the effects on floodplains. Specialised models can predict effects of various obstructions such as bridges, culverts, weirs and structures in the over-bank region into account.

An example of a well established hydraulic model is the HEC[4] (US Army Corps of Engineers - Hydraulic Engineering Center) model. The model comes in several varieties and with various couplings to analysis tools.

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[4] http://www.hec.usace.army.mil

DOWNLOADING MODELS

Several of the models described are freeware and can be downloaded from the Internet addresses given for use in education and science at no cost. These models cannot be used commercially without special agreement with the owner of the model rights. For some commercial models demo versions are available for download.

Although most models today are running under Windows, be sure to check that the model runs under an operating system that you have available. Some models also requires special software for data management, generation of model elements and data analyses.

In many cases demonstration data sets are supplied which are very helpful when evaluating the model. They may even be of use for the preparation of minor exercises or model experiments. Some model developers run newsletters and present lists of publications in which model results were presented and discussed. In most cases documentation is needed in order to operate the models properly. Document files are often to be downloaded separately.

For some models it is even possible to download the program code in order to be able to make modifications and further model development. This option is primarily for the experienced model user, but could be an option for a thesis or diploma work. It is then good practise to send an e-mail to the model owner stating the problem studied and the development need foreseen. This often leads to hints of new versions or contacts with students and researchers interested in similar problems.

The references given in this chapter are focussed on model descriptions and manuals. Scientific references and examples of model applications are often found on the home pages of the respective models.

Models for sediment transport

Soil erosion within a river system is bound to decrease the usefulness of regulated reservoirs and is therefore important to master by suitable measures. Existing methods to predict the useful lifetime of a reservoir is to assess the transport of suspended load by the river and assume that this load will settle in the reservoir. Since the source of the load is soils bordering the river system measures should be taken to decrease the soil erosion within the catchment. In order to achieve this one must have a proper concept of the erosion process, particularly of gully erosion and landslides. Since these two are related to high pore pressures models in future must include groundwater formation and flow pattern that will indicate where such erosion may occur. The only way to decrease pore pressure is by drainage. High pore pressure will appear where clay rich soil overlays fracture zones in hard rock areas.

For sediment transport, erosion and deposition in rivers there are varieties of the HEC model, e.g., HEC-6 to be used.

Soil-Vegetation-Atmosphere transfer models

In order to describe the exchange of water and heat between the Earth's surface and the atmosphere, Soil-Vegetation-Atmosphere transfer (SVAT) models are used. These models are often one dimensional, describing a column based on the groundwater surface and reaching up to some few metres in the atmosphere. The models involve more or less sophisticated descriptions of vegetation, sometimes as a static component and sometimes taking plant dynamics into account. The soil description can be more or less detailed and a few models also allow for treatment of soil frost. Snow routines are also an important issue in the Baltic region. This feature is incorporated in some SVAT models. A large number of SVAT models are today available, some are detailed research models and some more general and operational. SVAT schemes are also used in the Global Circulation Models (GCM) when assessing the impact of climate change. These schemes are in principle very similar to regular SVAT models but the scale treated is much larger and the formulations thus generally much simpler.

In large scale simulations two concepts are commonly used, the bucket model and big-leaf model. The bucket model is an extreme simplification of a runoff module. A box, the bucket, is gradually being filled with runoff, generated as a rest term of the water balance equation. When it is full it is tipped into the ocean. In the big-leaf model a single leaf covering the model element, often in the order of square kilometres, is modelled to represent all vegetation in the element. Although it is easy to criti-

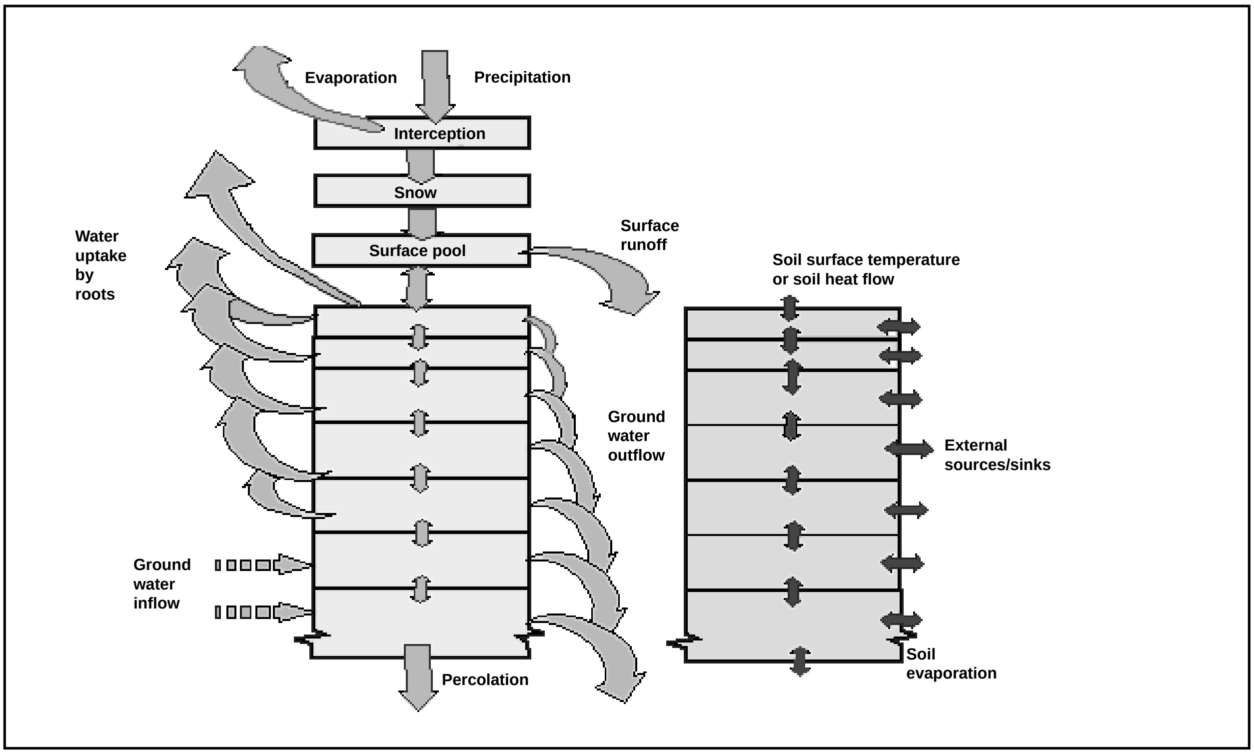

Figure 11.4. Model structure of the heat and water flow parts of the CoupModel (Jansson, 1998).

cise these concepts they work surprisingly well for large-scale applications. Refinements have also been presented of these concepts.

SVAT models use climatic data, e.g., precipitation, net radiation, wind, as input. The output is typical soil moisture, groundwater formation, soil temperature etc, but could also be latent and sensible heat flux, groundwater flux or runoff. One should be aware that in all cases the output data represents the point or possibly field scale and if data are presented to represent other scales additional aggregation has been preformed.

As an example of a SVAT model the model CoupModel[5] (Jansson & Karlberg, 2004) is presented below. CoupModel is an extended version of the SOIL model, incorporating nitrogen and carbon flux modules. This model is frequently used in a number of countries in the Baltic region and is adopted to simulate the climate, geology and vegetation of the region. It is also a freeware model, used in both scientific work and undergraduate education. The purpose of the CoupModel is to quantify and increase the understanding concerning hydrological and thermal processes in the soil.

The basic structure of the model is a depth profile of the soil; one set of boxes handle water flow and another handle heat flow (Figure 11.4). The model is thus capable of simulating coupled heat and water flows, a necessity in order to treat soil frost in a physically based matter. Processes such as snowmelt, interception of precipitation and evapotranspiration are also treated explicitly.

The basic assumptions behind the model equations are very simple:

- The law of conservation of mass and energy and
- flows occur as a result of gradients in water potential (Richard’s equation) or temperature (Fourier’s law).

The model focuses on the soil profile and processes related to this. The calculations of water and heat flows are based on soil properties such as: the water retention curve, functions for unsaturated and saturated hydraulic conductivity, the heat capacity including the latent heat at thawing/melting and functions for the thermal conductivity. The model can handle various types of vegetation such as forest, agricultural plants. The most important plant properties are: development of vertical root distributions, the surface resistance for water flow between plant and atmosphere during periods with a non-limiting water storage in the soil, how the plants regulate water uptake from the soil and transpiration when stress occurs, how the plant cover influences both aerodynamic conditions in the atmosphere and the radiation balance at the soil surface.

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[5] http://www.lwr.kth.se/Vara%20Dataprogram/CoupModel/

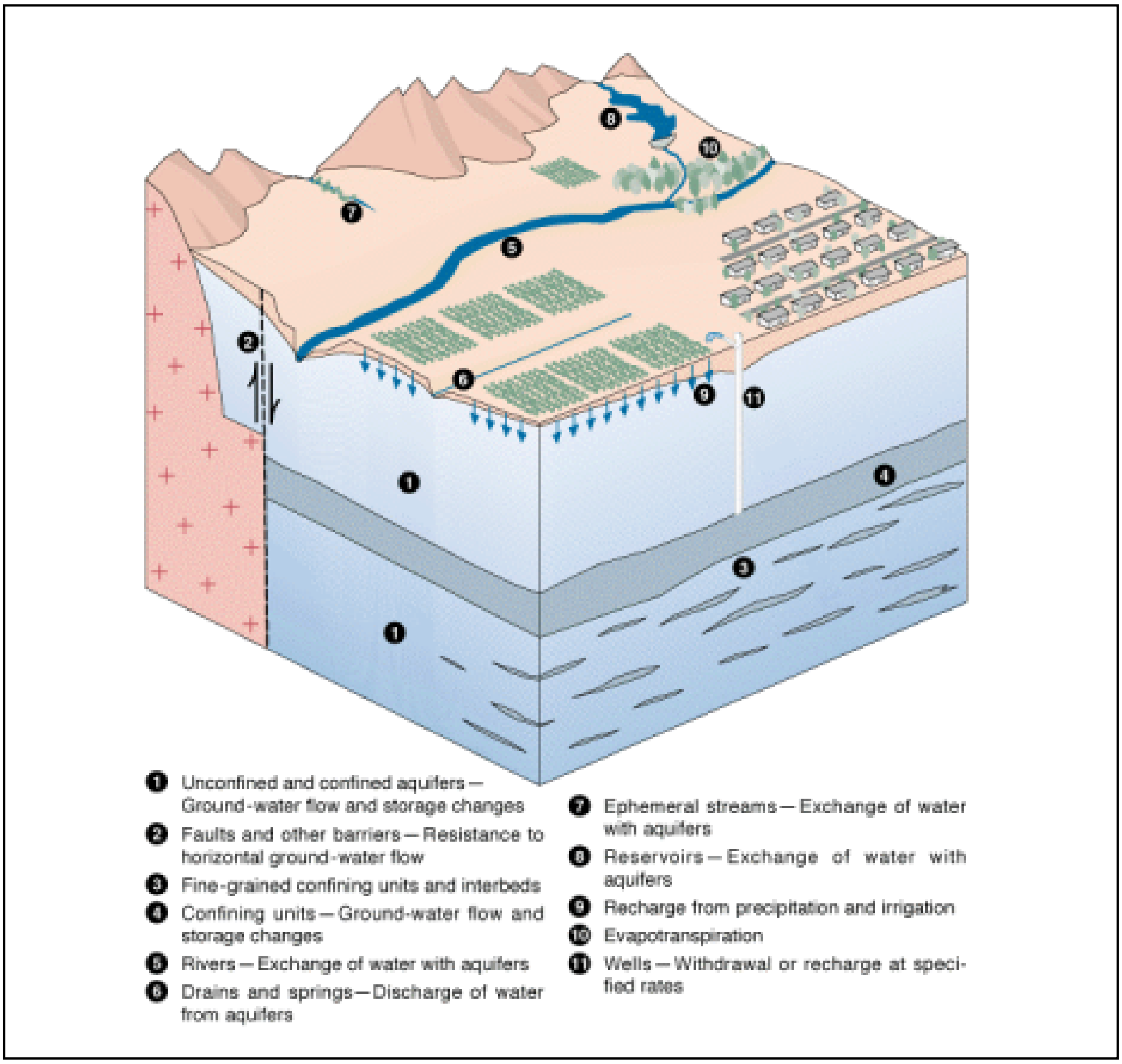

Figure 11.5. Features of an aquifer system that can be simulated by the USGS model MODFLOW.

MACRO[6] (Jarvis, 1994) is an example of a specialised model for water flow and reactive solute transport, e.g., pesticide transport, in macroporous field soils. The model is physically based, one-dimensional, and divides the soil porosity into two flow systems or domains (macropores and micropores) each characterized by a flow rate and solute concentration. The model can be coupled to MACRO_DB, a decision-support tool for predicting pesticide fate and mobility in soils. The system allows access to various databases on soils, compound, climate, and information on typical planting and harvest dates, root depths, etc. The user can also develop parallel databases for additional soils and new compounds.

Groundwater models

Groundwater models take over where most SVAT models end, i.e., at the groundwater surface, and are used to simulate systems for, e.g., water supply, contaminant remediation and mine dewatering. Many groundwater models also treat transport of dissolved substances in the groundwater. The basis for the calculations is the Laplace equation, describing groundwater flow. The numerical solution calls for a grid net that covers the aquifer studied. For three-dimensional models the work of generating the grid net can be considerable, especially if the aquifer boundaries are irregular. Special grid generating software is often needed and contouring programs may

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[6] http://www.mv.slu.se/bgf/Macrohtm/macro.htm

also be useful in order to visualise resulting groundwater surfaces.

MODFLOW[7] (USGS Modular Three-Dimensional Ground-Water Flow Model) is perhaps the most widely used groundwater model (Figure 11.5). The basic programme is developed by the United States Geological Survey (USGS) and available as freeware but there are also many extended versions sold by various scientific software companies. These versions are more fancy and have a better-developed user interface but basically produce the same results. MODFLOW is a three-dimensional groundwater flow model that simulates steady and non-steady flow in irregularly shaped flow systems. Aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Flow from external stresses, such as flow to wells, areal recharge, evapotranspiration, flow to drains, and flow through riverbeds, can be simulated.

Models for hydrochemical transports

As has already been demonstrated, some of the SVAT models incorporate or connect closely to hydrochemical transport models and most groundwater models also have a scheme for transport calculations.

The chemical state of natural waters is an environmental issue of great importance. At present the chemical state of surface waters is usually monitored in one way or another. In future this must be complemented by hydrochemical models, which allow prediction of the chemical states with land use practices as part of the input to soil, streams, rivers and lakes. A beginning has been made for predicting the effect of strong acid deposition on soil properties and groundwater quality.

Acidification of soils occurs in large parts of Europe due to release of sulphur to the atmosphere in local combustion. Since deposition rates of sulphur in Europe are known it is possible to assess the effect of acidification on soils, using feasible models. Eriksson (1998) developed the models SOILORG and SOILMIN for simulation of the chemical depletion of exchangeable cations in soils and the recovery that would take place when decreasing sulphur emission occurs. The transport medium in soils is soil water.

The range of models in this category is very large and we are approaching the area of general transport models, which is not really central to hydrological modelling. As an example the SOILN[8] (Eckersten et al., 1994) model, now incorporated into the CoupModel, presented earlier, is chosen.

SOILN simulates nitrogen flow in the soil and is much used within agricultural and silvicultural applications. The nitrogen load to surface waters and groundwater is often connected to land use and agricultural practises. The model can simulate use of both fertilisers and manure, from which plants take nitrogen in various rates. Soil mineral-nitrogen pools receive nitrogen by mineralisation of litter and humus, nitrification, fertilization and deposition, and loose nitrogen by immobilization to litter, nitrification, leaching, denitrification and plant uptake. All biological processes depend on soil water and temperature conditions.

Optimising water resource management

Optimisation models exists and are of importance in areas where water is needed for many different, often conflicting, purposes. Optimisation can then, hopefully, suggest arrangements for the most efficient sustainable use of available water. The procedure requires evaluation of the net yield of each use. There may be difficulties to put prices on social benefits and environmental properties. This is often a political assessment.

Coupled hydrological and meteorological models

Truly coupled hydrological and meteorological models do not yet exist. More and more advanced coupling schemes are however presented. The idea is that instead of taking measurements of precipitation, this input data are generated by a mesoscale meteorological forecast model. In this way hydrological forecasts would be improved and possible to extend further in time. The coupling should also work in the opposite direction, i.e., give the meteorological model information on, e.g., evapotranspiration, which is highly dependent on available soil moisture at the surface of the Earth. This would improve precipitation forecasts, that would improve evapotranspiration forecasts and a positive feedback would result.

The main reason why this wonderful idea has not already been implemented is that the hydrological and the meteorological systems are acting on very different

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[7] http://water.usgs.gov/nrp/gwsoftware/modflow.html

[8] http://dino.wiz.uni-kassel.de/model_db/mdb/soil-n.html

CASE: MODELLING THE WATER BALANCE OF THE BALTIC BASIN

The World Climate Research Programme, WCRP has identified the Baltic basin as one of the key areas for continental scale experiments. This is carried out under the BALTEX research programme (BALTEX, 1995). It is an interdisciplinary programme, with engagements from meteorologists, oceanographers and hydrologists, which aims at understanding the energy and water cycle of the Baltic basin. The hydrological modelling within BALTEX consists of the following four components:

- Development of a full hydrological model for the BALTEX region
- Use of hydrological models and observations to validate the hydrological components of the meteorological models.
- Development and intercomparison of hydrological models for selected river basins.
- Development of a coupled atmosphere/ocean/land surface model.

Within the EU funded NEWBALTIC project a macroscale hydrological model has now been set up and used for an estimate of the overall water balance of the entire Baltic basin (Graham, 1998). The model is based on the HBV-96 hydrological model (Lindström et al., 1997). It uses a subdivision of the drainage basin of the Baltic Sea into 25 sub-basins, ranging in size from 21 000 to 144 000 km^2 (Figure 11.6). The model covers the land area, including lakes, but excludes the sea itself and is thus a model of river runoff from land to the Baltic Sea.

Input to the hydrological model are daily synoptic meteorological data on precipitation and air temperature and output are daily simulated evapotranspiration, snow accumulation and melt, soil moisture dynamics, runoff generation and river flow. The model has been calibrated and validated against an existing database of monthly runoff (Bergström & Carlsson, 1994).

Figure 11.7 shows the overall simulated water balance of the terrestrial part of the Baltic basin, including lakes. It illustrates that a conceptual model captures the runoff very well. A closer look at the main water balance components reveals that snow and soil moisture have a dynamics of the same order of magnitude, if averaged over the entire basin, and thus are equally significant for the total Baltic runoff generation. The picture will, of course, look differently if subbasins are analysed in the same way.

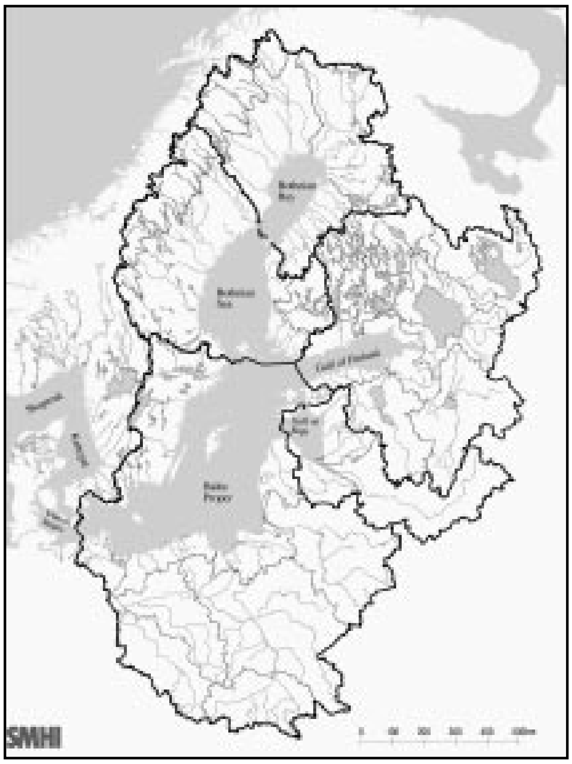

Figure 11.6. Subbasin boundaries used in the application of the HBV model to the Baltic basin (from Graham, 1998).

Although it can be argued that some of the variables in Figure 11.7 are model specific to some degree, the application of a hydrological model to the continental-scale basin of the Baltic Sea has resulted in the first consistent overall water balance compilation of the Baltic basin. It has also proved to be a very useful exercise for the harmonisation of climate models and hydrological models. This is the scale at which climate models and hydrological models can meet! Preliminary model intercomparisons have revealed several of inconsistencies in the different approaches and have also forced climate modellers and hydrological modellers to jointly analyse the behaviour of their models. This experience will become increasingly important for the assessment of the performance of regional climate models, which are presently being developed for regional climate change studies.

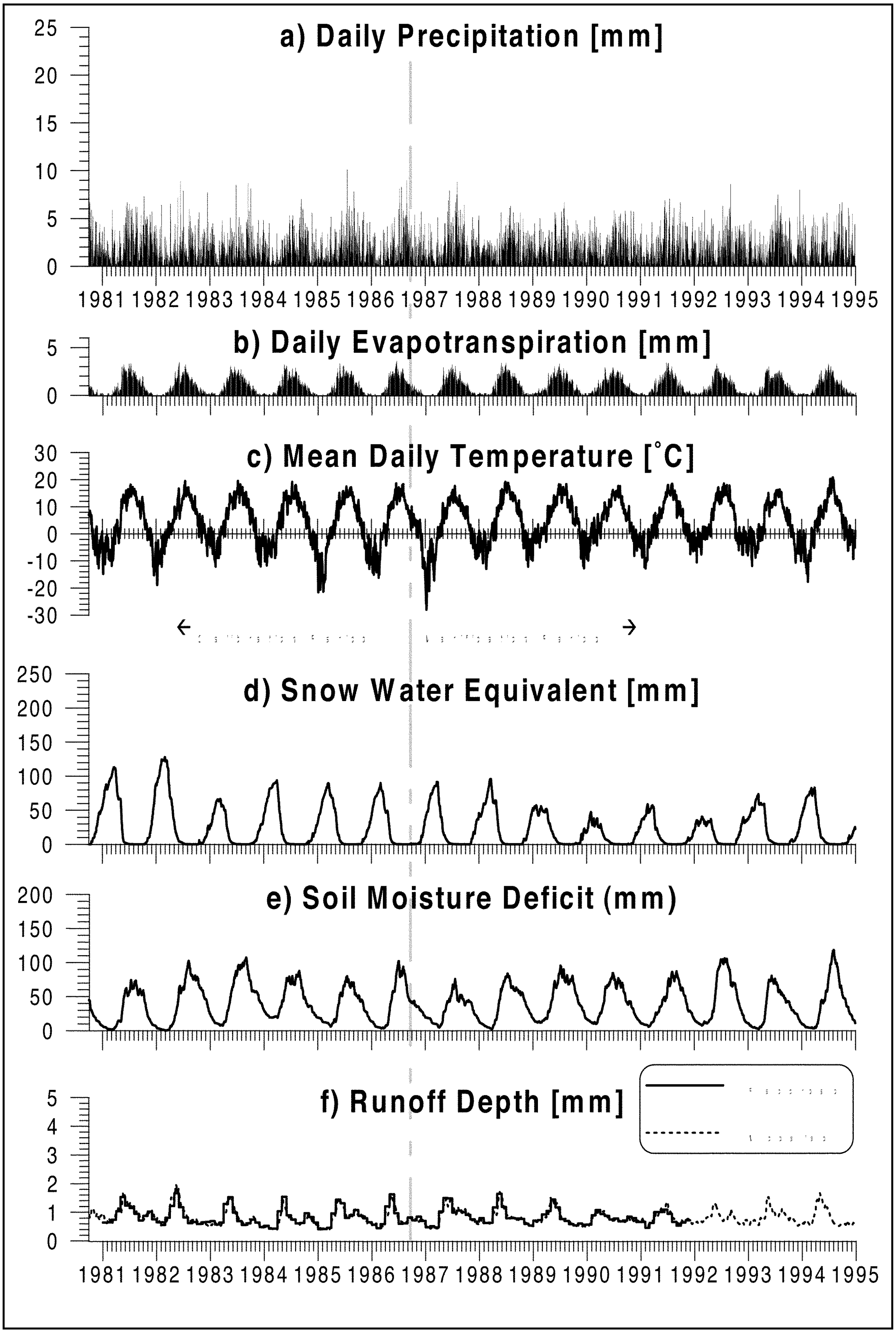

Figure 11.7. Simulated water balance of the Baltic basin by the HBV-96 model (from Graham, 1998).

time and areal scales. Precipitation is typically generated over the North Sea, at least frontal precipitation in the Baltic region, and knows nothing of the catchments that direct runoff and act as hydrological boundaries. A typical precipitation event occurs on a time scale of hours. Evapotranspiration is connected to soil water storage and is a process with a time scale of months.

The driving force behind the recent developments in the area is the increased interest in simulations of climate change. When normal forecast models only run for a few days, the GCMs are running for tens or hundreds of years. This puts the hydrological processes into focus since changes in the climate will result in changes in the hydrological regime that will in turn affect the climate. The feedback may be positive, enhancing climate change, or negative, counteracting a global warming. The later case may, e.g., occur if increased precipitation and temperature would result in increased evapotranspiration and cloud formation, thus decreasing the net radiation at the Earth's surface.

Part III

Human Impact and Water Resources

50 YEARS AGO ... AND TODAY

Our family photo album, which shows the summers we spent at a small shallow bay on the Swedish Baltic Sea coast called Revsudden, 25 km north of Kalmar, reflects the changing environmental status of the Baltic Sea. From 1944, we children are shown playing on a raft. The water is clear and the bottom pure sand. In the early 1950s, when we are studying jellyfish at the grassy coastline in the unusually warm water, the water conditions are still the same. In 1998 you see a 20-metre-thick belt of reeds (mostly Bolboschoenus (Scirpus) maritimus) along the shoreline; a scythe had to be used to cut our way out to the eutrophied water and muddy bottom (photo, various members of the Rydén family).

Lars Rydén

12.

A history of humans and the Baltic Sea

Per Jonsson & Johan Persson

The Baltic Sea a hundred years ago

What did the Baltic Sea ecosystem look like a hundred years ago? It is of course difficult to know for certain, since documentation of the research done during that time is, with a few exceptions, lacking. As a reference, we have the archives – especially the seafloor sediments – that nature itself supplies, on which we base more or less scientifically qualified guessing.

We know from past studies (Melvasalo et al., 1981) that the oxygen levels in the deeper areas were significantly higher than today. We also know that, starting at the end of the 1940s, macrobenthic fauna have faced tough conditions, though better than those of today. One report after the other showed that, in the 1950s, macrobenthic fauna was rapidly becoming extinct due to oxygen deficiency (e.g. HELCOM, 1987a; 1990). This coincided with the decreasing oxygen concentrations registered in the deep areas and, during the 1950s-1970s, with concentrations below the critical level of 2-3 mg/l in large areas deeper than 100 metres. This critical level is the limit of what most macrobenthic fauna tolerate. One hundred years ago, the oxygen concentrations in the Landsort Deep and the East Gotland Deep were about that low.

Sediments contain information on the increasingly tough conditions for the macrobenthic fauna. In sediments from this period of time, a transition from homogenous and oxygenated to laminated and anoxic/hypoxic sediment, which indicates decreasing oxygen concentrations, is often seen.

Sediments reflect the environmental conditions that prevailed when they were formed. When the oxygen concentration in deep water is high enough for benthic macro-fauna, the bottom sediments are bioturbated. The animals digging and mixing the loose top layer of the sediment cause this bioturbation. Today, when we take up a sediment core, we see that the sediment from this time normally consists of homogeneous clay, without visible varves or other structures.

