Collaborative Paper

REVIEW AND EVALUATION OF RESEARCH ON THE EUTROPHICATION OF LAKE BALATON
--A Background Report for Modeling

Gerrit van Straten
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PREFACE

A consistent management of the cultural eutrophication of lakes requires systematic analysis based on the joint and coordinated effort of a variety of disciplines. This notion led the Hungarian Academy of Sciences to the foundation of the Coordinating Council for the Environmental Research on Lake Balaton, as an answer to the growing concern about the slow deterioration of the water quality of the lake, one of the primary touristic resorts of Hungary. The same idea made IIASA's Resources and Environment Area adopt the problem of eutrophication of waterbodies as one of its study objects. Mutual contacts awoke mutual interest in each others work, and in April 1978 IIASA and the Coordinating Council signed an Agreement to establish cooperative links aimed at the further development of ecological models and their practical application in the case of Lake Balaton. For IIASA the existing data and research material promised to be an excellent basis for a case study, that could help to realize the objectives of the REN Area Task on Models for Environmental Management and Control. For the Hungarian partner, the cooperation gave access to IIASA's international scientific network and the ready availability of IIASA's computer facilities was also highly appreciated.

From the outset of the collaboration, a principal concern of the partners was the collection of the relevant data. In performing this activity it appeared that a broadening of the spectrum of research covered by the Hungarian partner was desirable. A solution was found in the formation of a subcommittee of the Hungarian Bureau of Systems Analysis for the Environmental Research of the Balaton in January 1979. Apart from the representation of the Computer and Automation Institute (MTA SZTAKI) and the Biological Research Institute (MTA BKI) of the first initiator, the Hungarian Academy of

Sciences (MTA), the official involvement of the National Water Authority (OVH) and its Research Institute for Water Resources Development (VITUKI) could be welcomed. Now, a rapid disclosure of the vital data followed soon after, thus enabling the set up of the IIASA computer data base, appended to this report in a graphical form. The realization of this data base, though not complete yet, is one of the first concrete achievements of the collaborative project.

The publication of this background report can perhaps be seen as the second major achievement of the cooperation. An overview and appraisal of relevant research and data material on Lake Balaton as presented in this report is of paramount importance for a comprehensive modeling effort, and it can only be said that it has been lacking for too long a time. The authors are aware of the fact that there may be different interpretations than their own, and they are, therefore, open to criticism that could improve the picture of the problem of the eutrophication of the Balaton.

The authors wish to express the hope that this report will be a stimulus for further ecological modeling research, in the interest of the international community, but even more so, in the interest of the actual protection of the "Hungarian Sea" itself.

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SUMMARY AND CONCLUSIONS

1. Typical characteristic features of Lake Balaton (surface area 596 km^2, watershed area 5180 km^2, length 77.9 km, width 7.7 km) are

   -- the shallowness (average depth 3.14 m); wind induced currents and waves cause a steady exchange between water and sediment. The lake water is rich in suspended particulate matter

   -- the relatively high summer temperature (24 C), and the nearly two month ice cover in winter

   -- the high amount of calciumbicarbonate and the high pH (8.3-8.7)

   -- the mostly agricultural watershed.

2. The long shaped form of the Lake, with the principle inlet (Zala River) on one end, and the only outlet (Sio-canal) on the other end, prompts to the segmentation of the lake into four consecutive throughflow basins. On a yearly basis the total inflow (957 mm) balances the evaporation losses (916 mm), whereas the outflow (671 mm) is about equal to the precipitation (628 mm).

   The renewal time of the four basins is 1 year for the Keszthely, 4 years for the Szigliget, 6 years for the Szemes and 9 years for the Siófok region.

3. Since 50% of the total inflow is concentrated in the Keszthely Bay there is a marked longitudinal gradient for most water quality variables. The effects of longitudinal mixing by wind are uncertain, but the mixing is not sufficient to destroy the longitudinal gradient.

4. The water quality of the lake is deteriorating, as is apparent from the rise in algal biomass and the rise in primary production, among others, in the last decade. The effects are most pronounced in the Keszthely region, but there is a danger of propagation towards the still less affected end of the lake. The primary production in the Keszthely Bay can be as high as 830 gC/m^2 yr (a hypertrophic value).

5. Open water phytoplankton is the most important primary producer (95% of surface is open water, 3% reeds, 2% submerged macrophytes). Usually there are two peaks of algae: diatoms in spring and a mixed phytoplankton dominated by Ceratium hirundinella in summer. In the Keszthely and Szigliget Bay blue-green algae (mainly Aphanizomenon flos-aquae) have started to be dominant in summer.

6. The phytoplankton patterns show a high variability among the years, indicating that the system is sensitive to environmental factors, especially differences in nutrient loading. A factor of variability within a year is formed by the influence of wind on transparency. Under favorable conditions photoinhibition occurs at the surface, except in the Keszthely and Szigliget basins where selfshading prevents inhibiting light intensities.

7. The growth rate limiting nutrient is phosphorus. The ortho-phosphorus concentration is always low (except perhaps in winter), which may be partly due to the absorption capacity of calcium carbonate particles. During algal growth there is a considerable biogeneous lime precipitation, which may cause some phosphorus coprecipitation too.

8. The fraction of organic phosphorus in the water, mostly in dissolved form, is high, suggesting a rapid death process (perhaps partly because of the unusual high temperatures). Grazing by zooplankton is not very important. Bacteria have increased with increasing intensification of the biological cycle, and are mainly responsible for the mineralization of the detritus organic material (and the recycling of phosphorus).

9. Although the sediment is relatively poor in organic material (2% by dry weight), part of the mineralization takes place in the sediment (about 1/3). The sediment phosphorus is bound partly to organic material, and partly to calcium-carbonate, whereas iron compounds seem to play a role in the binding of phosphorus too. Benthic algae developing under ice cover may be instrumental in mobilizing part of the phosphorus from the sediment in winter.

10. The oxygen condition is usually favorable (indicated also by the absence of ammonia). Occasionally anaeroby at the bottom has been observed during microstratification

in the Keszthely and Szigliget basin. Such conditions are undesirable and dangerous because phosphorus is easily released from anaerobic sediments. For this reason a further increase of nutrient loadings (leading to the internal production of oxygen consuming material), as well as organic waste discharges, should be prevented.

11. Because of the dominant role of phosphorus, increased loading of phosphorus must be held responsible for the deteriorating water quality. Some 50-70% of the ortho-phosphorus load is associated with sewage, a regular source throughout the years (though somewhat higher in summer). Particulate phosphorus loads are mainly associated with run-off, and highly fluctuating in time, since most of it (up to 80% of the total) is released during flood events.

12. The annual total phosphorus load to the lake is estimated to range between 700 and 1600 kg P/day, of which roughly 430-860 kg P/day is likely to be readily available for algal growth.

13. From surface area and slope conditions the longitudinal distribution of non-point (particulate P) load can be estimated as 1 : 1 : 0.45 : 0.3 from Keszthely to Siófok. The longitudinal distribution of direct and indirect sewage load (mainly ortho-phosphate) is roughly 1 : 0.4 : 0.4 : 0.65.

14. A very important source of available phosphorus is sewage water (about 45% of the total), and the further development of sewerage systems in the Balaton region will even increase the significance of this source. Therefore, (tertiary) treatment of sewage should be given high priority, the more so since rapid installment is possible and the effectiveness-cost ratio is favorable.

15. Other significant sources are live-stock breeding (liquid manure) and run-off (45% of the total phosphorus load). The application of fertilizer should be carefully controlled especially on the steep slopes close to the lake (vineyards).

16. The development of mathematical models should be encouraged as a guideline for research and data collection, and, eventually, as a powerful tool in the evaluation of the various management options of the future.

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1. INTRODUCTION

Lake Balaton lies at the foot of the Bakony hills in Trans-Danubian Hungary. With its nearly 600 km^2 surface area it is the largest lake in central Europe. The long-shaped, shallow lake is about 75 km long, 8 km wide and on the average 3 m deep. It is almost cut in two by the hilly peninsula of Tihany, where it is less than two kilometers broad. It is here that the lake reaches its largest depth of 11 m. Figure 1 shows The Balaton catchment area and its river system. By far the largest tributory is the Zala River at the south-western extremity. The lake's only outlet is at the Siofok outlet sluice in the far eastern end. Due to its shallowness the lake water temperature rises quickly to more than 20 C in summer, whereas the lake is usually covered by ice during the winter months.

Its nice summer climate, the fine scenery of the surrounding landscape and its good water quality make Lake Balaton a very attractive tourist resort, not only for the Hungarian population but also for many visitors from abroad. For this reason the Balaton Region forms a notable factor in the economy of Hungary.

In recent years scientists working in the field have observed certain changes in the water quality of the lake. Although not apparent yet for the modal visitor, there are clear signs of eutrophication, which form a serious threat for the present day's excellent suitability of the lake water for all possible forms of water related recreation. Scientists and those in charge of the management have recognized the danger, and it is realized that a comprehensive scientific, legal, economic and organizational framework is needed to stop the process of eutrophication and to maintain the lake's favourable conditon.

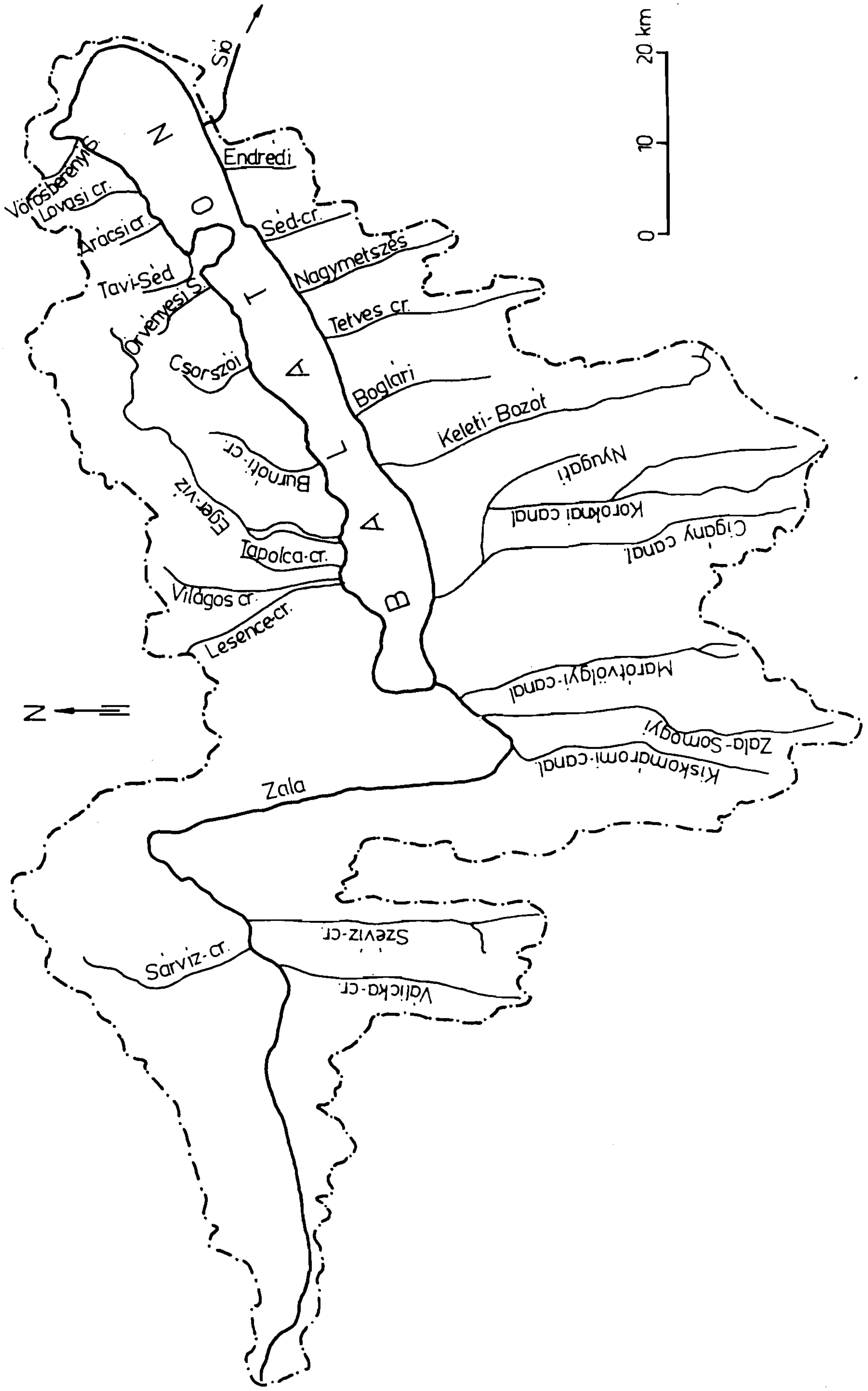


Figure 1. The catchment area and river system of Lake Balaton.

In this context the role of science would be to explore the causes of the water quality deterioration, and to develop tools which could help in the planning and selection of management alternatives. Since the process of eutrophication is extremely complex, both with respect to the processes in the watershed, as well as to the response of the ecosystem of the lake to changes in pollution loads, a comprehensive approach synthesizing the knowledge of different disciplines, and studying the phenomena in their mutual dependency is required. Mathematical modeling is one such approach, and perhaps the only one that fulfills the listed requirements. It certainly is a powerful technique to investigate the present and past state of the complex system, to elucidate and discover black spots in our knowledge, thereby providing directions on where to focus our measurement efforts, and finally to help the planning of management strategies.

This report attempts to summarize that knowledge about Lake Balaton and its watershed that is needed for any successful modeling approach. Directed towards the eutrophication problem with this specific goal in mind the data material and results of specific research have sometimes been reevaluated, and opinions of individual research scientists modified there where it seemed appropriate.

We start the discussion with a chapter on general characteristics of the Balaton watershed, because the natural conditions and the activities of man in the watershed are defining the water quality state of any lake. Here we confine ourselves to a global discussion to give a first impression of the problem. The next chapter on hydrology and hydrometeorology deals with water transport processes. The way in which pollutants are conveyed through the system forms an indispensable framework for any water quality modeling. Also the outstanding role of wind action in a shallow lake such as Balaton is reviewed. Next the present and past state of the water quality is outlined in the chapter on eutrophication and water quality. The observations point towards increased nutrient loadings. Thus, possible sources of pollution are discussed and where possible quantified in the chapter on nutrient loadings, with the emphasis on phosphorus. This completes the overview of available knowledge. However, the necessity of different (sub)models and the modeling possibilities are also lightly touched upon as a rough framework for future activities. And finally, a brief outline is given in qualitative terms of the feasibility of possible management alternatives, because, after all, the lake can only be protected by concrete measures.

2. GENERAL CHARACTERISTICS OF THE BALATON BASIN

2.1 GEOLOGY AND TOPOGRAPHY

An impression of the present topographical conditions in the Balaton region is obtained from the altitude map presented in Figure 2. In the Pleistocene, wind, alluvial deposits and volcanic activities shaped the basin after the recession of a sea which formerly covered the whole Carpathian area. The tectonic rift in which Lake Balaton is situated has been formed towards the end of the glacial era.

The geological background is reflected in different ways in the three subwatershed regions. The basin of the Zala River in the west mainly consists of hilly "pannonian" alluvial land. The southern basin is dominated by low hills of sand and loess, but there are also marshlands, most of them drained to-day. In the valley bottoms closer to the lake large alluvial cones have been formed. Finally, the northern basin is characterized by higher hills composed of limestone and dolomite, which gives this region an entirely different character. Here also the remainders of volcanic activity are found in the form of the cones of Szentgyorgyhegy and Badacsony.

2.2 THE BALATON CATCHMENT AREA

The main geometrical data on the Balaton catchment area are summarized in Table I. A full list of the tributaries and their sub-watershed data are given in appendix A. About half of the land surface area is drained by the Zala River. Its average discharge rate at the mouth of 9 m^3/s constitutes roughly 50% of the total inflow. Other significant tributaries are the Kétöles-Arok (5-10%), the Tapolca (5-10%) and the Egerviz (0-5%), all discharging on the northern shore of the Szigliget bay, and the Nyugati-Övscatoran (10-15%), which drains the marshlands south of the Szigliget bay.

Figure 2. The relief conditions of the Balaton basin.

The marshlands surrounding the South-western part of the lake has been mostly reclamed during the last century. However, some wetlands still remained, and they play a significant role in both discharge and quality of the connected tributaries. The most important area is the so called Nagyberek (Great Grove), together with similar areas covering 114 km^2 between Baltonmariafürdö and Fonyód. These so called "Berek waters" (grove waters) are discharged into the lake via pumping stations through the Nyugati-Övcsatornan and two smaller creeks. Another area of similar character is the 185 km^2 large Fenékpuszta - swamp (close to Keszthely), discharging into the lake through the Zala river.

There is a total of 99 stagnant water bodies larger than 0.5 ha in the catehment area. These include 31 fishing ponds and 13 reservoirs, mainly for irrigation purposes.

The Balaton watershed is rich in groundwater, both of karstic and subsurface nature. Although many studies are dealing with the groundwater situation in the region, reliable data on the ground water level are available in the shoreline zone only. The water table generally slopes towards the lake. Medicinal and thermal sources are also found in the region. The Héviz Lake (near Keszthely) is the most important, with a daily rate of 62000 m^3 thermal water of 32 C.

Table I. Subwatershed catchment area and elevation difference (after Baranyi, 1975).

	Area (km^2)	Elevation difference (m)
Zala watershed	2622	340
Northern streams watersheds	820	47-711
Southern streams watersheds	1175	117-212
Direct shoreline watersheds	562	-
The lake	596	-
Total catchment	5775	

2.3 LAND USE AND SOIL EROSION

Erosion has played a significant part in the conditioning of the lake and its basin, and is an important factor also today (see Figure 3). Due to the geological and topographical differences the rate of soil loss is relatively high in the Northern and moderate in the Southern subwatershed. According to a study by Horváth and Kamarás (1976) the annual soil loss for the total watershed is 13 x 10^6 t/yr, which is equivalent to 25 t/ha, yr. The Environment Research Program Proposal of 1975 mentions a general average soil erosion of 4 mm/yr, i.e. approximately 20 à 30 x 10^6 t/yr or 40-60 t/ha yr, whereas the lower and upper extremes are given as 25 and 170 t/ha yr respectively. It should be noted that a part of this material is retained in the watercourses of the catchment area. This explains why Jolankai (1976) found a delivery of only 4.3 t/ha yr in a sediment retention basis in a small southern sub-watershed.

Clearly, the erosion rate depends on many factors and varies highly from site to site. Apart from natural factors such as the slope, man influenced factors such as type of vegetation or crop grown, and land use practice, have a significant effect on the erosion. Table II, adapted from Horváth and Kamarás (1976) gives an impression of the various cultivation branches, and its slope distribution. This information is also useful to judge possible environmental impacts of land use, to be discussed later.

2.4 OTHER RELEVANT CHARACTERISTICS OF THE WATERSHED

Other characteristics of the watershed that may be of relevance from the point of view of environmental management, are summarized in Table III. The complete table, (David et al., 1972) is presented in appendix B. It can be seen that the Balaton region

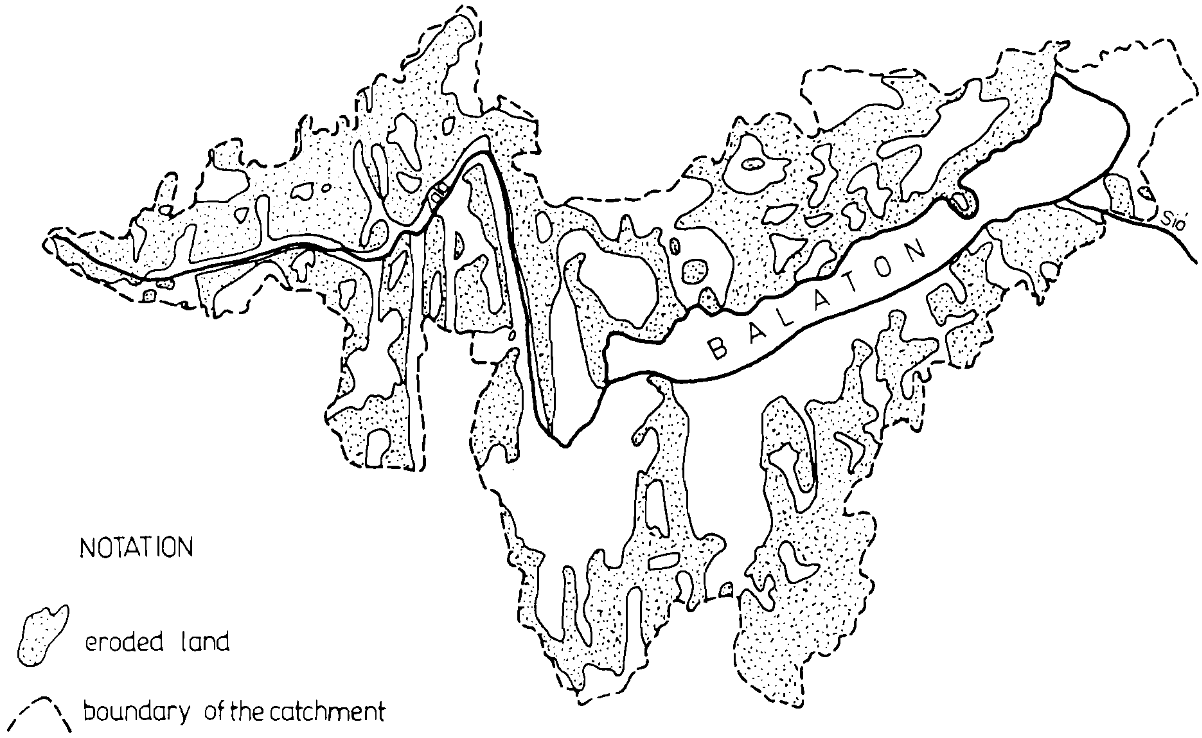


Figure 3. Erosion regions in the Balaton catchment area.

is mainly of rural character. The environmental impact of agriculture is therefor an important issue to be discussed in more detail in the chapter on nutrient loadings and its sources. The majority of the industries in the Balaton region is related to agriculture, and there are no heavy chemical or metalurgical industries. It is worthwhile to note the high amount of summer visitors. The number of one day visitors can amount to 600,000 on top days, and expectations are that this number can reach 1,000,000 in the near future. Most of them are concentrated along the 80 km of beachy shores.

Table II. Slope distribution of various land use types.

Land use type	% of total area	Percentage in slope categories <5	5-12	12-17	17-25	>25
Plough land	35	68	20	8	3	1
Meadow	8	100	-	-	-	-
Pasture	7	73	12	5	7	3
Orchard/vineyard	6	41	28	17	11	3

Table III. Some characteristics of the regional development in the Balaton catchment area in 1975 (after David et al., 1979).

Population/summer visitors	
Permanent population	420,000
Population connected to public water supply	243,000 (56%)
Population connected to sewage system	114,000 (27%)
Population density	81 persons/km^2
Visitor's day (mainly in summer)	5,560,000 person-days
Settlements/industry/agriculture	
Settlements	308
Industries	288
Large animal farms	23
Number of animals	100,000 animals
Fertilizer use P_2O_5 equivalents	70,000 t/yr
Water	
Total actual water use	96×10^6 m^3/yr
Domestic	44×10^6 m^3/yr (46%)
Industrial	16×10^6 m^3/yr (17%)
Irrigation	24×10^6 m^3/yr (25%)
Animal farming	12×10^6 m^3/yr (13%)
Effluent collected in sewage system	27×10^6 m^3/yr
Treated effluent discharge	6×10^6 m^3/yr (22%)

3. HYDROLOGY AND HYDROMETEOROLOGY

3.1 DATA BASE AND BASIC DATA

Because of its significance in Hungarian society the Balaton region has attracted the attention of hydraulic engineers and meteorologists already for a long time. Consequently a considerable amount of hydrological and hydrometeorological data is available. Continuous records on e.g. water stage and outflow, precipitation and other meteorological factors exist for more than 50 years, and form the basis of several detailed hydrological studies, including a statistical evaluation of the variables involved (Szestai 1967; Muszkalay 1973; Baranyi 1975; and others). Extensive information can also be found in the Hydrological Atlas of the Balaton, not only on hydrological but also on geological, morphological and water quality aspects, to mention a few. It is obvious that the richness of hydrological data provides a very good background for research related to hydrology and thus also for water quality and eutrophication modeling. Figure 4 presents an overview of the main hydrological and meteorological monitoring system, operated by the National Water Authority and the National Meteorological Service.

The long-term monthly averages for the most important variables are summerized in Table IV. In some cases data for the recent years 1971-1975 are given too. The annual average precipitation is 723 mm, while the period 1971-1975 as a whole was somewhat drier, mainly because of less rainfall in November, December and February. In those years winters were also slightly milder, and summers slightly cooler. The data on evaporation are calculated on the basis of a calibrated evaporation formulae using water temperature, air temperature and humidity, and wind data. Usually a good agreement is obtained with the energy balance method (Antal et al. 1973). It can be seen that evaporation

Table IV. Long term annual average values of some important hydrological and meteorological variables of Lake Balaton (after Baranyi, 1975a, 1975b, 1976; and Faludy and Urban (1976)).

		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual
Air temperature (C)	(1921-1975)	-1.0	0.7	5.4	11.1	16.1	19.1	21.4	20.6	16.7	11.0	5.9	0.9	10.7
Water temperature (C)	(1931-1975)	0.7	0.9	4.3	12.3	18.4	21.8	24.1	23.2	19.4	12.8	6.6	1.9	12.2
Global radiation (kcal/cm^2)	(1972-1973)	2.39	3.97	7.86	10.10	14.50	14.60	15.14	13.66	9.59	6.24	3.57	2.29	103.93
Number of days with ice cover	(1925-1970)	22	19	7	-	-	-	-	-	-	-	-	9	57
Number of stormy days (more than 15 m/s)														
Keszthely	(1961-1970)	7.7	8.5	8.6	8.6	8.6	7.9	7.9	7.3	5.3	4.6	6.6	6.4	88.0
Siófok	(1961-1970)	4.3	6.1	6.4	5.6	8.8	6.2	8.8	7.0	4.9	3.0	5.3	5.4	70.9
Water stage (cm) (0-level = 104.06 m A.S.)	(1921-1975)	72	77	85	90	91	87	80	71	64	60	62	67	76
	(1971-1975)	79	85	92	96	98	94	92	86	84	85	85	84	88
Precipitation on watershed (mm)	(1921-1975)	39	43	42	54	75	83	74	73	60	61	70	49	723
	(1971-1975)	36	27	32	57	70	83	91	82	51	56	49	31	665
Precipation on lake surface (mm)	(1921-1975)	34	34	40	48	66	66	62	68	58	51	57	44	628
	(1971-1975)	34	24	27	48	67	78	77	75	43	53	42	29	597
Evaporation (mm)	(1921-1975)	9	16	30	73	116	149	170	156	106	56	24	11	916
	(1971-1975)	13	23	34	71	113	137	145	136	99	57	34	14	876
Outflow (mm)	(1921-1975)	64	55	62	63	59	39	41	45	51	58	56	78	671
	(1971-1975)	86	23	13	27	63	38	36	29	40	50	58	137	600
Water intakes (mm)	(1971-1975)	1.0	1.2	1.4	2.2	2.6	4.0	4.2	3.8	2.4	1.6	1.2	1.2	26.8
Calculated inflow (mm)	(1921-1975)	81	111	135	103	81	75	65	51	50	53	72	80	957
	(1971-1975)	58	97	85	93	94	61	83	66	60	72	65	94	928
Combined discharge of Zala plus eight larger streams (m^3/s)	(1971-1975)	10.42	12.31	10.37	11.67	9.91	8.65	9.79	7.05	6.58	11.80	10.60	9.84	9.90

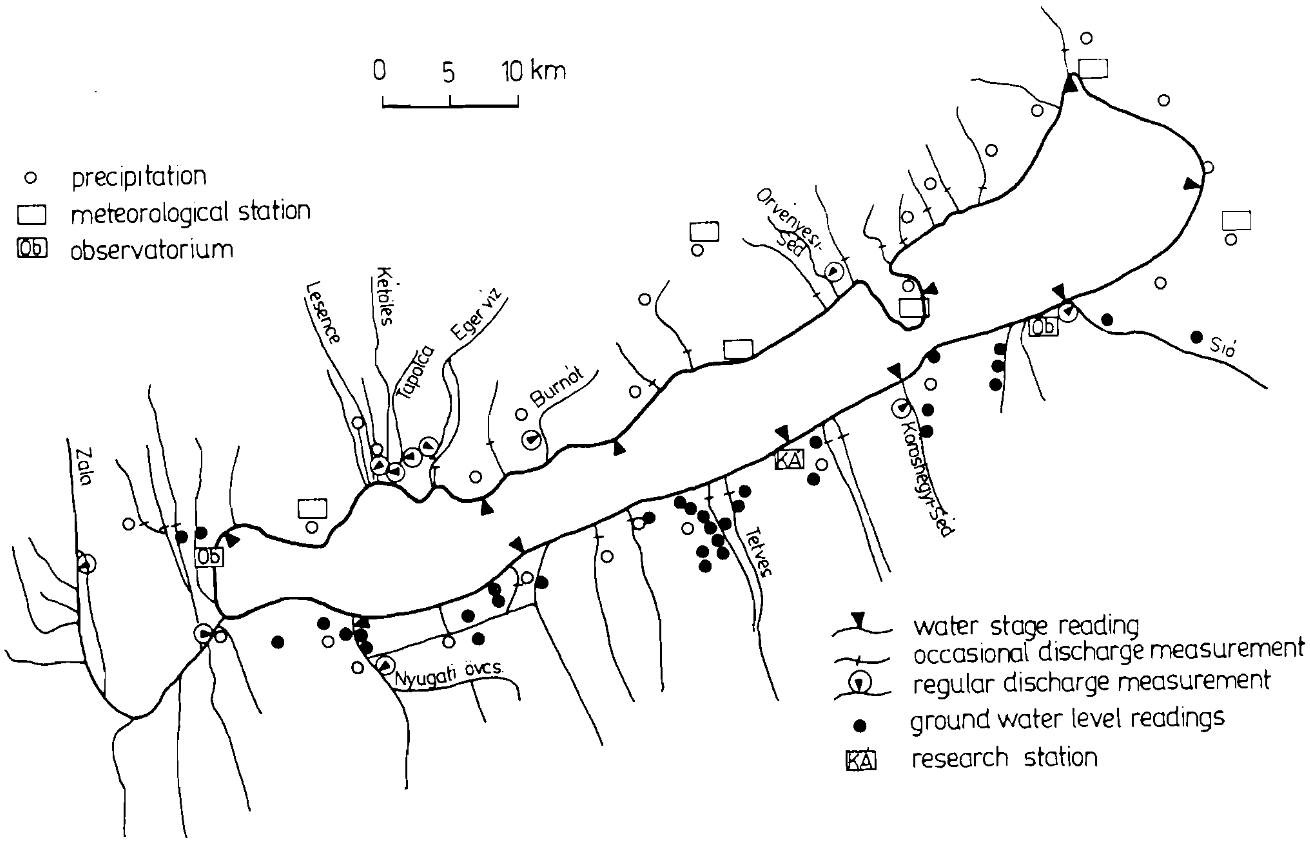


Figure 4. Meteorological and hydrological measuring stations.

losses (916mm) approximately balance the calculated inflow (957mm see section 3.4). Similarly the direct precipitation on the lake's surface (628mm) is canceled by the outflow (671mm), since the water level has been essentially stable over the period considered.

The other data given in Table IV are of special importance from the point of view of water quality. Due to the shallowness a relatively high water temperature (24C) is reached in the summer, a fact which is, of course, also of considerable touristic interest. In contrast, ice covers the lake in winter for about 57 days on the average. The number of stormy days indicated in the table, (i.e. days with wind velocities larger than 15 m/s) is of interest from the point of view of sediment resuspension, to be discussed later. It should be noted that due to chanelling in the mountain chain on the northern shore wind speeds are generally higher at Keszthely (western end) than at Siofok (eastern end).

3.2 WATER LEVEL

Already in historical times the water level at the lake has been subject to human intervention. According to Bendeffy and Nagy (1969) the natural balance between inflows, precipitation, evaporation and outflow at the Sió river was established at a water stage of 106.5-107 m.a.s. (meter above Adriatic Sea level), which is about 1.0-1.5 m above the present level. On the basis of archeological and archival data a reconstruction could be made

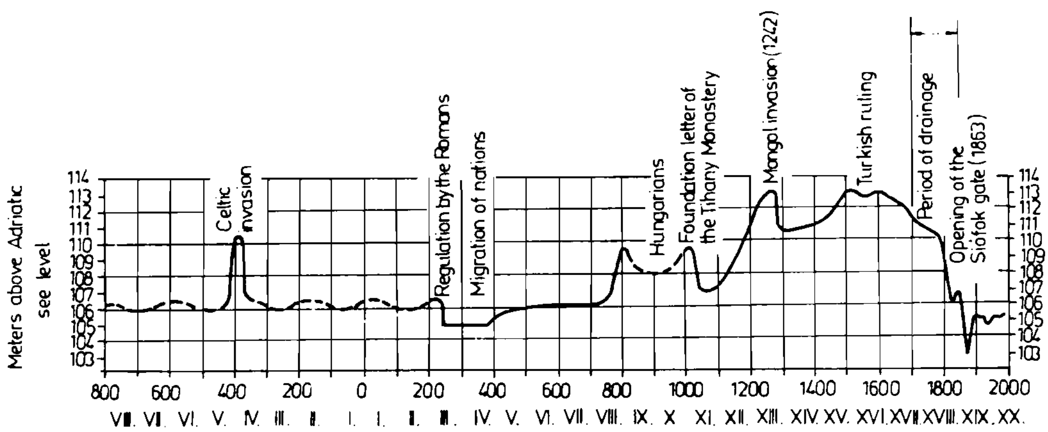


Figure 5. Historical changes of the water level of Lake Balaton (after Bendeffy, 1969).

of the water stage development during the past (Figure 5). Active water level regulation goes back as far as Roman times (3^d century A.C.), when a drainage canal and outlet gate were constructed, resulting in a decrease of water levels to about 104.5 m.a.s. During the migration of nations the Roman structures were destroyed, and elevations of 108-109 m.a.s. in periods of heavy rainfall sometimes occured. Defence structures against other migrating groups across the valley serving as natural outflow canal caused again extremely high levels. The maximum level was probably reached in 1242, when a reinforced earth-dike was built in the outlet valley as defence of the Tihany Monastery against the migrating mongol hords. In more recent times, starting in 1763, drainage works were carried out for land reclamation and navigation purposes. Finally, in 1863, the Siofok outlet gate was opened, primarily to protect the recently constructed railroad, but eventually the gate formed the onset of extensive regulation which resulted in the quasi-permanent water level range known at present.

The variability of the water levels during the last 50 years is shown in Figure 6 (Baranyi 1976). Extreme weather conditions lead to the maximum level of + 155 cm in 1947. The probability distribution on a monthly basis is presented in Figure 7, together with the upper and lower level limits set by the operation rules of the water authority. The upper level of + 100 cm, refering to the "0" point of the Siófok lake gauge at 104.09 m.a.s., is dictated by the elevation of existing structures such as shoreline protection and harbour constructions. Permanent higher levels would cause serious damage to private and state properties. Whether exceeding of the limit value can be prevented is determined by the capacity of the Siófok outlet gate. The capacity of 12 m^3/s at the time of construction in 1863 was insufficient for an appropriate level regulation. Later the capacity of the gate has been increased - in several steps - to 50 m^3/s. However, an appropriate level regulation within the + 40 and + 100 cm limits will only be possible after the widening of the Sió chanal to allow the release of this flow rate. The limited capacity of the

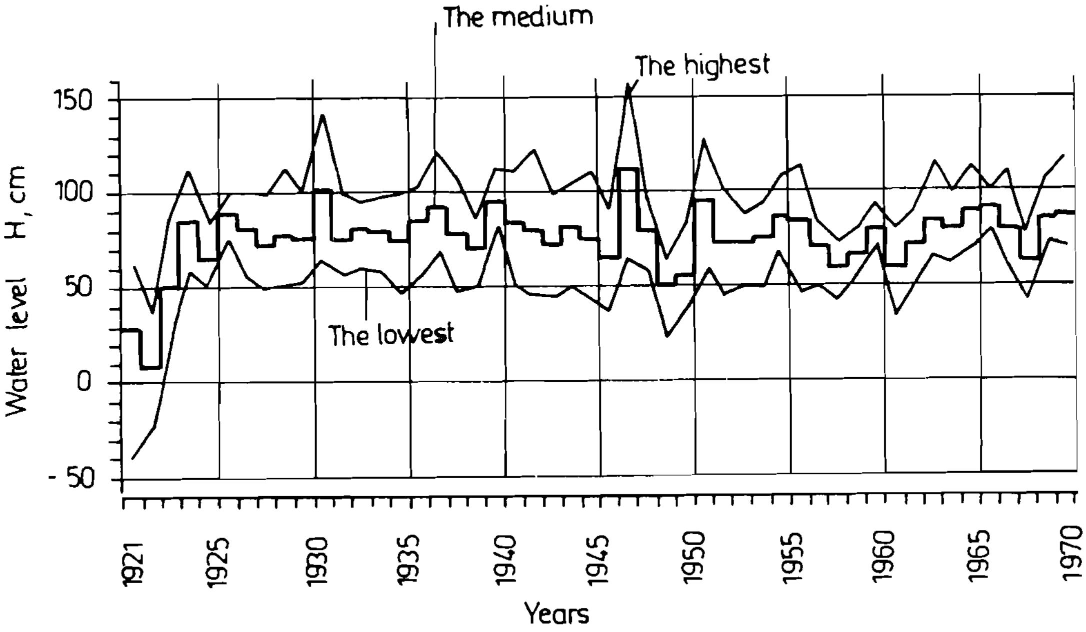


Figure 6. Maximum, average and minimum annual water level at the Siófok gate (after Baranyi, 1975) Zero mark at 104.09 m above Adriatic Sea level.

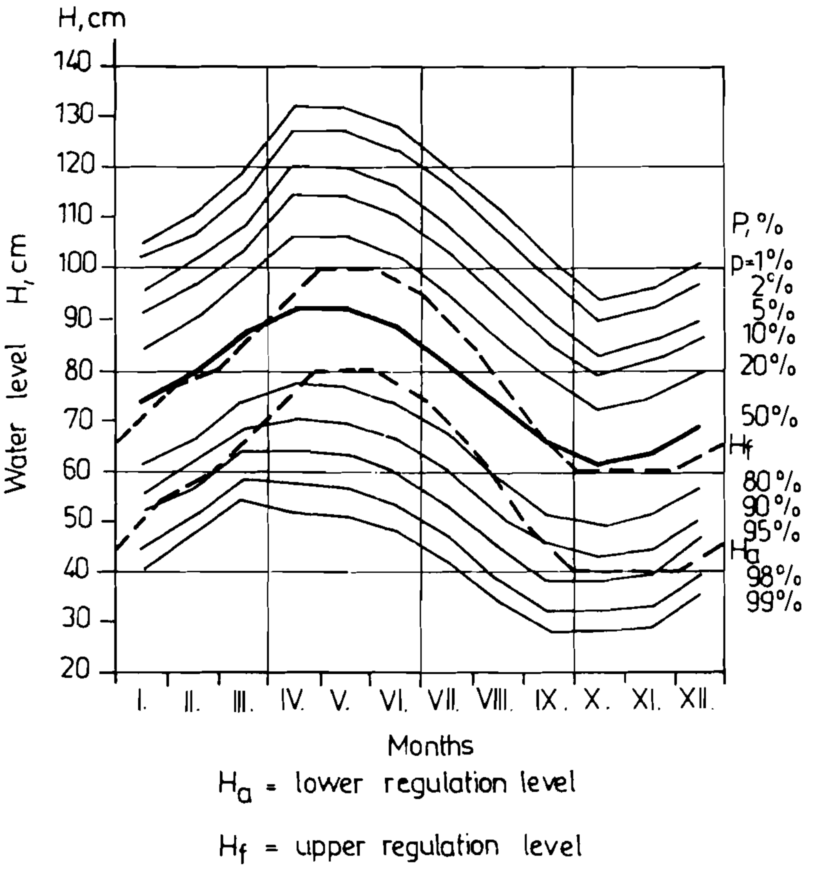


Figure 7. Probability distribution of monthly water level, based on data for the period 1923-1970 (after Baranyi, 1975) Zero mark at 104.09 m above Adriatic Sea level.

gate also necessitates a significant lowering of the water stage prior to the springtime rains to provide space for the coming high waters. This practice results in the annual release of 400 x 10^6 m^3 lake water of good quality, with the risk of prolonged low levels if the spring rains hold off. A possible solution is the expansion of the Siófok gate capacity, because the possibility of faster release would allow for higher water stages in the period before the rainy season. A capacity of 80 m^3/s would reduce the present level fluctuations by one-third. Another solution, the construction of a pumped storage reservoir of 120 x 10^6 m^3 in the Siófok region, has been proposed by Jolánkai Gy. et al. (1976).

3.3 HYDROGRAPHICAL DATA

From the point of view of ecological modeling not only the depth, but also the depth distribution is of interest. An isobathic map is given in Figure 8. The largest depth is 11.7 m in the straights of Tihany. The majority of the lake eastern from Tihany is about 4 m deep, whereas the part western from Tihany is in general between 3 and 4 m deep. The volume, surface area and mean depth as a function of the elevation is given in Figure 9. At the nominal water level of 104.8 m.a.s. the main dimensions are

Average depth : 3.14 m
Surface area : 593 km^2
Volume : 1861 x 10^6 m^3
Largest length : 77.8 km
Average width : 7.68 km
Length of shoreline : 195 km

It can be seen in Figure 9 that 9% of the lake's surface is shallower than 1.5 m, 30% is shallower than 3 m and the majority of the lake is less than 4 m deep.