If the oxygen levels are so low that no animals can survive, the sediments are normally laminated (Figure 12.1). The lamination is created by seasonal differences in the composition of the sedimenting material, and each lamina constitutes one annual varve. Some distinct varves are often followed by a layer of bioturbated and light sediment, followed by a constant lamination all the way up to the top of the sediment column.

By counting the varves in laminated sediment cores from the Baltic proper, Jonsson et al. (1990) described how the anoxic/hypoxic bottoms rapidly expanded during this time (Figure 12.1). It started in the 1940s, but the greatest changes occurred during the 1960s and 1970s, when some 2 000 square kilometres of Baltic macrobenthic fauna were extinguished annually.

From studies of long sediment cores, it is obvious that laminated sediments have been created naturally in various parts of the Baltic proper (Jonsson, 1990). The findings agree with the few oxygen data available from the late 19th century. These sediment studies indicate that the Baltic, due to its enclosed situation with strong stratification, has a poor buffer capacity regarding eutrophication.

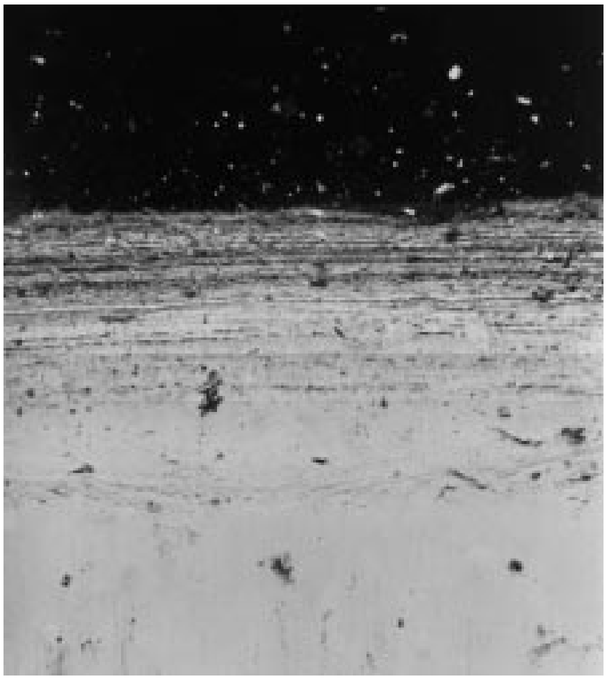

Figure 12.1. Sediment camera image of laminated sediments from the NW Baltic proper sampled in 1988. The height of the image is approximately 25 cm.

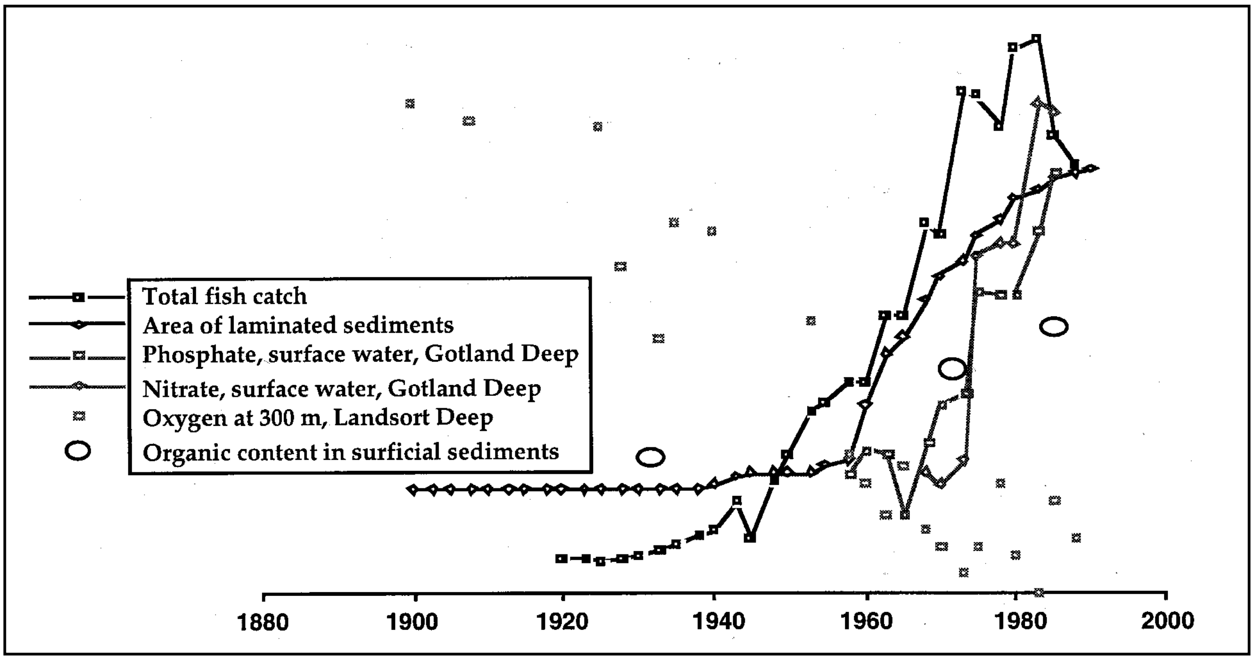

Figure 12.2. Recent eutrophication record for the Baltic proper in a relative scale, exemplified by the total fish catch (max. value: 900 000 tons), oxygen concentrations (max. value: 2.8 ml/l), area of laminated sediments (max. value: 70 000 km^2), nitrate concentration in surface water (max. value: 10 µmol/l), organic content in surficial sediment (max. value: 16.8 % Loss on ignition) and sediment sequestering of carbon deriving from net production (max. value: 9 g C m^{-2} yr^{-1}, compiled from Jonsson, 1992).

The fish catches, in biomass, have increased by a factor of 15 since the 1930s (Elmgren, 1989), probably due to a combination of eutrophication, improved fishing equipment and the reduction of the seal population (Hansson & Rudstam, 1990). Benthic macrofauna production has increased by a factor of two since the turn of the century (Elmgren, 1989). The organic content in the Baltic proper sediments (Jonsson & Carman, 1994; Niemistö & Voipio, 1981) has increased with a factor two since around 1930. This corresponds to an increased sequestering of organic matter in the offshore laminated sediments with a factor of 5-10 during the last decades (Jonsson et al. 1990; Jonsson & Carman, 1994).

Figure 12.2, compiling some important trends on a relative scale on the y-axis, indicates the large-scale eutrophication history of the Baltic proper during the 20th century. The area of laminated sediments started to expand in the late 1950s (Jonsson et. al., 1990). The organic matter in the surficial sediments doubled from 1930 to the late 1980s (Jonsson & Carman, 1994). Oxygen concentrations in the deep water of the Baltic started to decrease during the 1920s-1930s (Melvasalo et. al., 1981). Significant increases of nutrients have been recorded in surface and deep waters from the start of the measurements, around 1960 for P and around 1970 for N (Bernes, 1988).

Elmgren (1989) estimated the production of organic carbon in different areas of the Baltic ecosystem for the late 19th century. From this paper and information from sediment research (e.g., Jonsson, 1992), the situation in the Baltic Sea at the turn of the century can be outlined as follows:

- Discharges of nitrogen and phosphorus were 2-3 times lower than today, considering the large amounts of nutrients that are re-mobilised to the water mass by the erosion of old sediments.
- Since nutrient concentrations were much lower, estimate that the primary production is estimated at only about 50 % of today. The primary production constitutes the basis for the entire ecosystem.
- The water was clearer, due to fewer algae in the water.
- All bottoms had healthy populations of macrobenthic fauna, except in the deepest areas where natural oxygen concentrations were low and where laminated sediments therefore were formed naturally.
- The organic content in Baltic proper sediments was only half that of present concentrations. The organic content reflects the production of plants and animals in the water mass, and is an indication of the degree of eutrophication.
- The fish population was approximately half that of today.
- The seal population was 30 times larger than in the late 1980s. The seals, top predators in the Baltic ecosystem, consume large quantities of fish. At the turn of the century, Baltic seals probably consumed three times more fish than humans did.
- Humans caught only one tenth the amount of fish compared to today.
- Concentrations of heavy metals in the sediments were low (Table 12.1).
- Sediments showed traces of chlorated organic substances (Table 12.1).

Table 12.1. Preindustrial concentrations of organic matter, nutrients and contaminants in Baltic sediments

Parameter		**Concentration**	**References (below)**
Organic matter		**(% dw)**	
LOI	Loss on ignition	5.5-6.6	1
TOC	Total org.carbon	2.8-3.3	1
Trace elements		***(mg/kg dw)***	
As	Arsenic	5-12	2
Cd	Cadmium	0.1-0.4	2
Co	Cobolt	11-22	2
Cr	Chromium	30-65	2
Cu	Copper	20-58	2
Fe	Iron	11 000-71 000	2
Hg	Mercury	0.01-0.06	2
Mn	Manganese	0.3-5	2
Ni	Nickel	14-46	2
Pb	Lead	2-40	2
Zn	Zinc	50-171	2
Halogenated compounds		**(mg/kg dw)**	
EOX	Extractable organic halogen	10-13	3
EOCl	Extractable organic chlorine	3-5	4
EOBr	Extractable organic bromine	0.5-1.5	5
PCBs	Polychlorinated biphenyls	0.0	6
DDTs	Dichlorodiphenyldichloroethane	0.0	6
PCDDs	Polychlorinated dibenzodioxins	$9\text{-}15 \cdot 10^{-6}$	7
PCDFs	Polychlorinated dibenzofurans	$3\text{-}6 \cdot 10^{-6}$	7

1 = Jonsson & Carman (1994), 2 = Borg & Jonsson (1996), 3 = Kankaanpää (1997), 4 = Håkanson et al. (1988), 5 = Jonsson (pers. comm.), 6 = Nylund et al. (1992), 7 = Jonsson et al. (1993)

Natural or anthropogenic changes

In order to distinguish between natural and anthropogenic changes, we need methods that can describe the historical development in the Baltic Sea. For instance, we can:

- *perform long-term studies of water concentrations of different parameters.*
  The Baltic has one of the longest series of oxygen and salinity data in the world. The measurements started about one hundred years ago. Nitrogen and phosphorus have been monitored for 25 and 35 years respectively, which is longer than in most other sea areas.
- *repeat past studies.*
  Many pioneer investigations have been carried out, especially in the 1920s-1940s. In the 1920s, Stina Gripenberg studied the sediments and Christian Hessle investigated the macrobenthic fauna. During the 1940s, Mats Waern examined the macroalgal community in the Sea of Åland.
- *study sediment cores.*
  Sediments reflect changes in water mass and at the sea floor. In some respects they may act as a recorder of the historical development. By sampling sediment cores from the deeper parts of the Baltic and analysing them for different parameters, it is possible to obtain information about changes in the ecosystem, such as species composition, sedimentation rate, redox conditions in the sediment and input of contaminants.
- *analyse museum specimens.*
  Plant and animal specimens have long been collected and stored in museums. By analysing these matrices, much information has been obtained about long-term trends of contaminants in birds and mammals in the Baltic Sea.

The anoxic bottoms

Varved sediments have been interpreted as the animals in this region dying out from oxygen deficiency when the first varves appeared. After this, the oxygen conditions improved for a few years and the bottoms were colonised by animals that had survived somewhere nearby. Eventually the lack of oxygen became permanent, and the catastrophe was a fact for the macrobenthic fauna. Around 1990, about one third of the Baltic proper bottom area suffered from low oxygen concentrations; in these areas laminated sediments were deposited (Figure 12.2). At times (especially after the spring bloom) extensive sulphur bacteria mats (*Beggiatoa* sp.) cover large bottom areas. Sediments sampled from these bottoms most often smell of hydrogen sulphide, a gas that is poisonous for all higher forms of life.

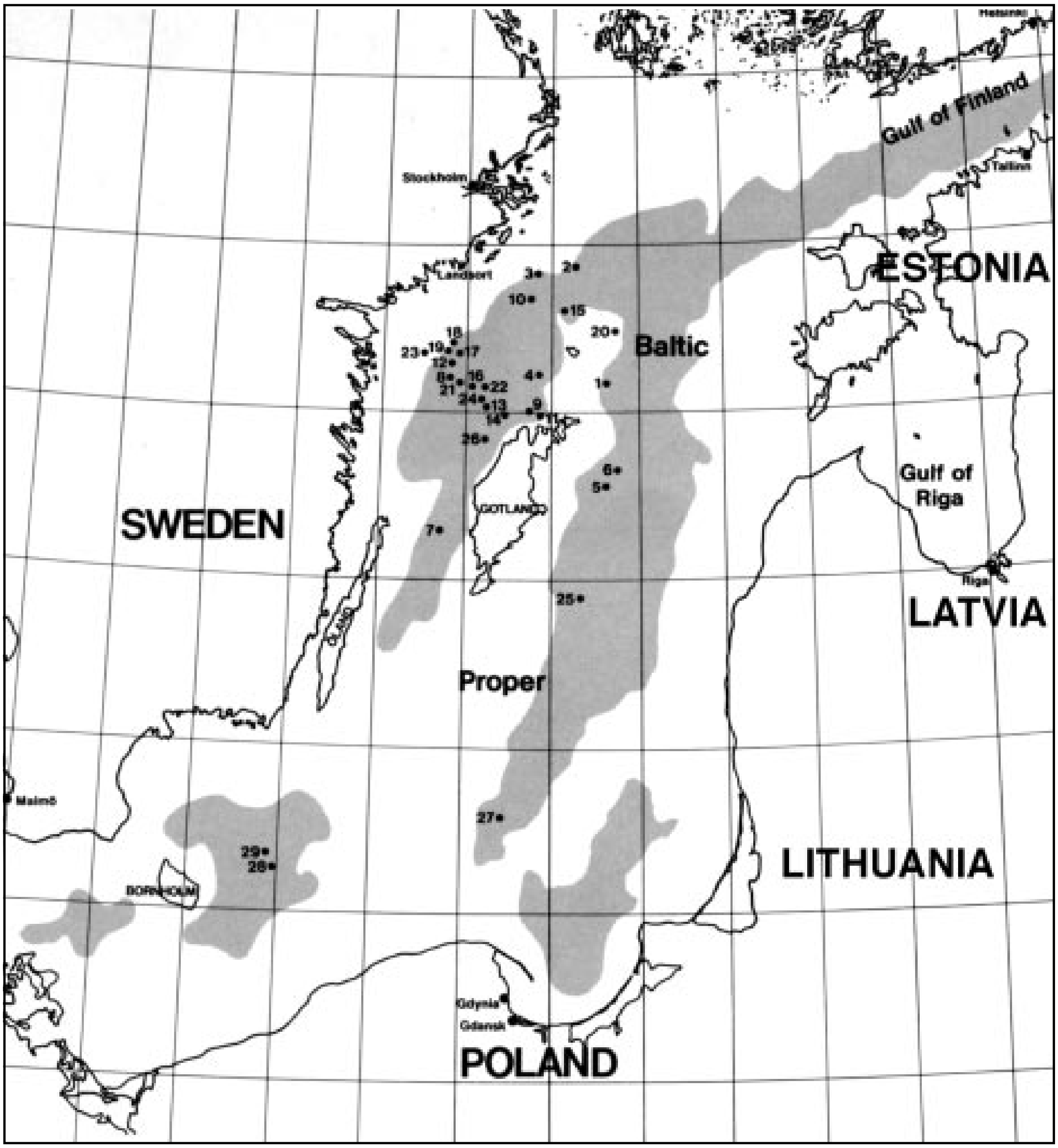

Figure 12.3. Probable extent of laminated sediments in the Baltic proper around 1990.

During the early 1990s several inflows of saline water occurred in the Baltic Sea, leading to improvements in near-bottom oxygen concentrations. This has been investigated in an intensive study area between Gotland and the Swedish mainland (area P23, see Figure 12.3). The dynamics of the laminated bottoms have been plotted together with data from sampling in the late 1980s (Figure 12.4). Investigations in the St. Anna Archipelago have been included as well. In the P23 area, improvements are indicated from the early 1980s and onwards. However, this is a misleading picture in that the benthic fauna, colonising these bottoms in the early 1990s, bioturbated the sediment down to the level of early the 1980s, thus creating a false time-scale for the improvements.

In the St. Anna Archipelago the laminated areas are substantially lower in relation to the total accumulation bottom areas. Substantial improvements in this archipelago area correspond with the trend in the offshore areas (P23). It is, however, not likely that the saline inflows in the early 1990s have changed the situation in this relatively shallow archipelago with a mean depth of 19 metres. The decline of the laminated area may be false due to difficulties in counting lamina in the upper parts of the cores from the St. Anna Archipelago. The sedimentation rates are much

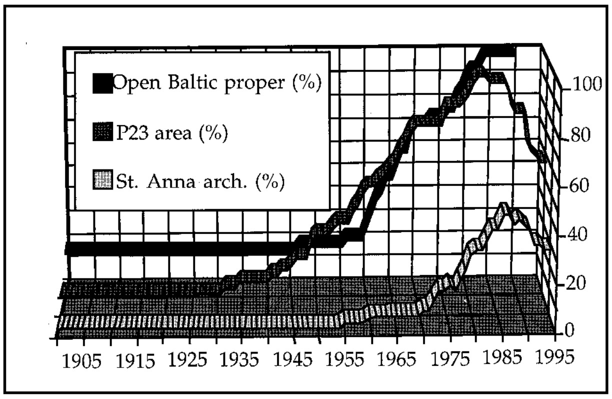

Figure 12.4. The proportion of laminated bottoms (in percent of the total number of investigated sediment cores) in the Baltic proper (35 cores; from Jonsson, 1992), the St. Anna Archipelago (48 cores; from Jonsson & Persson, 1996) and the P23-area in the open Baltic proper (40 cores, unpublished data).

higher in these cores; often as high as 1-2 cm in unconsolidated sediment.

Along the Swedish coast, in the Stockholm and St. Anna Archipelagos, sediment investigations have been conducted in approximately 45 areas (Jonsson, 1992; Anon., 1992; 1993; 1994; 1995; 1996; 1997; Jonsson & Persson, 1996). These studies give a relatively fair picture of the expansion of laminated sediments in coastal areas. In some places, oxygen depletion occurs naturally, normally in relatively enclosed, deep basins with shallow sills. Examples of such areas are Kanholmsfjärden and Möja Söderfjärd in the Stockholm Archipelago. However, most of the archipelago areas were not originally affected by oxygen depletion. During recent decades, the oxygen situation in the Swedish coastal zone of the Baltic proper has grown increasingly severe. Although great efforts have been made to reduce discharges of nutrients and organic matter, the laminated sediments continue to expand, indicating a great influence of the offshore eutrophication situation on the coastal oxygen conditions.

By comparing the organic matter concentrations in surficial sediments of the Baltic from the late 1980s with data from Gripenberg (1934), Jonsson et al. (1990) suggest a twofold increase in the organic contents during this period of time. The main part of the carbon deposited in the sediments 100 years ago originated from erosion of old sediments. Taking this into consideration, Jonsson et al. (1990) found an approximately tenfold increase in the amount of carbon originating from primary production and external sources (rivers and direct discharges) since the turn of the century. Organic material requires oxygen for breakdown. This substantial increase in the carbon input into the deep areas of the Baltic proper is today considered to be the primary reason for the current poor oxygen condition.

Nitrogen and phosphorus in the sediments

As mentioned earlier, concentration of phosphorus in water has been analysed since the late 1950s and nitrogen since the early 1970s. We are not certain of what the situation was before, but from what we know of the oxygen situation and the extinction of the macrobenthic fauna, we can assume that the nutrients started to increase rapidly in the 1940s. Concerning nitrogen, this was approximately two decades before the measurements started.

Is it possible to estimate the nutrient concentrations in the water mass from sediment concentrations of nitrogen and phosphorus? Much historical information can be obtained from sediment studies, but, unfortunately, it is not possible to estimate concentration changes of plankton growth limiting nutrients in the water mass. Nitrogen and phosphorus are much more mobile in the offshore sediments than, for example, most chlorinated compounds and heavy metals, and the nutrient flux between sediment and water is highly affected by changing oxygen concentration at the sediment/water interface.

The present situation

In Figure 12.1, an attempt is made to summarise the development of the Baltic during the last 100 years. The present situation can be summarised as follows:

- Despite large inflows of saline water from the Kattegat in the early 1990s, the oxygen situation in the deeper areas of the Baltic proper is poor. Oxygen concentrations in the deep water increased as a result of the inflows, but are now back at the low levels preceding the inflows.
- Primary production has been estimated to increase by at least by 30-70 %. In the Baltic proper the increase is larger, in the Gulf of Bothnia it is less.
- Algal blooms are considered to have become more common and more intense than at the turn of the century.
- Increased sedimentation has radically changed the conditions for macrobenthic fauna. On the average, macrobenthic production today is approximately twofold higher than at the turn of the century, despite the fact that macrobenthic fauna in the deeper areas of the Baltic proper today are almost extinct. At present, this is compensated for by a production rate 3-4 times higher in shallow areas.
- Water concentrations of nitrate and phosphate have increased substantially during the last decades in all areas, with the exception of the phosphorus levels in the Bay of Bothnia.

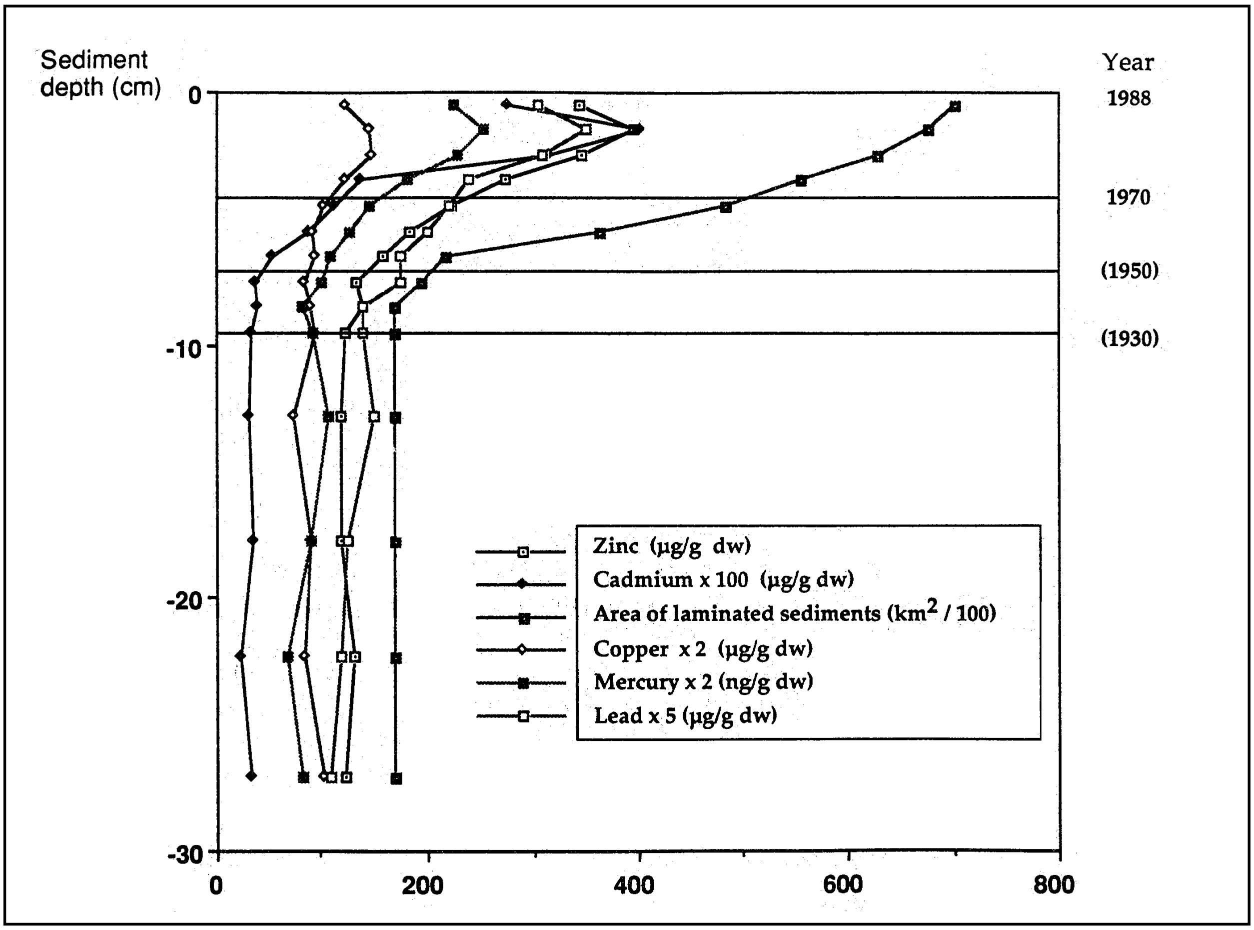

Figure 12.5. The mean vertical distribution of Cd, Zn, Cu, Pb, Hg in sediment cores (n=10) from the Baltic proper. The recent expansion of laminated sediments is also indicated. The dating has been performed by varve counting, to the year 1970 (sediment depth 4.2 cm). The levels for the years 1930 (7.0 cm) and 1950 (9.6 cm) have been estimated from the dry matter curve, assuming a constant mean deposition rate of dry matter (Jonsson et al., 1990) (from Borg & Jonsson, 1996).

- Organic content in the Baltic proper surficial sediments has doubled since the 1930s.
- Laminated sediments are formed on all accumulation bottoms below the halocline (i.e. deeper than 70-80 metres) in the Baltic proper.

Obviously, the Baltic has been subject to a significant eutrophication since the 1940s. This has led to extensive changes within different parts of the sea's ecosystem. Using terminology that has been established for lake eutrophication, the Baltic proper can be characterised as mesotrophic. Due to its natural conditions – depth, enclosure in relation to the oceans, stratification, etc. – the Baltic Sea is considered particularly sensitive to increased input of nutrients.

Sediments as a recorder of environmental history

How well do the sediments actually reflect the environmental conditions under which they were formed? There are many factors that complicate the interpretation of vertical sediment profiles.

In most sea areas, benthic fauna is abundant at the sediment/water interface. These animals normally mix the sediments so that temporal differences in the sedimentation are destroyed. Through bioturbation, recently sedimented, highly contaminated material mixes with underlying pre-industrial sediment. This leads to the possibility of rapid changes in contaminant input being diminished, which in turn means that these bioturbated sediments are inadequate for environmental monitoring. In these types of sediments, it may take several years, even decades, until decreased input of contaminants will be manifested in the sediments as decreasing concentrations.

In the Gulf of Bothnia, with the exception of a few coastal areas, bioturbated sediments dominate. Therefore, the conditions for effective sediment monitoring are poor in the Åland Sea, the Bothnian Sea and the Gulf of Bothnia.

As mentioned above, during the last decades, significant areas of accumulation bottoms in the Baltic proper have changed from bioturbated to laminated sediments. This seems to have implied large effects on the sediment's ability to trap organic contaminants and metals (Jonsson, 1992). Concurrent with the

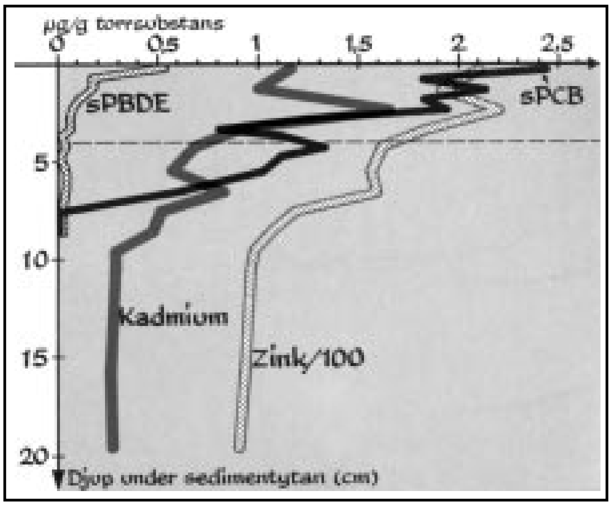

Figure 12.6. sPCB, sPBDE (polybrominated diphenylethers; from Nylund et al., 1992), cadmium and zinc (from Borg & Jonsson, 1996) in a naturally laminated sediment core from the Bornholm Deep, S. Baltic Sea.

turnover from bioturbated sediments to laminated, the concentrations of practically all contaminants increase dramatically (Figure 12.5).