3.4 THE WATER BALANCE AND RETENTION TIMES

In hydrological research it has become common practice to seperate the lake into four basins, namely the Keszthely basin, the Szigliget-Fonyód region, the Balatonszemes-Balatonakali region and the Siófok basin (see Figure 10 for the basic data). From the point of view of water quality modeling it is important to know the flows between the basins, and to have some idea of the time variability. These can be obtained from mass balance calculations. Most of the terms in the balance have already been discussed in the previous sections and can be estimated with reasonable precision. Precipitation is measured, outflow is obtained from records at the Siofok gate, evaporation is calculated fairly reliably from measured data, and the short-term variation in storage is readily obtained from measured level fluctuations. However, the situation is less favourable with respect to the inflow. Due to obvious economical and technological restrictions no continuous records are available for every single little creek out of the total of 31 permanent and 21 temporary water courses discharging into the lake. Although the density of the measuring network, and also the frequency of the measurements, are improved

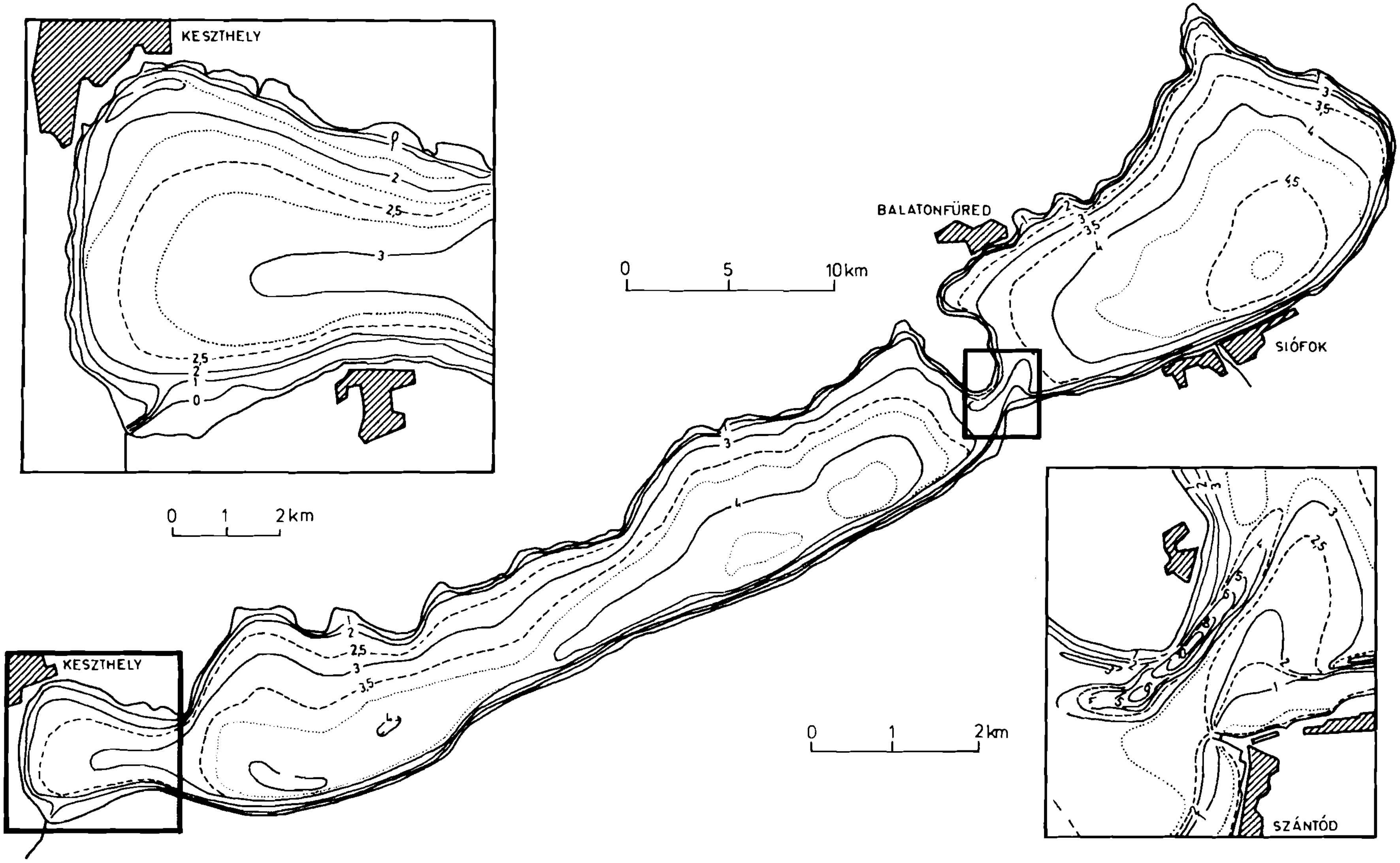


Figure 8. Isobathic map of Lake Balaton (reference point: long term average level at 104.90 m.a.s.). (After J. Sass, pers. comm.)

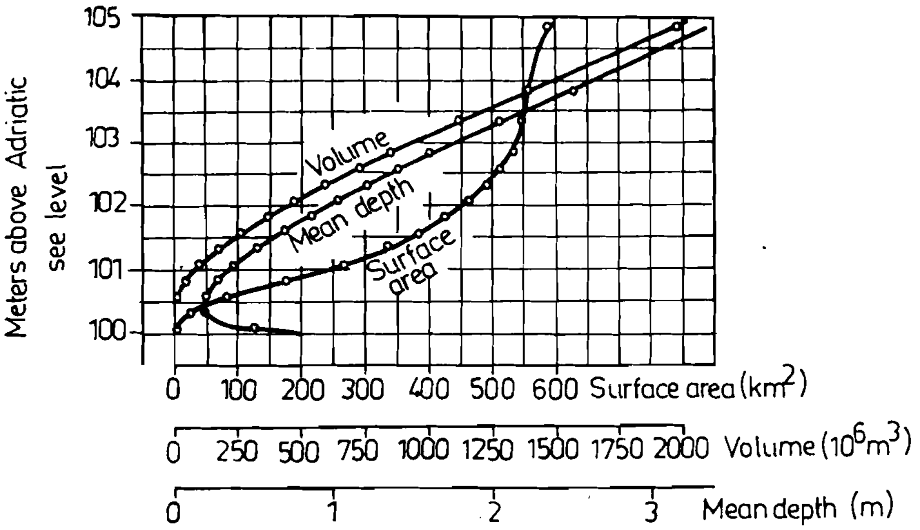
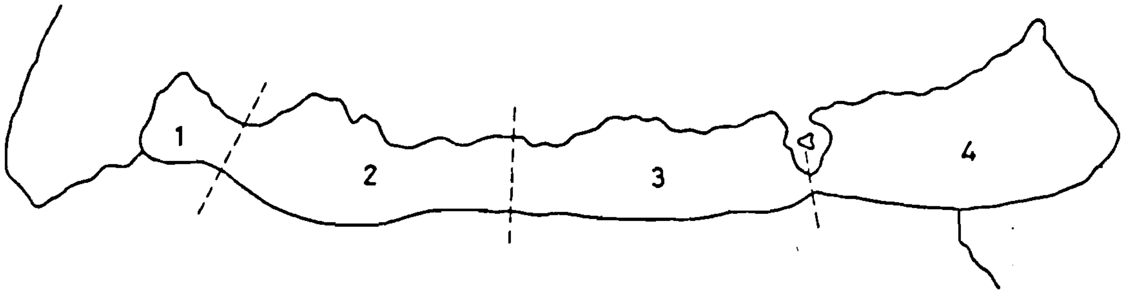


Figure 9. Geometrical data of Lake Balaton as function of water level (present average level: 104.90m.a.s.).



Part of the lake	Volume W (million m³)	Surface F (km²)	Depth h (cm)	Surface V (km²)
1.	82 4,3 %	38 6,4 %	228	2750 53,1 %
2.	413 21,8 %	144 24,4 %	287	1647 31,8 %
3.	600 31,6 %	186 31,1 %	322	534 10,3 %
4.	802 42,3 %	228 38,1 %	368	249 4,8 %
Lake Balaton, total	1907 100%	596 100 %	320	5180 100 %

Figure 10. The four Balaton basins and their geometrical data at average level (104.90m.a.s.) (after Baranyi, 1975). F = lake surface area; V = watershed surface area.

year by year, an exact determination of the inflows will remain difficult due to such situations as back-water flow in the confluences or discharge from the marshlands by pumping operations. Another element of uncertainty is formed by groundwater infiltration (although estimated to be negligible, i.e. 1mm/yr) and discharges of subsurface springs. Consequently the inflow must be calculated from the more reliable data on storage, precipitation, evaporation and outflow.

The results of the mass balance calculations for the four lake segments on the basis of long-term annual averages is given in Figure 11, expressed in cm watercolumn for each of the segments. It can be seen that the relative importance of the tributary inflow, as compared to evaporation and precipitation, is high in the Keszthely basin, and decreases towards the lower end of the lake, being insignificant in the Siofok basin. This fact explains partly the marked difference in quality among the four basins, to be discussed later. Figure 12 presents the balance terms in absolute units ($10^6 m^3$), seperated for the summer and winter half year. It turns out that the storage due to level differences is significant on this time scale (cf. Figure 7). Clearly, evaporation is highest in the summer season. In the winter halfyear precipitation is lower than in summer, but tributary inflow is higher, demonstrating the retardation of run-off in the watershed.

A more detailed calculation of segment tributary inflow and segment outflow, for monthly averages, is given in appendix C. Note, however, that individual years can differ considerable from this long-term average picture, as demonstrated e.g. by the differences between 1921-1975 and 1971-1975 data in Table IV. Of course, the stochastic nature of the weather is responsible for these variations, reflected both in evaporation and precipitation. As an illustration the probability distribution of the monthly precipitation is given in Figure 13. Variations in precipitation also affect the tributary inflow. However, the relation between rainfall and run-off is very complex, as already shown by the comparison of summer and winter halfyear. Figure 14 (Baranyi 1976) gives an impression of the degree of correlation between yearly precipitation and total tributary inflow.

Closely connected to the waterbalance is the consideration of the retention time in each of the lake segments. In this respect an interesting study by Baranyi (1972) should be mentioned. Based on the differences in tritium content of precipitation and tributary inflow a calculation could be made of the composition of the water to its origin in each of the basins. The results are shown in Figure 15. Here inflow is the sum of tributary inflow and inflow from the former segment. Again it is clear that the inflow plays the main part in the Keszthely Bay, and that the relative importance of the inflow decreases towards the Siófok basin. From the point of view of water quality also the difference in exchange time among the basins is of interest. The time for full replacement of the basin volume is 1 year for the Keszthely, 4 years for the Szigliget-Fonyód region, 6 years for the Szemes-Akali region and 9 years for the Siófok-basin. This result is also shown in Figure 16. Consequently one might expect that the

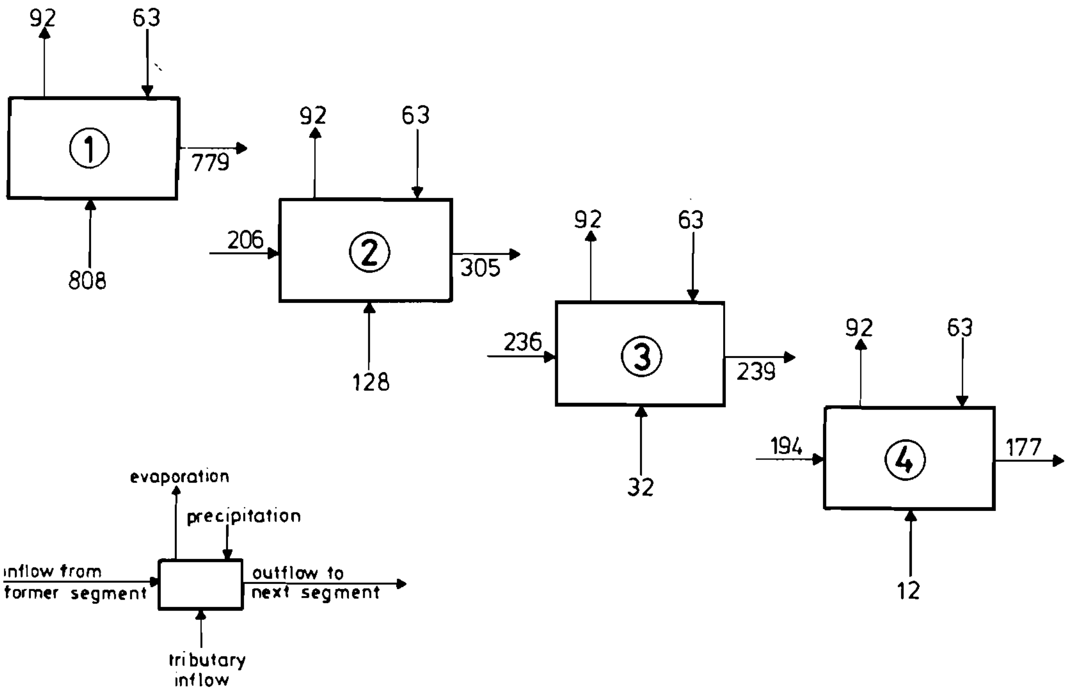
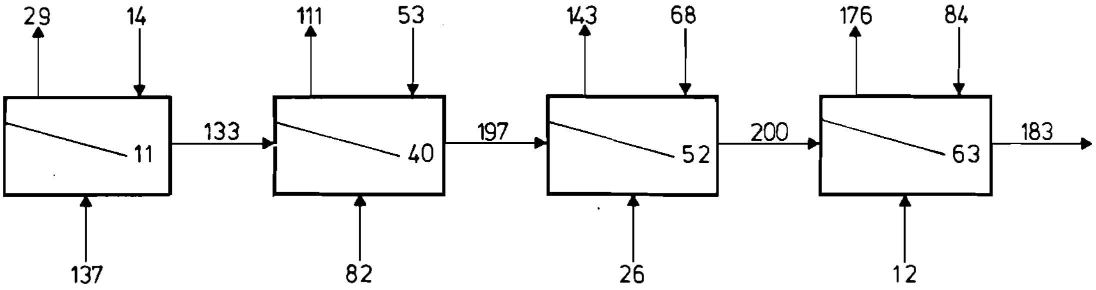


Figure 11. The long-term annual water balance for the four lake segments, expressed in cm water column.

SUMMER HALFYR. (april - september)



WINTER HALFYR.(october - march)

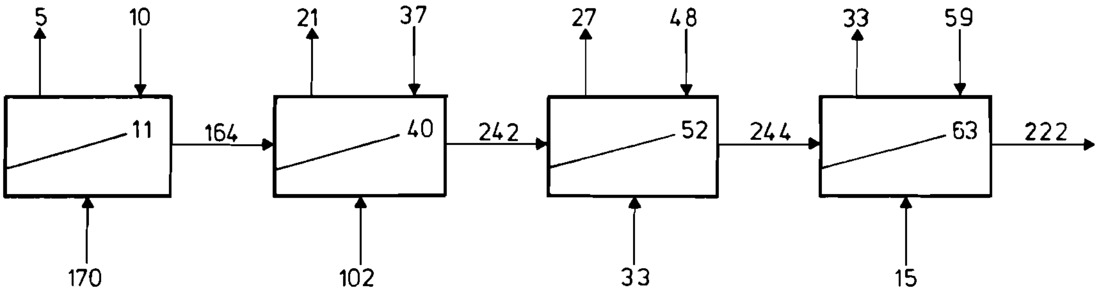


Figure 12. Water balance per lake segment (in 10^6 m^3): upper half--summer half-year (April-September); lower half--winter half-year (October-March).

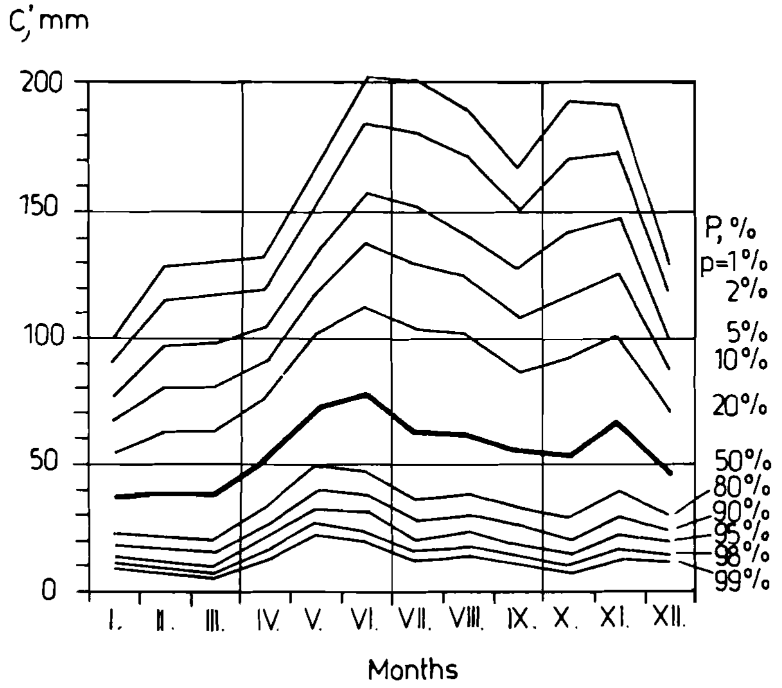


Figure 13. Probability distribution of monthly precipitation, based on data for the period 1921-1970 (after Baranyi, 1975).

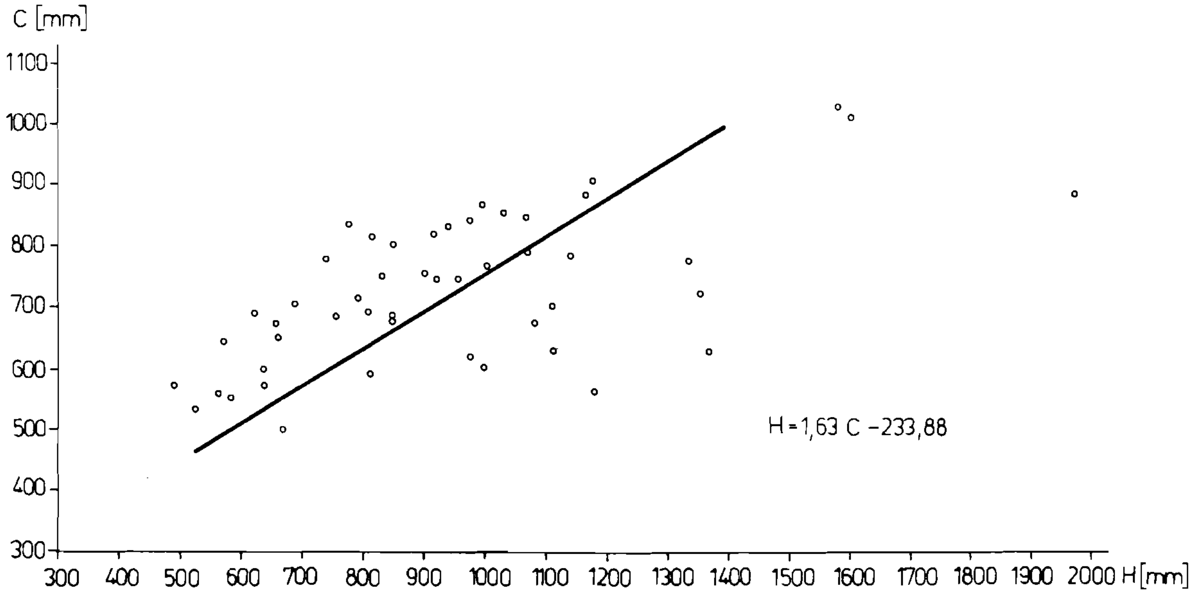


Figure 14. Relationship between annual precipitation and inflow of Lake Balaton.