Metals such as cadmium and copper are trapped more efficiently in the laminated sediments, due to these metals' tendencies to form insoluble sulphide complexes under oxygen free conditions (Kremling et al., 1987; Skei et al., 1988; Borg & Jonsson, 1996). During recent decades this has often occurred in the deep waters of the Baltic proper. Concerning persistent organic compounds such as PCB, DDT and chlorinated dioxins/furans, the increases may be due to several factors affecting the environmental fate of these compounds. Decreased mineralisation of the organic matter in the surficial sediments and changed lipid content may be significant factors. These drastic changes in the recently laminated sediments limit the use of them in historical retrospective studies in this type of sediment.

It is possible to obtain a satisfactory description of the historical development of contamination in the Baltic during the 20th century using sediments. Probably the best archives are in the natural and continually laminated deep-sea sediments in the Baltic proper. In these sediments no such dramatic changes have occurred in the sedimentation environment as in the recently laminated. In approximately 15-20 000 km^2 of the accumulation bottoms in the Baltic proper we find this type of continuously laminated sediment (Jonsson et al., 1990). In Figure 12.6 an example is given on the down-core distribution of PCB and PBDE (polybrominated diphenylethers; Nylund et al., 1992) as well as cadmium and zinc (Borg & Jonsson, 1996) in a naturally laminated sediment core from the Bornholm Deep in the southern Baltic Sea. PBDEs, a substitute for PCB as a flame retardant, show substantial increases from the 1970s and onwards. The concentration curves for PCB and DDT as well as the environmentally relevant heavy metals cadmium and zinc show more gradual increases than in a recently laminated core. Despite the ban of PCB in the Baltic area, the PCB levels increase towards the surface, even after 1970.

Toxic industrial pollutants

The perhaps best known record of anthropogenic discharges to the Baltic Sea during the 20th century has been obtained for the pulp mill discharges of chlorinated compounds, measured as extractable organic chlorine (EOCl). From knowing when important internal process changes were introduced within the industry, an estimate of the discharge record has been obtained (Wulff et al., 1993). The discharges to the Baltic, mainly from Swedish and Finnish pulp mills, started to increase from less than 100 tons/year in the 1940s until the 1970s-80s, when 600-800 tons EOCl were discharged annually. During the past ten years, the pulp mill discharges of organochlorines to the Gulf of Bothnia have decreased dramatically to a level of less than 40 tons in 1992 and are presently approaching zero.

Jonsson (1992) found that the annual burial of EOCl in the offshore sediments of the Baltic proper showed the background situation until the early 1950s. During the 1960s-70s the sediment burial increased rapidly, reaching its peak values of six times the background in the mid-1980s, thereafter decreasing somewhat.

The highest concentrations as well as the highest risks for effects of persistent organic pollutants in the environment are normally at the top of the food chain. Aquatic chains are often longer than in other environments; it is in these chains that severe effects have been observed. Since the ban of DDT and restrictions on the use of PCBs in the early 1970s, considerable attention has been devoted to possible trends in the levels of organic pollutants in the marine environment. Today, long-term monitoring is performed in some of the states around the Baltic Sea. Especially in Sweden, an extensive monitoring program has been running since the late 1960s. Environmental hazards like PCBs, DDTs, PCNs and PCDD/Fs are currently being monitored.

In the Baltic Sea, substantial downward trends have been observed for DDTs and PCBs in biota during the last 15-25 years (Odsjö & Olsson, 1987; Olsson & Reutergårdh, 1986; Bignert et al., 1993). sDDT and sPCB in herring from the Baltic proper decreased by approximately the factors of 8 and 4, respectively. The decreases have been assumed to be due to the restricted use of these contaminants in the Baltic area. However, this conclusion has been questioned by Jonsson (1992), who suggested that the downward trend of sPCB in herring might be in part an effect of the changed distribution of PCB within the ecosystem due to eutrophication.

Such a suggestion is supported by contrary time trends of PCBs in sediment cores from the Baltic proper, where the eutrophication is most pronounced. Sediment profiles indicate substantially increased burial of PCBs in the Baltic proper sediments from the 1950s and onwards (Niemistö & Voipio, 1981; Perttilä & Haahti, 1986; de Wit et al., 1990; Nylund et al., 1992; Kjeller & Rappe 1995; Jonsson & Kankaanpää, in press). These coincide in time with the expansion of laminated sediments and clearly increasing organic content in the sediments (Jonsson, 1992).

In a sediment core from the Bornholm Deep (Nylund et al., 1992), polybrominated diphenyl ethers (PBDE) showed a more rapid increase towards the sediment surface than did sPCB and sDDT. This may be an indication of a recent substantially increased use of PBDE as a flame retardant, but may also be an indication of different degradation rates and/or water solubility. However, recent investigations of PBDEs in pelagic biota that have been used for monitoring of PCBs and DDTs show clearly increasing concentrations during the last decade (Sellström, 1996). PCDD/Fs are still present in relatively high concentrations, although downward trends similar to those of PCBs and DDTs have been observed. Other chlorinated compounds such as toxaphene, chlordane and methyl sulfones have been identified in the Baltic Sea.

During the past ten years, the pulp mill discharges of organochlorines to the Gulf of Bothnia have decreased dramatically. From a maximum of 600 tons of EOCl in the early 1980s, the discharges reached a level of less than 40 tons in 1992. During the same period of time there was also a dramatic qualitative change of the chloroorganic substances present in effluents from the bleaching of pulp. PCDD/Fs and polychlorinated phenols have now reached such low levels that these compounds can no longer be used as tracers of bleach-plant effluents, and there seems to be a general and dramatic decrease in the concentration of all polychlorinated substances (Dahlman & Mörck, 1993). Other studies have shown that chlorinated structures still existing in organic matter from ECF (elemental chlorine free) bleaching of pulp are similar to those found in naturally occurring humic substances (Dahlman & Mörck, 1993; C. Johansson et al., 1994). However, resuspension of sedimented organic matter may remain a substantial source of organochlorines for a very long time. This may be particularly important in the Gulf of Bothnia, where land uplift may cause erosion of contaminated sediments.

Atmospheric transport of pollutants

In general, the PCB and PAH distribution pattern is characterised by higher concentrations in the southern Baltic proper (400-500 μg/kg LOI), decreasing northwards in the Baltic as well as in the Kattegat and Skagerak area. Broman et al. (1993) reported concentrations of PCBs in the Baltic Sea which are in fair agreement with investigations performed in 1989 (Gustavson & Jonsson, 1999), and concluded that this south/north gradient was most likely a result mainly of atmospheric deposition.

Some of the sources contributing to the load of organochlorines entering the Baltic Sea may be very remote. Compounds like PCBs and DDT are present everywhere (e.g. Iwata et al., 1993), and some investigators have suggested that there is a global redistribution of semi-volatile persistent organic compounds from warm to cold regions (P. Larsson & Okla, 1989; Wania & Mackay, 1993). Since the Baltic Sea is located in a climatic zone where deposition of important groups of chlorinated compounds present in the atmosphere can be expected, this may be a source of concern in a long-term perspective. The oligotrophic Gulf of Bothnia may be particularly vulnerable to toxic substances also in the future (P. Larsson et al., 1992).

Improvements in the 1990s

Today it is obvious that PCBs and DDTs have contributed substantially to the serious situation for sea birds and mammals in the Baltic Sea during the 1970s-80s. However, a number of other substances may also have been of importance for the effects. Since many halogenated compounds show a high degree of co-variation, it is often difficult to find out which substance is responsible for the registered effects. It is probably more common that several compounds contribute than that one single substance is responsible for the entire effect.

At present the situation in the Baltic Sea is far better than it was around 1970. The discharges of chlorinated compounds from pulp mills have decreased drastically and the recipient situations have clearly improved during the late 1980s and the 1990s. Some effects concerning reproduction, recruitment and growth rate for fish are still detectable in connection with modern bleaching techniques.

Concurrent to the decreasing concentrations of DDTs and PCBs in biota, improved conditions have been registered for several formerly threatened bird species, including the sea eagle, the guillemot, the osprey, the marsh harrier and the peregrine falcon. The thickness of guillemot eggshells has increased and is, at present, not causing any reproductive problems for this species. The sea eagle is increasing in numbers and reproduction is approaching the situation present during the 1950s, before the severe problems started.

Also, an encouraging sign is obviously that the seal populations are recovering from the severe reproduction damages and defects that were present in the 1970s. However, the Baltic seals still show more defects than what can be considered normal. Most populations have increased in numbers during recent years. This has lead to seals being considered such a problem for fishermen that hunting might be introduced again.

In a description of environmental threats to the Baltic Sea, one certainly has to include the reproduction problems of the Baltic salmon, *Salmo salar*. Despite increased catches in 1974, a significantly enhanced mortality rate was registered for newly hatched fry at the smelt production units operated by the hydropower industry. Excess mortality among the yolk sac fry, the M74-syndrome, has varied throughout the years (N. Johansson et al., 1993). Since the late 1980s the mortality rate has been steadily increasing. So far, however, it has not been possible to establish any relation to known environmental hazards, although this has been the working hypothesis since the 1970s. Recently, it has been indicated that eutrophication may have played a role in creating the syndrome. Fryes showing M74 symptoms may be fully cured by treatment with thiamine.

To conclude, the situation in the Baltic Sea concerning effects of chlorinated compounds is dramatically better today than it was in 1970. However, this does not mean that we can rule out problems with environmental hazards in the Baltic. Eutrophication may have contributed to the decreased concentrations of PCBs and DDTs in biota and hereby hidden the problem with environmental hazards.

The heavy metals

Several studies on trace elements have been performed in the Baltic Sea area (see Perttilä & Brügmann, 1992).

Spatial distribution of trace elements

In the Gulf of Bothnia, where nodules frequently occur (Boström et al., 1982; 1983; Ingri, 1985), Borg & Jonsson (1996) showed that small nodules in the sediment enhanced the concentrations of Cd, Co, Ni and Mn, and therefore rejected these samples when presenting the large-scale distribution patterns of trace elements in the Baltic. Borg & Jonsson (1996) demonstrated clearly different distribution patterns for some of the elements analysed. High concentrations of arsenic (Figure 12.7), exceeding the background with a factor of more than 50, are found in the Bothnian Bay, decreasing southwards. This is opposite to the expected pattern when considering the naturally higher levels in saline waters. The former huge anthropogenic load of As from smelter emissions in the Bothnian Bay most likely still influences the large-scale distribution pattern of arsenic.

Mercury concentrations in the Bothnian Bay sediments average four times higher than in the Baltic proper, probably due to smelter emissions in the north. In coastal areas of the Bothnian Sea, clearly enhanced levels are found close to chlor-alkali industries and pulp mills. High correlation between EOCl and Hg indicates nearby or identical sources of these parameters.

The distribution pattern of cadmium (Figure 12.8) is quite different to those of As and Hg, as the mean exceeds the background by a factor of 10 (extreme values 50) in the Baltic proper. Patterns similar to, though not as extreme as for Cd, were found for Cu, Pb and Zn with the highest concentrations occurring in the northern Baltic proper. Cr, Co, Fe and Mn were evenly distributed throughout the Baltic system. Concerning the Gulf of Bothnia, from a different set of data, Leivuori & Niemistö (1993) found distribution patterns similar to those found by Borg & Jonsson (1996).

Increased binding of trace elements under reduced conditions

Perttilä and Brügmann (1992), among others, showed enhanced levels of Cd, Cu, Pb, and Zn in the reduced sediments of the northern Baltic proper compared to the oxidised sediments in the Gulf of Bothnia. Kremling et al. (1987) and Dyrssen & Kremling (1990) showed that reduced conditions enhanced the water concentrations of Fe, Mn and Co. Elements like Cd and Cu, that are liable to form insoluble metal sulphides and precipitate, were found to decrease substantially in the anoxic deep water of the Gotland Deep. In the super-anoxic fjord Framvaren, in southern Norway, Skei et al. (1988) found sudden increases of loosely bound Cd, Pb and Zn in the surficial, upper 24 cm, varved anoxic sediment, compared to the underlying homogeneous sediment. This coincided in time with the opening of a channel into the former lake in 1855.

Reduced conditions with the presence of hydrogen sulphide have frequently occurred over large areas in the deep water of the Baltic proper during recent decades (Melvasalo et al., 1981; HELCOM,

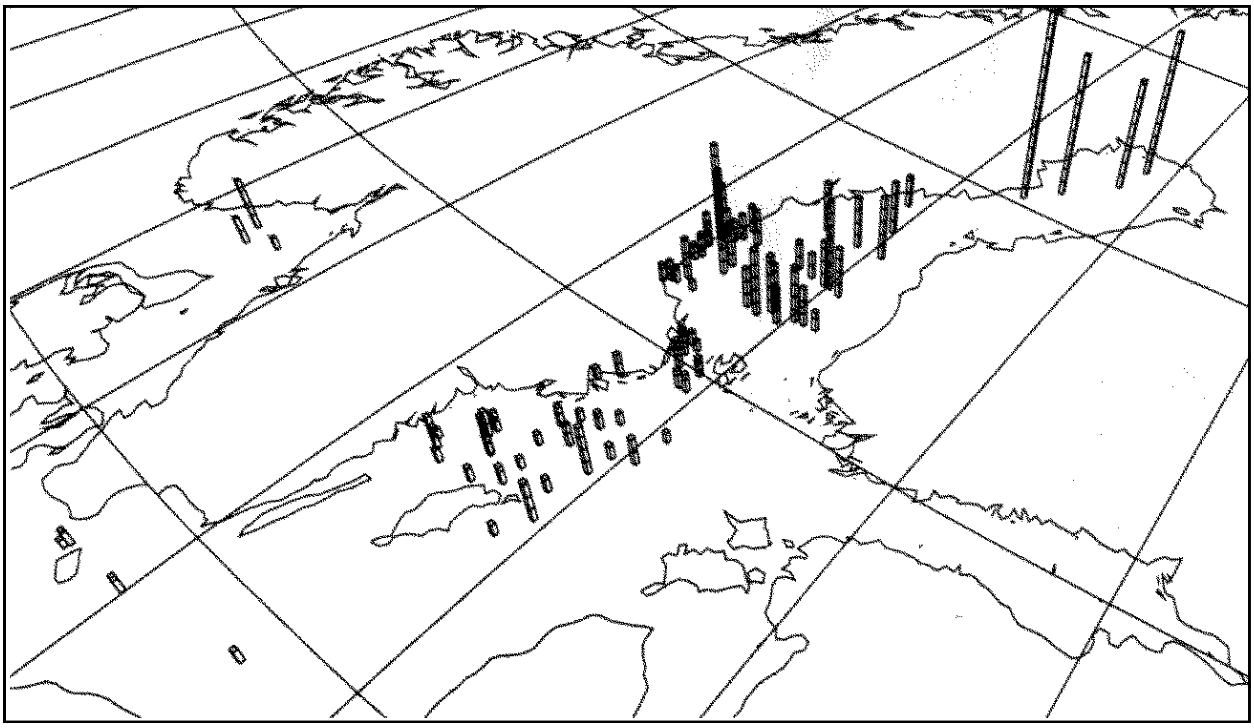

Figure 12.7. Arsenic in surficial (0-1 cm) sediment. 1 unit of scale = 10 µg/g ds (from Borg & Jonsson, 1996).

1987a; 1990). The enhanced levels of Cd, Cu, Pb and Zn in the reduced sediments of the Baltic proper are, to a certain extent, most likely due to formation and precipitation of insoluble metal sulphides. Subsequently, the high concentrations in the northern Baltic proper do not necessarily depend on nearby pollution sources, but might also be an indication of transport from distant sources into the Baltic proper. It may thus rather indicate a more effective recent trapping in the reduced sediments of the Baltic proper, compared to the oxic sediments of the Gulf of Bothnia, than a substantial direct input of these metals to the Baltic proper. Substantially improved oxygen conditions in the deep water may lead to a rapid release of large amounts of Cd, Hg, Pb and Zn (Perttilä & Brügmann, 1992).

Trace element mass balances

By using literature data on the deposition rate for dry matter in different parts of the Baltic Sea (Niemistö et al., 1978; 1984; Voipio, 1981; Jonsson et al., 1990) Borg & Jonsson (1996) calculated the annual sequestering of metals in the sediments. Enckell-Sarkola et al. (1989) estimated the annual input of trace elements to the Gulf of Bothnia for the mid-1980s, which coincides in time with the estimates on the annual sequestering in the sediments.

There seem to be substantial discrepancies between the annual load of trace elements to the Gulf of Bothnia and what actually was sequestered in the sediments. The results in Table 12.2 indicate that approximately half the load of cadmium, copper, lead and zinc is exported to the Baltic proper. For arsenic and lead, the high import values may be fictitious. Bioturbation of the oxic sediments may cause erroneously higher values in the surficial sediments due to influence of former substantially higher smelter emissions during the 1960s and 1970s. This process may also have affected some of the other elements, most likely causing underestimates of the true exports.

The total annual sediment sink for cadmium in the Baltic Sea has been estimated to average 113 tons (Borg & Jonsson, 1996), of which the main part (90 tons) is deposited in the Baltic proper. An estimate of the total load of cadmium to the Baltic (HELCOM, 1987b) averaged 140 tons/year during the 1980s. Taking into account the 600 tons of cadmium dispersed in the water mass in the early 1980s (HELCOM, 1987b), it was calculated from the Baltic Sea water balance (Wulff et al., 1990) that about 14 tons annually are transported to the Kattegat through the Danish Sounds. From this perspective, an estimated annual sediment sink of 113 tons seems quite reasonable.

Heavy metals in sediment cores

Borg & Jonsson (1996) sampled 20 sediment cores, generally 25-40 cm, from different parts of the Baltic Sea. The interpretation of the vertical distribution of the cores from the Gulf of Bothnia was hampered by bioturbation of the sediments, which probably causes slow responses to the changing load of metals entering the Gulf. Despite substantially decreased discharges from smelter emissions during the last 15 years, the concentration profiles described increases towards the sediment surface.

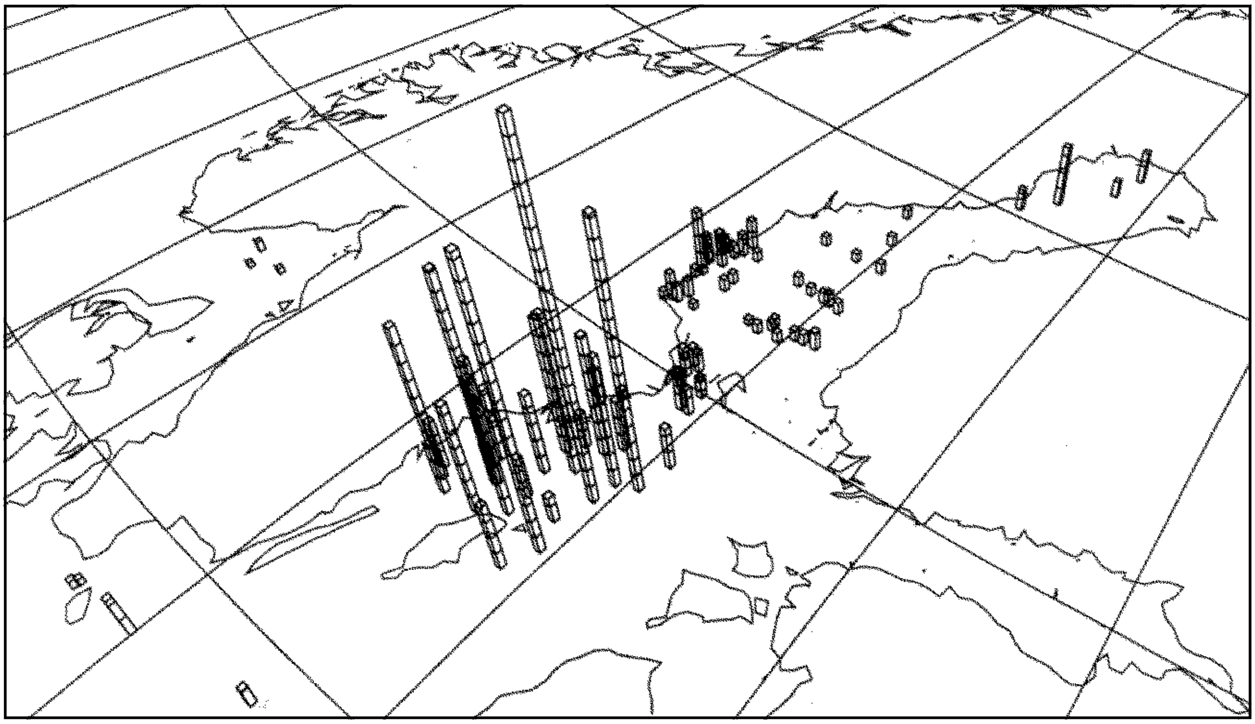

Figure 12.8. Cadmium in surficial (0-1 cm). 1 unit of scale = 0.5 µg/g ds (from Borg & Jonsson, 1996).

For the Baltic proper, the lack of bioturbation in the laminated sediments creates the prerequisites for retrospective studies of sediment cores. The time resolution is dramatically better than in the Gulf of Bothnia, although there may be a delay phase of several years in reacting to the changing load, due to the extensive areas of transportation bottoms in the Baltic proper.

Since the bottoms of the Baltic Sea describe a mosaic of varying bottom conditions, it may be hazardous to draw far-reaching conclusions on the historical record of only a few coring sites, assuming these to be representative for a large area. By compiling a dated ”mean core” for the Baltic proper (Figure 12.5), based on varve countings and analysis of 131 samples from 9 sediment cores, a fairly good base for drawing some conclusions about the pollution history of this sea area has been obtained. However, remobilization processes within the sediment may cause interpretation problems. On the basis of renewed sampling of two sampling sites in the Baltic proper with an interval of 12 years, Tervo & Niemistö (1989) found differences in vertical distribution, especially for zinc. This would indicate either mobilisation processes within the sediment or problems related to ship positioning, sampling and analysis. Therefore, detailed interpretation of retrospective trace element studies of Baltic sediments should be considered with due reservation. With these limitations in mind, however, the general pattern of the overall pollution history of the Baltic proper may be outlined from the vertical distribution in the sediments.

Until about 1930 no significant changes can be distinguished. From about 1950 and onwards, clear increases occur for Cd, Zn, Pb, and Hg, increasing more rapidly during the late 1960s and early 1970s,

Table 12.2. Comparison of estimated load (mid-1980s; Enckell-Sarkola et al., 1989) and estimated sequestering in the sediments (1980s; Borg & Jonsson, 1996) of the Gulf of Bothnia (incl. Bay of Bothnia and Bothnian Sea) of arsenic, cadmium, copper, lead, zinc and mercury. The net export (-) to the Baltic proper and the excess (+) in the sediments of the Gulf of Bothnia have been calculated

Element	**Estimated load**	**Estimated sediment sink**	**Export (-)**	**Excess (+)**
	(ton/year)	(ton/year)	(ton/year)	(% of load)
Arsenic	79	570	+481	+609
Cadmium	16	6	-10	-63
Copper	1 000	370	-630	-63
Lead	250	380	+130	+52
Zinc	3 800	2 200	-1 600	-42
Mercury	4.5	2.1	-2.4	-51

reaching maximum concentrations around 1980, thereafter somewhat decreasing. At two sites in the central and northern Baltic proper, Tervo & Niemistö (1989) found similar distribution patterns with subsurface maxima for Cd, Cu, Pb and Zn, dated to the end of the 1970s. Fe and Mn, being markedly redox-dependant, naturally show a different pattern, as well as Co, Cr and Ni, and appear with about the same concentrations all through the core, or somewhat decreasing towards the sediment surface.

The recent expansion of the laminated sediments (Jonsson et al., 1990) has also been plotted in Figure 12.1. High correlations were found between this curve and the mean metal concentration profiles for Cd, Pb, Zn, Hg ($r^2 > 0.97$), and Cu ($r^2 > 0.79$). This may indicate either increased redox-induced trapping for these sulphide-binding metals or an actual pollution history that is described by the curves for these metals. At some sites where continuous lamination has occurred for hundreds of years, the metal concentrations have successively increased without any steep increases during recent decades. As no dramatic redox changes seem to have occurred in the naturally laminated bottoms, sediment cores from this type of bottom probably contain the best retrospective information about the pollution history of the Baltic proper.

13.

POLLUTION OF SURFACE WATER

Lars Håkanson, Ryszard Kornijów & Sten Bergström[1]

Many kinds of impact

The population of the Baltic basin interacts strongly with its water resources. Water is used for human consumption, industry, irrigation, power production, shipping, fishery and recreation, among many other purposes. There are also many indirect effects. The water resources are affected by land use such as urbanisation, agriculture and forestry. The problem is not limited to activities within the basin. For example, the problem of acidification of lakes is related to the transport of acidifying pollution from distant industrial areas, and the radioactive outfall from the Chernobyl disaster in 1986 is still affecting the fish population in many of the lakes of the Baltic basin.

Many of the rivers in the Baltic basin are subject to river regulation. This means that water is stored in reservoirs to be used when needed. This is particularly pronounced in Sweden where hydroelectric power is used to cover approximately half the demand for electricity. Hydropower is an attractive renewable source of electricity but it has environmental impacts. The most striking are found in the reservoirs, which may have annual amplitudes of up to 30 metres and in the long dry reaches of the river as water is conveyed to the power station. River regulation also has significant impact on the flow of the rivers.

The development of hydropower gives rise to artificial runoff conditions, where the natural rhythm is distorted. Most of the flow peaks (but not all!) are stored in the reservoirs and the winter flow is increased. The short-term variability is increased to meet the short-term fluctuations in power demand.

Even if water availability may become critical in certain regions and at certain times in the Baltic basin, the greatest problem related to water resources is pollution. Acidification of rivers and lakes threatens the ecosystem and has long been counteracted by artificial liming, in particular in Sweden. Nutrients and other pollutants in the wastewater from municipalities (point sources) and agriculture (non-point sources) accelerate eutrophication and shorten the lifetime of lake and river ecosystems. The Baltic Sea itself is also strongly affected by this human activity on land, manifested by an increased frequency of algae bloom, loss of oxygen and survival problems for the fish population.

Non-point source pollution also strongly interacts with climate. During wet years more nutrients are washed out than during dry years (Figure 13.1). Winter runoff is particularly critical, as the concentrations of nutrients in the rivers are generally higher than during the periods of active vegetation in spring and summer. This means that the transport of nutrients in the rivers often peaks during mild and wet winters, like the ones in the late 1980s. The strong climate dependence of transport of pollutants complicates our chances to detect human induced effects. It is thus meaningless to try to assess the environmental status of the water systems of the Baltic basin without consideration of the climatological and hydrological conditions.

Ecologists raise a number of questions on the pelagic conditions of the water body of the Baltic Sea but there are several factors to be taken into consideration. The bloom of algae, which affects oxygen conditions, is the result of a complex interaction between input of nutrients and climate. Fish populations suffer from pollution and catch by the fishing industry but they also have a natural variability that is related to the climate via oxygen conditions and the salt-water balance.

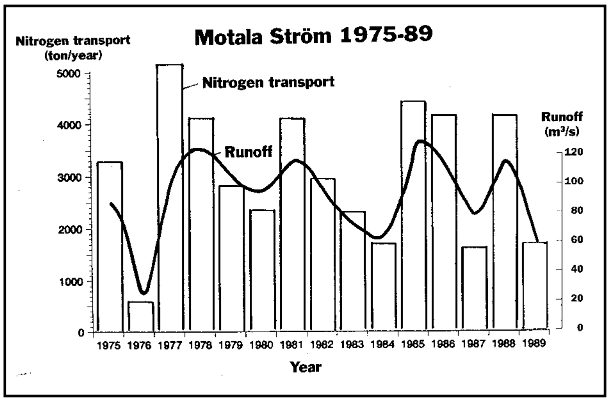

Figure 13.1. Climate interacts with pollution. Annual runoff and transport of nitrate in Motala River in Sweden. Note the low values in the dry year 1976 and the high values during a wet year like 1977 (prepared by Maja Brandt, SMHI).

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[1] Lars Håkanson is the main author, Ryszard Kornijów contributed with the parts on states of lakes and Sten Bergström with the introduction.

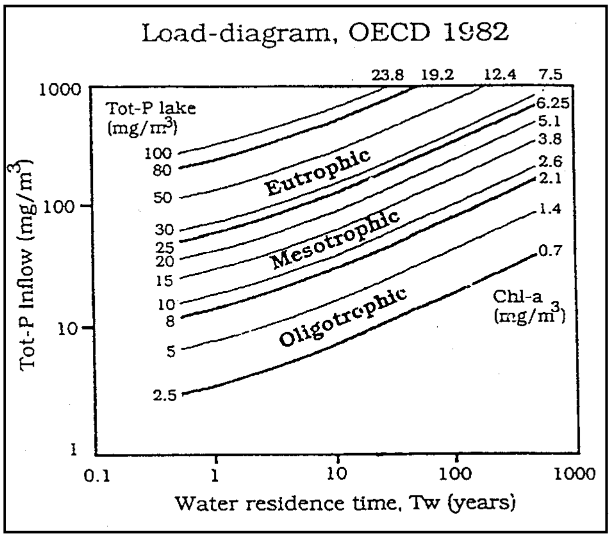


Figure 13.2. The OECD-model for lake eutrophication illustrated as a load diagram. The diagram relates tributary inflow concentrations of total phosphorus, to theoretical lake water retention time, lake concentrations of total phosphorus and lake concentration of chlorophyll (from Wallin et al., 1992. Based on OEC, 1982).

Lake eutrophication

Some 1-5 % of the total population of Swedish lakes show clear changes in ecosystem structure due to eutrophication (SNV, 1993). Most Swedish lakes, however, are oligotrophic forest lakes. Most lakes influenced by anthropogenic eutrophication (there are also naturally eutrophic lakes) are relatively large (and hence important natural resources), shallow and located in agricultural landscapes in the southern part of the country. There are also some lakes, like Lake Norrviken (Ahlgren, 1970), north of Stockholm, which have been heavily polluted by sewage effluents or nutrient emissions from specific point sources.

The Vollenweider model

Richard Vollenweider (Vollenweider, 1968; 1976) presented his first load models for phosphorus for lakes in the late 1960s. Descriptions, verbal 'models,' and elaborate 'logical explanations' – then at a rudimentary stage – dominated water management. The practical usefulness of most results and models was often negligible, as was the predictive power. Aquatic ecosystems were rightly recognised as extremely complex, and this gave legitimacy to the predictive failure. The arguments were that a large number of factors could influence the primary production of a lake and that many different nutrients and chemical forms of nutrients had to be considered, differently in different lakes, different seasons, for different species of algae and plankton, and so on. All of this had to be studied before anything useful could be said or predicted about the status of the ecosystem. Different ways to halt and reverse eutrophication were suggested, but many treatments were expensive, speculative and untested.

Vollenweider approached the problem the other way around – he tried to simplify! By means of simple mass-balance calculations and statistical regressions using what then seemed a large set of empirical data, he could demonstrate that in many lakes, reducing the input of total phosphorus (Total-P) could reverse eutrophication. The mean lake annual concentration of Total-P (not fraction so-and-so) could thus be lowered. At first, this was met with scepticism. But his results proved to have predictive power and practical applicability. Since then, many studies have demonstrated where the Vollenweider approach can – and cannot – be used. Different alternative models have been presented, and the most successful all have one thing in common with the basic Vollenweider model: simplicity!

Thus, total phosphorus has long been recognised as the most crucial limiting nutrient for lake primary production (Ahlgren, 1970; Schindler, 1977; 1978; Bierman, 1980; Boynton et al., 1982; Wetzel, 1983; Persson & Jansson, 1988; Boers et al., 1993). The literature on phosphorus in lakes is extensive. Nitrogen is generally recognised as the most limiting nutrient in marine areas, and both elements are of vital importance in estuaries and brackish waters, like the

Table 13.1. Characteristic features in lakes of different trophic levels. Note that there is considerable overlap between the different categories, for example that in oligotrophic lakes the concentrations of Total-P may vary within a year from very low to high values (modified from Håkanson & Jansson, 1983)

Trophic level	Primary prod. (g C/m^2·yr)	Secchi (m)	Chl-a (mg/m^3)	Algal vol.[1] (g/m^3)	Total-P[2] (mg/m^3)	Total-N[2] (mg/m^3)	Dominant fish
Oligot.	<30	>5	<2.5	<0.8	<10	<350	Trout, Whitefish
Mesot.	25-60	3-6	2-8	0.5-1.9	8-25	300-500	Whitefish, Perch
Eut.	40-200	1-4	6-35	1.2-2.5	20-100	350-600	Perch, Roach
Hypert.	130-600	0-2	30-400	2.1-20	>80	>600	Roach, Bream

[1] = Mean value for the growing period (May - Oct.)
[2] = Mean value for the spring circulation

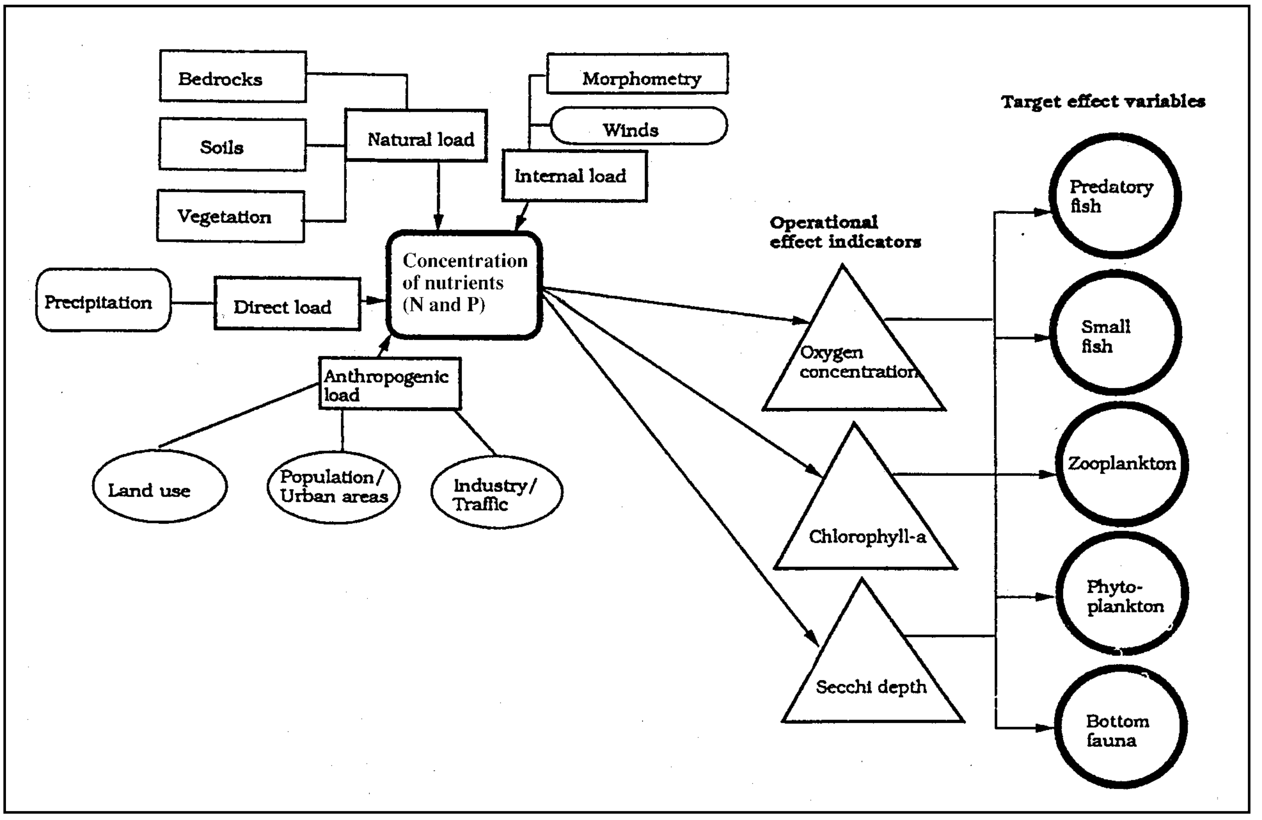


Figure 13,3. The character of the drainage area influences lake water quality. This is a statement that is simple to make, but how could it be quantified? It is evident that the geology, hydrology, land use and precipitation influence the inputs of substances to lakes, including the key nutrient in lakes, phosphorus. It is an important task to relate drainage area characteristics and lake characteristics and to predict variables of primary biological importance, like lake total-P, which in turn may be related to simple, important indicators of ecological effects (like oxygen concentration), and to the target effect variables (like reproduction and abundance of key species)(from Håkanson, 1994).

Baltic (Redfield, 1958; Ryther & Dunstan, 1971; Myers & Iverson, 1981; Nixon & Pilson, 1983; Howarth & Cole, 1985; Howarth, 1988; Hecky & Kilham, 1988; Ambio, 1990; Nixon, 1990).

Numerous publications exist on lake eutrophication as well. The famous Vollenweider model (Vollenweider, 1968; 1976; and later versions, e.g. OECD, 1982; see Figure 13.2), and the analysis behind this load model, constitutes a fundamental base for practically all environmental assessments of phosphorus in lakes. This approach has played a predominant role in lake management, but these concepts have not yet fully penetrated into marine or terrestrial ecology. The main reason for this may be that limnologists are trained with an ecosystem perspective, i.e. to study entire lakes. In lake models, the effect variables are generally linked to the concepts of hypertrophy (extremely productive lakes), eutrophy, mesotrophy and oligotrophy, which are related to defined mean annual concentrations of total phosphorus in the lake water (Table 13.1.).

Effects of eutrophication

The most interesting aspect is not to predict a simple mean concentration of a chemical element like total phosphorus (= Total-P), but to predict *ecological effects* related to lake Total-P. From Figure 13.3, however, it is clear that lake Total-P can be quantitatively

Table 13.2. Trophic categories in Baltic coastal areas. All variables are expressed as mean values for the growing period May - Oct. (from Wallin et al., 1992). Chl-a = Chlorophyll; SedS = Net sedimentation; O_2B = oxygen conc. in bottom water; O_2Sat = oxygen saturation (from Håkanson, 1994)

Trophic level	**Secchi** (m)	**Chl-a** (mg/m^3)	**Total-N** (mg/m^3)	**Inorg-N** (mg/m^3)	**SedS** (g/m^2·d)	**O_2B** (mg/l)	**O_2Sat** (%)
Oligot.	>6	<1	<260	<10	<2	>10	>90
Mesot.	3-6	1-3	260-350	10-30	2-10	6-10	60-90
Eut.	1.5-3	3-5	350-400	30-40	10-15	4-6	40-60
Hypert.	<1.5	>5	>400	>40	>15	<4	<40

related to almost any ecological effect variable or key functional group characterising the lake ecosystem. Table 13.2 gives a list of such ecological effect variables related to nutrients: Secchi depth, chlorophyll-a, bottom fauna state index, fish state index, hypolimnetic oxygen demand, oxygen concentration, etc. It is evident that the concentration of lake Total-P can be influenced by emissions from many types of sources: point sources (e.g. domestic sewage, industries and fish farms), atmospheric deposition (to the lake surface and the catchment area), internal loading (linked to resuspension, diffusion, etc.) and, often most importantly, tributary input. The characteristics of the catchment, such as bedrock, soils and land use, regulate the concentration of Total-P in the tributaries to the lake.

Traditional mass-balance models treat lakes as reactor tanks. The basic ingredients of these models are summarised in Figure 13.4. This figure underlines the connections to catchment population and land use, the relationships between total phosphorus (Total-P) and primary production (chlorophyll) and the quantitative links to widely used operational indices in water management, like Secchi depth and hypolimnetic oxygen demand (HOD).

It is evident that models of the Vollenweider- or OECD-type are very useful in practical lake management, but the models also pose problems. They are, in fact, quite simplistic, which implies that many inherent problems may arise if such models are used for predictions regarding individual lakes. Most of these problems are also emphasised in the basic publications (Vollenweider, 1968; 1976; OECD, 1982), but since those caveats are often ignored in practical water management (SNV, 1993a) there can be dire consequences, e.g. in evaluations of point source emissions in individual lakes (see Håkanson & Johansson, 1995).

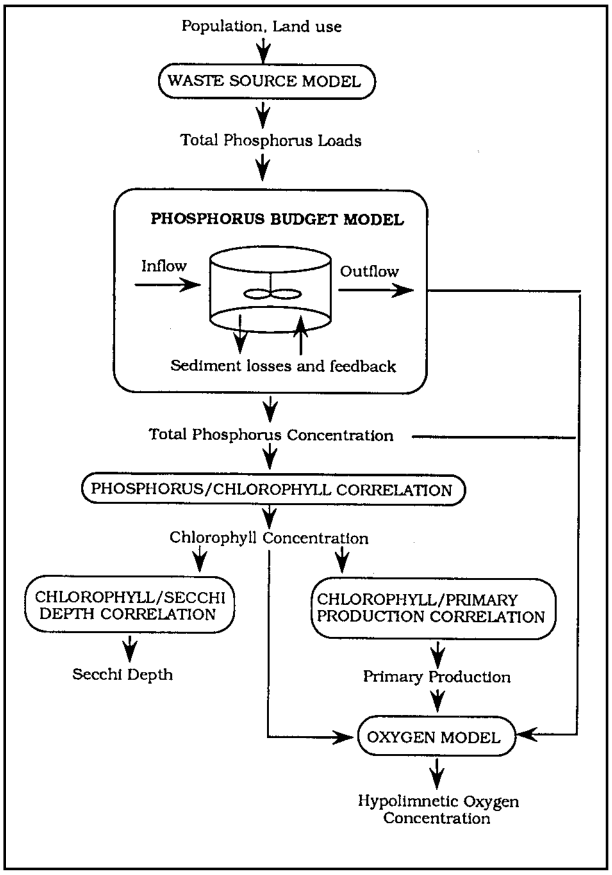


Figure 13.4. Basic elements in many traditional, holistic management models for lake eutrophication (see Chapra & Reckhow, 1983. From Håkanson & Peters, 1995).

All models of the Vollenweider-type generate uncertainties in the prediction of the Total-P concentration for individual lakes, and especially for lakes with specific point sources, like fish farms, because they do not account for:

(1) *Seasonal variations in phosphorus fluxes*. It is very important for both Total-P fluxes and phytoplankton production to account for seasonal variations in temperature, mixing/stratification, water clarity and load of phosphorus from different sources. Models of the Vollenweider type are generally derived from situations where the maximum Total-P-load to the lake occurs in spring (in connection with high water discharge) and should therefore not be used for e.g. fish farm emissions, which are largest during harvest in fall (Håkanson et al., 1988).

(2) *Bioavailable load of Total-P.* The ratio between bioavailable P (≈ dissolved P) and Total-P varies within and among lakes. This ratio is defined by the K_d-value, the partitioning (or distribution) coefficient (Håkanson & Peters, 1995). Today, there are no practically useful submodels for predicting and describing K_d for phosphorus in lakes.

(3) *Internal loading of phosphorus*. The Vollenweider type models do not account for internal loading. This is in fact very difficult since many complicated processes regulate internal loading, e.g. wind/wave induced resuspension, slope processes, seiche activity, diffusion, bioturbation, etc. (Håkanson & Jansson, 1983; Pierson & Weyhenmeyer, 1994; Weyhenmeyer, 1996).

(4) *Retention of phosphorus in lake water*. All models of the Vollenweider type oversimplify the retention of phosphorus in lakes since they do not account for seasonal variations related to stratification and mixing (Håkanson & Peters, 1995).

(5) *Validated quantitative models*, which relate the relatively simple chemical variable, lake concentration of phosphorus, to the interesting target variables for lake eutrophication effects, such as maximum volume of phytoplankton or concentration of chlorophyll-a. Such submodels are not included in the basic Vollenweider approach. The trophic level is determined from general, schematic tables (like Table 13.1) or via a subsequent step from empirical regressions using long-time averages of lake Total-P

concentrations. Such regressions could imply large uncertainties if used for individual lakes.

The state of a lake

Does water quality always depend on phosphorus concentration? Vollenweider knew that the main responsible factor for the trophy of freshwater ecosystems, and consequently for their water quality, was phosphorus (or, less often, nitrogen). This was the basis for his load models for phosphorus in 1960. Due to its simplification, the model has some shortages, as already discussed. As will be shown, some other shortages of the model appear in applying it to shallow lakes.

The scatter diagrams, which appear so convincingly to show relationships between mean Total-P concentration and summer chlorophyll-a, are based on logarithmic transformation, which masks the variability. An arithmetic plot of the same data shows a large range of chlorophyll-a concentrations at the same Total-P concentration. This suggests that at high phosphorus concentration, the phytoplankton standing crop can be controlled by other factors than nutrients, most probably connected to trophic interactions within the different food webs present.

The food web definition

The food web is a concept of intersecting food chains, i.e. chains of eating and being eaten that connects relatively large carnivorous animals to their ultimate plant food. An example of a food chain from a lake might be:

Phytoplankton → cladoceran → roach, pike

As seen from Figure 13.5 the food web of even so relatively simple habitats as the lake pelagic is a complex structure. It is very difficult to explore all the possible trophic interactions not only between the separate species but sometimes also among the groups of species that belong to the same trophic level. The reason for this is that both the food resources and the feeding mode and diets of the consumers vary on a daily and seasonal basis. Moreover, food compositions of animals often change as they grow. For instance, pike smaller than ca. 5 cm eat mainly plankton crustaceans and only when the fish grow bigger do they become more piscivorous. But even then the fish occasionally feed upon other types of prey including large crustaceans, frogs, small birds and mammals.

The food web interactions are particularly complex in shallow lakes, where more than just nutrients are involved in their degradation and restoration (Moss et al., 1996; Jeppesen, 1998).

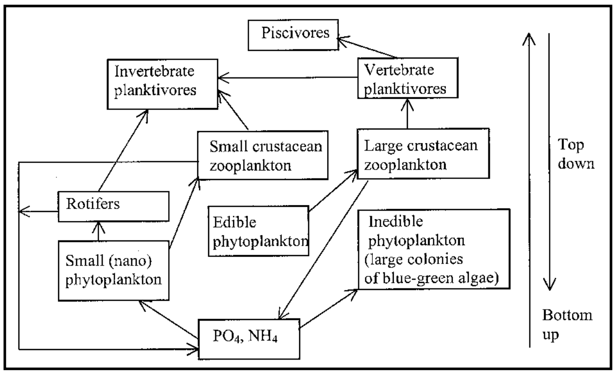


Figure 13.5. Outline of the food web in a lake pelagial. Notice that the scheme only presents relations between the groups of organisms that belong to the same trophic level and not between the separate species (modified from Carpenter et al, 1985).

Our knowledge of food webs in water ecosystems, although not always complete, provides a basis for an elucidation of their function and a formulation of some concepts and theories that can be applied in management, conservation and restoration measures.

‘Bottom-up’ versus ‘top-down’ control mechanisms

A prevailing view a decade or two ago was that food webs are primarily regulated via the available resources. According to this concept the concentrations of phosphorus and nitrogen regulated algal communities and determined the nature and production of consumers in the intermediate and upper levels (the so called ‘bottom-up effect’) (Figure 13.5). By way of example, nutrients and light affect the density of phytoplankton, which, via a food chain, influences the density of the consumers – zooplankton, planktivorous and eventually piscivorous fish. Recently, the ‘bottom up’ theory has been subject to opposition from a new concept called ‘top-down’ control, which claims that organisms situated in the upper trophic levels are very important to the ecosystem structure and energy flow (Figure 13.5). For instance, phytoplankton can be regulated by filter feeding zooplankton, which in turn is regulated by planktivorous fish. The following example, of an extreme situation found in a small English lake, Lake Little Mere (Moss, 1998) near Manchester, may help to illustrate these relationships:

Until late 1980 the lake was heavily polluted with effluent from a small sewage treatment plant. Despite an extremely high concentration of ammonium-nitrogen and phosphate-phosphorus (ca. one milligram per litre of each), the water of the lake was crystal clear in summer and a diverse plant community flourished there. The reason for this became clear when huge quantities of the water flea zooplankton (cladoceran) *Daphnia magna* were found in the lake water. This species is very big (up to 4 mm long) and feeds upon (grazes) the phytoplankton, very efficiently filtering it off the water. The water fleas were abundant in the lake because, due to the high load of organic matter, the water was so severely deoxygenated that fish, otherwise eager to gorge upon such vulnerable prey as *Daphnia*, could not survive in the lake. Thus crustaceans could prosper and effectively prevent any algal blooms in summer, in spite of the high nutrient concentrations in the water. Experiments carried out in the lake in special cages (enclosures) stocked with fish revealed that, especially at the reduced coverage of macrophytes, the density of crustaceans decreased and algae started to grow (Moss et al., 1998). Thus, in cases of diminished 'top-down' effect (predatory control) exerted by crustaceans, the algae depended more on the influence of nutrients and were regulated by 'bottom-up' mechanisms.

There was a discussion in the literature on the relative importance of 'bottom-up' and 'top-down' mechanisms but it is now assumed that both 'bottom-up' and 'top-down' mechanisms act simultaneously, complementing each other (McQueen et al., 1989). The 'bottom-up' effect is believed to control the food web on a long-term basis while the 'top-down' mechanism works more on a short-term basis. Similar mechanisms are found, as was noticed much earlier, in the terrestrial ecosystems. For example, the standing crop of a species of grass in a pasture is, in the long-term, affected by soil fertility ('bottom-up' control), but occasionally, cattle ('top-down' control) may remarkably reduce the grass biomass. It therefore seems that in both terrestrial and water ecosystems, nutrients may determine the potential production, but grazing may determine the extent to which the potential is realised.

In freshwater ecosystems the relationships governed by 'bottom-up' and 'top-down' mechanisms can be modified by a number of factors and particularly by abundance of macrophytes (vascular plants and stoneworts – large algae of the family *Characea*) and the structure of fish populations in a lake. These two agents may decide what kind of lake we are dealing with.

The model of alternative states of lakes

Shallow freshwater lakes, whose depths do not exceed a few metres, are most numerous and ultimately most important to both people and wildlife. A few years ago it was realised that a majority of shallow European and American lakes can exist in two alternative states: dominated by macrophytes or dominated by phytoplankton (Figure 13.6). Each state is able to persist, once established, over a wide range of nutrient concentrations, stabilised by a variety of buffer mechanisms (Scheffer et al., 1993).

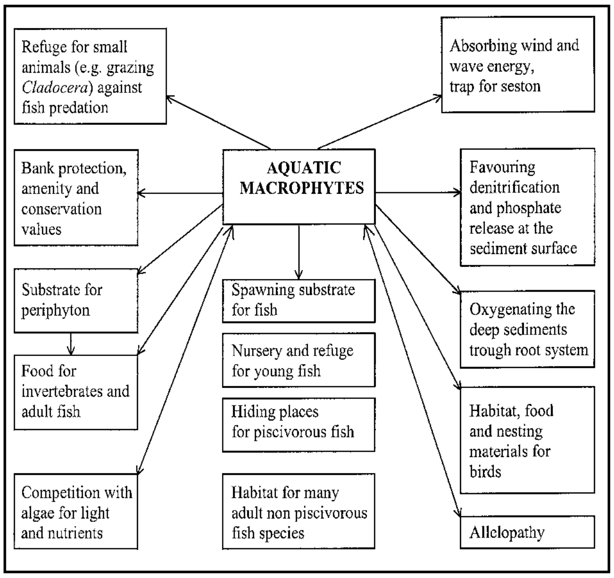


Figure 13.6. The relationships between aquatic macrophytes, other organisms and abiotic processes in fresh waters (based on Moss, 1998).

The first, macrophyte-dominated state is typical of lakes having transparent water and large bottom areas covered by diverse beds of macrophytes, frequently composed of stoneworts (*Chara*), water lilies (*Nuphar*, *Nymphaea*) and pondweeds (*Potamogeton, Myriophyllum, Ceratophyllum*). The macrophytes support rich communities of invertebrates, fish and birds. Interactions between these components constitute a buffer mechanism stabilising the whole system and reducing the chances of damage to individual components.

The importance of macrophytes includes a) their consumption of nutrients that prevent phytoplankton build-up, b) allelopathy, i.e. the release of organic algal inhibitors into the water and c) providing filter feeding crustacean with physical havens (shade, oxygen-less areas, physical structures) from fish predators. The macrophytic bed itself also minimises wave energy, disturbance of sediments (resuspension) and consequently, favours a clear water state. These items have been summarised in Figure 13.6.

The second, phytoplankton-dominated, state is characterised by an increased phytoplankton population, lack of macrophytes and undesirable changes in the fish communities caused, among other reasons, by summer or winter kills. The conservation and amenity values of such lakes are very low. Among hundreds of phytoplankton species there are always some able to respond quickly to the changeable weather and trophic conditions. Unpalatable or grazer-resistant forms with spines or larger size, making them too difficult to handle, replace algae being grazed by cladocerans with time. There are also species, e.g. among blue-green algae, that form long filaments that clog the filtering apparatus of crustacean grazers. Phytoplankton communities start their growth early in spring and built large populations, efficiently taking up the nutrients and shading the bottom. In these ways they suppress any macrophyte growth from seeds or over-wintering shoots. In addition, the development of macrophytes may be inhibited by chemicals released by some toxic algae, as well as retarded by a dense fur of periphyton growing on the surface of vegetation.

Open water, lacking in macrophytes, does not provide refuge for zooplankton, which then can be easily removed by fish. Fish always prefer the large cladocerans, which are the most efficient filtrates, so that the grazing pressure on the algae is negligible. The growth of phytoplankton will finally be inhibited by scarcity of nutrients and/or light. A rain of dead algal cells will enrich the sediments with organic matter, which can bring about three negative consequences. Firstly, the sediment laid down by algal cells is amorphous and does not provide a firm rooting substrate for macrophytes. Secondly, the sediment of algal origin can be easily resuspended, e.g. by wave energy, worsening the light climate. Thirdly, decomposition of organic matter deoxygenates near-bottom water layers, which induces release of phosphorus and nitrogen into the water column, supplying new algal generations with new nutrient resources. The loss of macrophytes implies a lack of spawning and hiding places for predatory fish, which results in a diminishing of their populations. Small zooplanktivorous fish, released from predation, can rapidly increase in number and thereby the pressure on the zooplankton. All these mechanisms can stabilise the algal-dominated state of a lake.