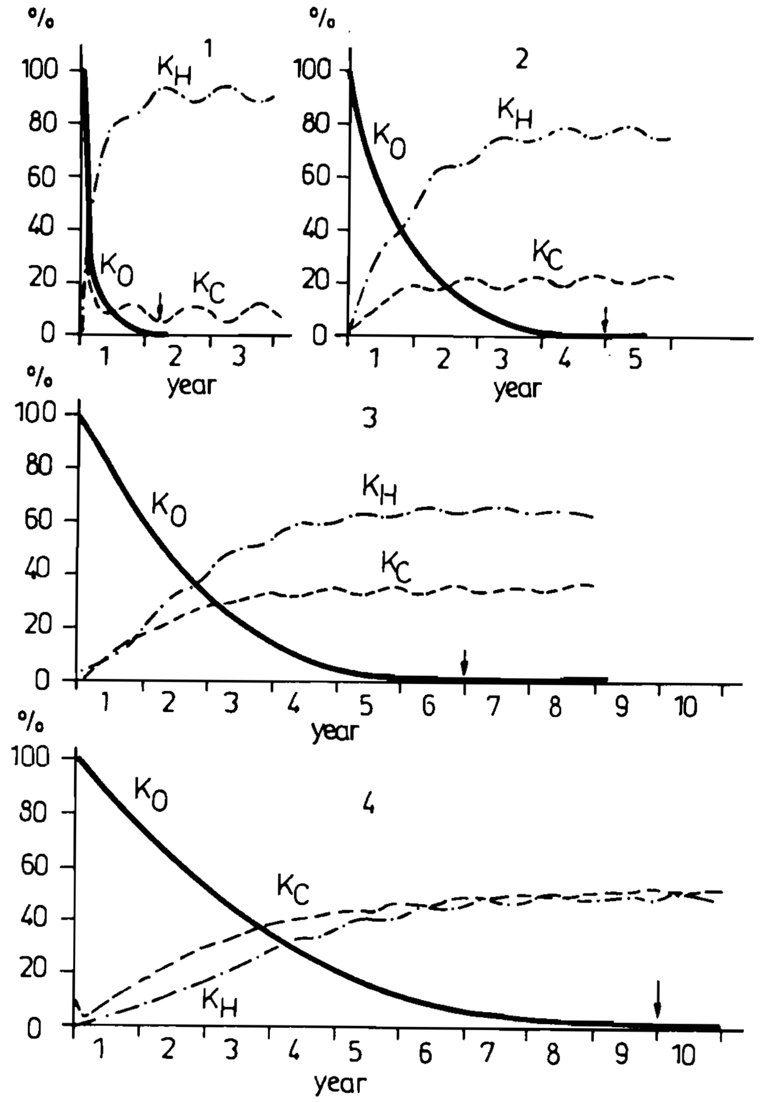


Figure 15. Contribution of precipitation and inflow in the renewal of water in the four Balaton basins (after Baranyi, 1976)

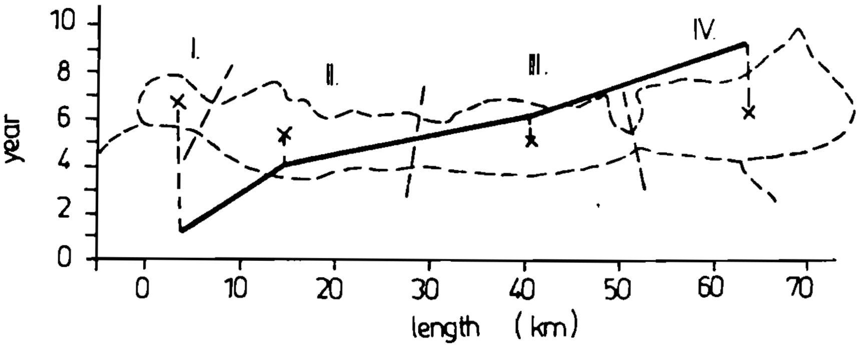


Figure 16. Average water exchange period in the four Balaton basins (after Baranyi, 1976)

response time of water quality to input fluctuations differs considerably among the basins.

3.5 HYDRODYNAMICS

The water balance calculation given in the previous section suggest a smooth flow between adjacent segments. In reality short term fluctuations induced by wind occur. Wind generated currents and waves also play a significant role in the resuspension of sediments. These hydrodynamical phenomena will be briefly reviewed in this section. A more detailed diccussion in relation to ecological modeling is given elswhere (Somlyodi, 1979).

Wind induced flow patterns have been analyzed by laboratory studies, and additional field experiments. A complicating factor in hydrodynamical research is that the wind direction is not uniform along the lake. The prevailing northern wind is similarly frequent at the measurement locations (20% of all cases), but the southern winds are oriented more eastward at Keszthely and more westward at Siofok.

A typical result obtained at steady wind in the hydraulic scale model study of the western part of the lake is shown in Figure 17 (Györke 1976). The flow patterns observed in the model suggest that the different basins can be considered as fairly independant entities. But the same investigations reveal also that during periods of abating winds exchange flows between the basins do occur.

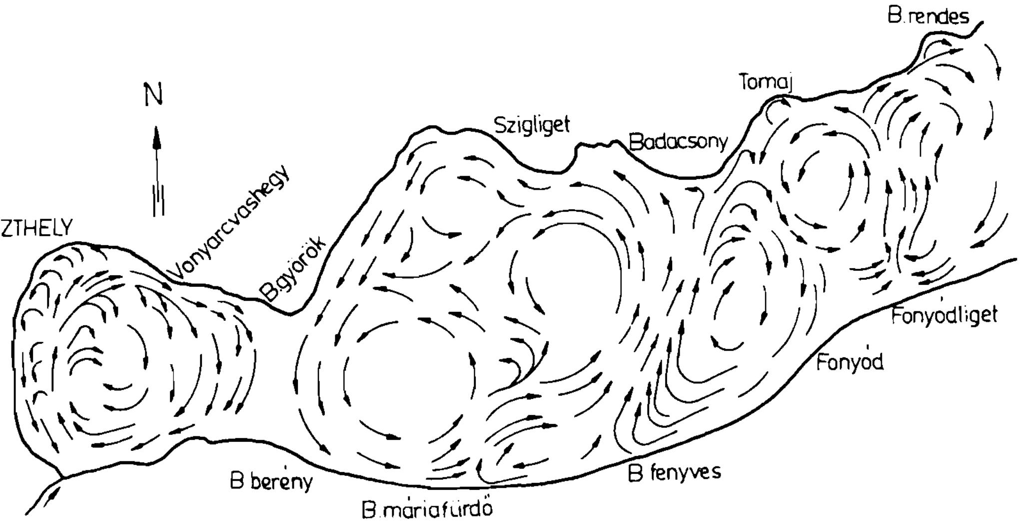


Figure 17. Flow pattern caused by dominating wind in the western part of Lake Balaton (after Györke, 1975).

Steady winds of longer duration, especially in longitudinal direction, may lead to considerable wind set ups (see Figure 18), up to half a meter difference over the lake length. Subsequently, seiche motions resulting from changing wind speed or direction can cause serious flow oscillations in longitudial direction. Flow amplitudes up to 1 m/s have been measured in the Tihany straits, as illustrated in Figure 19. Under such conditions significant mixing of the water masses in adjacent segments can be expected, although again a quantitative evaluation in terms of an exchange coefficient is difficult.

From the above it can be stated that the dynamical exchange of matter between the different lake segments due to wind induced currents constitutes a factor of uncertainty, that has to be taken into account in ecological modeling. It should be pointed out, however, that a clear, consistent concentration gradient does exist for the relevant variables along the longitudial axis of the lake (see next chapter), implying that wind mixing is not sufficient to cause complete mixing. Apart from the effect of wind on the longitudinal mixing also mixing phenomena in the vertical are wind controlled. During prolonged calm periods in summer vertical microstratification due to warming up at the surface has been observed. The percentage of calm weather varies between 8-16 at Siofok and between 17 and 32 at Keszthely. However, most of the time even moderate winds generate sufficient vertical mixing to prevent stratification. Wind induced motions, mainly in the form of waves, also affect the resuspension of sediment from the lake bottom. Several investigations exist on the

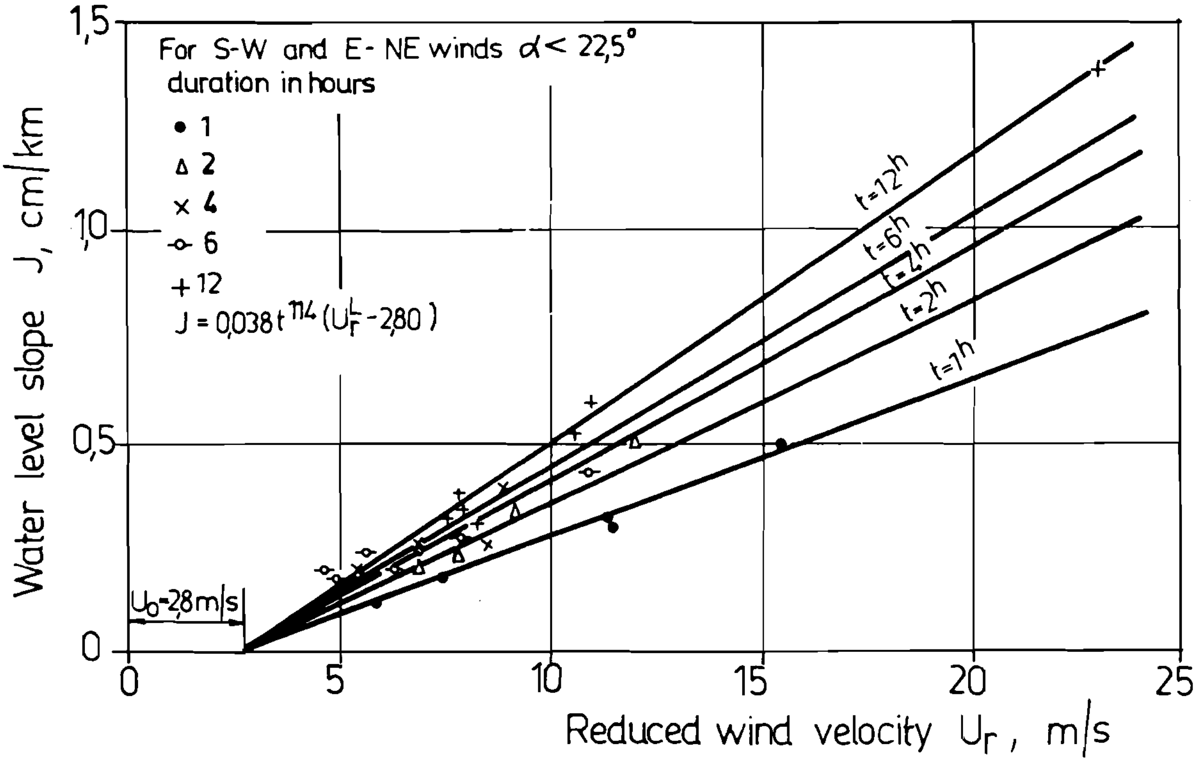


Figure 18. Wind set-up caused by longitudinal winds (after Muszkalay, 1973).

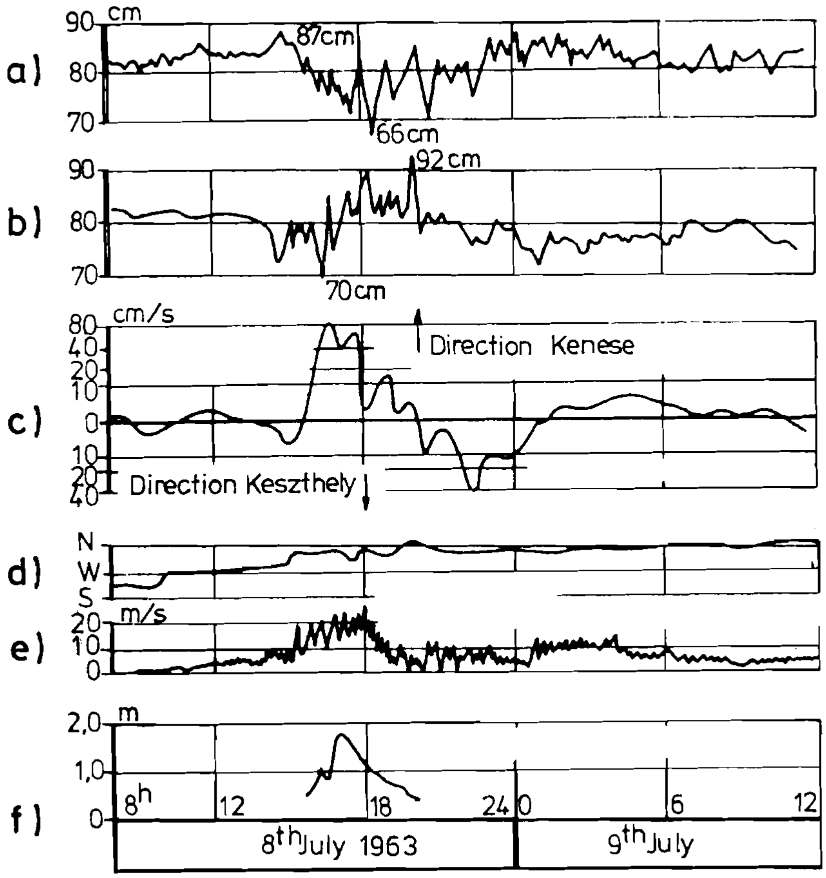


Figure 19. Seiche movements as a consequence of the storm on July 8th. 1963 (after Starosolszky, 1971), (a) water level at northern end; (b) southern end; (c) velocity of the currents in the Tihany straights; (d) wind direction; (e) speed; and (f) wave amplitude.

relation between wind speed and wave height (e.g. Figure 20, Muszkalay, 1973). Much less information is available on the relation between wave height and suspended solids concentration. From observations of the suspended solids concentrations (see appendix D) it seems that values of 20-40 mg/l can be maintained at winds of 5 m/s or more, i.e. in the majority of time. However values larger than 100 mg/l, up to 200 mg/l, occur only at storms (15m/s or more). Generally the lake clears up in about 3-4 days after a storm (see Entz, 1964). Since suspended solids is the major factor defining the under water light climate it is obvious that this ecologically important element has a highly dynamic character in lake Balaton. The other potentially significant effect of resuspension on the ecology of the lake, namely its role in the release of nutrients from the sediment, will be reviewed in the next chapter.

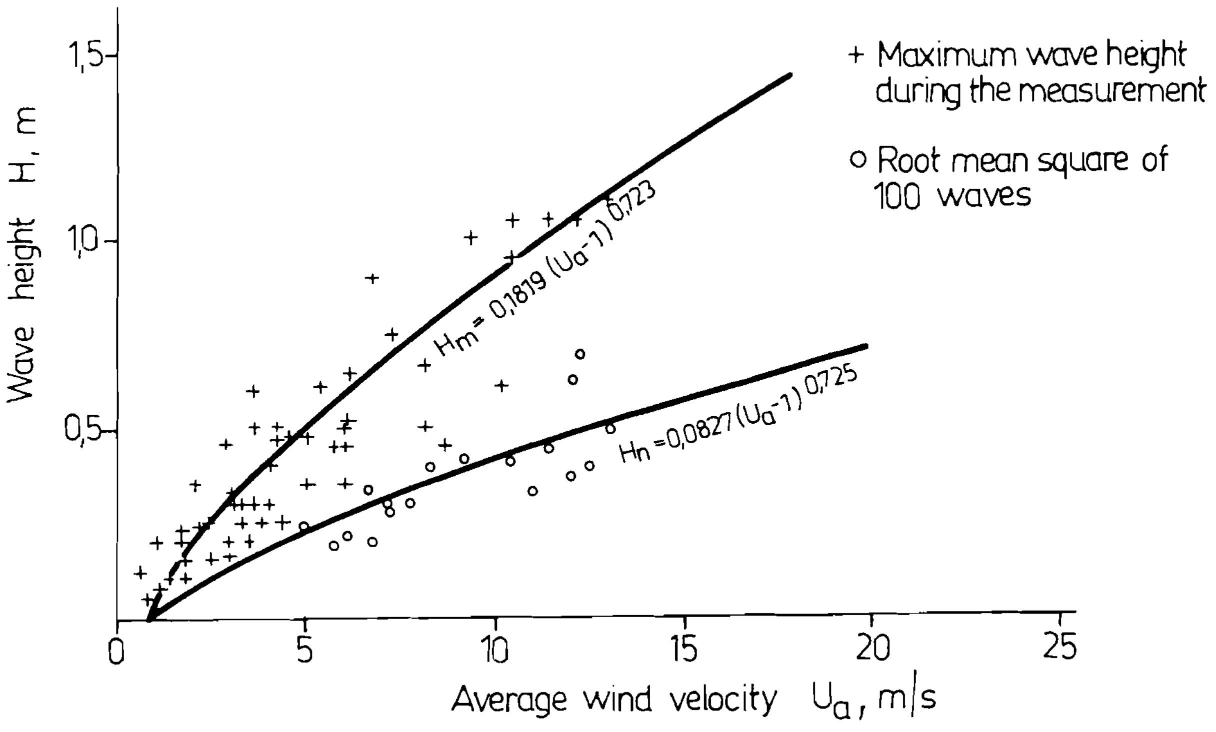


Figure 20. Relation between mid-lake wave height and average wind velocity (after Muszkalay, 1973).

4. WATER QUALITY AND EUTROPHICATION

4.1 INTRODUCTION

Surely, a great deal of the fame of the Balaton region as an area of outstanding recreational value stemmed from the lake's fine waterquality. Precursory to the discussions in the next sections Table V presents some important water quality data along the longitudinal axis of the lake. It can be stated that even today most parts of the lake still have a very good waterquality.

At the same time it is true that the progressive development in the watershed has not passed without adversive effects on the lake. The first signs of increasing cultural eutrophication have been ovserved more than ten years ago (see later). The relatively high peak chlorophyll-a values presently occuring according to Table V in the most polluted section of the lake, the Keszthely Bay, are a distinct indication for the deterioration process. One should bear in mind, however, that algal concentrations disgusting enough to refrain people from bathing and swimming (between 100 and 200 μg/l) have as of yet only been observed once or twice, and only in Keszthely Bay. And although the trend is without doubt precarious, no strong effect on the recreational value of the Balaton has become apparent to the average holiday visitor.

Nevertheless, since the Keszthely Bay receives the major tributary inflow its development must be considered as a warning sign for the danger of extension and propagation of its presently less favourable conditions to other parts of the lake. Therefore every effort should be used to maintain the lake's present good water quality and to stop the process of eutrophication before it is too late.

Table V. Some water quality values at various stations along Lake Balaton for the year 1977.

		Total-P	Total-N	O_2 saturation %	pH	$KMnO_4$ O_2 consumption	TDS	$K_2Cr_2O_7$ O_2 consumption	BOD	toxic	oil	Chlorophyll-a (µg/l)
Keszthely	min:	0,069	1,22	67,2	8,30	6,6	382,0	12,0	1,10			12,1
	max:	0,094	1,92	151,8	8,38	9,2	566,0	30,0	9,4	none	none	76,5
	mean:	0,080	1,60	125,0	8,35	7,6	437,0	22,0	5,38			40,0
Szigliget	min:	0,052	1,08	69,2	8,38		396,0	12,0	3,40			10,5
	max:	0,087	2,01	150,3	8,48		554,0	22,0	6,20	none	none	65,1
	mean:	0,060	1,45	120,0	8,42		432,0	18,0	4,22			35,0
Fonyód Akali	min:	0,050	0,95	83,4	8,40	4,9	280,0	8,0	0,7			6,7
	max:	0,074	1,78	147,9	8,46	7,5	600,0	24,0	6,6	none	none	57,6
	mean:	0,060	1,30	115,0	8,42	5,8	428,0	19,1	2,96			22,0
Tihany	min:	0,027	0,55	84,6	8,46	4,6	370,0	14,0	1,0			3,0
	max:	0,050	1,28	144,3	8,50	7,5	598,0	20,0	4,6	none	none	13,6
	mean:	0,035	0,95	110,0	8,49	5,8	430,0	17,0	2,8			6,0
Siófok	min:	0,022	0,72	71,0	8,48	4,2	386,0	6,0	1,2			2,0
	max:	0,095	1,52	144,9	8,52	6,3	614,0	20,0	7,6	none	none	14,0
	mean:	0,034	1,00	110,0	8,50	5,2	436,0	16,4	3,2			6,0

In this chapter we discuss the information on hydrochemistry and hydrobiology of the lake, that would be relevant for the modeling of the lake's complex processes, as a tool for further research and a guide for management decisions. First, the special hydrochemical features of the Balaton are discussed. Here we pay attention to the nutrients for algal growth too. Than the major live forms of the lake are reviewed. Finally a separate section will be devoted to the sediment.

4.2 CHEMICAL CHARACTERISTICS OF LAKE BALATON

4.2.1 Major ions

A first comprehensive study of the main chemical composition of the Balaton and its tributaries was conducted in the fifties (Entz, 1959). Table VI presents an ion balance calculated according to this study. Although the data are based partly on rather infrequent measurements (but this in all possible tributaries), still a good first impression of lake Balaton's chemical nature can be obtained. The first remarkable fact is the relatively high calcium and magnesium bicarbonate content, reflecting the major dolomite composition of the watershed. Correspondingly the m-alkalinity is high (4-5 mval/l, with the lower value during algal growth in summer) and the lake is buffered effectively on a pH of 8.3 to 8.7. Secondly, a considerable biogeneous lime precipitation takes place. Finally, from the inbalance of calcium and bicarbonate removal it follows that less organic material is decomposed in the water than produced during a year, and a nett

Table VI. Ion balance of the Balaton (after Entz, 1959).

	Inflow (18 m^3/s)			Balaton		Outflow (12.1 m^3/s)	Storage difference
	mg/l	Equiv. %	g/s	mg/l	Equiv. %	g/s	g/s
K^+	5.6	2.2	100	6.1	2.4	75	25
Na^+	18.1	14.2	325	27.0	16.9	325	0
Ca^{2+}	80.6	33.7	1450	32.0	23.1	385	1065
Mg^{2+}	36.1	49.9	650	47.8	57.6	580	70
CO_3^{2-}	0.0	0.0	0	4.0	2.1	50	-50
HCO_3^-	336.8	82.2	6060	280.0	74.1	3390	2670
Cl^-	9.0	3.8	160	12.0	5.2	145	15
SO_4^{2-}	46.1	14.0	830	55.0	18.6	665	165

loss to the sediment of some 10,000 tons organic carbon per year can be computed from the data (in 1956). More recent data on the major chemical composition on different stations in the lake are shown in Table VII. Peculiar is the longitudinal distribution of calcium and magnesium. Calcium is highest at the inflow of the major tributary (in the Keszthely Bay) whereas magnesium shows a reverse tendency. No fully satisfactory explanation of this phenomenon is known. Most likely the biogeneous lime precipitation reduces calcium to levels lower in the lake than in the Zala River input while this mechanism does not occur for magnesium. Its reverse gradient may be due to the concentrating effect of evaporation. It should be noticed that the so called Berek waters, mentioned in section 2.2, are rich in magnesium sulphate. A comparison of the recent data with the lake data of Table VI seems to indicate that the calcium and sulphate concentrations increased and the magnesium and bicarbonate content decreased somewhat during the last decades.

4.2.2 Phosphorus and Nitrogen Components

Of special interest with respect to the modeling of the lake's water quality are the data on phosphorus and nitrogen components, as the major nutrients for algal growth. The results of the regular surveys on the lake are presented in a concise form in appendix D for the four basins. An impression of the longitudinal distribution can be obtained from Figure 21. Here the three year mean and maximum observed values are shown for total phosphorus, total dissolved phosphorus and total particulate phosphorus, together with the same data for chlorophyll-a for comparison. A very pronounced longitudinal gradient exists, clearly reflecting the important role of the Zala River as a source of pollution.

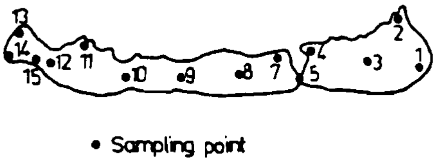
A closer look to the actual values of the different phosphorus fractions reveals some interesting features. Most notably, ortho-phosphorus is always very low (some 5mg/m^3), at least in the periods when measurements were done. Unfortunately, no data are available for the winter during ice cover, although some evidence exists that higher values are to be expected in winter. The total phosphate is for more than one half to two-third in the particulate form, most of which is of organic nature. Indeed, according to this data base phosphorus bound to particulate inorganic material is very low and of the same order as the ortho-phosphate fraction. Of the dissolved phosphate again practically all is of organic nature, leading to the conclusion that most of the total phosphorus in the water is somehow related to the biological activities in the lake. The high proportion of organic phosphorus in dissolved form points towards a primary producer death process of considerable intensity. Mineralization of both dissolved and particulate (detritus) material must be a prime mechanism to replenish the ortho-phosphorus pool which would otherwise be depleted rapidly at the given phytoplankton developing rates. However, other assumptions are possible too, for instance that fractions other than ortho-phosphate are utilized as the actual nutrients, or that ortho-phosphate is supplied from the sediment or from desorption from particulate inorganic material.

Table VII. Maximum, minimum and average values of the main kations and anions for the period of 1970-1975 (after Németh and Pásztó, 1976).

a) Kations

Sampling point no.	Ca^{2+} (mg/l)			Mg^{2+} (mg/l)			Na^{+} (mg/l)			K^{+} (mg/l)		
	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean
1	30	40	36	46	46	43	17	24	22	5,0	7,0	5,9
2	31	44	37	40	47	44	17	24	22	5,0	7,0	5,9
3	32	45	36	40	51	44	18	24	22	5,0	7,0	5,9
4	32	56*	38	33	46	43	17	24	21	5,0	7,0	5,8
5	28	56*	38	34	47	41	14	22	21	4,9	7,5	5,7
7	32	64*	40	28	46	41	16	22	21	4,8	7,0	5,6
8	34	68*	40	26	45	40	16	22	20	4,8	7,0	5,5
9	32	60*	41	34	44	39	16	24	20	4,6	6,5	5,5
10	28	60*	42	34	52	40	15	22	20	4,6	6,5	5,3
11	36	68	49	32	50	38	11	22	17	4,2	8,0	5,0
12	28	65*	44	31	47	38	14	22	20	4,0	6,5	5,3
13	32	75*	47	28	43	36	17	24	21	4,4	7,0	5,6
14	38	96	62	27	41	33	12	38	23	4,0	6,5	5,4
15	38	80*	50	27	45	36	14	24	20	4,4	7,0	5,5

*Data measured on 25.03.1975.



b) Anions

Sampling point no.	Cl^{-} (mg/l)			SO_4^{2-} (mg/l)			HCO_3^{-} (mg/l)			CO_3^{2-} (mg/l)		
	min.	max.	mean	min.	max.	mean	min.	max.	mean	min.	max.	mean
1	19	25	20	77	96	89	185	260	220	0	36	17
2	19	25	22	70	106	89	155	270	230	0	42	15
3	17	24	20	70	94	89	195	260	220	0	30	16
4	18	28	21	64	94	88	195	260	220	0	31	16
5	18	24	21	79	94	87	195	270	220	0	30	17
6	18	25	21	70	94	95	195	270	230	0	30	15
8	18	23	20	66	90	83	190	340	230	0	30	15
9	18	23	20	51	89	82	200	280	230	0	24	14
10	17	23	20	72	89	82	200	280	230	0	24	14
11	14	23	18	32	86	72	185	370	260	0	31	13
12	18	25	20	67	86	78	180	310	240	0	31	15
13	14	27	21	61	86	73	180	320	250	0	24	12
14	16	35	22	42	84	63	195	430	300	0	30	10
15	18	27	21	48	84	73	200	350	250	0	36	14

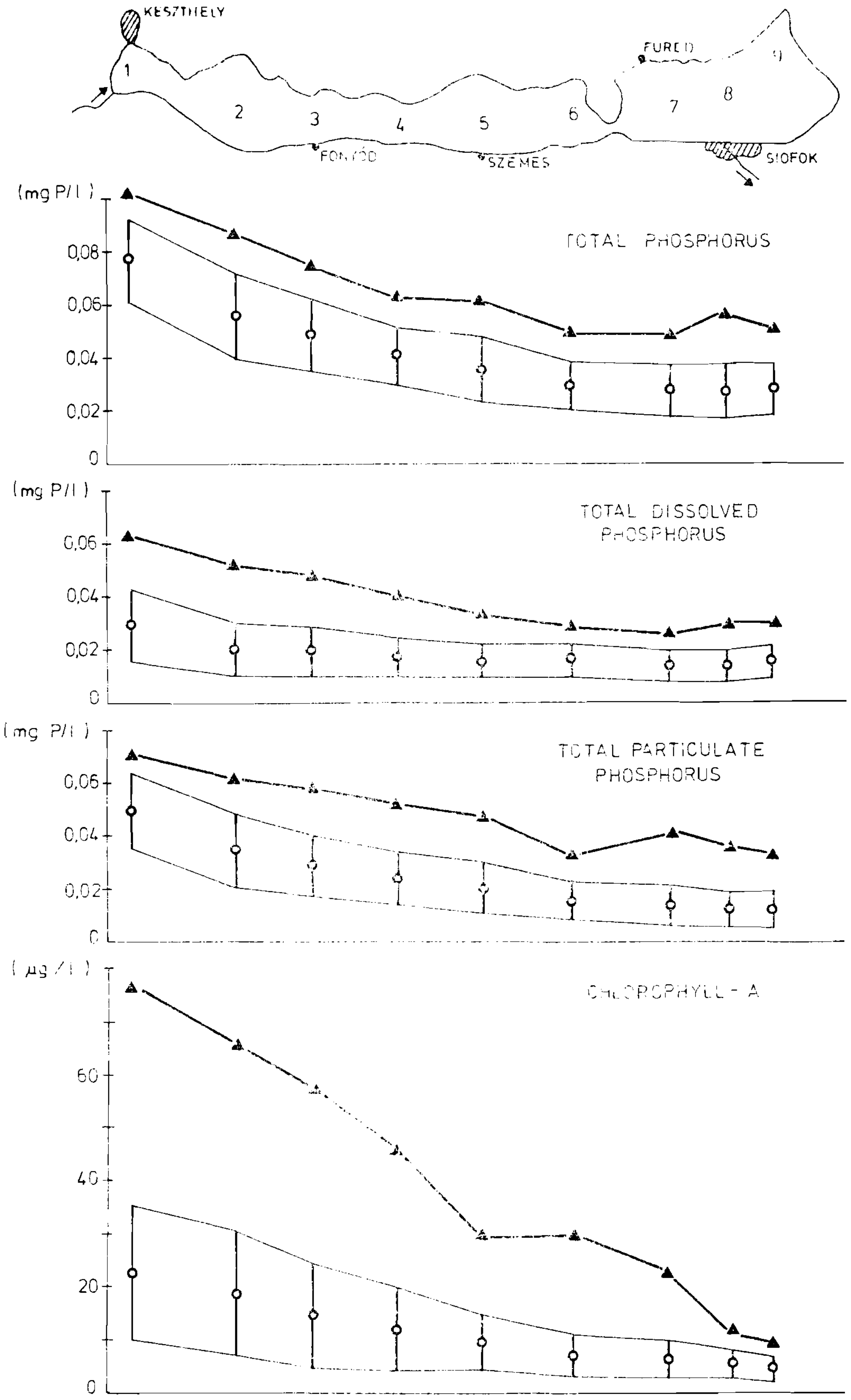


Figure 21. Longitudinal distribution of phosphorus and chlorophyll-a over the period 1976-1978.
o : average; bars: standard deviations;
▲ : maximum value

The picture obtained from the phosphorus data is largely supported by the observations of the nitrogen fractions. Apart from the nitrate most nitrogen is in organic form, ammonia generally being absent due to the favourable oxygen conditions. The ratio of dissolved and particulate organic nitrogen is larger than one, in contrast with the ratio of the corresponding phosphorus components.

4.2.3 BOD and Dissolved Oxygen

Although most of the phosphorus and nitrogen is associated with organic material, the organic material concentration itself is still relatively low. According to Felföldy's saprobity classifications (Felföldy, 1974) the lake falls into the oligo-beta mesasaprobe category, that is it meets first quality class requirements according to CMEAstandards. Under normal wind mixing conditions no dissolved oxygen problems occur. This favourable situation is endangered both by increased organic loadings resulting from an expansion of sewerage systems, as well as by the organic material produced in the lake as a result of increased eutrophication. According to the calculations of Herodek (Herodek and Tamás, 1975) the 100,000 tons/yr of organic carbon generated by phytoplanton is an order of magnitude larger than that represented by direct pollution loads. Thus, major importance is attributed to the abatement of nutrient loadings in the protection of the favourable oxygen conditions. It should be noted, however, that major BOD discharges should be prevented too, since they may play a triggering role in the mobilization of nutrients from the sediments by enhanced deoxygenation, at least locally. (Oláh, 1975). That this hypothesis is not entirely imaginary is illustrated by the low oxygen contents found near the bottom of the lake in Keszthely Bay during a temporary stratification (Tóth, 1976).

4.3 HYDROBIOLOGY

4.3.1 Macrophytes

About 3% of the surface area of the lake is covered by reed. Reed belts have always existed on the northern littoral zone, but in the last two decades they grow intensively along the southern shore too. The reed stand in 1975 is shown in Table VIII. Reeds can potentially propagate until depths up to 2 m. The chemical composition of the inner zone of the belts is determined by the presence of reeds, e.g. low pH, low dissolved oxygen, free CO_2, but in the outer zones the water is similar to that of the open lake. Reed and the epiphytic algae growing on the reed stems are supposed to retain phosphorus from water discharged from the shore. (Tóth, 1972a, Oláh et. al., 1977).

Table VIII. Water surface covered by reeds in Lake Balaton.

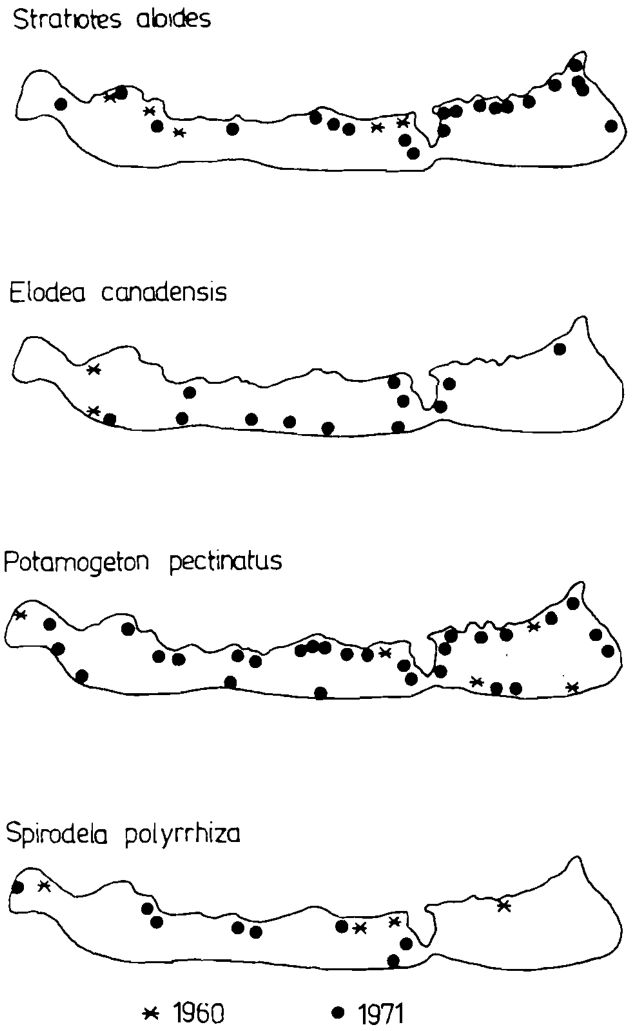
Shoreline	Length m	Area ha	Average width m
Southern shore	41,810	529	126
Northern shore	68,060	1,151	169
Total	109,870	1,680	153

According to subjective estimates some 2% of the lake surface is covered by submerged macrophytes. The most important species is Potamogeton perfoliatus. The largest invasion of this species occured in the Keszthely Bay, where the water is shallower and more wind-protected, and the mud contains much nutrients. In 1969 9.6% of the surface of this basin was covered by Potamogeton perfoliatus (Kárpáti and Kárpáti, 1975). The standing crop (without the underground parts) was 0.1 kg air dried weight/m^2. But in 1973 Potamogeton perfoliatus stands had disappeared from those parts of the basin that are deeper than 2 m, as a consequence of the light shading effect of the increasing phytoplankton biomass discussed below. On the other hand, in the different small shallow bays of the lake, where enough light penetrates to the bottom, macrophytes typical for eutrophic waters expand rapidly. Figure 22 presents a picture of this propagation (Tóth L., 1972b). It should be borne in mind, however, that the distribution of submerged aquatic weeds is limited by the mechanical action of the waves, and, consequently, at least 95% of the surface of the Balaton will remain open water, free of macrophytes.

4.3.2 Phytoplankton

Standing Crop. Systematic investigations of the algal composition using the modern Utermöhl counting technique have been conducted in the years 1965-1967, 1974 and 1967-1978 for samples collected at monthly intervals at five locations along the longitudinal axis of the lake (Tamás 1967, 1969, 1972, 1975, Vörös 1979). The average volume of the individuals was obtained for each species from microscopic measurements, and from this the biomass was calculated assuming a specific gravity of 1 g/cm^3 (Tamás 1974a).

Diatoms are the dominating species in the cool seasons. Until 1974 Cyclotella bodanica and Cyclotella ocellata are most abundant, but presently they are replaced by Synedra acus and Nitzschia acicularis. In summer more pronounced differences in phytoplankton between the basins exist than in the cool seasons. In the largest part of the lake Ceratium hirundinella is the dominating species, while in the Keszthely and also the Szigliget basin blue-green species, mainly Aphanizomenon flos-aquae have started to prevail.


Stratiotes aloides

Elodea canadensis

Potamogeton pectinatus

Spirodela polyrrhiza

Figure 22. Propagation of various weed species (after Tóth L., 1972).

The biomass increases towards Keszthely, and it shows an increasing tendency for the last 14 years in all the basins. Usually there is a separate spring and summer maximum. The increase of biomass in time is demonstrated in Figure 23. Expressed in cell numbers the increase is even larger because bigger species are replaced by smaller ones. Apart from biomass and cell numbers also chlorophyll-a data are available from two different agencies (Tóth L., 1976, Tóth F. et.al., 1976). An impression of the temporal and spatial distribution can be obtained from Fig 24. Averages for the four basins for recent years are computed from the data from both data collection programs and presented in appendix D. Clearly, large differences among the different years exist. This demonstrates the importance of the external variables such as meteorological conditions and nutrient loading conditions, where the latter are highly fluctuating due to the precipitation pattern in the different years, as discussed in the next chapter. Also the algal composition differences contribute to the variability of the chlorophyll-a pattern. Similar to the biomass chlorophyll-a shows a definite longitudinal gradient towards Keszthely

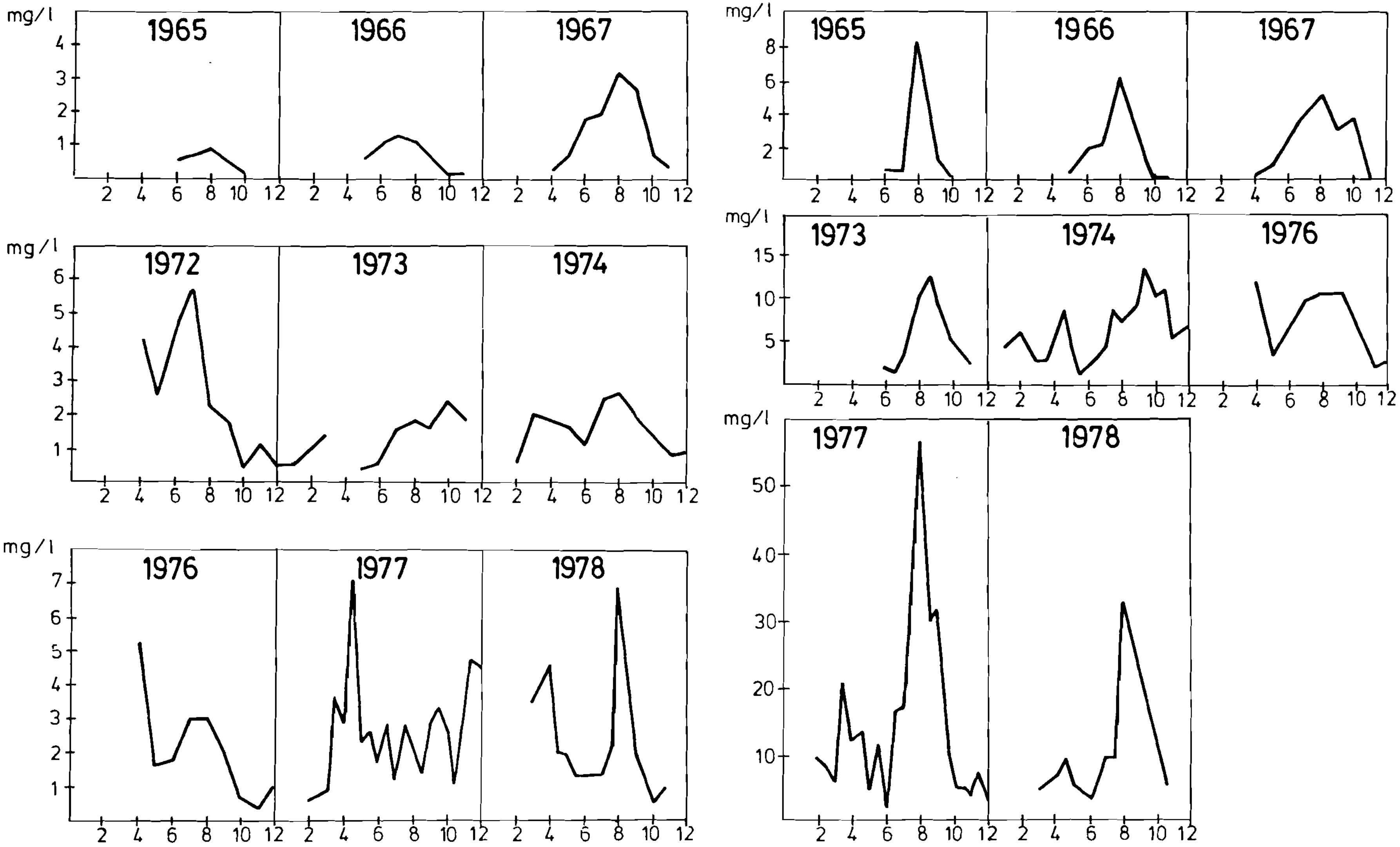


Figure 23. Increase of biomass at Tihany and Keszthely since 1972 (after Vörös, 1979).