The mechanisms stabilising each of the alternative states, so called buffers (Figure 13.7), can be destroyed, causing a lake to switch from one state to another. It is always more likely, however, that a lake will change from being clear-water and macrophyte-dominated into an undesired phytoplankton-dominated lake.

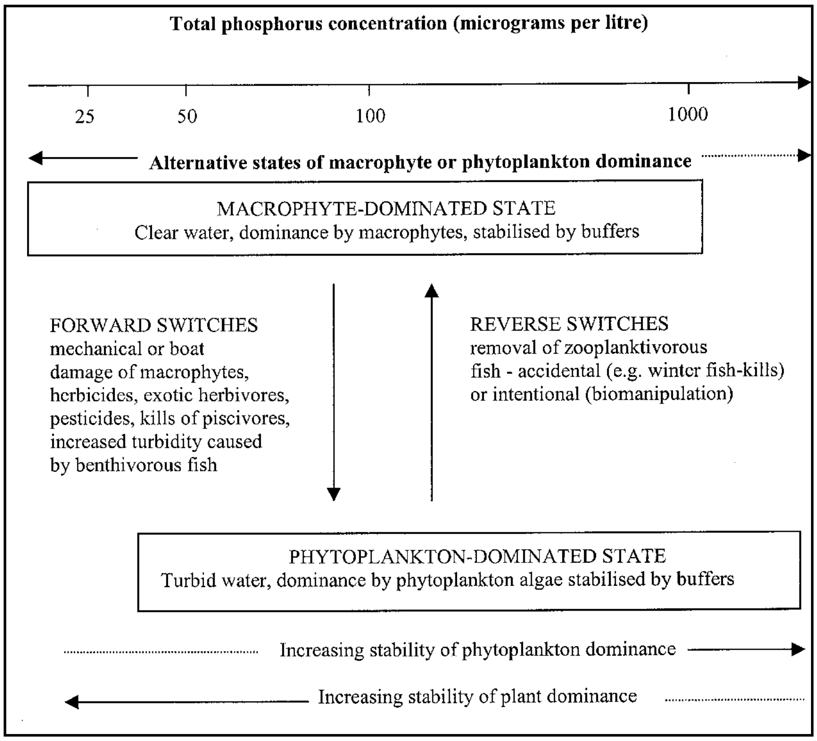


Figure 13.7. The model of alternative stable states of shallow lakes over a wide range of phosphorus concentrations. Switches needed to change one state into another are relatively independent of nutrients (based on Moss, 1998).

Switching from one state to another

From macrophytes to algae

The factors that can convert macrophyte dominance into algal dominance fall into two groups. The first group includes any activity resulting in the destruction of macrophyte beds, e.g. mechanical cutting, boat damage, use of herbicide, grazing by non-native animal species, and finally, rising of water levels, which reduces the light available to vegetation (Figure 13.7).

One example occurred in the Netherlands, where the macrophyte growth was so luxuriant in the small Lake Zwemlust, used by local people as a swimming pool, that in 1961 a herbicide was used to get rid of 'weeds.' This resulted in a rapid change to dominance by blue-green algae, which persisted until measures were taken to restore the lake in the 1980. Another example is the theory that many lakes in England became turbid as a result of their being stocked with populations of benthivorous common carp (*Cyprinus carpio*). This fish stirs up the bottom sediments while foraging for prey, mobilising large amounts of phosphorus and damaging roots of vegetation.

The second group of factors, which may turn the lake into a phytoplankton-dominated state, involves destruction or reduction of the grazing potential of invertebrate grazers (mostly cladocerans), which remove phytoplankton algae as they develop. This may happen as a result of contamination of lakes by pesticides or other

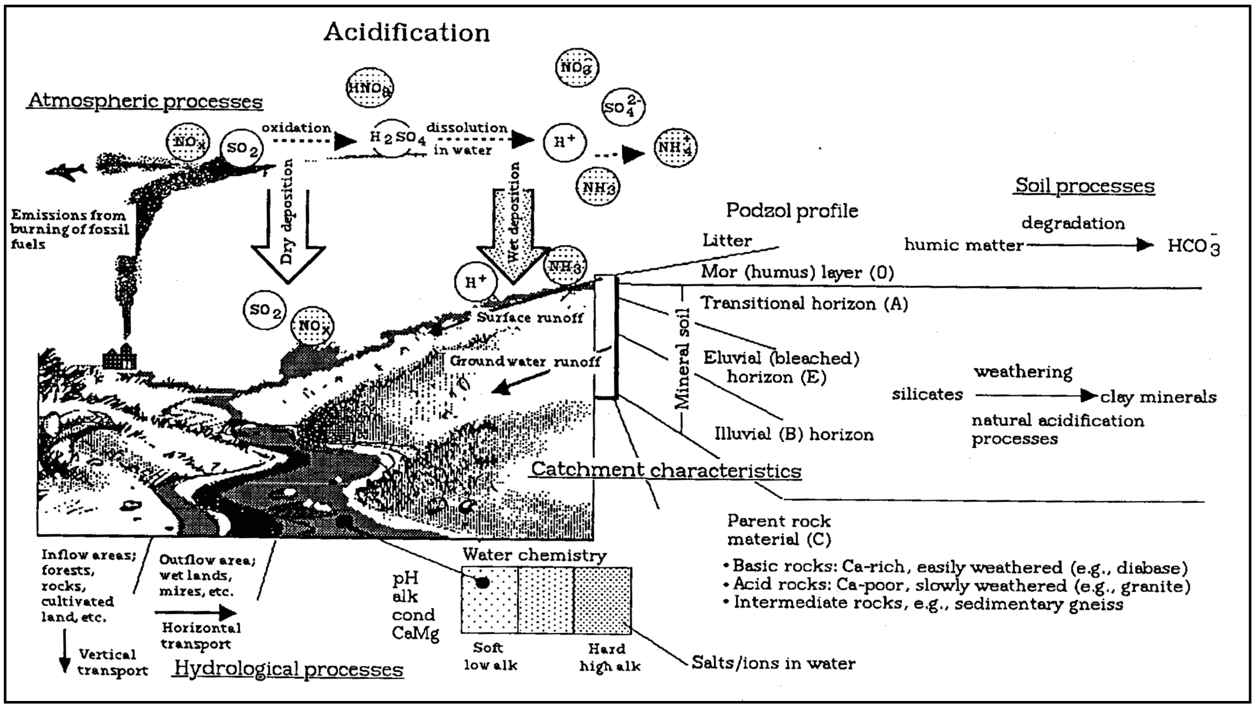


Figure 13.8 Major processes and routes of transport of natural and anthropogenic compounds affecting the acidity of rivers and lakes. The processes and fluxes illustrated in this diagram are discussed in the text (from Håkanson & Peters, 1995).

chemicals, e.g. heavy metals. A similar effect can be obtained by stocking the lake with a large population of planktivorous fish or by ridding the lake of predatory fish. The latter may be a result of moderate oxygen depletions, which are lethal mainly for oxygen-loving predators, like perch and pike. Then the effects of reduced predation pressure on planktivores will cascade down the food chains; eventually affecting the photosynthesis of submerged macrophytes through shading from epiphyton and phytoplankton (Brönmark & Weisner, 1992).

Reversed from algae to macrophytes

Among the known natural mechanisms that can change the dominance among the producers into the direction of macrophytes are severe summer or winter fish-kills (Brönmark & Weisner, 1992; Kornijów, 1997). Oxygen depletion has to be strong enough even to eliminate fish that are resistant to low oxygen-concentrations, such as crucian carp (*Cyprinus carpio*) or tench (*Tinca tinca*). Then, grazing by water fleas successfully controls development of phytoplankton, in spite of high concentrations of nutrients. Nutrients can be incorporated and accumulated (luxury uptake) into the tissue of macrophytes. Once established, the plants will be able to compete successfully with algae for nutrients and light. In addition, macrophytes will support many plant-associated invertebrates as alternative food for zooplanktivores (Diehl & Kornijów, 1998) and provide refuge for water fleas against fish predation. Among the plants there will be good habitats for spawning and hunting by piscivores, which in the future will control populations of planktivores. All these mechanisms may contribute to stabilising the macrophyte-dominated system (Moss et al., 1996; Jeppesen, 1998). However, in order to establish them it is very important either to stock the lake with piscivores to enhance the effect of lake recovery or not to stock the lake with planktivores for at least one year after the fish mortalities (Kornijów, 1997).

Acidification

The literature on the acidification of land and water and its ecological damage and economic consequences has grown exponentially. Important publications include Likens et al. (1979), Ambio (1976) and SNV (1981; 1986). There are many models and modelling approaches to address the acidification of aquatic and terrestrial environments and to propose remedial measures for acidification and even entire books of literature references on acid precipitation (e.g. Seip, 1989). In Sweden, lake liming has become a major industry; about 8 000 of Sweden's lakes have been limed.

Figure 13.8 illustrates the sources of acidification. The burning of different *fossil fuels*, (coal, oil, petrol, etc.) results in emissions of many types of compounds (SO_2, NO_x, etc.), whose atmospheric oxidation ultimately gives rise to a deposition of H^+, i.e. to acidification. Acidifying substances, mainly sulphur

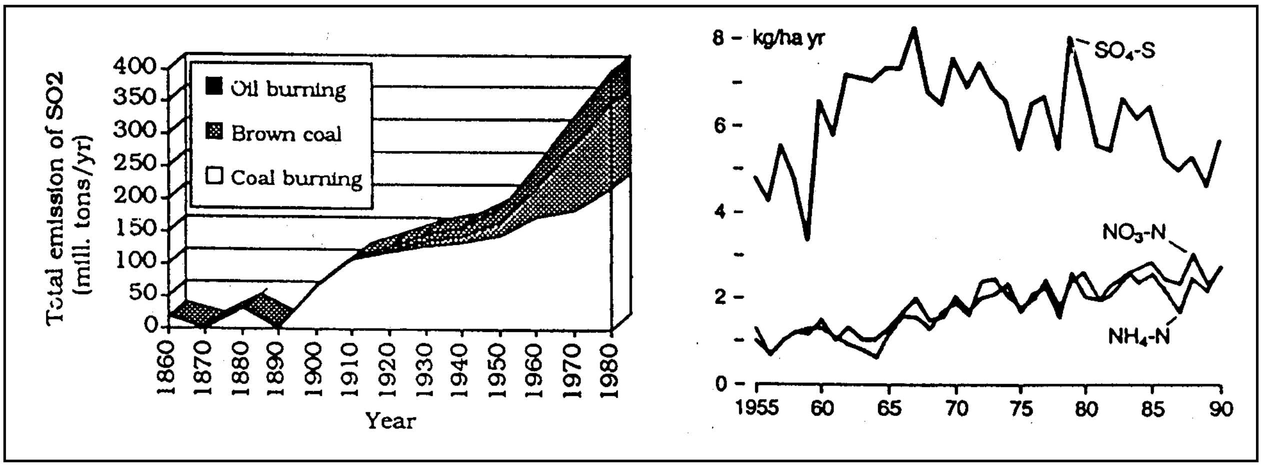


Figure 13.9. Left panel: Quantities of sulphur emitted from burning fossil fuels (based on data from Overrein et al., 1980; Ministry of Agriculture, 1982; SNV, 1982; 1986). Right panel: Wet deposition of sulphur and nitrogen in central Sweden from 1955 to 1990 (from SNV, 1991).

and nitrogen, are deposited on land and water as *wet* and *dry deposition*. The latter is often very difficult to quantify. The acidity of lakes and rivers is influenced by many *natural processes,* but especially by the *degradation* of organic matter and the *weathering* of different minerals. Weathering rates and the acid/basic properties of the runoff water depend on the chemical characteristics of the parent rock. Basic rocks, like limestone, are generally rich in Ca and easily weathered. Acidic rock, like granite, is neither.

Whether both natural and anthropogenic factors influence the acidity of fresh waters was the subject of intense debate in the late 1960s and 1970s. Mass-balance calculations taken from extensive field measurements (Eliassen & Saltbones, 1983) now provide a quantitative basis for ranking different processes. There is no longer any serious doubt that anthropogenic acidification is a major cause of severe problems locally and globally.

Figure 13.8 highlights several important facts:

- Acidification is not a local environmental problem of short duration (Granath, 1980; Dickson, 1986). It is a major, regional-to-global problem linked to the burning of fossil fuels and intimately associated with modern life and technology.
- Acid rain crosses all national borders. It affects most types of ecosystems as well as most branches of the environmental sciences.
- Since 1860 emissions of SO_2 have increased from less than 20 million to about 400 million tons per year (Figure 13.9, left panel), mainly due to the burning of coal. Figure 13.10 gives a map of the wet deposition of sulphur in Sweden during the 1970s. The deposition was then, and still is (Figure 13.9, right panel), very high in the southern part of the country and decreases from south to north. The load of sulphur is high in Sweden, as is the sensitivity to acid rain since the soils are generally morainic with a low buffering capacity. The exceptions from this general rule are the counties of Scania and Gotland, which lie on calcareous bedrock; the rest of the country is dominated by acidic bedrock like granite and gneiss. Considerable cost has been spent on significantly reducing the emissions of sulphur (see below) from Sweden (see SNV, 1991), but the trend (Figure 13.9) still shows an *increasing* deposition of nitrogen and only a *slow decrease* in sulphur. The emission reductions between 1980 and 1990 for sulphur in other European countries (21 %) have been much smaller than those in Sweden (58 %).
- The burning of fossil fuels also results in the emission of many types of metals, e.g. Hg.

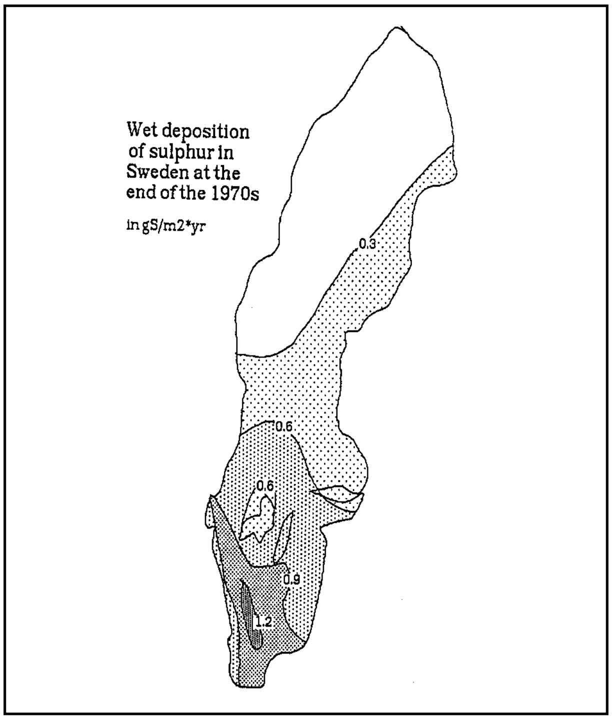


Figure 13.10. The wet deposition of sulphur in Sweden at the end of the 1970s. (redrawn from the Ministry of Agriculture, 1982).

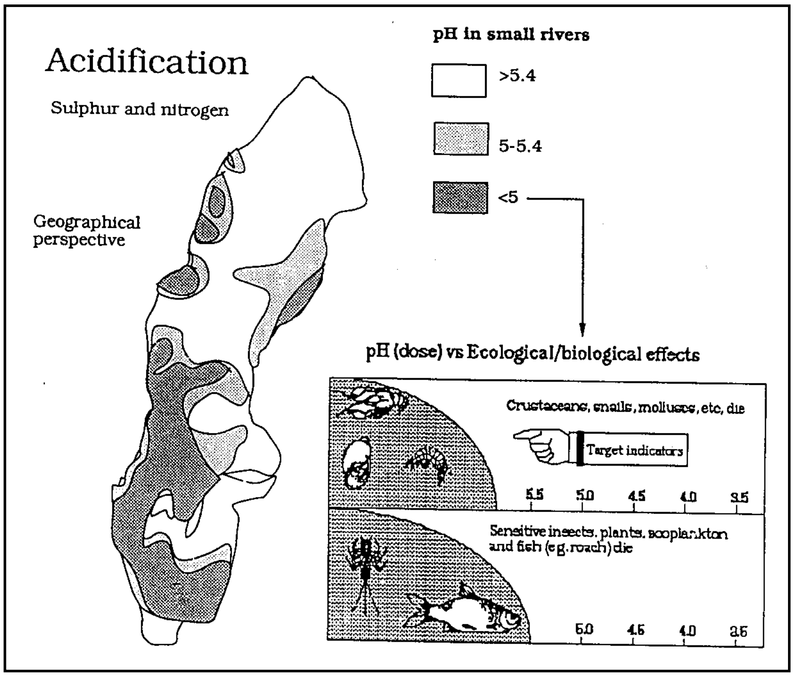


Figure 13.11. A map of Sweden illustrating the lowest measured pH in small rivers (1971 to 1985) and lake pH associated with different ecological effects (based on SNV, 1986. From Håkanson & Peters, 1995).

- The problems associated with fossil fuel emissions (e.g. acidification of lakes, rivers and forests, eutrophication of the sea and metal contamination) can only be stopped through international co-operation.

The effects of acidification

A list of the ecological problems that acidification produces in lakes and rivers could be made very long and one fundamental component of the problem is the *geographical extent*: pH has been significantly altered by acid rain, not in just a few rivers and lakes, but in entire regions. It has been shown (SNV, 1986) that the pH in about 4 000 small rivers from 1971 to 1985 had values below 5. This means that *many key organisms are extinct* (Figure 13.11). In Sweden, about 16 000 lakes have been drastically altered by anthropogenic acidification (Henrikson & Brodin, 1995).

Acidification, however, is not a threat to *all* aquatic ecosystems and all organisms. Acidification usually causes great damage to groundwater systems (wells, etc.) and to oligotrophic lakes. Eutrophic lakes and marine ecosystems withstand acid rain much better, due to their better buffering capacity. Thus groundwater ecosystems and oligotrophic lakes are target ecosystems for acid rain research.

One well-documented consequence of soil and groundwater acidification is that many metals are dissolved at low pH and that elevated metal concentrations have been measured in waters of wells, rivers and lakes. This is serious for toxicological reasons since metal toxicity and bio uptake are generally much higher for metals in ionic forms than for metals bound to carrier particles or in solid form. Especially cadmium can, in acidified soils and waters, reach concentrations above the critical limits. Thus, the leaching of many metals from the organic soil layer is highly pH-dependent.

Note also that very high lake concentrations of aluminium appear at low pH. Aluminium works in more or less the same manner in lakes as in water purification plants, where large quantities of technical $AlSO_4$ are added to increase flocculation and sedimentation of pollutants in waste water. If the Al-concentration reaches above 100-200 µg/l, fish gills are clogged by aluminium flocs and the fish die from suffocation. So, Al is not toxic in the same sense as e.g. Cd (see Pärt, 1983; Block, 1991), but the end result of high Al-concentrations in lakes is that fish, i.e. key functional organisms, die.

How long will acidification continue? Since the burning of fossil fuels is the basic cause of acidification of terrestrial and aquatic ecosystems in many parts of the world and since humans are likely to continue to use oil, coal and petrol, the acidification problem will probably be with us for many decades, even centuries, to come.

14.
FLOODING

L-C Lundin & Sten Bergström

Introduction

On a worldwide basis over the past 25 years, more than 750 million people have suffered distress and disruption on account of flooding. Estimates point to almost 120 000 lost lives due to flooding over the same period. The flooding situation in the Baltic region is generally not as severe as that of areas in the world hit by monsoons or hurricanes. Still, regional disaster can be considerable. During summer 1997, 500 000 hectare were inundated when the Odra River flooded over. More than 100 lives were lost in Poland and the Czech Republic (Kundzewicz, 1998) and the economic losses in Poland alone were estimated to be well over $ 700 million.

Flooding is generally considered a problem but we should remember that it could also be a blessing in disguise. The Nile River culture in the millenniums B.C. was based on the regular flooding and inundation of the Nile River valley, sustaining the fertility of the valley agriculture. The water stage was recorded in the Nile River as early as 3500 B.C. and a flood warning system was operating. This system relied on fast rowers bringing the news on the water stage downstream.

The mechanisms behind flooding are not different from the usual mechanisms, presented in Chapter 7, of runoff formation. The difference is merely a question of magnitude. An extreme runoff event, i.e. a flood, occurs when runoff is considerably higher than expected, i.e. the extreme flows are not necessarily very high in absolute numbers. Tol et al. (1995) give a definition that also demands that the socio-economic damage be substantial, taking an ethnocentric view of the problem. Another common definition has a more generic point of departure: a flood causes inundation of areas not normally inundated. This means that as soon as the river water extends over its natural or man-made borders, there is a flood at hand. It should be noted that during perfectly natural conditions this is likely to happen every one to three years. Floods are thus a natural part of the dynamics of a river. A problem with this definition is that it mixes up the terms *flood* and *inundation*, making them synonymous with each other. In Norway, where floods occur regularly, a definition is sometimes used whereby a flood is present as soon as the runoff exceeds the average flow. This means that most Norwegian rivers are flooded about a third of the year.

Severe floods of the 90s

Naturally the effect of a flood strongly depends on the population density of the area where it occurs. The most severe recent flood, in summer 1998, was the one in the Yangtze River in China, which took the lives of 3 650 people according to official statistics. China's annual floods in 1998 were earlier, heavier and more widespread than usual, with the north-east and provinces in south and central China along the Yangtze River affected the most. The Xinhua news agency reported that in 1998 natural disasters struck a total of 350 million people and that 20 million people required emergency evacuation. Of this total, floods, landslides and mudflows affected the fate of 240 million. More than 8 million houses were destroyed and 16 million were damaged, giving a total cost for damages of $ 36.5 billion. In early June 1995, the Yangtze River experienced another very severe flood, taking the lives of 1 200 more people and stranding 5.6 million. The cause of flooding this time was extensive rainfall.

In Dacca in Bangladesh, 450 people were killed as the city was inundated in the summer of 2004. A total of at least 1 300 people were killed over South Asia in this particular monsoon rain flooding. In spring the same year, floods and landslides took an estimated 3 300 lives in Haiti and the Dominican Republic. Less than half of the victims were actually found, probably making the figure an underestimation. In April 1993, 100 people were killed in north-western Colombia as the banks of the Tapartó River burst and inundated a rural area. A similar situation occurred when the Paraguay, Paraná and Iguaçu Rivers overflowed their banks, inundating hundreds of towns and villages and leaving some 30 people dead.

During the summer of 1993, the most devastating flood in recent American history occurred in the upper Mississippi River basin. The severe flooding caused an unprecedented amount of destruction to many communities, homes, businesses and natural ecosystems. Most of the tributaries from Minnesota to Missouri were affected. Soil moisture levels in the central United States were already high in the autumn of 1992. Winter rain and snow contributed further to nearly saturated soil conditions. Persistent storms rumbled across the basin from June to August, giving almost twice the normal precipitation at some locations. Over 1 000 of the 1 300 levees designed to hold back floodwaters failed and over 70 000 people were displaced by the floods. Nearly 50 000 homes were damaged or destroyed and 52 people died. Damage was estimated to be between $ 15 and 20 billion.

The winter flooding of the Rhine, Main, Meuse and Waal Rivers in 1995 should also be mentioned. Large numbers of citizens had to be vacated and the losses to property were considerable.

However, in absolute runoff terms, these floods were not particularly extreme. The largest estimated flood is 280 000 m^3/s for the Amazon River and many large rivers (e.g. the Congo, Brahmaputra and Yangtze Rivers) generally exceeds 100 000 m^3/s. It is notable that the so-called *jökulhlaups* of the Icelandic glaciers, resulting from the breaking of ice-dammed lakes, can also reach similar magnitudes. In the recent *jökulhlaup* of Vattnajökull in autumn 1996, the flow culminated at 45 000 m^3/s flowing from Grímsvötn along a 50 km long path beneath the outlet glacier Skeiðarárjökull out to the alluvial plane, Skeiðarársandur.

Causes of flooding

Most floods are caused by excessive rainfall. It is not primarily a question of amount but of rainfall intensity and areal extent. In general, an increase in precipitation leads to a proportionally higher increase in runoff. Another important issue is the initial moisture state of the surface. If soil moisture contents are high there is little storage available in the ground, causing a rapid rainfall response in river flow. One of the most important issues is the storage capacity of the soil moisture zone. Often, low storage capacity in the soil moisture zone coincides with high groundwater levels, but this is not always the case; during winter, groundwater levels can be low and soil moisture contents high.

In soils with high infiltration capacity, which is the common situation in the Baltic region, surface runoff is rare and the rainwater is retarded as it passes through the ground. For winter-floods, however, frozen-soil conditions often cause low infiltration capacity and surface runoff. The role of the vegetation in the catchment is of course important. In catchments with sparse vegetation, erosion is a frequent problem, causing rapid surface flow with high sediment loads. Vegetation with high evapotranspiration and interception capacity, such as forests, contribute in decreasing and dampening the runoff. Although these processes are important for smaller catchments they are not normally of importance for generating flooding in larger rivers.

The landscape is formed in response to the runoff rates occurring over an average year. Dry areas have infrequent small gullies or creeks, draining the region, whereas humid areas tend to have larger and more frequent streambeds. This natural drainage system handles the runoff in most situations but tends to overflow if runoff is so high that it cannot be dealt with, gradually extending the width of the riverbed. Marshlands, deltas and lakes act as reservoirs where flow peaks are dampened. Flooding of such natural systems does not normally create serious problems for society, unless settlements are located too close to the river or the wetlands and lakes are exploited. Extensive upstream erosion is coupled to sedimentation on the riverbed in the valleys, gradually decreasing the capacity of the riverbanks to check large flows.

The most important factor in flooding, aside from climate conditions, is the extent of lakes and man-made reservoirs in the catchment. The direction and form of the catchment is also of importance to flood development. Circular catchments yield higher flows because the mean distance to the river mouth is small and steep catchments yield higher flows than flat ones. These factors may vary between subbasins within the catchment. Since the resulting flood along the river is dependent on the timing of contributions from the tributaries, such variations may be important when analysing the flood development.

When population pressure is high, people are tempted to exploit areas that inevitably will be flooded. Extensive paving of surrounding areas and the banking and canalisation of the river cause the flow to take a more rapid course and may increase the damage done by a flood. This is often a problem in more developed parts of the world. It should be noted that the impact of e.g. paving has to be considered in combination with other effects. Paving part of the basin can actually decrease runoff if the drainage from the paved areas has ceased as the drainage from the rest of the area starts to contribute to the runoff. A systemic view of the basin and consideration of the importance of concurring events are to be recommended.

In the northern part of the Baltic region, flooding is also caused by excessive snowmelt, sometimes in combination with ice jams. Snowmelt in combination with rainfall can cause very high flows. Ice jams occur if the breaking ice is obstructed and forms a dam-like structure across the river. Water is dammed, increasing the pressure on the ice and a jam brake will occur, creating a so-called icefloe. Some rivers, e.g. the Torneå and Daugava Rivers, are well known for their ice jams and icefloes. If the river is monitored, the ice jams can be blasted away before dangerous situations occur. In previous centuries icefloes were also a severe problem in Central Europe but they have now almost entirely disappeared. The causes for this are not clear. Canalisation and regulation, changing concurrence of melt-water and ice melt as well as the release of warm sewage and cooling waters have been suggested.

Bursts of banks or dams are also a common cause of flooding. Such events often come without warning, causing severe death tolls. To some extent, warning systems can be of help but lead times are often very short.

Floods are often characterised by the time of their occurrence during the year. Spring floods in the Baltic region are generated by excessive snowmelt or a combination of snowmelt and rainfall. During summer and autumn, floods are normally pure rainfall floods. In the southern part of the region winter floods occur, caused by excessive rainfall on already wet ground. When analysing flood occurrence it is important to take flood origin into account since the development of the different floods are quite different. Rainfall floods are very rapid, often increasing the runoff by several magnitudes in hours or days followed by a recession of the order of days, whereas spring floods are more gradual in their development, most often with several peaks. Spring floods normally extend one or several weeks. Another reason to make distinctions among floods is that their impact is dependent on the season they occur. Spring floods have very little impact on agriculture, because the crop has hardly developed, whereas rainfall floods can have severe impact on crop and farmland in agricultural areas.

The Rhine River flood of 1995, an example

The development of a flood is often very rapid and the event passes in a week or two. After that, however, areas may stay flooded for extended periods and the time to repair damages is counted in months or years. The Rhine River flood of 1995 is an interesting example that involved a number of coinciding conditions.

January 1995 was wetter than normal in France, Germany, Belgium and the Netherlands. Precipitation was 1.5 to 3 times the average. Over a period of nine days the water level rose continuously above the inundation level. The rainfall of 22-30 January was very intense, exceeded only in 1923 and 1993 (KNMI, 1995). It was also areally extended and of long duration. Soils were frozen in the area and soil moisture levels were high, giving a rapid surface runoff, and the rainfall also coincided with snowmelt in the mountains of the Ardennes and Alps. The peak runoff in the Rhine River increased to 2 200 m/s^3, six times the average runoff.

The inundation is thus dependent on the ability of the river to accommodate such a large flow. Exploitation of the riverbank can considerably increase flood damage if it is done without consideration. There are reasons to believe that riverbank exploitation plays an important role on the effects of floods in the Rhine catchment since a similar runoff rate to that experienced in 1995 had been coped with earlier and had had less serious effects.

Magnitude of a flood

The magnitude of a flood is dependent on the size of the drainage basin, i.e. the size of the rain-collecting area. This aspect is treated by the concept of specific runoff, q, normally given in l/s km^2. Annual average values in the Baltic region range from 5 to 14 l/s km^2 for the larger catchments, whereas annual maximum values reach a few hundred. For very small catchments during e.g. thunderstorms, values can be much higher and for urban areas dominated by impermeable surfaces, specific runoff may exceed 10 000 l/s km^2 (Otnes & Ræstad, 1978). For large catchments Otnes & Ræstad (1978) gives a rule of thumb stating that

$$q = \frac{k}{\sqrt{A}}$$

where k is a constant depending on region and A is the catchment area.

Impact of climate change?

Some studies, e.g. in USA and Germany, indicate that runoff has increased over the last 50 years. Speculations that this is connected to a global change in climate have also been presented. Even if solid research reports with this conclusion are still lacking, the risks involved are considerable and insurance companies are worried about the increased frequencies of flood damages.

It is difficult to separate climate-change effects from other human alterations of the river and land-use in the catchment and from natural variability of the climate. In the climate-change scenarios an increased flood frequency is predicted. So far the observed floods can be explained by the natural variability in climate, often in combination with man-made alterations or gradual changes.

The recent floods in north-western Europe, in 1993 and 1995 (e.g. Dister, 1995), and the flood in USA in 1993 were all primarily caused by excessive rainfall on saturated soils. Following the 1993 flood of

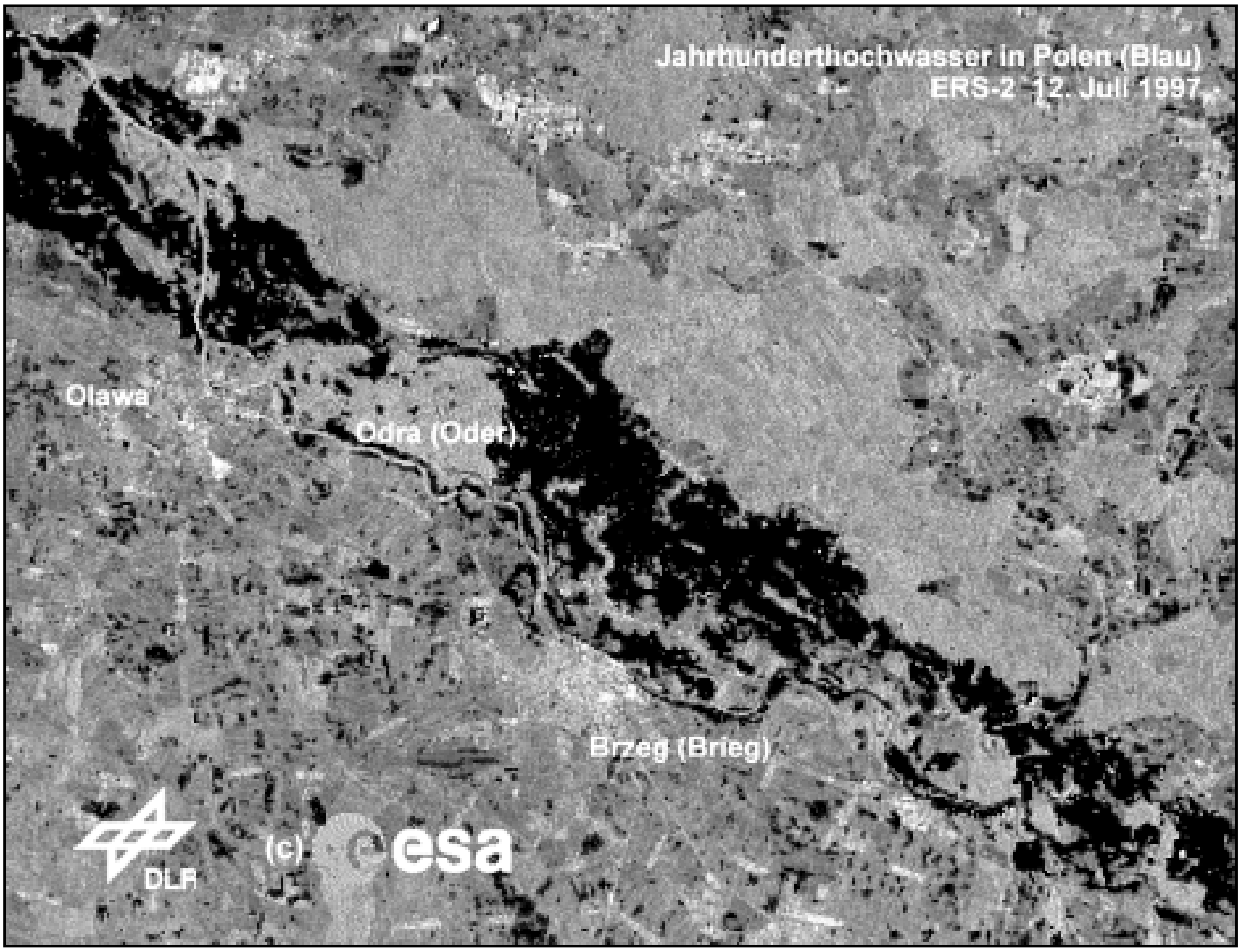


Figure 14.1. Part of the Odra River inundation shown on a composite ERS-2 radar satellite-image. The area shown is 40 by 30 km^2. Black colour indicates water. The image was produced by DLR.

Meuse River, Waterloopkundig Laboratorium (1994) investigated the flood records of the river and found a rising trend, on the order of 10-12 %, in the runoff peaks since 1911. They could conclude that the reasons for the trend were changes in land-use, river infrastructure and urbanisation. Since the forested area in the catchment grew 10 % during the period, deforestation could be ruled out. In Sweden, Lindström (1999) was unable to find similar general significant trends. It should be kept in mind however that in some climate scenarios, a climate change is not accompanied by an increase in runoff or flooding frequency.

Extreme events in the Baltic region

Extreme hydrological events occur frequently in the Baltic basin. Most of them have limited impact on buildings, structures and farmland, mainly because the population density is moderate in the region. A few runoff events, however, have had significant consequences for the river valley population. Most tragic in recent years was the Odra River flood in July 1997 (Figure 14.1). This was the worst flood of the century in the area. It affected the entire area of eastern Germany, south-western Poland, north-eastern Hungary, Romania, the Czech Republic and northern Slovakia.

As soon as the floodwater started to retreat, people looked for the reason behind the great flood. Was the flood a result of changes in the landscape or in the climate? One important reason behind the extent of the damages was the transformation of marshes in the Oderbruch area into fields, carried out during Frederick the Great, some 250 years ago. Another reason put forward, although there is some doubt as to the possible magnitude of such effects, was deforestation in Poland and the Czech Republic.

The issue of river management was raised after the severe inundation in the region and calls for a stop to further canalisation of the river were put forward. Settlements tend to slowly move towards the riverfront if there are a number of years without flooding. Strong legislation and supervision is needed to avoid this.

Inundation of the Odra River region is only one of many extensive ecological problems. Biological and chemical hazards continue to exist due to the risks of disease spreading and contamination from flooded dumping grounds, chemical works, gas stations, etc. The effects may occur several years after the flood. However, so far no major problems have been reported from the region. As for the sea itself however, tremendous amounts of sediments and nutrients were washed out into the Baltic Sea and caused problems for fishing for an extended period.

Extreme events in Scandinavia

In 1995 the highest flood in this century occurred in several rivers in Norway and Sweden, and the so-called 100-year areal precipitation hit the north-eastern Swedish coast in July 1997. Flooding problems were also reported from Sweden and Poland in the summer of 1998.

Despite these spectacular recent hydrological events it is often difficult to identify a statistically significant increase in flood frequencies. In-depth analyses of runoff trends in Sweden reveal no such trends (Lindström, 1999; Fig. 14.2). There are also several historical indications of floods higher than the ones observed during the period of instrumentation.

One interesting observation from the analysis of Swedish floods is that critical timing of flood-generating factors seems to be equally, or even more, important to flood generation than the isolated extreme precipitation. For example, the flood of 1995 was caused by the combination of a cold spring, which delayed snowmelt, and heavy rainfall. In 1997 a few extreme precipitation events caused increased damage due to their unusual occurrence in spring and autumn when soil moisture was high.

The sensitivity of the runoff regime to climate has been strongly demonstrated during the recent mild winters. The strong zonal activity with massive winter precipitation from the west has resulted in dramatic snow accumulation in north-western Scandinavia. Glaciers are growing, hydropower production in Norway and Sweden has peaked and spillways have been activated, with some unexpected consequences.

Human impact on flood risks

Flooding problems have triggered a debate on human impact on flood risks. Apart from climate change this discussion is mainly focused on forestry and reservoir operation and on dam safety. More and more frequently urbanisation, physical planning and the development of the infrastructure in unsuitable locations have been identified as other important factors.

Risk assessment

The risk of a flood of a certain magnitude, often referred to as the 100-year flood or the 1 000-year flood, is very difficult to assess. To perform a proper statistical estimate records from several hundreds or thousands of years would be required. Advance statistical methods give estimates based on assumptions that the measured flows are samples from a certain theoretical distribution, but substantial uncertainties remain.

A different approach can be taken using a hydrological model. Series of extreme rainfall events, soil water contents, snow melt and flow events, collected from actual observations or generated as synthetic but plausible events, can be merged together with regulation information on the dam to create ‘worst-case scenarios.’ Scenarios with coinciding rapid snowmelt, intensive rainfall and full soil water storages can then be simulated to generate estimates of reasonable dimensioning flows for dams or floods.

Forestry

In the mass media both forest drainage and deforestation have been accused of being responsible for recent flooding in Sweden. At a first glance this might seem reasonable since the water uptake and transpiration are reduced after deforestation, interception losses are reduced and snowmelt is more intense on open land than in the forest due to a more efficient exchange of energy. On a catchment scale, however, we must consider the joint dynamics of all these factors. For example, deforestation creates a patchiness in the catchment which makes snowmelt less synchronised, which might result in less peaked runoff. Active forestry, including drainage, has also led to increased total biomass in Sweden even if some cleared out areas look dramatic.

Several attempts have been made to quantify the effects of forestry on flood risks in Sweden (see e.g. Brandt et al., 1988; Iritz et al., 1994). The conclusion is that the effects can be rather dramatic, but only on the local scale. It has not been possible to detect any effects of forestry on the flood risks of the larger river systems, where in Sweden we have the worst problems with flooding. It is evident that the effect of forestry on flooding in large rivers is of a much smaller order of magnitude than those of the natural variability of climate.

Reservoir operation and dam safety

Hydropower production is used to fulfil Norway’s total demand for electricity, some 50 % of Sweden’s demand and 25 % of Finland’s. Most northern river

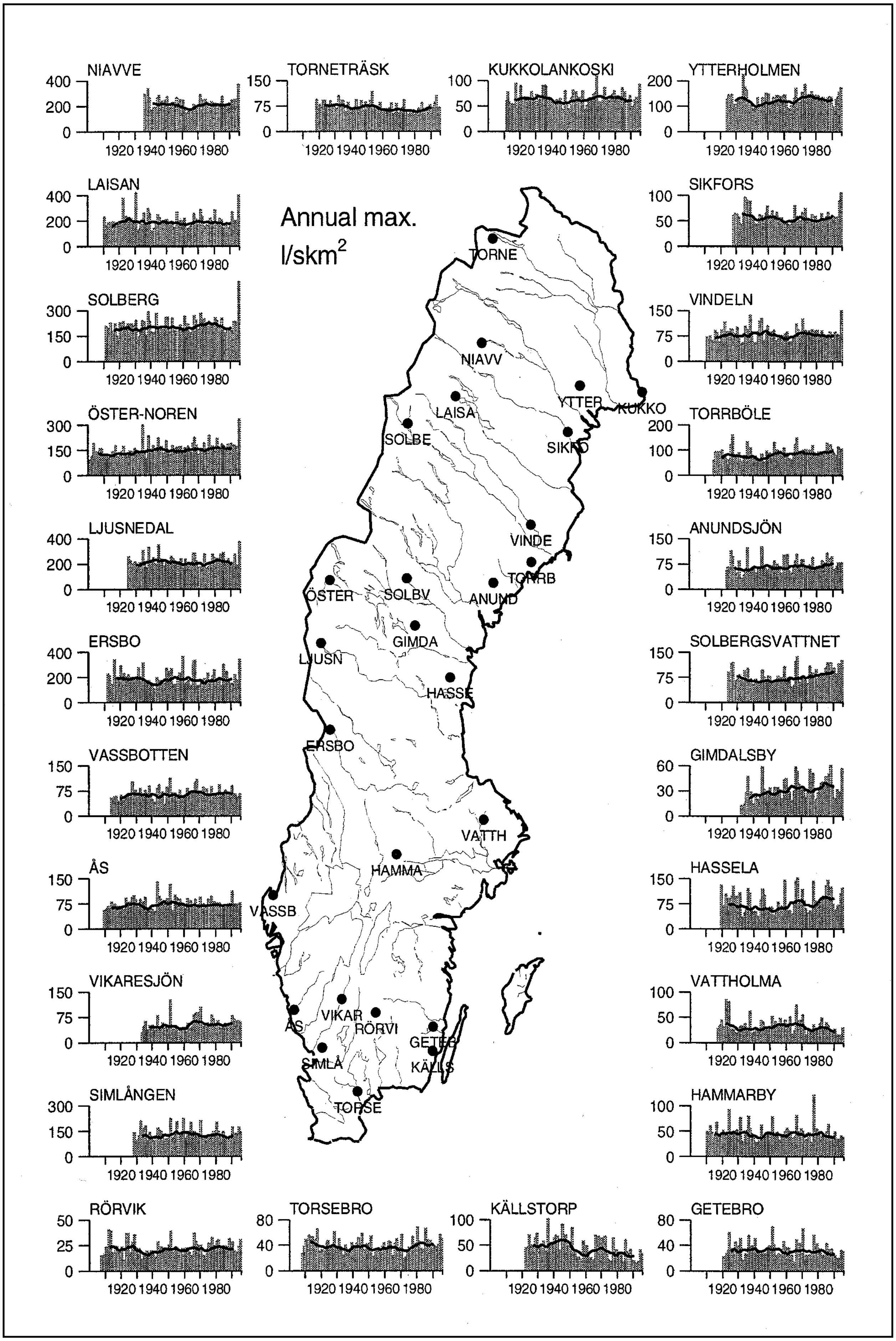


Figure 14.2. The highest recorded runoff (l/s km^2) for each year for selected stations in Sweden (bars) and moving average over 10 years (thick curve) (from Lindström, 1999).

systems are therefore regulated to some degree. In some systems as much as 70 % of the mean annual runoff can be stored in reservoirs for production of electricity in wintertime. The consequence is a regulated flow in these rivers, which reflects energy demand more than natural runoff generating processes. Most of the peak flows can be stored, but only as long as there is storage capacity left in the reservoirs of the river system.

In August 1993, after late snowmelt and a rainy summer, reservoirs were full and the spillways were activated in many of the rivers of northern Sweden. As expected, this resulted in floods of the same magnitude as would have been the case if the rivers had not been regulated. Two years later an even worse flood occurred in spring. This time the reservoirs were nearly empty and most of the water could be stored in the regulated rivers, while the situation became dramatic in areas without major reservoirs. The two events in 1993 and 1995, exemplified by the graph from Luleälven River (Figure 14.3) below, serve as good examples of the complexity of a system where humans and nature interact under extreme conditions.

In August 1998, the 1993 event was more or less repeated. High flows occurred in both the Ångermanälven River and Umeälven River at a point in time when reservoirs were full. Again there was discussion of changing the regulation strategy. Bergström & Lindström (1999) concluded that river regulation leads to a general flood reduction but that summer and autumn floods may under certain circumstances increase instead. They also concluded that, ‘There is a tendency to underestimate flood risks. Floods occur often enough to cause damage, but seldom enough to sometimes be overlooked in the comprehensive planning.’

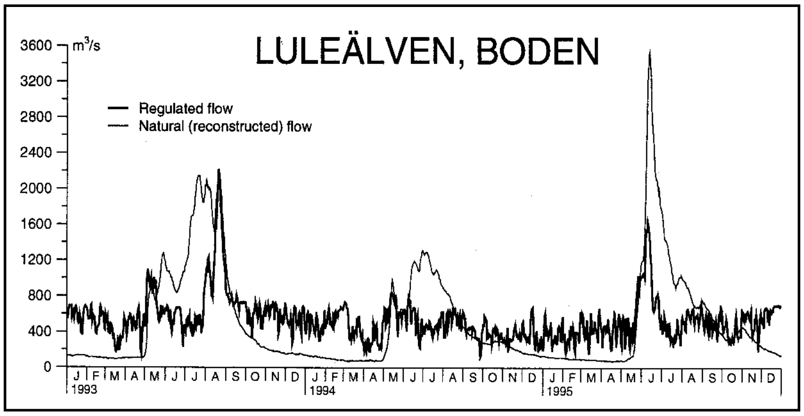


Figure 14.3. Three interesting years in Luleälven River in Northern Sweden. The impact of regulation is clearly shown but also the return to near-natural flow conditions when the spillways were activated in August 1993. The flow would have become critical without available storage capacity in the spring of 1997! (from Bergström & Lindström, 1998).

There are several major dams within the Baltic basin. Although no major dam disaster has ever occurred in the area, dams are always a potential hazard. Incidents and smaller dam failures have confirmed this. A hydrological re-evaluation of all major Swedish dams has been carried out, based on new guidelines adopted in 1990 (Norstedt et al., 1992). This is the result of lessons learned from floods in the 1980s, which culminated in the failure of the relatively small Noppikoski dam in September 1985.

Comprehensive planning and development of infrastructure

It has often been confirmed that the comprehensive planning and development of infrastructure is not always in harmony with natural hydrological variability. There are examples of municipalities with an estimated annual risk of flooding of more than one in 100. The conception that the existence of reservoirs guarantees protection against floods has also been challenged. The public has to be reminded that the reservoirs are intended for energy production and not primarily for flood protection.

The flood in Sweden in 1993 was not very extreme from a non-regulated perspective, but river regulation changed its return period from one in five years to one in 30 years. Thus river regulation did not generally cause higher floods, but it gave a false sense of security and thus it aggravated the hydrological ‘surprise.’ A lack of dialogue was also revealed between various sectors in society. It could be shown that spillways had been built with a capacity that was not in harmony with the physical development downstream, and vice versa.

Floodplain management

Floodplain management is applied to reduce the negative impact of floods. The basis for floodplain management is that the cost of a management plan is lower than the costs of flood damages. Two approaches can be taken, flood control and damage control.

Flood control can be achieved by means of dams, dikes and levees, and by canalisation. Dams are used to withhold the flood peak as much as possible. The effect of dams has a tendency to rapidly decrease downstream. Dikes and levees keep the areas behind them dry until they are overtopped. These constructions may however increase downstream water stages and flow velocities due to the caused constriction. Canalisation involves the straightening and deepening of the river channel so as to decrease the water stage. Channels may however have adverse environmental effects and often only temporary beneficial effects. One must thus be aware that all these measures may lead to a further development of the flood plain, possibly creating an even more damage-prone situation. Building dams and canals increases the area that can be used for agriculture and building projects, but when – not if – a large flood occurs, the damages will be worse than before the plan was implemented (see e.g. G.W. White, 1975; Belt, 1975). It is important to realise that flood-control measures can only reduce flood frequencies at a particular location, often increasing the frequency elsewhere, but they cannot eliminate flooding.

Damage control deals with flood proofing, removal of structures, flood warning and floodplain zoning so that damage to existing structures, such as houses and roads, is minimised and future structures are not constructed in zones that have a high risk of flooding. Flood proofing involves the construction of buildings to withstand a flood with minimal damage. If structures can be removed from flood-prone areas no damage will occur during the next flood. Warning of imminent floods gives residents the opportunity to remove loose property and build temporary protection, e.g. by sand bags, around houses. The most important advantage, however, is that warnings are effective in reducing the loss of lives. Land-use control that limits future damaging development along the river is referred to as floodplain zoning.

Mapping of flood risk

When an estimate of the likelihood of flood occurrence has been made, based either on observations or model simulations, the next step is to identify the areas that are likely to be inundated if the 10-, 100- and 200-year floods occur. This is done by use of Digital Elevation Models (DEM), describing the elevation of the land in the floodplain in a Geographical Information System (GIS) and a hydraulic model calculating the water stage at a specific runoff along the river stretch. In addition, information on dams, bridges and roads is required. The model needs to be calibrated using measured water stages and discharges. The result is presented in a GIS as a flood risk map, indicating areas affected by inundation during the various floods studied. From such data, areas that should under no circumstances be used for settlements can be identified. The flood risk map is thus a tool for both comprehensive planning and implementation of flood warning measures.

In reality people may already live in areas affected by a 100-year flood, occurring with a probability of 63 % within a given 100-year period. Such a flood may not have occurred for several hundred years. This is in fact not especially unlikely, just as is it not unlikely to see two or even three 100-year floods in a lifetime.

In Sweden, the Rescue Services Agency initiated a study to identify the flooding risk along 10 000 km of flood stretches. The work started in 1998, carried out by SMHI, the Swedish Meteorological and Hydrological Institute. The maps identify areas that will be inundated by a 100-year flood and by the calculated highest flood, estimated using a hydrological model as described above. A hydraulic model converts the modelled discharge into water stages along the river stretch.

15.

HUMAN IMPACT ON GROUNDWATER

Erik Eriksson & Sivert Johansson

Groundwater contamination

The groundwater contamination process can be described as follows: contaminants from surface sources enter the soil as non-polar liquids or dissolved in infiltrating water. In the soil, part of the contaminants is adsorbed in a way that allows a fraction to remain in solution. Under such circumstances the rate of movement of the contaminants appears to be much smaller than that of the infiltrating solutions, an effect that can be expressed by a retardation factor which varies depending on the nature of the soil material. Organic matter in the soil is an efficient adsorbent for non-polar substances: benzene, petrol and chlorinated hydrocarbons, to mention a few. Polar compounds, such as acids, bases or salts of the above may be adsorbed on mineral surfaces, in which case clay minerals are the most important. For each particular contaminant, as a rule, there is data available of organic matter for estimating the storage capacity, or of mineral surfaces for estimating the retardation factor. Sooner or later the contaminants in the unsaturated zone will reach the groundwater surface and spread laterally as a plume. Here, too, the aquifer material will affect the rate of the plume spread.

Contaminants accumulate in the soil in various ways. Landfills, dumps and surface impoundings for wastewater are obvious surface sources. In the ground, flaws in petrol storage tanks and wastewater systems may occur. Further sources are pesticides used in agriculture and runoff from paved areas and from industrial material piles.

Prevention of groundwater contamination can be achieved in many ways. Land disposal should never be permitted on groundwater recharge areas. The only permanent groundwater discharge areas to be selected should be ones with adequate installations to collect and decontaminate drainage water. Surface impounding at industrial sites should either be located in discharge areas or lined with resistant material and provided with a soil drainage system that allows leakage water to be collected and decontaminated.

Table 15.1 A balance sheet for Swedish agriculture (Brink, 1980)

Input	kg/ha	Output	kg/ha
Precipitation	10	Harvest	83
Biol. fixation	16	Leaching	28
Manure	38	Lost as gas	25
Fertilizers	80	Storage inc.	8
Total	**144**	**Total**	**144**

Mines are sometimes used for disposal of contaminated material. Any loss of water by leakage will contaminate adjoining groundwater supplies unless the water level in the mine is kept at a level where the mine acts as a sink. Withdrawn water is then decontaminated. If this proves itself impractical, lined surface impounding and decontamination of collected rainwater is the only rational answer.

Wastewater transfer nets in urban areas seem to develop leaks with time, depending on the properties of the ground and the construction. In recharge areas this leakage will contaminate the groundwater. Pumping groundwater at a rate high enough to keep a small but adequate groundwater inflow into the area can prevent the spread of contaminants. The extracted water may be decontaminated and put back into the aquifer or, if considered permissible, drained into freshwater systems.

Septic tanks are frequently used in rural areas for domestic waste disposal. The wastewater flows through two or three tanks where organic material breaks down into soluble substances, which are released into the soil, where a final destruction of organic matter takes place along the plume created by the wastewater and infiltrating rainwater. The breakdown zone is usually limited in size to a few metres. Nutrients in the wastewater are released but only nitrate is mobile. Phosphorous will accumulate up to a point of saturation, which, however, in rural environments and domestic waste is distant in terms of time.