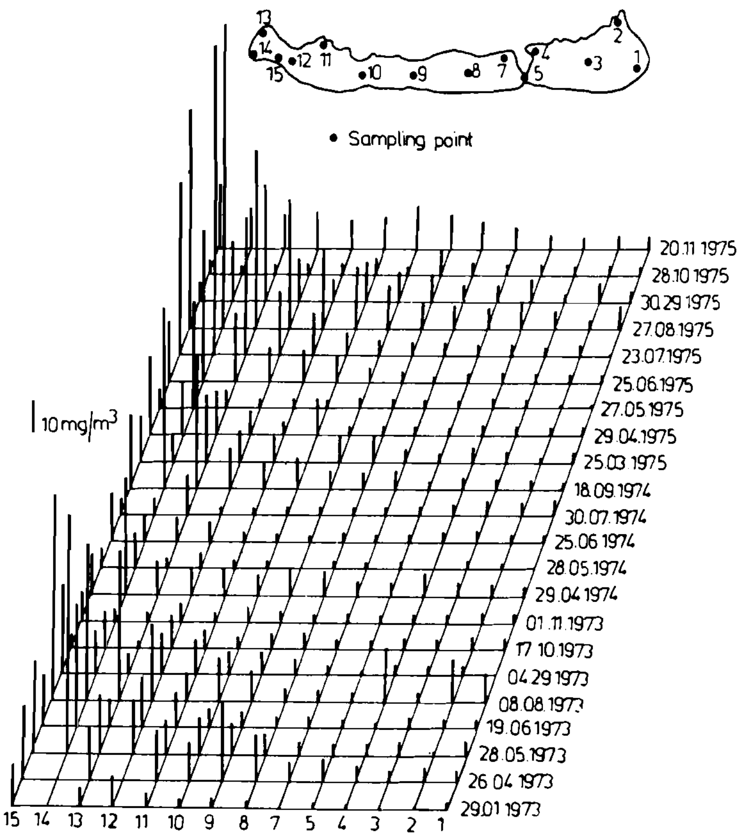


Figure 24. Temporal and spatial variation of Chlorophyll-a (after Tóth F. et. al., 1976).

(cf. Figure 21). Usually, there is a strong correlation between chlorophyll-a and biomass. It should be noted, however, that the relation is more complex in the Keszthely Bay, because the chlorophyll-a content of the blue-greens is relatively low (Vörös, 1979).

Primary production. The biomass standing crop is the result of primary production and death processes. Therefore primary production is a more dynamic indicator of the intensity of the biological cycle, and, from the modeling point of view, the ratio of primary production and biomass is an important characteristic of the system. Primary production measurements have been conducted using the ^{14}C-technique (Herodek and Tamás, 1973, 1974, 1975, 1978). The uptake of labeled carbonate at four different depths in situ during four hours at noon was measured, and an estimate of the daily primary production was obtained by adding the values for the different depths and extrapolating the results for the time between sunrise and sunset minus two hours. Since light is a key factor in algal growth, transparency profiles in the vertical have also been measured. As discussed in the previous chapter the transparency depends very much on the wind conditions, and is therefore highly variable. The vertical distribution of the primary production reflects this variability. In heavy storms, when transparency is low, the production is limited to the upper 1-2 m, while after long calm periods the light penetrates so far that the productive zone is extended to the bottom. In most parts of the lake photoinhibition occurs near the surface, and the maximum generally occurs at 1-2 m below the surface. It is interesting to note, however, that in the Keszthely and Szigliget basin usually no photoinhibition occurs, and the euphotic zone is mostly less than 2 m thick. This is attributed to the self-shading by the relatively high phytoplankton concentrations.

A summary of the results of the primary production measurements is presented in Figure 25. In addition some observations have been made in 1961 and 1963. In Tihany the primary production maximum changed very little between 1961 and 1972, but it doubled from 0.6 g C/m^2 day in 1972 to 1.3 g C/m^2 day in 1977. The value of 2.6 g C/m^2 day in 1974 in Szigliget was preceded by a maximum of 0.6 g C/m^2 day in 1963. The most striking results are the extreme primary production values in the Keszthely Bay. Whereas in 1963 the maximum was 0.8 g C/m^2 day, in July 1973 an absolute peak of 13.6 g C/m^2 day was observed, comparable only with the highest values reported for the most productive European lakes. Correspondingly the primary production - biomass ratio is 3-4 day^{-1} in the Keszthely Bay, a very high value. In Tihany this ratio is two to three times lower.

On the basis of the measurements estimates for the yearly primary production have been calculated. The values range from 96 g C/m^2 yr for Tihany (1972-73) to 830 g C/m^2 yr for Keszthely (1973-74). They are shown for the different basins in Figure 26, together with the scales for the trophic state suggested by Rohde and Winberg. If primary production is accepted as the best indicator of trophic state, Lake Balaton, previously mesotrophic, is now in the eutrophic and, in some places and at some times, hypertrophic ranges.

4.3.3 Benthic Algae

In the summer benthic algae are not very important. Counts on samples taken in 1965-1967 produced no more than some hundred cells per cm^2, and the biomass varied from 0.8 to 94.7 mg fresh weight/m^2 (Tamás, 1974b). This is three orders of magnitude lower than the biomass of phytoplankton. Also the primary production of the phytobenthos measured in 1972-1973 in Tihany was normally very low. However, when the lake was covered with ice without snow a significant diatom carpet developed on the mud surface (Herodek and Oláh, 1973). In such periods wind mixing is absent, and the water is extremely clear allowing the light to reach the bottom. The measured primary production was 0.4 g C/m^2 day. From the increase of the dissolved oxygen concentration under the ice (9.6 mg/l in twenty days) an accumulation of about 12 g organic carbon per m^2 can be computed, i.e. more than the organic carbon content of all organisms in summer. The amount of phosphorus stored in the cells is considerable, constituting a potential nutrient source through the mechanism of swirling up and subsequent decomposition in the water as soon as the ice melts.

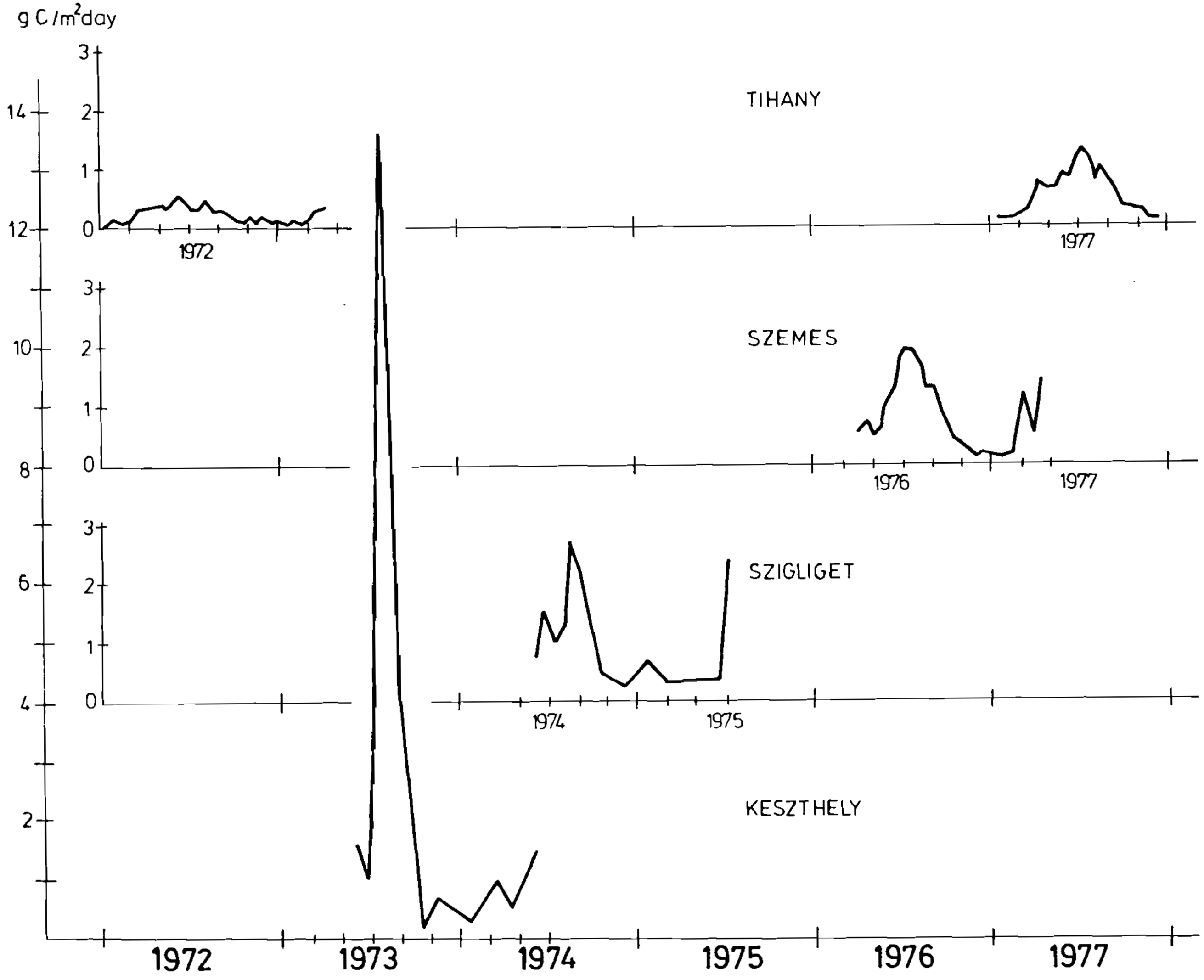


Figure 25. Primary production in the four basins since 1972.

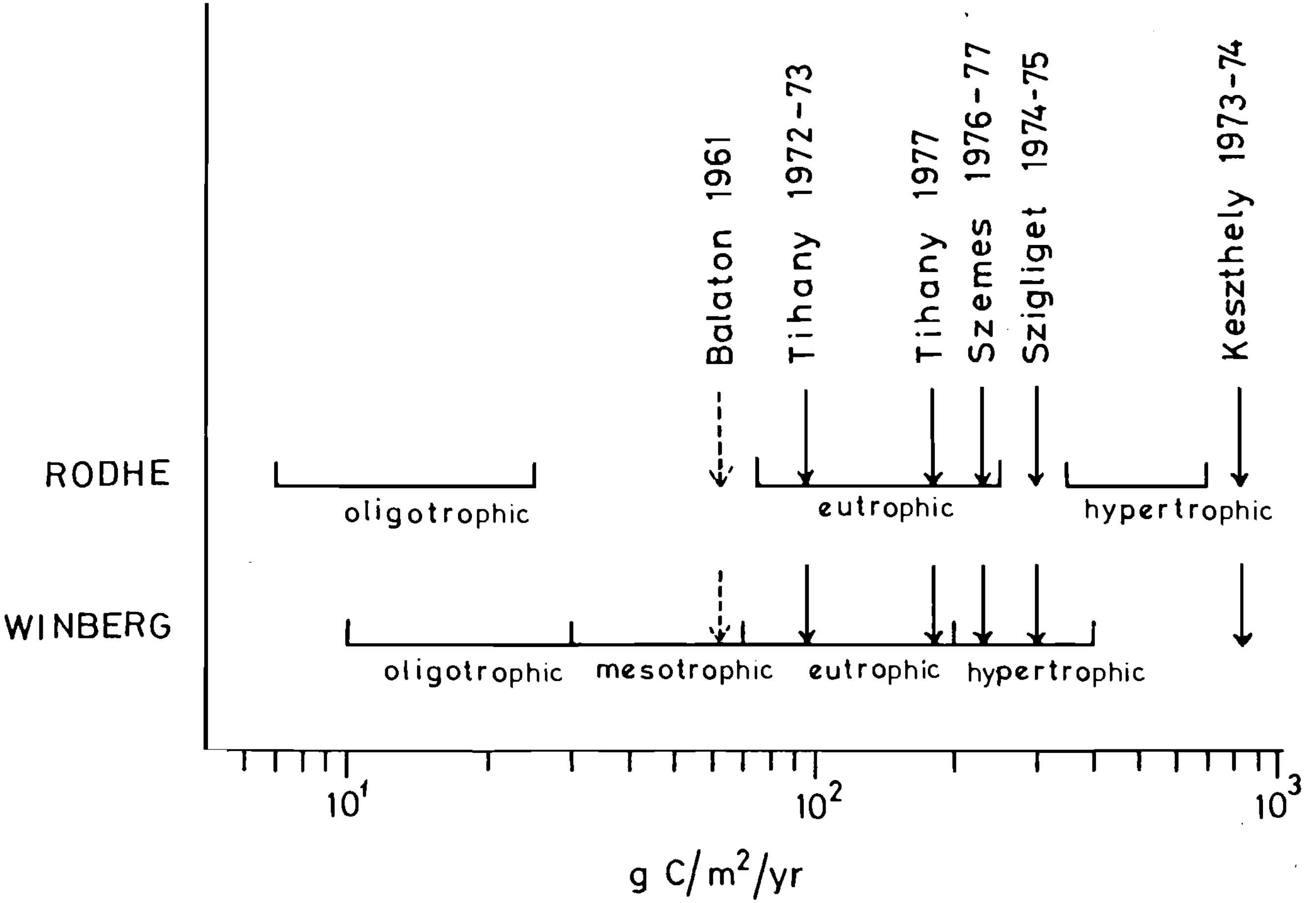


Figure 26. Yearly primary production in the different Balaton basins as compared to the trophic state scales of Winberg and Rohde.

4.3.4 Bacterioplankton

The total bacterial numbers observed at Tihany and Keszthely are presented in Figure 27. In the early years bacteria counts showed a minimum during summer in the less eutrophicated parts of the lake, but recently summer peaks typical for eutrophic waters are observed even at Tihany. From the figure it is clear that despite of the fluctuations from year to year there is a definite increase in bacteria numbers. Only limited information on the limnological importance of the bacteria is available. According to an estimate made for the late sixties (Oláh, 1973) the bacterial production (2.8 x 10^5 metric ton fresh weight/year) would correspond to 1/3 of the primary production at that time. Since the accumulation of organic matter in the lake is low (see section on sediment), and the consumption of phytoplankton by animals is low too (see below), most of the organic matter, produced by the algae must be decomposed by the bacteria.

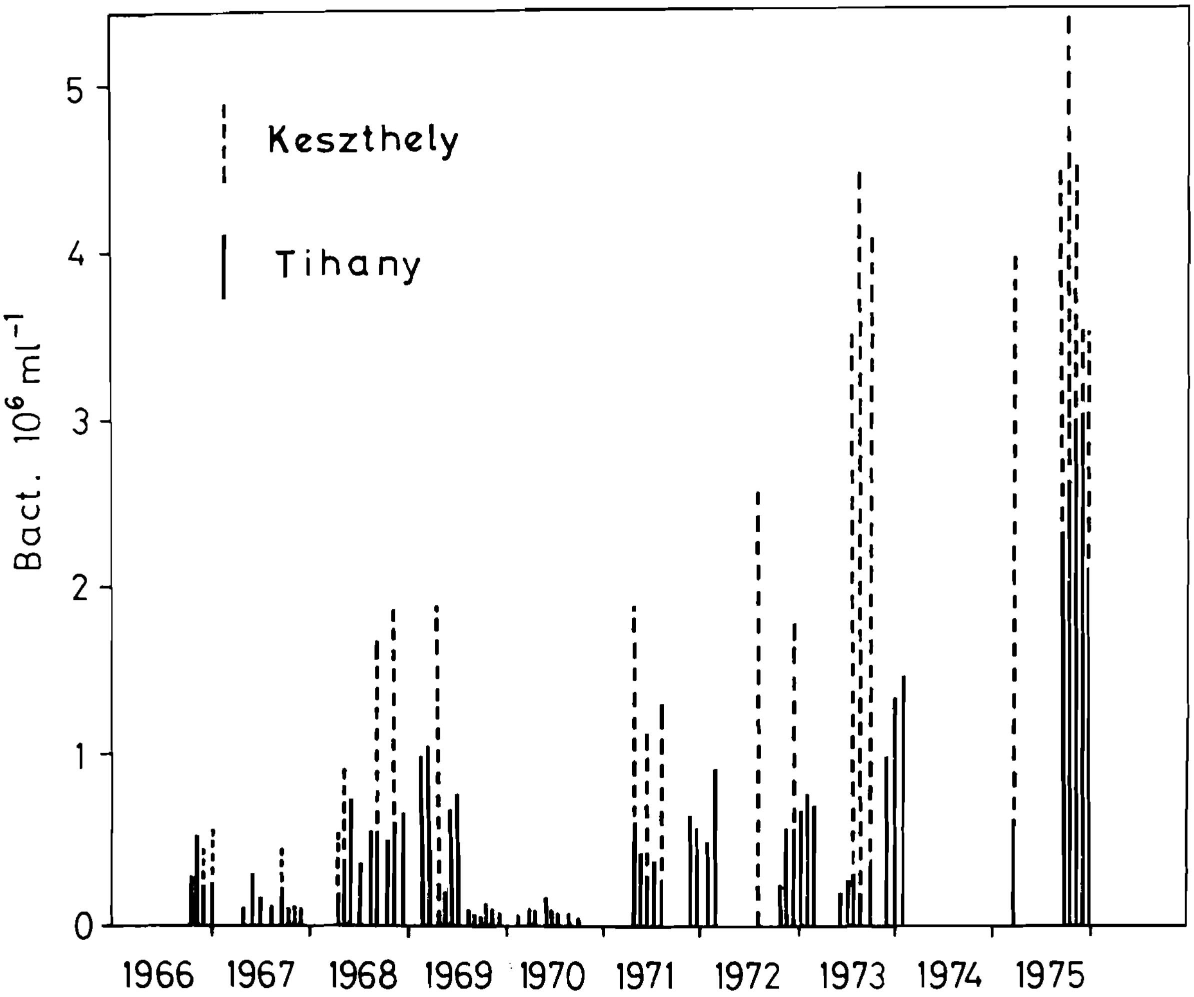


Figure 27. Bacterial numbers at Tihany and Keszthely since 1966 (after Oláh et. al., 1978).

4.3.5 Zooplankton

The zooplankton consists of protozoons, rotiphers, mollusc larvae and crustaceans. The crustaceans are the most imported in the metabolism of the lake, but even their quantity is low as compared to that in other lakes. In the period 1965-1967 the average biomass was 1.1 mg fresh weight/l in the Keszthely, 0.9 mg/l in the Szigliget and 0.7 mg/l in the other parts of the lake, i.e. 1/5 to 1/10 of the phytoplankton biomass. (Ponyi, 1977). The nutrition and population dynamics of the prevailing Eudiaptomus gracilis, a filter-feeder, was studied in detail (e.g. Zánkai and Ponyi, 1976). The egg numbers are high, and correspond to the trophic state of the basins. But at the same time the number of copepodits and adults are low in all the basins (e.g. 7 ind./l at Tihany), indicating a high mortality of as yet unknown origin. The nutrition depends on food concentration and temperature. One adult filters 1.4 ml lake water per day in summer and 0.1 ml/day in winter. The production of this species was estimated as 0.36 g C/m^2 yr at Tihany and 0.41 g C/m^2 yr at Keszthely. Apparently, zooplankton consumes only a low fraction of the phytoplankton, and they are not a major link between algae and fish.

4.3.6 Zoobenthos

The most important representatives of the zoobenthos are the chironomid larvae. Some data are reported in the literature. During 1964 Chironomus plumosus reached a maximum of 1900 ind/m^2 and 32 g fresh weight/m^2 (in the order of 1 g C/m^2) in the middle of the lake in autumn. (Entz, 1965). In 1973-74 Tanypus punctipennis reached a maximum of 9800 larvae/m^2 (1.4 g C/m^2) in February, at the end of the ice-cover period. In summer the biomass dropped to 0.1 g C/m^2. According to the same study the energy flow through the Tanypus punctipennis population would be about 4% of the total primary production (Oláh, 1976). Both biomass and species composition of the zoobenthos are affected by the increasing eutrophication.

4.3.7 Fish

In the Balaton 47 fish species are known. The annual commercial fish yield amounts to 1200 metric tons, mostly bream (Abramis brama, 70-80%) and pikeperch (Stizostedion lucioperca, 6-12%). The average biomass of the bream is 160 kg/ha, the annual net production 73 kg/ha, the annual catch 17 kg/ha, and the survival rate is 38%. (Biró and Garádi, 1974). The bream feeds mainly on benthic animals, and its population seems to have increased in the last decade. The much more valuable pikeperch is a predatory fish predating on smaller fishes. The average biomass is 10 kg/ha, the annual net production 5 kg/ha, the annual catch 2 kg/ha and the survival rate 35%. The population decreases due to the loss of natural shore, the high fishing pressure and the deletorious effects of cultural eutrophication (Biró, 1977).

In May 1965 there was a large fish kill (500 metric tons) in the whole lake. Pollution by DDT was held responsible for this, but no unambiguous proof could be obtained. DDT is no longer in use in Hungary at present. A smaller fish kill (70 metric tons) occured in February 1975, restricted to the second basin of the lake. The cause has remained unknown.

4.4 THE ROLE OF THE SEDIMENT

Due to a combination of a large free surface area and shallowness there is a steady interchange between the waterbody and the lake sediment in lake Balaton. Currents and waves induced by the wind play a major role in the movement of the bottom deposits. Generally, the southern shore is more exposed to the wind so that a broad strip along the shore line consists of sand mainly. Most of the organic detritus is sedimented in the deeper parts and along the northern shore.