Underground petroleum tanks will, sooner or later, develop leakage whereby petroleum products enter the soil and may contaminate groundwater and adjacent water supplies. To prevent the spread of oil, a drainage system with monitoring sensors must be installed at the same time as the oil tanks in order to facilitate proper recovery of oil products from the groundwater. In

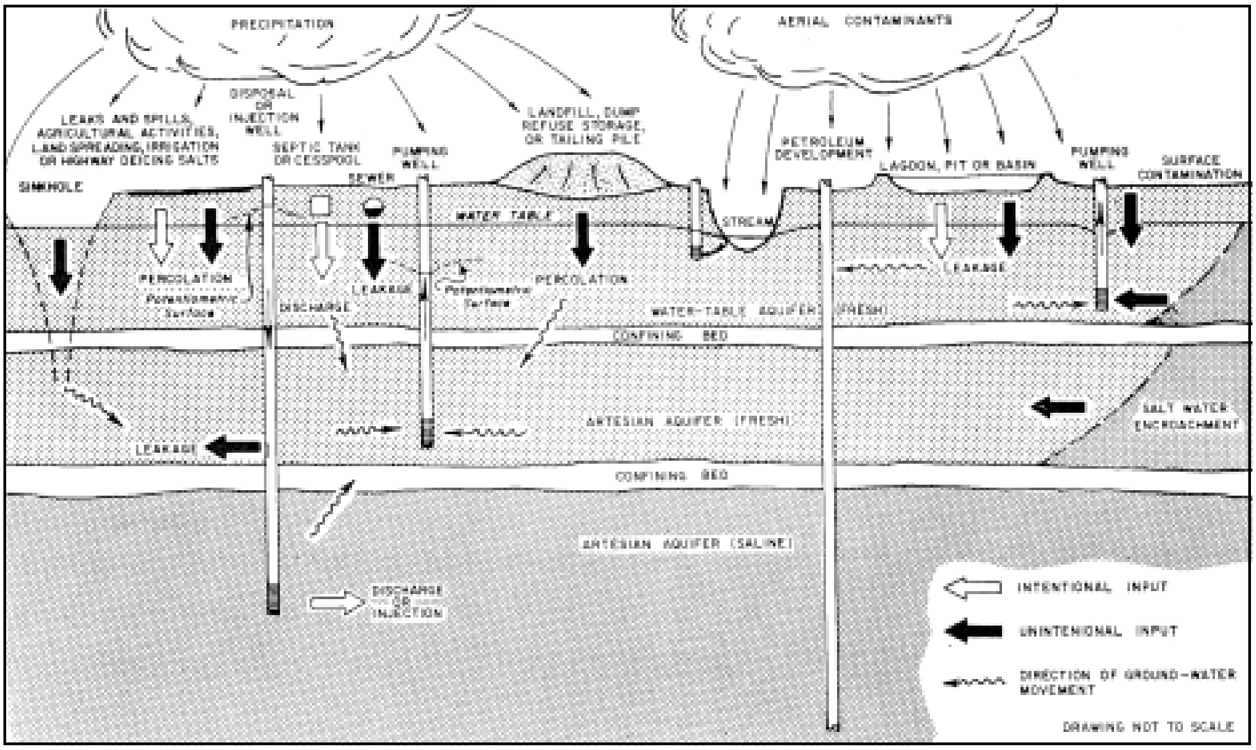


Figure 15.1. Typical routes by which groundwater becomes contaminated (EPA-600/3-77, USA).

severe cases of oil contamination it may be necessary to excavate soil material from the site and replace it with fresh soil.

Decontamination of soil *in situ* is usually a long-term project if it is to take place by means of rainwater leaching and retrieval of contaminated water by drainage systems. An estimate of the required time is obtained from the actual storage and the retardation factor for the contaminant and may readily reach tens of years.

Effects of agriculture

Nitrate in groundwater in agricultural areas may originate from the following sources:

- Atmospheric deposition of ammonium and nitrate
- Nitrogen fixation by plants
- Nitrogen in manure
- Nitrogen in fertilisers

A balance sheet for Swedish agriculture (Brink, 1980) shows the average yearly state of nitrate in groundwater in Sweden up until that year (Table 15.1).

In more recent years (R. Andersson, 1986; Gustafson, 1997), efforts have been made to decrease the leaching that affects groundwater by growing so-called catch crops as the last crop of the growing season. In this way leaching losses during late autumn/early winter are prevented since the excess nitrogen is stored in the residue of the catch crop, which is ploughed into the soil. The first crop in the next growing season will now benefit from this storage when it is released. Nitrate leached from agricultural fields in groundwater discharge areas will appear in surface water as well as in shallow groundwater, increasing the nitrate concentrations to levels considered unhealthy for human consumption, particularly for babies. At present, high levels in groundwater also appear sporadically in a few places in South Sweden which are not directly associated with agricultural soils. Extracted groundwater from private shallow wells may, however, have a higher frequency of high nitrate concentration, which is due in part to improper well design, allowing surface water to enter the well. In public waterworks using groundwater, high nitrate concentrations are less frequent, one reason being the large size of these reservoirs, which dampens single peaks in concentrations.

Nitrate leakage from agricultural land may be particularly noted in shallow aquifers in seasonally influenced discharge areas, which also happen to be the best agricultural soils. Because of the large-scale groundwater flow pattern, any leakage of nitrate will be contained within the cone of depression formed by extracting the groundwater. In such areas groundwater moves towards its outlet into drainage channels, streams and into surface waters. It is under these conditions that shallow wells will show high nitrate concentrations. To avoid these high concentrations drilling new wells of sufficient depth lessens the cone of depression that prevents inflow of surface water. In hard rock areas these demands may be difficult to meet unless wells are localised to deep fracture zones.

Ammonia in shallow wells is usually an indication of poor well construction, allowing surface water free access to the well. Ammonia in groundwater is rare since the ammonium ion is strongly adsorbed on clay mineral surfaces and therefore does not frequently occur in soil solution.

Effects of forestry

In modern forestry, trees are felled at a mature state and stem-wood is removed at the felling site. Stumps, branches and twigs are left behind to decompose. The first process is therefore decomposition of these remnants, which brings back at best half of the amount of base cations accumulated in the trees during their growth. Decomposition temporarily increases the content of organic matter and the resulting nitrogen may be retained in organic compounds. However, because of the increased access to air and heat the decomposition rate of accumulated organic matter will tend to decrease the total store of organic matter, thereby releasing nitrogen as nitrate.

At the start of replanting the ground is well prepared for undergrowth, which also brings about a prolific assembly of grasses and herbs. These will usually use up some of the nitrogen storage but it appears that nitrification can cause at least a temporary loss of nitrate to groundwater. While the newly planted trees develop the undervegetation will return to its original composition.

In groundwater discharge areas clear felling will cause a rise in the groundwater level, i.e. the discharge area expands because evapotranspiration decreases. On margins towards bogs the increase in groundwater level will favour the growth of mosses, which in turn decreases the evapotranspiration. The raised groundwater table will also create reducing conditions in that part of the soil profile that had an earlier accumulation of ferric oxide. A reduction of iron into ferrous iron then takes place. Shallow groundwater with high iron concentration appears. The only way to avoid such a state is to drain the discharge areas to root depth.

Forestry does not seem to influence the groundwater within recharge areas aside from a few years after clear felling, when a temporary decrease may take place because of decreased evapotranspiration.

Road nets, mining and waste disposal

In some parts of the Baltic region waste salts from salt mines are used to melt the ice from roads during winter. Considerable amounts are spread and these affect the soil water close to the road. Where the roads pass recharge areas the chloride is added to the groundwater storage. In discharge areas the chloride is washed into the surface water without affecting the underlying upflowing groundwater. No adverse effects on groundwater quality are expected.

Mining is frequently combined with enrichment plants for sulphide. The residue, usually nearly-pure quartzite, is used as landfills in valleys, essentially in groundwater discharge areas. The lost chemicals will appear in the surface waters that drain the site. Wastes from salt mines are usually dumped into rivers. No harm to groundwater is expected unless water extracted close to the river induces recharge from the river.

Municipal waste disposal sites are usually situated in groundwater discharge areas. In this way the leakage ends up in surface waters. Treatment plants for leakage may be necessary.

Accidental release

Road accidents involving transport vehicles may trigger off the release of petrol products and other chemical substances, some of which may be poisonous. The standard procedure when such accidents occur is to remove the soil that has been soaked by the product and bring it to waste disposal sites where the leaching can be controlled.

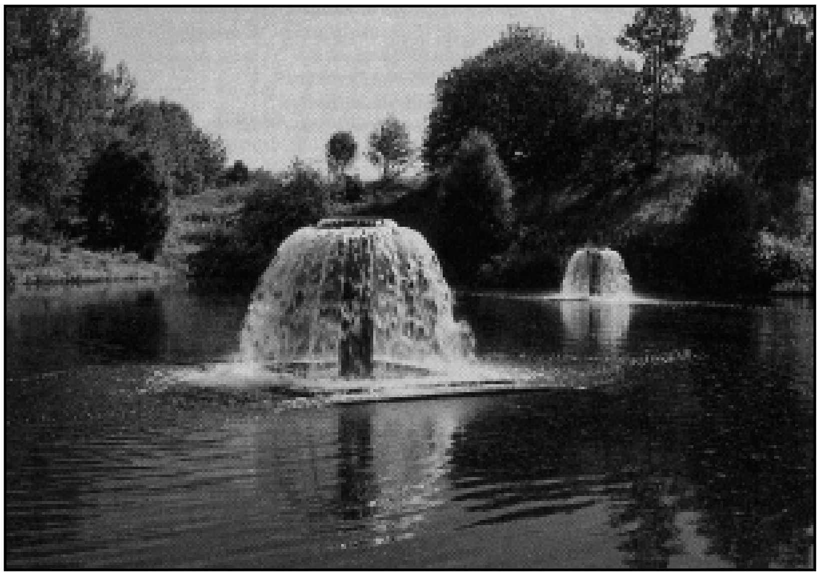
Underground oil reservoirs appear to have a limited lifetime and at present a program for checking petrol stations is in operation in Sweden. Here, too, the affected soil has to be removed. If the petrol stations are situated on groundwater recharge areas then such leaks may damage the groundwater storage. When the stations are situated on discharge areas the groundwater will be only slightly affected.

Pesticides

Matthess & Isenbeck (1987) proposed a classification of chemicals used for plant protection in agriculture, arranged according to the type of pest considered. These categories are: herbicides, insecticides, nematicides, acaricides, molluscicides, rodenticides, fungicides and bactericides. Groundwater contamination is likely to occur from:

- *herbicides* where the active substances are triacines, urea derivates and phenoxycarbon acids,
- *insecticides* with chlorinated or brominated hydrocarbons, carbamates and organic phosphorous derivatives
- *nematicides,* with chlorinated or brominated hydrocarbons, carbamates and organic derivatives.

Some of the substances are salts and therefore soluble. Others have polar character and are also easily soluble in water. A third group has non-polar properties and has a very low solubility in water. They are, however, adsorbed by organic matter in the soil. There is a fair amount of data on the chemical properties of pesticides, which makes it possible to estimate their fate in soils. In addition they degrade in soil at known rates. An excellent account of this is given by Matthess & Isenbeck (1987).



15.2 Infiltration of water from Fyris River on the top of Uppsala esker at Stora Vallskog near Uppsala city (courtesy of Uppsala municipality, 1999).

Provision of drinking water

Aquifers in use are designed for a yearly maximum extraction rate based on the aquifer data obtained at the time of construction. However, there is always an increase in demand for water because of increased standard of living and increasing population. Soon the demand will exceed the permissible water extraction rate of the aquifer. Transfer of water from more distant aquifers is always costly when long pipelines are required. It is therefore appealing to use nearby surface water sources, provided the water quality is unaffected. Natural conditions usually differ from place to place and a general recommendation of how to tackle the problem is therefore not feasible. There are, however, some situations that can be discussed in general terms, such as the following cases involving open aquifers:

- Infiltration through river banks
- Infiltration from nearby lakes
- Infiltration in special wells to which water is piped
- Infiltration through specially constructed ponds to which surface water is piped

Bank infiltration

Bank infiltration solution is well suited to rivers that cut deeply into fairly coarse deposits, e.g. glacial sorted coarse sediments recharged by local rainfall. If the bottom of the aquifer is well below the riverbed, an increase in the depth of production wells should be made, lowering the groundwater surface so as to permit a natural recharge from the river. Since water passes through sediments it will be filtered before extraction. Some change in water quality may take place but can be predicted from a minor pre-study if necessary information is lacking.

Infiltration from nearby lakes

Infiltration from nearby lakes is a somewhat similar situation to the previous case. Good knowledge of the aquifer is required, since distances to the surface water source may vary and the hydraulic conductivity may be critical. Infiltration from a lake takes place along the wave-eroded part of the shore down to a particular depth depending on the size of the lake, perhaps just a few metres. The bottom under the wave-eroded part is usually clogged by fine sediments and will resist water flow. The groundwater table must be well below the level of the lake surface. Filtering the water is usually sufficient, unless the lake water contains high concentrations of fine sediments.

Infiltration in special wells

If surface water is available but the situation does not permit direct infiltration into the aquifer, lake water must be piped to special wells fitted with screens for particle removal which otherwise could clog the well. If the water contains suspended sediments it may be necessary to let the water pass through a sedimentation tank. This is a fairly common method to increase the capacity of a reservoir.

CASE STUDY:

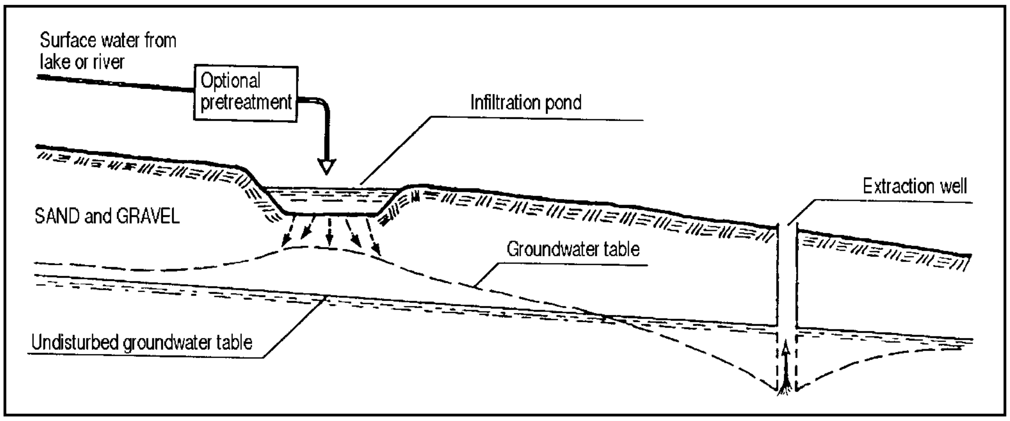
RECHARGE FROM SPECIALLY CONSTRUCTED PONDS IN THE UPPSALA WATER SUPPLY

Special precautions must be taken to prevent the entry of any harmful substance when suspended sediment and organic matter contaminate the surface water source. A case from the aquifer for the city of Uppsala in Sweden may be described. The water is taken from the Fyris River just north of the city and is led upwards to a pond on top of the nearby esker from which water infiltrates into the unsaturated zone, about 15 m above the groundwater table. The river mainly flows through wide agricultural areas with heavy clay soils. Even at low flow rates the turbidity of the water is high and at high flow it takes on a yellowish-grey colour, being highly loaded with suspended matter. The infiltration pond was therefore constructed as a filter for the water, fitted with mechanical devices for the removal of the clogged part of the filter. The frame of the pond is made of concrete within which a sand layer rests on the esker. On top of this sand layer there is a layer of quarts sand. The surface of this sand is levelled by means of a trolley on a rail. The river water is entered slowly to prevent damage to the sand surface. When the surface area appears clogged the trolley is employed to remove about 1 mm of the quartz sand layer, after which the infiltration is continued. When nearly all the quartz sand has been used up a new layer of quartz sand is applied.

Water passing the sand layers then enters the unsaturated zone and flows downwards by the force of gravity. During the passage of this aerated zone microbes have had time to establish a zone where, at a few metres depth, the oxidation of the organic matter takes place. Below this zone there are no microbes or organic matter.

Simpler devices involving only surface pond infiltration are also used, particularly on eskers and where available freshwater is much less contaminated. If, however, the pond is part of the aquifer the oxidation of organic matter within the water may be slower, making the oxidation plume larger. For a pond in the unsaturated zone oxidation will be much more rapid. The advantage of infiltration through the unsaturated zone is a favourable oxidation environment, precipitating iron and manganese dissolved in the water.

Erik Eriksson



15.3 Scheme of artifical groundwater production with pond infiltration (Brandesten, 1983).

16.

HUMAN IMPACT IN LAKES LADOGA AND ONEGA

Nicolaj Filatov & Dmitry Pozdnjakov

Lake Ladoga

The largest glacier-formed lake in Europe and the sole source of fresh water for five million inhabitants of the city of St. Petersburg, Russia, Lake Ladoga (latitude 59-61 °N) was created some 12 000 years ago. It measures c. 220 km by c. 83 km with a water surface of c. 17 800 km^2. With average and minimum depths of 51 m and 230 m, respectively, Lake Ladoga encapsulates 900 km^3 of fresh water. The Lake Ladoga watershed extends over 100 km from north to south and about 600 km from east to west, with an areal extent of about 260 000 km^2 (Viljanen et al., 1996). The water renewal time of Lake Ladoga is 11 years, which indicates that the ecosystem is rather conservative (Petrova, 1990).

Morphologically and morphometrically, Lake Ladoga is inhomogeneous and can be subdivided into a northern and a southern region, each characterised by distinctive coastline and distinctive littoral and pelagic bottom relief. Northern Ladoga is deep, with a jagged coastline comprised of numerous long and narrow fjords. Bottom relief is markedly non-uniform with cleavages c. 150-200 m deep, neighboured by bottom elevations in the form of underwater hill chains that frequently rise over the surface and form more than 600 rocky islands in northern near-shore and pelagic lake areas. Southern Lake Ladoga is considerably less deep and the depth progressively diminishes southwards. The southern coastline is formed by a number of large open bays with depths of 5-10 m.

The Lake Ladoga watershed also displays well pronounced north-south differences: forests with a predominance of coniferous species densely cover the north-western, north-eastern and northern catchment areas while eastern and southern catchment areas are generally devoid of trees and often swampy, but also arable in many areas due to artificial drainage.

Lake Ladoga receives water from over 30 large rivers and is also host to smaller tributaries. Being seventy-four meters wide, however, the Neva River is Lake Ladoga's singular outlet. The Neva River provides passage for Lake Ladoga water to the Gulf of Finland and, ultimately, to the Baltic Sea. The annual discharge of the Neva River into the Gulf of Finland is 80 km^3 with an average discharge rate of 2 500 m^3/s.

The Lake Ladoga drainage basin belongs to the taiga subzone with its moderate climate, warm and moist summers and cold and cloudy winters (Anonymous, 1966). The thermo regulating effect of the lake has an impact on the annual air temperature dynamics, especially in transitional/ interseasonal periods. Thus, the mean air temperature in January on Valaam Island in the centre of the lake is 2.7 °C higher than that in the skerries area in the north. The mean air temperature in July over the lake pelagic region is 0.9 °C lower than that over the shore areas. The lowest annual air temperatures are recorded at the stations located on the eastern shoreline (+ 2.9 °C) while the highest occur on the southern shoreline (+ 3.8 °C). The average duration of the ice-free period for the Lake Ladoga area varies from 103 to 181 days, these variations being mainly due to the effect of latitude and local conditions.

The atmospheric processes common to most of north-western Russia affect the wind regime formation within the Lake Ladoga area. The distinguish-

Figure 16.1. Lake Ladoga map compiled by Patrik Steen.

ing feature of the Ladoga wind regime as compared with Lake Onega's is a relative homogeneity of the recurrence of wind direction. The dominant wind directions are south-western, southern and south-eastern. Western, north-western and northern winds are also frequent. The most rare are eastern winds. The difference in the recurrence between the dominant and the least frequent winds is only 2-3 fold.

According to the data available (Molchanov, 1946), cloudiness over Lake Ladoga is lower than that over the neighbouring areas. The mean annual value of total cloudiness over Lake Ladoga and the adjacent area is about 4 degrees. The probability of overcast skies in summer is 46-50 %, in spring and autumn, 65 %, and in winter up to 80 %. Mean annual total cloudiness is rather evenly distributed over the lake area but the difference between the cloudiness values from the offshore and shoreline stations is less than 0.3 degrees. The total cloudiness is an important factor affecting the amount of solar radiation reaching the underlying surface. With a total cloudiness of 7 degrees, Lake Ladoga receives between 50 and 60 % of the total incident radiation. The data from meteorological stations on the Lake Ladoga shoreline as compared with stations a distance away from the lake show that the incoming solar radiation in the warm period increases due to lower cloudiness. Most of the total annual radiation (85-88 %) is supplied in spring and summer.

The characteristics of the ice cover on lakes and climatic parameters show a rather complicated correlation, e.g. ice thickness, and the time of ice break-up depends on a multitude of factors. In the case of Lakes Ladoga and Onega the ice-free period coincides with the changes of the air temperature, i.e. there is a certain correlation between the water temperature increase and the ice-covered area decrease.

When the southern part of Lake Ladoga begins to freeze up (December-January), the central part of the lake continues to cool down. In spring, ice melting proceeds in a south-north direction. The water in shallower areas warms up and cools down faster, hence freezing and ice break-up occur earlier in these areas.

Human impact on Lake Ladoga

Not including the five million inhabitants of St. Petersburg the human population within the catchment is slightly over one million people, with 75 % of them living in towns. Local industry is largely oriented towards paper and cellulose production as well as the production of wood-based chemical compounds and merchandise. More than ten large pulp mills are located along the Lake Ladoga coastline, with many other industrial enterprises located on the banks of the inflowing rivers. Local industry is also focused on processing raw materials for the production of aluminium, cement bricks and chemical fertilisers. Several decades ago a number of metallurgic and oil refineries and industrial machinery production plants were established, and industrial effluents are either being directly injected or carried as river discharge into the lake proper.

Local agriculture is mainly rural in nature, oriented towards supplying urban customers with milk and associated dairy products, poultry, beef and pork, processed meat, potatoes and vegetables. Consequently, a large number of cattle and poultry collective farms have been established in the strand area.

Being a large, deep and cold body of water, Lake Ladoga's trophic status was predetermined to be strictly oligotrophic. Actually, it persisted from the lake formation until the latter part of the 1960s, at which time the trophic state of the lake began changing in a manner that could not be attributable to environmental influences of purely natural processes. The lake has ultimately developed a stable mesotrophy with extensive seasonal water surface bloom events.

Until the early 1960s, the concentration of dissolved oxygen in the littoral area fluctuated from 9 to 15 mg/l (90-120 percent saturation). In 1968, water transparency, as measured with Secchi disk, was 3.5 m on an average. Concentrations of nutrients remained at low levels: total phosphorus was in the rage 1-15 mg/l, nitrate loading varied between 0.1 and 1.2 mg/l, and ammonium (NH4) content did not exceed a value of 0.24 mg/l.

However, in 1987-89, the mean phosphorus concentration in summertime increased up to 21 mg/l in the pelagic area and up to 32 mg/l in the littoral zone. In 1992-1993, the total phosphorus concentration ranged from 15 to 29 mg/l; spatial and temporal variations in the water quality distribution are very characteristic of the lake (Slepoukhina et al., 1996).

Prior to the onset of anthropogenic eutrophication, the phytoplankton community of Lake Ladoga encompassed over 380 species, subspecies, forms and varieties: 45.5 % *Bacillariophyta*, 33.2 % *Chlorophyta*, 20 % *Cyanophyta*, 3.7 % *Chrysophyta*, 1.0 % *Pyrrophyta*, 0.8 % *Xantophyta* and 0.8 % *Euglenophyta* (Petrova, 1990). This composition is appropriate to large temperate oligotrophic lakes.

However, beginning in the late 1970s, the algal biomass began to increase rapidly, attaining values considerably surpassing those registered in the early 1960s. The algal biomass upsurge came about concomitantly with serious alterations to the phytoplankton species composition. *Cyanophyta* and *Cryptophyta* seized the leadership in the summer phytoplankton. Concentrations of some algae

(*Diatoma elongatum* var., *Oscillatoria*, *Microcystis* and others) associated with eutrophic waters have dramatically increased. Conversely, once abundant *Attheya zachariasii*, *Rhizosolenia eriensis* var. *morsa* and *Dinobryon* spp. have nearly completely disappeared (Petrova, 1990). The annual primary productivity in Lake Ladoga exhibited a spectacular increase from about 15 g C/m^2 in 1976 to ~140 g C/m^2 in 1985 (Petrova & Torzhevik, 1987). The areal distribution of primary productivity in the lake acquires features a pronounced inhomogeneity: coastal waters qualify as mesotrophic and even eutrophic types, whereas pelagic areas are still oligo-mesotrophic. Extensive blooms of blue-green algae have been observed in late summer throughout the whole lake area. However, in the late 1980s, the algal maximum biomass decreased again, reaching only half of that registered in the 1970s. This observation, along with others, prompted a conclusion that the lake trophy dynamics were experiencing variations, which could be categorised as stages in the lake's newest historical development. Four phases were identified (Petrova & Torzhevik, 1992), as follows.

Four stages of human impact

The first phase covers a period of five years from 1976 till 1980. It is characterised by high phosphorus concentrations in Lake Ladoga (26 mg P/l, on the average) resulting from strong phosphorus injections into the lake, which have been taking place during the late 1960s and early 1970s. That was a period of an exponential rise of all quantitative indicators of the phytoplankton community, as well as a period when algae taxa characteristic of eutrophic water bodies became predominant in the phytoplankton assemblage. At the end of 1980, the floristic diversity (about 8-9 dominants) of phytoplankton in Lake Ladoga attained its peak while the productivity rates became largely stable. Decomposition processes developed and the bacterioplankton counts increased in both epilimnion and hypolimnion. For the first time, algal fungi in the littoral zone were reported to attain very high counts in succession of the phytoplankton vernal peak in the area of warm stratified waters. This stage was marked by a rapid accumulation of organic matter (primarily as detritus) in the lake. However, no alterations to the oxygen regime in the lake were registered at that time.

The second phase (1981-1983) is characterised by a considerable decrease in the total phosphorus concentration (down to 23mg P/l). The phytoplankton productivity became unprecedently (since the late 1960s) stable throughout the vegetation seasons. Decomposition processes gained acceleration: bacterial decomposition rates exceeded by 3-3.5 times the rates of primary productivity, which was conducive to a considerable decrease in suspended and dissolved organic matter abundance in the lake. However, at the end of 1983 the interannual fluctuations in dissolved organic matter content were substantially diminished.

During the third phase (1984-1986), the total phosphorus concentration continuously decreased (down to 22mg P/l). The phytoplankton community displayed serious changes: oligotrophic forms began regaining their dominant role in the pelagic areas. The concentration of dissolved organic matter still remain at a level of 9.5-9.8 mg/l. Plots of kinetic biochemical oxygen demand (BOD) have transformed from exponential to linear, and BOD levels crawled lower and lower. The oxygen regime in the lake, for the first time, exhibited a lack of balance. Dissolved organic matter levels in near bottom waters only reached 70-90 %.

At the fourth stage (1986-1989), the total phosphorus concentration dropped down to 21 mg P/l. Oligotrophic phytoplankton in pelagic areas became steadily predominant, although productivity levels in the lake remained very high. Bacterial decomposition processes decreased, bringing about both a decrease in dissolved organic content in the water body and an accumulation of organic matter in sediments. Depletion of oxygen levels was recorded in samples from the entire area of the lake. The lake ecosystem found itself profoundly destabilised.

In the years that have passed since the 1980s, the Lake Ladoga ecosystem remains essentially unbalanced. Provoked by eutrophication, the critical status of the lake's ecology is further aggravated due to chemical pollution injections. According to Iofina & Petrova (1997), Cd, Cr, Hg, V, Pb and Ce produce a lethal effect on many planktonic and algal fungi taxa. Moreover, the toxicity due to for instance Hg or V suppresses blue-green algae dominance in the summer plankton. In response to increasing toxic impact, the primary productivity of algae decreases.

The lake Ladoga fauna

The indigenous zooplankton community in Lake Ladoga is spatially heterogeneous. Three different areas have been distinguished among the zooplankton spatial distribution: the northern archipelago, the deep pelagic zone and the southern shallow area constituting the Volkhov River Bay. These areas are found to be specific not only in terms of zooplankton community features but also in terms of hydrophysical and water quality parameters. The pelagic zone and deep archipelago zooplankton exhibited remarkable stability throughout the entire monitoring period, which was from 1948-1997. The biomass of zooplankton remains at low levels and no definite trends are yet noticeable in its time series variations. *Copepoda* have been prevalent in the zooplankton community during the observation period, which is pertinent to low productive (oligotrophic) water bodies (Slepoukhina et al., 1997). However, the coastal region, with the highest water temperatures and the highest nutritional levels, displays various degrees of eutrophication (from mesotrophic to eutrophic) evidenced by appropriate changes in zooplankton species composition and associations productivity (Andronikova, 1996a; b).