The organic content of the mud is roughly 2% by dry weight, a relatively low value most likely due to the steady swirling up of the topmost layers. About half of the dry weight is calciumcarbonate, and the majority of the rest consists of fine grain silica components. Some data material is available on the concentration of nutrients in the sediment. Figure 28 shows a spatial distribution of the total phosphorus and total nitrogen content per unit dry weight (Tóth L., 1976). In agreement with this Oláh et. al., (1977) reported total phosphorus values of 400-600 mg P/g

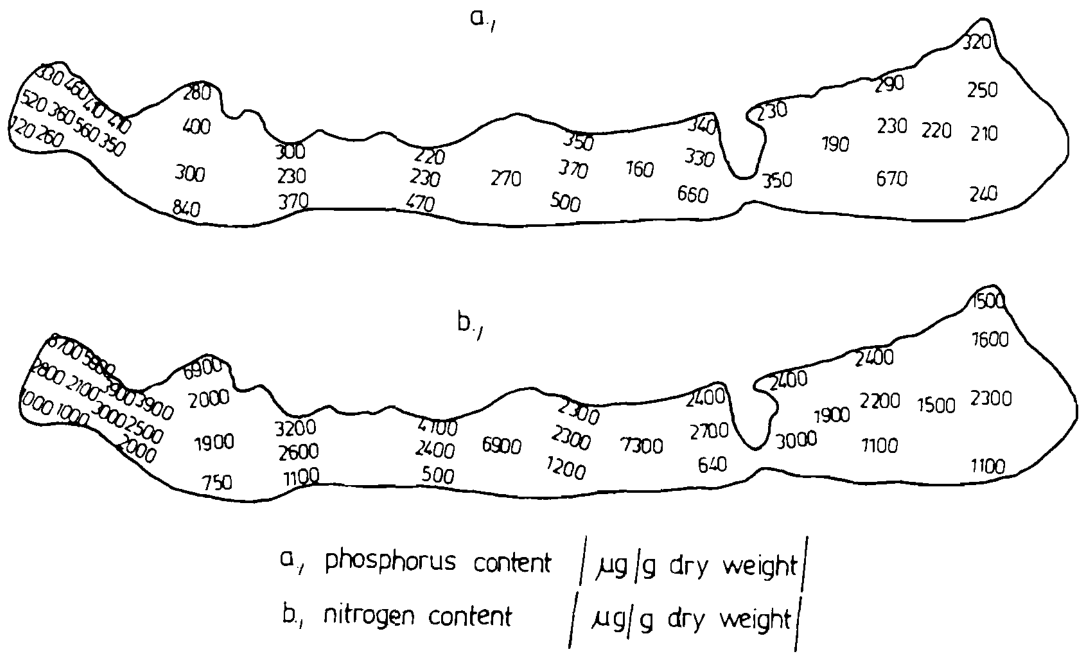


Figure 28. Total phosphorus and nitrogen content of the sediment (after Tóth L., 1976).

dry sediment, without a clear longitudinal gradient. The few measurements available indicate that a considerable fraction of this phosphorus is bound to organic material. Under the assumption that most of this material is detritus a carbon to phosphorus ratio of 60 to 80 might be a reasonalbe estimate, so that, with 2% organic carbon content, an organic bound phosphorus concentration of 250 to 300 mg P/g dry weight can be expected, i.e. 30-60% of the total. Extraction experiments indicate that between 20 and 30% of the sediment phosphorus is probably bound to calciumcarbonate (Oláh et al., 1977). Recent results seem to attribute a similar important role to iron compounds in the binding of phosphorus (Dobolyi, pers. comm.).

Even fewer reliable measurements data are known for the interstitial water. According to Dobolyi (pers. comm.) the following concentrations have been observed: iron 13-15 mg Fe/l, calcium and magnesium 40-60 mg/l, ortho-phosphate 70-100 mg P/l. These data refer to the anaerobic part of the sediment. No vertical gradient in the interstitial water could be detected within the vertical resolution that can be reached experimentally (5 cm). It should be noted that the oxidized zone of the sediment is only a few centimeters thick (see Figure 29, Oláh, 1975).

A question of extreme importance is how much of the phosphorus is the mud is biologically available for algal growth in the water, preceeded by the question how much is really released. An indication of the importance of exchange by wind action can be obtained from an analysis of the events on April 28 and 29, 1977, on the

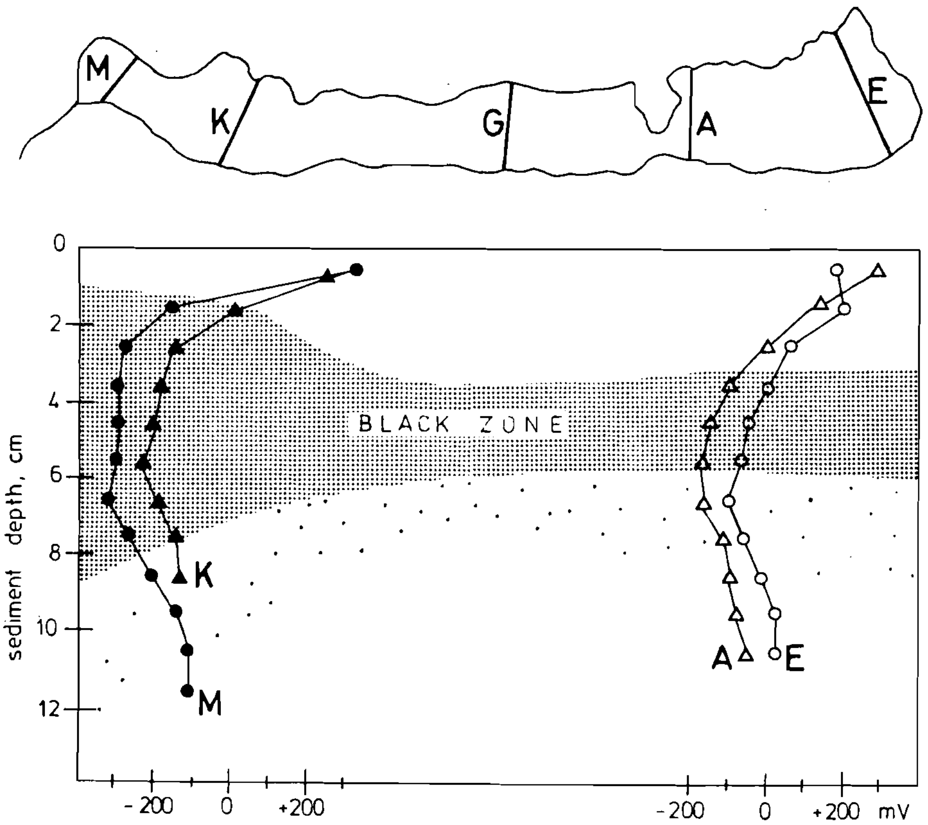


Figure 29. Redox profile and thickness of oxidized zone (after Oláh, 1975).

basis of the phosphorus data according to appendix D. A heavy storm prevailed during the second day, sweeping up the lake's sediments as indicated by the sharp rise in suspended solids. Consequently, a likewise dramatic change was observed in the particulate phosphorus fraction, not only in inorganic form but also, and even more in organic form. This underlines the importance of the organic phosphorus in the sediment, and mineralization of this material will recycle phsophorus to the algal system. One may postulate, however, that it does not make much difference whether this mineralization occurs in the watercolumn or in the top layer of the mud. In contrast to the particulate fractions no rise in dissolved phosphorus was observed, and consequently the direct mixing up of phosphorus rich interstitial water seems to have a less important effect. Furthermore, it appears that much calciumcarbonate particles are brought into the water, of which especially the very fine particles remain after the storm. According to Oláh et. al., (1977) these particles are very effective in adsorbing dissolved phosphorus. In the picture above wind mixing would not be an extremely important factor in the release of available phosphorus during storms, but more research is needed.

Under anaerobic conditions (simulated in the laboratory) a considerable phosphorus release has been observed ranging from 1-4 mg P/m^2 day from midlake to Keszthely Bay respectively. (Oláh et. al., 1977). However, as pointed out earlier, such conditions hardly occur in practice. Release rates by diffusion in calm periods under normal aerobic conditions would be an order of magnitude lower at least.

Summarizing the above one has to state that relatively little is known about the sediment and its possible or potential role as an internal nutrient source, and there is a need for more detailed and concentrated research in this area.

5. NUTRIENT LOADING

In this chapter the available information on nutrient loading will be summerized and discussed. The discussion will be centered around phosphorus as the most generally limiting nutrient. Another reason for the emphasis on phosphorus rather than nitrogen is, that phosphorus is certainly a better controllable factor than nitrogen in a watershed so much oriented towards agriculture as is the Balaton basin.

There are two different, but complementary approaches to the nutrient loading problem. In the first approach data are obtained from monitoring the incoming streams and direct effluent discharges to the lake. The regular monitoring points available for this purpose are shown in Figure 30. Of the streams 20 are included in the regular water quality sampling network. The sampling frequencies vary between 6 and 52 (for the Zala, since 1975) samples per year. Furthermore, from 2-6 measurements yearly are available for some 50 larger point sources in the area. Apart from the regular sampling network results from a field study in a subwatershed aimed at the detailed determination of the run-off loading contribution are of interest.

The second approach tries to evaluate the phosphorus cycling flows associated with the different activities in the water basin. From this, estimates of the nutrient losses to the lake are made based on available evidence ranging from detailed measurements to rough rules-of-the-thumb.

In the next sections the results of the two approaches are presented, evaluated and compared. Also the longitudinal distribution of the loading is estimated and where possible account is given to the important question how much of the total phosphorus reaching the lake would be really available for algal growth.

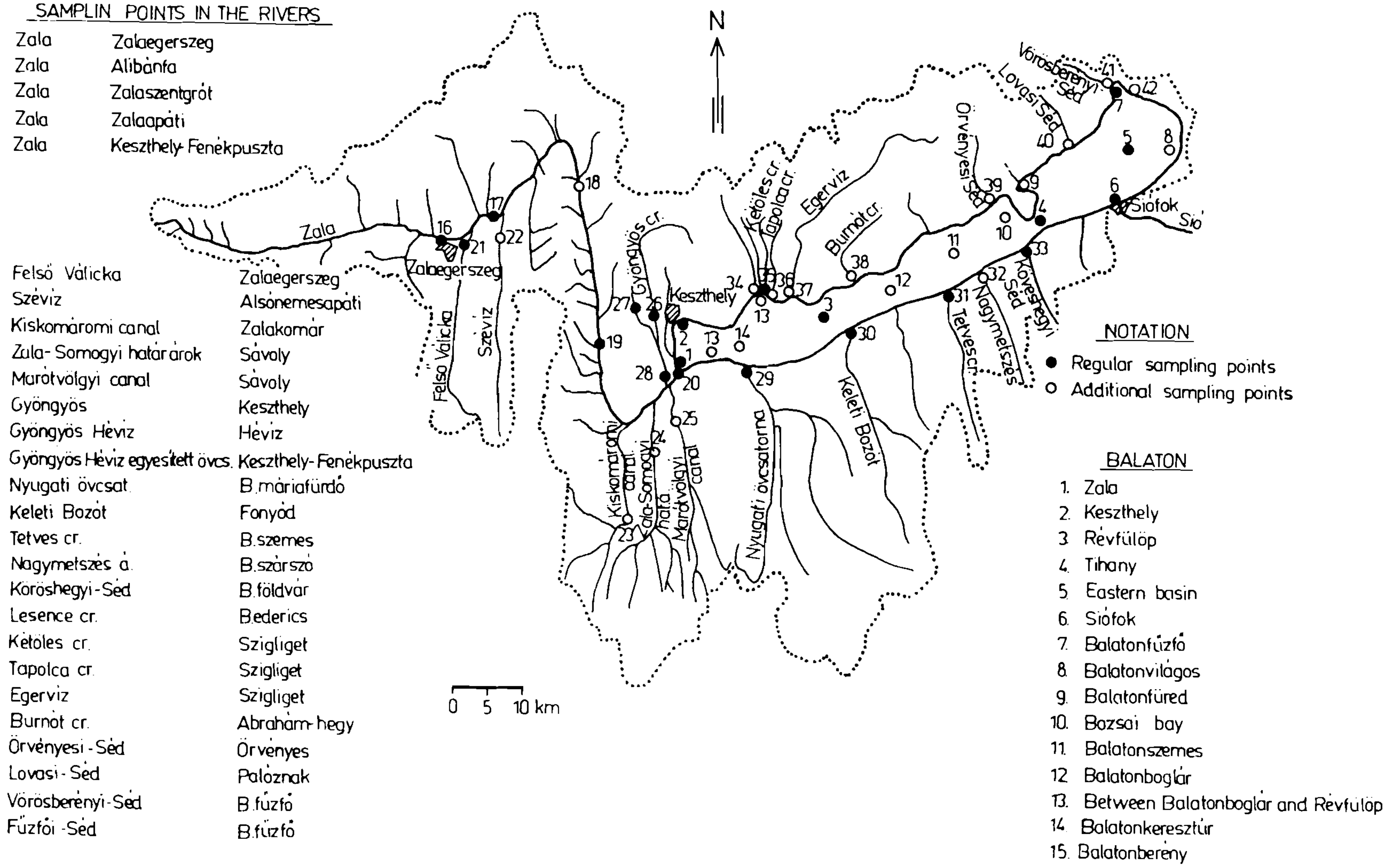


Figure 30. Water quality sampling stations in the Balaton basin.

5.1 IN-STREAM MONITORING OF NUTRIENT LOADS.

One of the earliest nutrient loading estimates was made by Jolánkai (1976) who used the monthly monitoring network data for 1972-1974. These data are shown in Table IX for phosphorus and in Table X for nitrogen (first and third column). Estimates for the contribution of sewage are given too. However, based on more detailed measurements in the Zala River, starting from 1975 on a weekly, and sometimes daily basis, Joó (1976) corrected the table, based on the observation that much of the nutrient loading occured during storm water events. If only monthly measurements are done, these events are easily missed, and the loading is underestimated.

Table IX. Phosphorus load, 1972-1974: (1) Jolánkai (1976), based on low-frequency monitoring network; (2) Joó (1976), extrapolated based on detailed monitoring in the Zala.

	Total-P (kg/day)			
	Total		From sewage	
Source	(1)	(2)	(1)	(2)
Zala	215	550	61	61
Northern shore streams	172	450	10	10
Southern shore streams	173	450	10	17
Direct sewage	132	150	132	150
	692	1600	213	238

Table X. Nitrogen load, 1972-1974: (1) Jolánkai (1976), based on low-frequency monitoring network; (2) Joó (1976), extrapolated based on detailed monitoring in the Zala.

	Total-N (kg/day)			
	Total		From sewage	
Source	(1)	(2)	(1)	(2)
Zala	690	2740	664	664
Northern shore streams	520	2100	100	100
Southern shore streams	276	1100	68	68
Direct sewage	1024	2000	1024	2000
	2510	7940	1856	2832

Accordingly, the data for the smaller streams are extrapolated on the basis of the ratio between correct loading and loading estimates from monthly observations for the Zala (second and fourth column). In these columns also the waste water loadings were updated on the basis of more accurate measurements.

It is important to note that the evaluation of loading data from a few years of observations does not give a complete picture of the average loading conditions, or trends in the loading. From Tables IX and X it can be seen that the storm events may carry as much as 50 to 70% of the total load. Thus, years with many stormwater events probably will cause higher nutrient loadings. The degree of time variability is illustrated in Figure 31 showing the results of the weekly monitoring for the Zala River, since 1975, and also in Table XI. From this and the previous tables it can be concluded that the phosphorus load may differ by a factor of two or three among the years. Comparison of total and orthophosphorus in Table XI shows, that the variation in the latter on a half-year basis is much less than in total phosphorus. This suggests that much of the ortho-phosphorus load is associated with regular sources, i.e. waste discharges or effluents. The reported ortho-phosphate waste discharges (between 40 and 60 kg/day for the Zala region) make up 50-70% of the total orthophosphorus load. On top of the sewage part comes a fluctuating contribution, as is illustrated by the monthly data shown in Figure 32. The slightly increasing trend might be associated with the progressing development in the watershed (population, sewage systems).

From Table XI and Figure 31 it can be concluded, that most of the event-based total-phosphorus load is in the particulate form, underlining the importance of run-off and erosion.

In order to provide a better inside in the extent of run-off and erosion processes a special study was conducted during 1975 and 1976 in a small subwatershed (70 km^2), in which disturbing processes were minimal (Jolánkai and Dobolyi 1976, Jolánkai

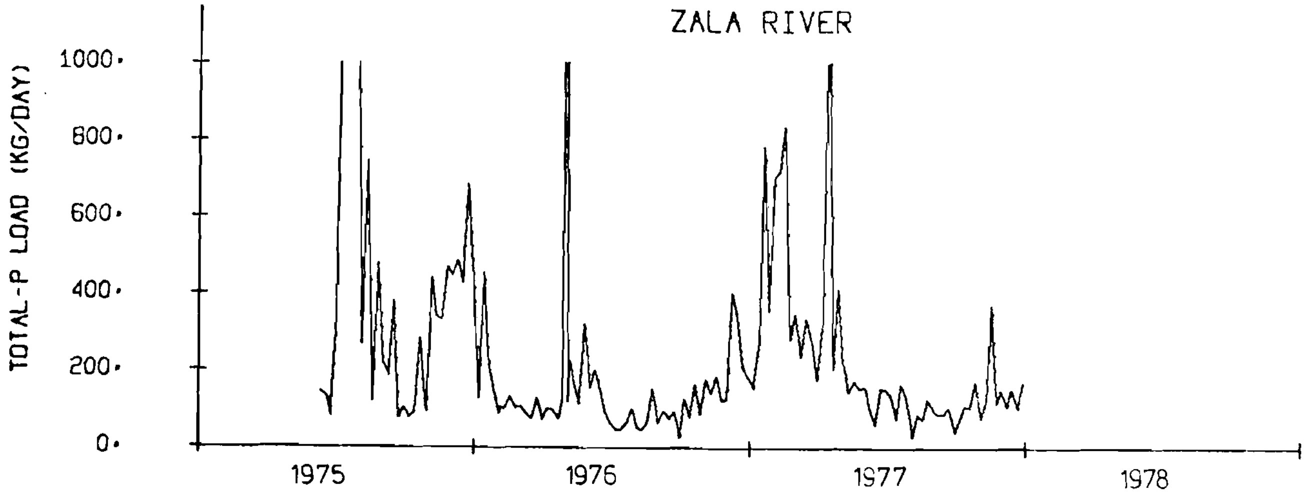


Figure 31. Total phosphorus load carried by the Zala River.

Table XI. Nutrient loads from the Zala watershed (calculated from weekly data of the West-Transdanubian Water Authority).

		1975 1st	1975 2nd	1975	1976 1st	1976 2nd	1976	1977 1st	1977 2nd	1977
Average flow:	m^3/s									
from weekly data			7.7*	-	6.8	4.6	5.7	11.3*	3.8	7.5
from water balance			5.0	-	6.8	4.1	5.5	8.2	3.7	6.0
PO_4-P	kg/day		106	-	110	50	80	97	84	90
Total-P	kg/day		700*	-	170	112	115	350*	116	233
NO_3-N	kg/day			-			1100			930
Total-N	kg/day			-			1700			2300

Waste water in the watershed:

		1975	1976	1977
PO_4-P	kg/day	56	51	45
Total-P	kg/day	117	70	95
NO_3-N	kg/day	214	-	38
Total-N	kg/day	603	678	700

*Data from weekly monitoring less certain because of considerable flood waves in these periods.

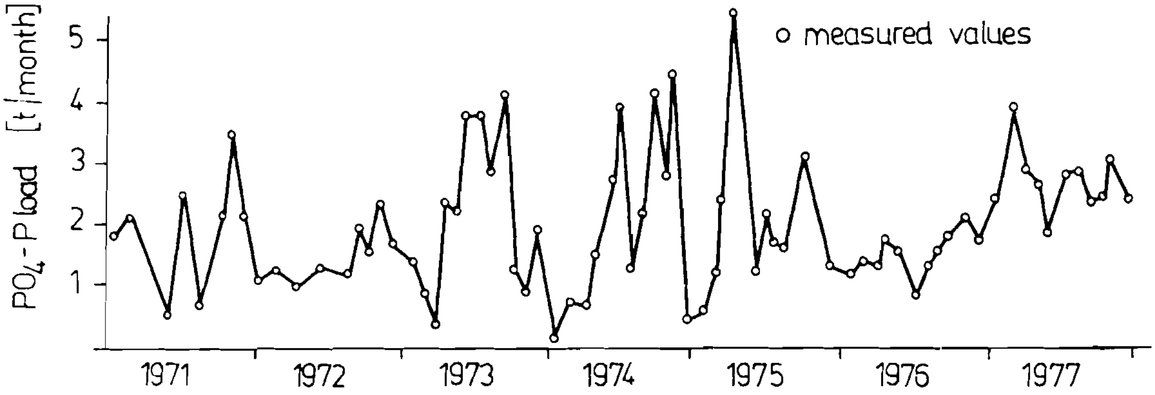


Figure 32. Monthly ortho-phosphorus load carried by the Zala.

1977). The measurement frequency was high, sometimes up to 3-15 measurements per day during rainfall episodes. Table XII provides a summary of this nutrient run-off study.