At least 385 species and forms of bottom-residing macro invertebrates were identified in zoobenthos from Lake Ladoga in the 1950s and 1960s; about 85 % of these species were collected within the littoral area. Since that time on, no serious changes have been registered in the zoobenthos community parameters. The species composition of macro benthos and the low levels of its biomass (the average values are less than 3 g/m^3) still typify Lake Ladoga as an oligotrophic water body (Petrova & Torzhevik, 1992).

The fish fauna of Lake Ladoga in the beginning of this century was reportedly rich. Then, Lake Ladoga provided perfect habitat conditions for altogether 48 species and forms of fish (Kudersky et al., 1996). Of these, 25 species had commercial importance, with salmonids, coregonids and pikeperch being the most valuable. The construction of hydroelectric dams in the rivers, along with timber floating, extensive fishing and other factors, has drastically curbed the reproduction of some fish species. Atlantic sturgeon (*Acipenser sturio*) and Volkhov whitefish (*Coregonus lavaretus baeri*) became endangered species facing extinction. Due to irrational fishery methods, the fish catches in Lake Ladoga experienced serious fluctuations. However the measures undertaken in the early 1960s to control fishery resulted in a sensible increase in the total annual catch. Nonetheless they proved to be insufficient to conserving such noble species as salmon, *Salmo salar* L. m. *sebago*, brown trout, *Salmo trutta* L. and migratory whitefish stocks (Viljanen et al., 1996).

Since 1990, it has become evident that anthropogenic-related deterioration of the aquatic environment has resulted in a considerable decrease in the total fish catch. A worsening of habitat conditions has led to a decline in the whitefish stocks and, especially during the last few years, to a drastic decline in perch pike. Anoxia conditions in hypolimnetic waters affect fish as well as benthic populations. They bring with them a dramatic reduction of food availability for major fish species, leading to additional undermining of fish resources in Lake Ladoga.

Dedicated research indicates that extractable organic halogens and polychlorinated hydrocarbons as well as DDT accumulate in Lake Ladoga fish (Kostamo et al., 1997). At the same time heavy metal ions (Hg, Cd, Pb, Cu, Co, Cr, Zn, Mn, Al, V and Ce) are found in fish in quantities exceeding the relevant tolerable levels. As a consequence of the accumulation, many fish suffer from severe pathologies such as physical deformities, liver cirrhosis and brain diseases.

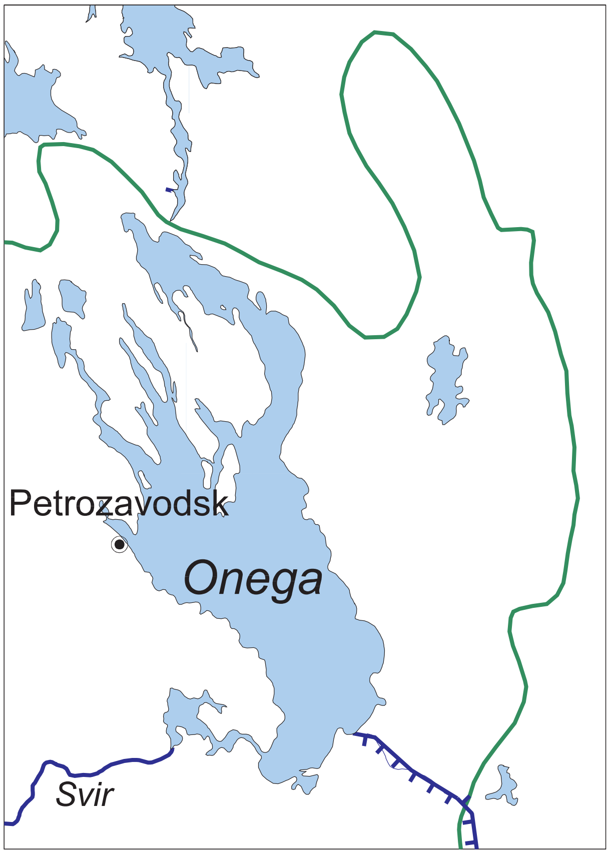


Figure 16.2. Lake Onega map compiled by Patrik Steen.

Lake Onega

Lake Onega is one of the great lakes of the world and the second largest freshwater body in Europe after Lake Ladoga (Molchanov, 1946). In its geographical position, Lake Onega is the superior of the GEL (Great European Lakes) system. It is located within the marginal zone of the Baltic crystalline shield where the shield borders the Russian plain (platform). The area of the lake is 9 900 km^2 while the water volume is 291 km^3. The greatest length of the lake is 290 km and the width 82 km. The mean depth is 30 m and maximum depth is about 120 m. The drainage basin is 66 200 km^2. Precipitation in the Onega Lake area is in the vicinity of 600 mm per year.

Climate

Lake Onega is notable for high cloudiness throughout the year. The clouds are generally rather evenly spread over the water area. No big differences are observed in the distribution of total and low altitude cloudiness in the centre of the lake and in the shoreline areas. The mean annual total cloudiness over Lake Onega is 7-8 degrees. The highest values of total and low altitude cloudiness throughout the year are recorded in autumn, with the maximum coming in November. The recurrence of overcast days (8-10 degrees) in this period reaches 83-88 %. Cloudiness decreases considerably from November to March and never exceeds 4 degrees for low altitude and 6.5 degrees for total cloudiness after March. Spatially, the degree of cloudiness is largest over the Petrozavodsk and Povenets Bays, except for November-December when the highest cloudiness is observed over the lake rather than over the shoreline. Petrozavodsk is a rather large industrial town (with a population of about 280 000) that produces fairly high aerosol concentrations conducive to a considerable rise in cloudiness over the area, and thus to a decrease in the incident solar radiation.

Latitudinal differences in the sunshine duration over the Lake Onega water area do not appear until April, while in December-March the index is almost the same for the northern and southern parts of the lake. The amount of solar radiation that can reach the underlying surface depends on both the geographical latitude and the specific features of atmospheric circulation processes. A large water body like Lake Onega transforms these processes, creating local circulation patterns that clearly express themselves near the shoreline through frequent changes of the wind direction. We have used the data from meteorological stations as well as satellite, ship and actinometric observations to characterise the specific features of this local atmospheric circulation. The local circulation demonstrated by the NOAA satellite images of Lake Onega can be seen quite clearly.

The thermal status of the lake and its seasonal fluctuations affect a number of meteorological processes. The characteristic features of the temperature regime in the Lake Onega area have developed due to the effect of its huge water volume. The air circulation and ambient environments also affect the formation of atmospheric precipitation over the lake proper and the adjacent territories. Prevalent throughout the year is the marine air coming from the Atlantic, which is responsible for high precipitation. The mean annual precipitation over Lake Onega is 524 mm.

Regarding the ice cover on Lake Onega, the number of ice-free days has been reduced from 225 to 217 during the period from 1880 to the present.

Long-term observations (over 40 years) of Lake Onega indicate that climate warming did not make a significant effect on the ecosystem condition, as was observed in small water bodies in Finland and Karelia (Virta, 1996). Climatic changes in the XXI century may cause considerable changes in the GEL ecosystems and speed up the eutrophication rates.

Chemistry and biology of Lake Onega

In addition to its large dimensions, Lake Onega is remarkable in the sense that it is one of the least mineralised inland water bodies on the planet. The concentration of dissolved salts in the lake is 39-46 mg/l. The mean concentration of nutrients amounts to 10-14 mg/l for phosphorus, 0.52-0.65 mg/l for nitrogen and 0.3-0.5 mg/l for silica. The dissolved oxygen concentration varies from 10.4 to 14.4 mg/l and is close to the relevant saturation level.

The Onega Lake phytoplanktons are comprised of more than 430 species: *Bacillariophyta* account for 35 %, *Cyanophyta* for 19 % and *Chlorophyta* and *Chrysophyta* for 7 % each. Diurnal primary production in springtime may reach 5-11mg C/l.

The lake periphyton encompasses more than 506 types of algae, the major constituents of which are *Bacillariophyta* (60%) and *Chlorophyta* (28%). The annual periphyton production is 0.7-0.8 g C/m^2.

There are 62 associations of Lake Onega higher plants. *Phragmites ausralis* account for ca. 62 % of the macrophyte stands area. *Nuphar lutea* is fairly abundant (6 %) for an oligotrophic lake. The total area of macrophyte stands is as high as 2 800 hectares, which is 0.24 % of the Lake Onega water surface. The macrophyte annual production is 2 800 tons.

The limnic heterogeneity of the lake affects the spatial distribution of bacterioplankton. The mean concentration of bacterioplankton is approximately $0.1\text{-}0.3 \cdot 10^3$ cells/ml and the production levels are found at 0.05-0.2 mg C/l.

The protozoan plankton indigenous to Lake Onega comprises 130 types of organisms. Despite their small sizes, the protozoan plankton plays a very important role in cycling the matter of Lake Onega. The protozoan plankton productivity is distributed nonuniformly throughout the lake: in the open parts the mean monthly biomass in June-October is as low as 0.01-0.04 g/m^3, whereas in July it is 0.05-0.092 g/m^3, which is still characteristic of an oligotrophic water body. In bays (which are almost invariably subjected to anthropogenic eutrophication) the production levels are 3-4 times higher.

The Lake Onega zooplankton community encompasses 202 species including 90 crustaceous species and 112 rotifers. The production of prey and predatory zooplankton in the littoral zone over the summer period comes to about 56.2 g/m^2 and 14.9 g/m^2, respectively. In the pelagic zone the prey and predatory zooplankton production is 19.3 and 3.4 g/m^2, respectively.

Bottom biotopes are composed of 530 types and forms of invertebrates, of which about 80 % are mainly restricted to the lake littoral zone. The dominant group is comprised of oligochaetes. The pelagic zone silt habitats accommodate assemblages of relict crustaceous species (*Gammaracanthus loricatus* Sars, *Pontoporeia affinis* Lindst., *Pallasea quadrispinosa* Sars, *Mysis oculata* var. *relicta* Loven).

Eutrophication

With the exception of shallow small bays, Lake Onega was originally oligotrophic. However, during the last decades, the industrial and agricultural impact resulted in a substantial violation of the initial trophic status of this water body. The first pronounced changes brought about by eutrophication were reported back in the 60s in the Kondopoga and Petrozavodsk Bays. Since that time on, the eutrophication process has been spreading further towards the pelagic zone. Presently, except for the central region, the entire lake is consumed to one extent or another by anthropogenic eutrophication due to the impact of navigation, river discharge, runoff, industrial effluents, etc. Recent studies indicate that even in the pelagic part of the lake, there are changes indicative of anthropogenic eutrophication. These changes are as yet still moderate, leaving the lake status within the margins of oligotrophy. These changes are primarily confined to a stable quantitative increase in benthic community parameters; during the last decade the benthos counts increased three-fold.

Bacterioplankton concentration is presently assessed at 0.4-0.7·10^6 cells/ml, as against 0.2·10^6 cells/ml reported in the 1960s. There are also alterations to the zooplankton community: the rotifers counts have gone up significantly. In 1964-1967, the rotifers accounted for 3 % of the benthic biomass, in 1989-1993 their proportion increased up to 60 % and in 1995 up to 80 %. The concentration of *Asplanchna priodonta*, which is a good indicator of trophy, increased from 130-900 organisms per m^3 to 2 800-6 400 organisms per m^3 over the last 35-40 years.

As was pointed out above, the most significant alterations to the hydrobiological status took place in large bays of Lake Ladoga. The structural reconstruction of plankton communities displays a reduction of biodiversity and changes in the ratios of major systematic groups. In the lake phytocoenosis, blue-greens, chlorococcus and *Tribonema affine* become abundant. Eutrophication alterations to the lake food-chain also brought about changes in the zoocoenosis status: the number of calanoids diminished by comparison with *Cyclops* while the relative proportions of *Cladocera* and rotifers increased significantly. In the benthic community the role of oligochaetes becomes much more pronounced.

The bays become a secondary source of lake pollution. During periods of enhanced hydrodynamic activity in the lake, the eutrophic waters from the bays are transported to the lake's central regions. The most dangerous periods in this sense occur in spring and summer when the waters that have accumulated in bays during the winter stagnation period become involved in the full lake water-exchange process.

The ichthyofauna of Lake Onega is comprised of approximately 50 species of fish. The most important marketable species are shallow-water cisco and smelt. The fishery productivity of the lake is rather low, about 1 kg/ha, and the total annual catch is under 3 000 tons.

17.

PROTECTING WATER RESOURCES

Lars Rydén

Protection of water wesources in international documents

Human impact on water bodies is one of the most serious threats to the quality of human life. The next century is predicted to be critical for billions of people as to access to water resources in areas such as Africa, large parts of Asia and other arid and semiarid areas.

This situation is clearly reflected in the major international documents on development. Protection of water resources has a central place in worldwide efforts to achieve sustainable development. In Agenda 21 with its 40 chapters, both chapter 17 on "Protection of the oceans, all kinds of seas including enclosed and semi-enclosed seas and coastal areas..." and chapter 18 on "Protection of the quality and supply of freshwater resources ... " are about twice as long as any of the other chapters. Chapter 18 has seven programme areas of which one deals with protection of water resources, water quality and aquatic ecosystems. Here the following activities are listed:

- water resources protection and conservation
- water pollution prevention and control
- development and application of clean technology
- groundwater protection
- protection of aquatic ecosystems
- protection of freshwater living resources
- monitoring and surveillance of water resources and waters receiving wastes
- development of national and international legal instruments

Although the Baltic region is, in a global comparison, a favoured area, the Baltic Sea itself is unusually sensitive due to its slow water exchange, low salinity and shallow depth. It is also evident from the previous chapters that there are a large number of areas in the region where water bodies have been very severely polluted and where remedies and restoration efforts are still lacking.

The measures to protect water address weak points of water management of cities, industries and agriculture. Much of this will be covered in book 2 in this series, but some aspects will be summarised here. It is also important to stress that in fact practically all environmental pollutants sooner or later end up in water – directly as air pollutants that precipitate or indirectly as leakage from waste dumps or just any land surface. Protecting water is thus a very comprehensive activity. In the long term it will require that we develop a non-polluting society.

The background – all pollutants ultimately end up in water

The awareness of the need to systematically protect water resources is of rather recent origin. Large-scale and severe impact on waters is a consequence of increased urbanisation and intensified land use in agriculture and forestry as well as the use of water as a carrier for waste, especially toilet waste, and industrial effluents.

A major part of water pollution is caused by point sources, especially cities and industries. Before sewage systems were introduced in urban areas, toilet- and other wastewater from households was led directly to the closest watercourse, as well as waste from smaller or sometimes larger industries. Obviously this water then became inadequate for human use or consumption and had a negative impact on the aquatic ecosystems. The impact on the freshwater used by the city and its inhabitants might also be dramatic if there was a connection to the sewage.

> *The widespread scarcity, gradual destruction and aggravated pollution of freshwater resources in many world regions, along with the progressive encroachment of incompatible activities, demand integrated water resources planning and management. Such integration must cover all types of interrelated freshwater bodies, including both surface water and groundwater, and duly consider water quantity and quality aspects.*
>
> (From Agenda 21, Chapter 18, Protection of the quality and supply of freshwater resources.)

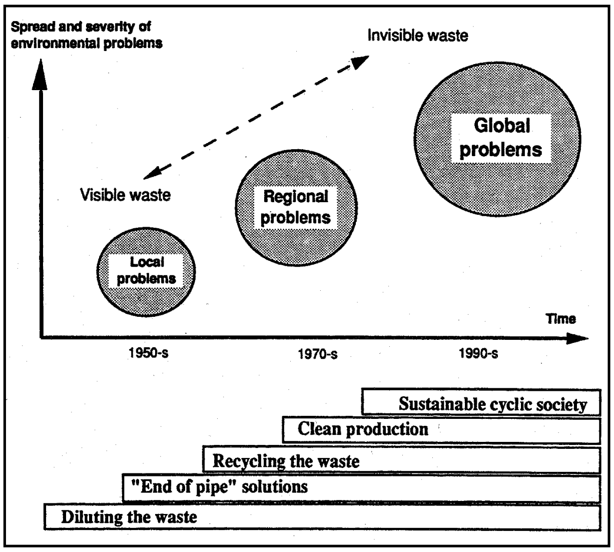


Figure 17.1. Development of environmental problems from the 1950s to today, and countermeasures (Tiberg, 1992).

This was made very clear during a classical study in London during a cholera epidemic in 1859. This was one of several similar events in larger cities, another being the cholera epidemic in St Petersburg in 1996. In all these cases water became the carrier of disease. Today this is still a major threat to human, especially child, health in the developing world.

The construction of sewage systems to lead wastewater to surface water bodies far away from the city and its intake of water has since developed on a larger scale during the first decades of the 20th century. But it was not until the damaging impact on the recipients became all too evident that the importance of treating the wastewater before letting it out was developed. Building wastewater treatment plants started on a larger scale in the market economies of the 1950s and is still going on. But it was not until the present that this has become important in many parts in Central and Eastern Europe. In addition treatment technologies are being developed and being made more sophisticated, which is reflected in an ongoing rebuilding and extension of the treatment plants.

The non-point sources are less straightforward to address. Leakage of nutrients from agricultural land and forestry areas is one such diffuse source that has been a major threat to the Baltic Sea itself, as evidenced by its eutrified status. There are several reasons for this. One is the increased use of inexpensive artificial fertilisers from the late 1950s up to today. More fertilisers are added to the crop than it can use and the surplus flows into surface waters. The manure of the animals, where a considerable part of the added nutrients are found, is too often just discarded or used in such as way that it spills into the water or evaporates as ammonia. An ongoing specialisation of land use, also starting around 1960 and resulting in whole areas concentrating on either crop or animal production, compounds this situation: an unbalanced nutrient budget resulting in diffuse pollution.

Car traffic represents another important diffuse source of pollution that ultimately ends up in surface water bodies. This was negligible up until the 1950s but has since increased several-fold. Combustion of fossil fuel gives rise to nitrogenous oxides, which are released with the exhaust gases. Similarly exhaust gases from industry and power plants, etc., give rise to air pollution that sooner or later reaches surface waters or land as precipitation or particles.

One might say in general that earlier pollution was local and hit the local water body. From the 1960s on it became regional with the eutrophication and acidification of water as the most typical components. Even later, in the 1980s, environmental damage reached the global scale with sizeable impacts on the earth's atmosphere when pollutants were travelling with large air streams to the polar regions or changed the global systems e.g. through global warming.

Surveillance and monitoring

Although many sources of pollution are obvious and should be addressed without delay, a more systematic approach requires access to reliable data. Data will be necessary for all kinds of environmental action, be it legal action or economic sanctions such as taxation measures. Most importantly they will be needed to trace the sources of environmental impact, understand its consequences on ecosystems and constructively address the causes of pollution.

It is the role of assessment and monitoring programmes to address this need. The Baltic Sea itself is in fact one of the best examples of the importance of such a programme. Monitoring of pelagic and benthic systems has been in operation in the Baltic Sea for more than 40 years. It started as and continues to be a research programme, although today government authorities are in charge of routine measurements. The programme has been of utmost importance for present improvements in the Baltic marine environment.

This programme has served as a model in organising several other monitoring programmes of regional sea basins. For example such a programme is now organised in the Gulf of Thailand. Other relevant action exists in many other regions, e.g. the Rhine River on the European continent and the Great Lakes district in North America.

Pollutants do not recognise national borders and a successful environmental programme must adapt to this fact. A monitoring programme should thus be international. In the Baltic Sea area this was recognised early through the creation of the Helcom convention in 1974. The secretariat, situated in Helsinki, has from its start co-ordinated the monitoring of all the participating countries. This co-operation improved dramatically after the political change and the adoption of a new and more far-reaching convention in 1992.

A monitoring programme should foremost develop a proper sampling strategy to ensure that analytical efforts provide meaningful and interpretable data. The chemicals to be measured should include not only toxic substances, such as heavy metals and organic pollutants, but also other substances that exist in amounts that are deleterious to the environment. In particular it is important to include nitrogen and phosphorus, which are the cause of eutrophication.

Environmental impact is caused by pollution of air, water, soil and food and all these sources need to be monitored. Samples should be taken not only in open air or water but from biological samples as well. Data on pollution of water thus needs to include an analysis of benthic long-living organisms and fish fauna. This will make it possible to look for substances hazardous to humans via food – in particular seafood and fish – and to set up databases for toxic substances found in different matrices such as sediments, organisms and water.

Biological monitoring also provides essential information on the ecological effects of pollutants. A search for specific toxicological endpoints in the flora and fauna as well as in the human population, such as ethnic minorities with specific food habits, needs to be conducted. In the Baltic Sea dramatic examples of this are the selective accumulation of PCB's in the grey seal and the specific effects of DDT's on birds of prey, or for that matter, radioactive caesium, which hit the Sámi population particularly hard due to their unusually large intake of reindeer meat.

Combating industrial pollution – the vision of the closed factory

When the damaging effects of the effluents and exhausts of industry became evident, not least in coastal areas and major rivers, the first measures to be implemented were at one time the end-of-pipe technologies. Industrial wastewater was then typically treated together with household wastewater. In other cases it was piped directly to the recipient without treatment, especially in cases of larger industries far from urban centres. These industries were typically pulp- and paper industries, forest industries, metallurgic industries and mines. Today many industries are required to build a local treatment plant.

A more recent and much more promising strategy is to change production technologies so that the wastewater does not contain environmentally harmful substances. A clear example is how the pulp factories found ways to remove chlorine gas as a bleaching substance in the 1980s and 1990s. This focus on technologies – pollution prevention as source prevention – is the recommended approach in several documents, including Agenda 21.

Industrial pollutants however also reach water bodies via chimneys. Combustion of fossil fuel leads to enormous amounts of acid rain and eutrophication though production of nitrogen oxides. Also heavy metals and POP, persistent organic pollutants, are emitted along with the effluents or are exhausted with the flue gases and end up in the environment – and sooner or later in water bodies. Again pollution prevention involves cleaner production but also, especially for the heavy metals, end-of-pipe approaches, which may allow the recovery of the heavy metal and its recirculation to be a resource in the production plant.

A modern industrial plant is one where all the resources end up in the final product that leaves the factory and not as pollutants, to the benefit of the factory owner as well as the environment. This is also reflected in the water use strategies of a modern industrial plant. Process water is recirculated in the factory, which environmentally becomes an almost closed entity.

But this is not enough. A major route for pollutants from factory to environment is through the consumer. Consumer products may even be designed for diffusion in the environment, e.g. lead in leaded gasoline or in bullets for hunting. Others may diffuse because of less careful handling, such as chemicals for gardening. Even when this does not apply, at some stage everything becomes obsolete and turns to solid waste. Careful management of solid waste is thus an important and integrated part of a non-polluting society, just as is careful consumption and a lifestyle on the part of the general consumer that is not damaging to the environment.

Agricultural pollution – the challenge of nutrient recycling

Agricultural impact on waters is connected to nutrients, nitrogen and phosphorus salts, and to a smaller and diminishing extent, pesticides. Nutrient leakage became prevalent with the use of artificial fertiliser from the 1960s and later became cheap enough to allow considerable overuse and thus industrialised large-scale agriculture developed. Although some measures have been taken to reduce nutrient leakage it is essentially a problem that has not been addressed properly. Nutrient leakage is still occurring and is a major threat to surface waters in the region, most importantly the Baltic Sea itself. To change this efficiently is a far-reaching challenge to our society.

The remedies to nutrient leakage comprise rather demanding requirements and in fact will in the end lead to a completely new approach to nutrient management. Obviously a more precise assessment of how much fertiliser should be applied is one such approach, which makes sense since the surplus only represents an additional cost and environmental load. This is not especially difficult with artificial fertilisers but much more so with manure. Another strategy is to combat leakage though so-called buffer strips – a few meters of green zones between the fields and the water – and winter crops that will take up both nitrogen and phosphorous in plants that are to be harvested. Finally a larger share of wetlands in the drainage basin and naturally flowing rivers and streams will improve the capacity of self-treatment, in particular denitrification, and thus diminish the concentration of nutrients in the water that reaches the recipients, in particular the Baltic Sea itself.

The imbalances of industrialised agriculture on a regional scale are at present only partly addressed by legal requirements. There are thus limits to the number of animals allowed on a specified area. In the long term the need would be for crop and animal production to be matched: fodder for animals should be produced in the sub-drainage basin where the animals are, and the manure from the animals should be used on the fields where this fodder is grown. Even more so, when animals are slaughtered, the remnants should be composted and used on the farm where they grew up. And finally, sludge from wastewater treatment in the urban centres where the meat is eaten should end up on the fields where the fodder once grew. The requirement of nutrient recycling to protect waters from eutrophication is thus a challenge to our present way of running a large-scale society.

The dilemma of the downstreamers

Polluted water provides an especially clear illustration to the fact that pollution spreads to other people than those who caused it. The phrase “dilemma of the downstreamers” is meant to show that all those affected by a pollutant are in a way downstreamers, not only those actually living downstream a polluted water course, but also those hit by pollutants brought to them by other elements than water.

The situation of the downstreamers prompts us to formulate a number of very fundamental questions: who owns the environment, the water, the soil and the air? Who is responsible for the environment, especially to protect it? Who has the right to utilise – sometimes exploit – the environment and its water, soil and air?

If these questions are difficult in just one community, then it is even more so in an international context, e.g. when a river flows from one country into another.

The answers to date have focused on legal measures, economy and – sometimes, but too seldom – ethics.

Recently, the “polluters-pay” principle has gained in acceptance on the legal arena. Although the principle appears clear, its implementation is not. So far it has been used mostly for raising the requirements of those whose activities are obvious sources of pollutants that are damaging to others. In some, not many, cases there have been clear economic consequences for the polluter. But strictly speaking the principle requires that we have a reasonable grip on the damages caused by a pollutant and the economic consequences of such effects. Today such data exist in only a few cases, one being the costs caused by damages of sulphur dioxide, i.e. acid rain. But here it is very difficult to point to the responsible source of pollution. In fact even when this is possible not much is done. The efforts to find the culprits when it comes to pollution are far weaker than those taken to find the offenders of parking regulations. A case in point are the ship captains who prefer to clean their oil tanks in the middle of the Baltic Sea. They are never charged for their crimes: not by the oil-killed birds, nor by those who expect to swim on a clean and beautiful beach or by those who planned to go fishing. Instead the society uses paid employees and many volunteers to clean up the birds and beaches. For the major threat to the Baltic Sea, eutrophication, the principle that polluters pay is of no relevance and so it is for most polluted waters.

There is, however, some room for optimism when it comes to environmental responsibility. Several of the environmental disasters concerning international waters have led to constructive co-operation rather than conflict. The commissions set up between several countries to protect transboundary rivers are in many cases very efficiently working organisations. The very old Rhine Commission had its moment of test when some 15 years ago a large chemical industry in upstream Switzerland made a major chemical release into the river, which killed fish all the way to the Netherlands. A major programme was set up to combat the pollutant and prevent a repeat. In the Baltic region the Odra Commission was formed in the early 90s between Germany, Poland and the Czech Republic. Other challenges for international co-operation are the Lake Peipus drainage basin where Russia and Estonia have already started co-operation, the Daugava-Dvina River where Russia, Belarus and Latvia are the partners, and lastly co-operation on the Nemunas which flows from Belarus to Lithuania into the Baltic Sea.

Conclusions

Efficient protection of freshwater resources is a major challenge to our societies on all levels: technically, legally, economically and politically. Although most of this remains to be addressed, the problems are now recognised and partly defined. The importance of this challenge is gaining acceptance in our societies and much more far reaching measures than those presently being implemented will probably obtain political acceptance. Proper water management, leading both to sufficient and environmentally clean water resources, is closely linked to the development of sustainable societies and is a long-term process. Increased knowledge, understanding and skills are first steps in this important process.

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