Several interesting conclusions can be made on the basis of this data material. Perhaps the most striking effect is that not less than 80% of the total-P load is contained in the floods. Most of this phosphorus is in particulate form (more than 80% of the total, as compared to 50% during base flow). Generally, the concentration of particulate phosphorus increases with increasing discharge rate. It should be noted that it is possible to explain these results in two ways: it may be due to surface run-off or to resuspension from the sediments in the brooks and creeks. However, the lack of increase in total organic carbon (TOC) during flood periods suggests that the first mechanism is dominant, and whatever the mechanism may be, phosphorus accumulated in the brook sediments must originate from the land in this agricultural watershed anyhow. Apart from the phosphorus the nitrogen is of interest too. Here the picture is completely reverse, conforming the easy leaching of nitrate even during base flow.

Table XII. Summarized results of nutrient run-off studies carried out on a sub-watershed of the Tetves Creek (70 km^2) during 1975 and 1976 (after Jolánkai, 1977).

		NO_3-N	Total-P	Dissolved P	PO_4 P	TOC	TSS
Base flow	kg/yr	13300	2370	1260	540	23570	214,000
Floods	kg/yr	3350	10410	1790	1150	21140	2,746,000
Total	kg/yr	16650	12780	3050	1690	44510	2,960,000
Average	kg/day	45.6	35.0	8.36	4.61	122	8110
Yield	kg/ha,yr	2.37	1.82	0.44	0.24	6.35	422

On the basis of the calculated yield coefficient of 1.82 kg P/ha yr Jolánkai computed the total-P loading as 2590 kg/day for the whole Balaton by extrapolation. However, the detailed data on the Zala River indicate for the Zala watershed a total-P yield of 0.7 kg P/ha yr at most. This can be explained by the lower average slope in the Zala region (see appendix A). Similarly, the average slopes are different for all four watersheds connected to the four basins. If the value found for the Zala is taken as the lower limit, a slighty higher value than that found for the Tetves basin as the upper limit, and if a proportionality with the square root of the average slope is assumed, the yields are estimated as 0.7, 1.1, 1.6 and 2.2 kg P/ha, yr for the four basins from Keszthely to Siofok respectively. Consequently, an extrapolated load of about 1350 kg P/day, exclusive sewage, is calculated, which is in good agreement with the values given in Table IX.

5.2 PHOSPHORUS LOAD FROM SOURCE EVALUATION.

In the second approach to the phosphorus loading problem an evaluation is made of the phosphorus cycle associated with the various activities and processes in the watershed. The main sources of phosphorus pollution are listed in Figure 33. Also shown are estimates for the different loadings according to a study by Horváth and Kamarás (1976), and with respect to the contribution of rainfall and dust on data from Dobolyi and Horváth (1973), (rightmost colum). It should be emphasized, however, that some of the data quoted are, in fact, debatable if confronted with evidence from other literature sources and from the previous section. Furthermore, the picture is far from complete and additional research seems to be needed.

In order to reassess the contribution of each of the sources a brief discussion follows below, leading to the restated source contribution shown in the encadred fields of Figure 33.

a) Fertilizer use and erosion

A summary of the present and planned fertilizer use in the Balaton region is given in Table XIII.

The basin average for 1975 of 243 kg/ha arable land is equivalent with roughly 27 kg P/ha, or some 8500 tons P/yr (23,000 kg P/day). Clearly, the amount of fertilizer used in the watershed is one or two orders of magnitude higher than the total phosphorus load estimated in the previous section. The first principal question is: how much of the phosphorus applied is lost to the waterbody? And a second question is: which percentage of this loading is potentially available for algal growth? In the international literature contradictory answers are given. One of the reasons why this problem is hard to solve is that, in practice, it is difficult to distinguish between phosphorus already present in the eroding soil and phosphorus adsorbed to the soil originating from fertilizer application. It is obvious that the question can not be fully solved on the basis of data available for the Balaton.

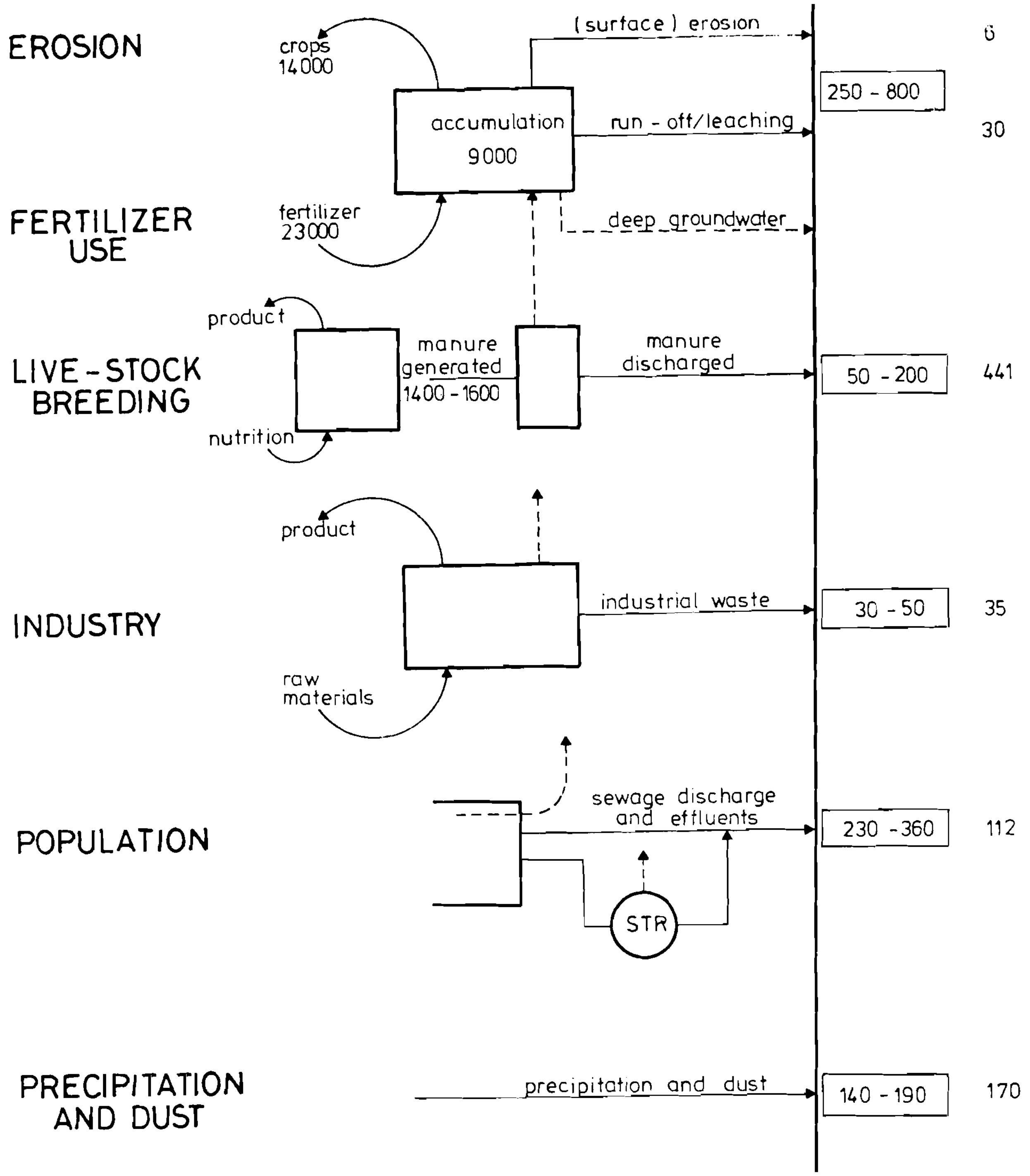


Figure 33. Total-phosphorus loads from different sources (in kg/day) right-most column: after Horváth and Kamarás, 1976; encadered column: this report. Potentially available phosphorus: see text.

Table XIII. Present and planned fertilizer application in kg fertilizer equivalent per ha arable land (Balaton Atlasz, 1975).

Year	N. basin	S. basin	Zala basin	Total Balaton
1971	213	204	181	194
1975	289	285	205	243
1980	388	350	250	305
1985	448	430	285	357

Therefore we limit the discussion to some remarks and considerations.

-- The value of 36 kg P/day for erosion and fertilizer loss together, qiven by Horváth and Kamarás seems to be an order of magnitude too low in the light of the data presented in the previous section. If one adopts the common assumption that 1 to 2% of the applied fertilizer is lost to the environment a total P-load of 230-460 kg P/day results. On the other hand, most of this phosphorus would be in particulate form, and with a readily soluble fraction of, say, 20% the fertilizer loss would correspond with some 40-80 kg P/day available phosphorus, more in agreement with but still higher than the value mentioned by Horváth and Kamarás.

-- Irrespective of the above it is clear that the fertilizer use represents a significant potential danger. An increase in the loss percentage from 2 to 3% only, for instance by inadequate timing of the fertilize application, would bring some additional 250 kg P/day of total phosphorus to the surface water.

-- If one reckons that at most 60% of the fertilizer applied is taken up by the harvested crop, and if the loss to the water is not more than 1-2%, some 40% of the fertilizer would accumulate in the soil. This is equivalent to an annual accumulation of 10 kg P/ha. Although the sorption capacity seems high enough to endure such enrichment it is uncertain how long this process could last without loss to the open water. Since significant soil enrichment has not been reported a perhaps more likely hypothesis is that most of this surplus phosphorus is eroded from the land. This does not necessarily mean that it also reaches the lake immediately. In the Zala region, for instance, the sediment delivery ratio, i.e. the ratio of the suspended solids discharge to the lake and the calculated sediment losses (see chapter 2.3), is only a few percent. This implies that most of the eroded material is settled somewhere in the watershed, building up a large potential reservoir of particulate phosphorus that might be mobilized at extreme storm water events.

-- Although on the average the fertilizer use is about 25 kg P/ha much higher values are applied occasionally, and most notably in wineyards. At first sight the role of wineyards seems to be limited because wineyards and orchards occupy only 6% of the total land surface (cf. appendix B). However, they are usually situated on the steepest slopes (see Table II in section 2.3), and moreover very often directly along the lake's shores. Consequently, the sediment delivery ratio is close to one and the proportion of readily soluble phosphorus is probably higher. Thus, the contribution of wineyards to the loading can be quite significant and should be taken into account, the more so since the direct run-off will not be detected by any stream monitoring program.

b) Livestock breeding

Large scale specialized livestock breeding farms are mostly situated in the north-western part of the Balaton catchment area, thus contributing to the Keszthely and Szigliget basins mainly. According to Ábrahám (1976) about 800-900 x 10^3 m^3 liquid manure is generated annually. With concentration data given in the same publication a yearly generated amount of 1450 kg P/day results. This is in good agreement with the estimate of 1600 kg P/day given by Horváth and Kamarás. According to the latter authors approximately a quarter of this amount reaches the surface water at present. This would be a significant loading, especially because these wastes mostly consist of soluble or readily soluble phosphorus. However, for the same reason the nutrient value is quite high, facilitating the economic utilization in agriculture, and it may be expected that this source can be controlled effectively in the near future. It must also be noted that such high orthophosphorus loading do not show up in the stream monitoring, suggesting that the estimate of 25% loss is too high.

c) Sewage loading

An important point source of pollution is formed by domestic sewage discharges, originating from the inhabitants, and, in summer, from the tourists too. According to Szabó (1976) settlements and population in the Balaton watershed are as follows (cf. also appendix B).

Table XIV. Settlements and population.

	Number of settlements			Population in 10^3		
	Watershed	Shore	Total	Watershed	Shore	Total
Zala	176	1	177	176	4	180
Northern	50	24	74	44	62	106
Southern	49	17	66	65	54	119
Total Balaton	275	42	317	285	120	405

In the Zala region approximately 20% of the population is connected to a public sewage system, and between 30 and 40% in the other Balaton regions. The total amount of sewage is estimated on roughly 25 x 10^6 m^3/yr (1975) of which at present circa 1/5 is treated. With an average value of 4.5 g P/m^3 the phosphorus load associated with sewage can be estimated as roughly 300 kg P/day. (cf. also Table IX). An increase of this amount may be expected with the further construction of sewage systems as part of the regional development, if not at the same time tertiary treatment plants are installed.

It should be pointed out, that the sewage loading is not evenly distributed over the year as demonstrated in Tables XV and XVI. Thus, during the two summer peak months July and August the normal discharge is doubled. An impression of the variability among the years can be obtained from Table XVII. Generally, no very strong fluctuations are observed for nutrients.

For modeling purposes also the distribution of the sewage load in the longitudinal direction is of interest. Clearly a complete picture can only be obtained by evaluating the measurement results for each sewage treatment plant. Since these data are not available at present a rough preliminary estimate has been made based on the population density, the sewage-connection ratio and the tourist intensity. The results are shown in Table XVIII.

d) Precipitation and dust

The contribution of precipitation and dust directly falling onto the lake's surface has been studied recently by Dobolyi and Horváth (1978). Based on the data obtained the following loading estimates can be made (Table XIX).

Table XV. Seasonal variation of direct sewage nutrient discharges on the Northern shore in 1975 (Kiss, 1976).

		Off-season	Tourist-season
Total-N	kg/day	119	338
Total-P	kg/day	28	60

Table XVI. Seasonal variation of direct sewage nutrient discharges on the Southern shore (data obtained from Kaurek, South Transdanubian Water Authority).

		Off-season	Tourist-season
Total-N	kg/day	181	263
Total-P	kg/day	32	71

Table XVII. Waste water pollution loads on the Southern catchment area (kg/day) (based on data of the South Transdanubian Water Authority).

	1974	1975	1976	1977
NH_3-N	308	160	173	
NO_3-N	4	2	12	
Kjeldahl-N	340	263	238	303
PO_4-P	51	33	31	
Total-P	118	71	108	103
BOD_5	700	1020	2130	
TSS	295	645	1110	

Table XVIII. Preliminary estimates of total phosphorus loading contribution from sewage to each of the basins.

	kg/day	
Basin	Direct sewage	Indirect sewage
I	± 20	± 100 (Zala)
II	± 30	± 20
III	± 40	± 10
IV	± 80	-
	± 170	± 130
	Total: ± 300 kg/day	

Table XIX. Nutrient loads from precipitation and dust directly on the lake's surface.

Nutrients	Load (kg/day)
Total-N	2893
NO_3-N	503
NO_2-N	33
NH_4-N	2341
Total-P	170
PO_4-P	104

It should be noted that the load of 100 kg P/day for orthophosphate would correspond with a rainfall concentration slightly less than 100 mg P/m^3, which is one order of magnitude larger than the concentration observed in the lake's waterbody.

e) Other sources

A few other potential nutrient sources exist that have not been studied yet, but which contribution cannot be neglected a priori

-- pollution caused by water contacted recreation (bathing etc.). On top days in the tourist season about 600,000 visitors recreate on the lake's shores.
-- quanotrophy, i.e. pollution by water-birds. Especially in autumn huge amounts of water-birds are staying on the lake until it freezes.
-- increasing commercial navigation (tourist boats), though generally the tourist vessels operate under strict hygienic rules.

5.3 SUMMARY OF PHOSPHORUS LOADING AND LONGITUDINAL DISTRIBUTION

To conclude this chapter on nutrient loadings we summerize the discussion in the previous sections with a table of the restated total phosphorus input estimates. (Table XX, cf. also Figure 33). Also a very rough attempt is made to indicate which part of the total phosphorus would have to be considered as available for algal growth. The longitudinal distribution of the non-point source pollution is approximately 1 : 1 : 0.45 : 0.3 for basin I through IV respectively, and 0.1 : 0.25 : 0.25 : 0.4 for the sewage contribution, exclusive the Zala sewage load.

Table XX. Tentative estimates of present total and available phosphorus loading of Lake Balaton.

	Total-P		"Available"-P		
	kg/day	%*	Fraction available	kg/day	%*
Fertilizer loss, erosion, run-off resuspension	250-800	46	0.2	50-160	16
Liquid manure	50-200	11	1.0	50-200	20
Industry	30-50	4	1.0	30-50	6
Direct sewage	150-200	15	1.0	150-200	27
Indirect sewage	80-160	10	0.9	70-140	16
Precipitation	140-190	14	0.6	80-110	15
Total	700-1600			430-860	

*Percentages based on median values.

6. POSSIBLE CONTROL OPTIONS AND THE ROLE OF MODELING

As substantiated in the previous chapter there is little doubt that the increased nutrient loading, especially of phosphorus compounds, must be held responsible for the deteriorating water quality of the lake. Therefore, most logically, measures to prevent further escalation of the eutrophication process should in one way or another, concentrate on the reduction of the phosphorus inputs.

The choice of suitable measures or combinations of measures will be based largely on a judgement of the ratio between effectiveness on one hand, and costs on the other hand. In this context 'costs' should be interpreted in a broad sense, that is to say that any decision process somehow will have to take into account possible adverse (or beneficial) effects that can not be expressed in terms of money in a straightforward manner. How to deal with these intangibles is not of our concern now. Rather, we would like to list the different control options proposed and make some qualitative comments on the cost-effectiveness ratio in a more strict, if one likes technical, sense, given the information layed down in the previous chapters. But before doing this some remarks have to be made on aspects of effectiveness, and on the potential role of (water quality) models in the decision on different management alternatives.

When speaking about effectiveness of a measure with respect to eutrophication it would be usefull to make a two-step distinction. First, there is the effectiveness of a measure to reduce the inputs to the lake. The evaluation of this type of effectiveness might be straight-forward, such as in the case of tertiary treatment or sewage deviation, or require a more comprehensive insight in the processes that determine inputs, such as in the case of improvement of fertilizer application or land use techniques. In the latter case a mathematical model would be a very helpful tool to link the various complex phenomena in a systematic way, and to analyse the impact of different management options ("a watershed model"). Second, once the input reduction has been assessed, there is the need to evaluate the effectiveness of this reduction with respect to the process of eutrophication. For instance, a measure effective in reducing the unavailable phosphorus input to the lake will not be of much help in the control of eutrophication. Also in this category belongs the spatial distribution of the input reduction, because it is to be expected that an equal reduction of inputs has more effect in highly polluted regions of the lake than in lowly polluted regions. Clearly, the prediction of the reaction of the lake to changed inputs is of paramount importance in the evaluation of this second step of effectiveness. Here a sound quantitative judgement is virtually impossible without the help of mathematical models ("a waterbody model"). This is obvious from the complexity of the ecosystem as described in the previous chapters.

Perhaps at this place a further example to elucidate the importance of water body modeling might be helpful. In discussing the effects of reducing nutrient inputs on eutrophication it should be realized that a lake system is not necessarily an easily reversible system. In other words, due to the buffering capacity of the lake sediments long delays in response to loading reductions might occur. In the case of Lake Balaton there are reasons to believe that the situation is still rather favourable in this respect. This is because the presently low storage of organic material in the sediment and the high calciumbicarbonate content which will remain effective in keeping dissolved inorganic phosphorus concentrations low. However, it would be shortsighted to conclude that these processes will last for ever and cannot be inactivated. Continuous high loadings may distrub the equilibrium, especially if they lead to anaerobic conditions at the bottom of the lake, and this could spoil the lake for years and years. Clearly, whether this occurs or not can only be answered with the help of a sufficiently comprehensive model. Of course, the development of such a model is not an easy task. After all, no model can be better than its underlying data base (stressing the need for adequate data collection). But even if the desired model does not yet exist, the process of its development is of tremendous help to detect dark spots in our knowledge, and to guide appropriate research efforts. Therefore, encouraging modeling efforts now facilitates problem-solution in the future.

In the meantime there is no reason to postpone management decisions until science has solved all relevant problems. Some measures could already be taken because their effectiveness is beyond doubt. No more would it be necessary to apply sophisticated economic optimization techniques here. Rather, relatively rough judgement would be sufficient in the preliminary stages of management, whereas the time for improved techniques will come later if decisions become more subtile and if associated costs become more excessive.

Let us, with this rather lengthy introduction in mind, briefly review the possible and proposed management alternatives for Lake Balaton. (Without claiming completeness).

The first and most important control tool would be the treatment of sewage waste water effluents, especially those in the Zala region and those discharging directly into the lake. A very high phosphorus reduction ratio can be achieved with relatively easy technical means, and at relatively low cost, so that the primary effectiveness of sewage treatment is high. Also the secondary effectiveness is high because sewage contains mostly phosphorus components that are easily available for algal growth. Full-scale tertiary treatment experiments are in progress in Balatonfüred. Another solution to prevent phosphorus inputs from sewage would be the deviation of (treated or untreated) sewage from the lake through a system of pipelines. Such proposals have been made, and are now considered for implementation in the Balaton Recreational Region, immediately around the lake. Figure 34 presents an overview of this concept. Sewage will be partially diverted from the lake's watershed, disposing the remainder in sewage irrigation and fish breeding ponds. Of course, deviation finally guarantees a maximum retention. However, there are some drawbacks too. The most obvious one that the deviated pollution will cause water quality problems elsewhere is perhaps less important in the given situation (the plan envisages extended treatment plant capacities for this reason). A more serious problem is that such a plan requires a long construction time, and in order to prevent the negative irreversible effects mentioned before, additional measures that can be implemented faster, such as tertiary sewage treatment, will not become superfluous. Finally, the diversion plan does not include the sewage from the Zala region.

A second important management strategy is the reconstruction of the Kis-Balaton (small Balaton), shown schematically in Figure 35 (Lotz, 1976). The essential feature of this solution, being under discussion as a set of alternative plans, is that along the downstream end of the Zala River a reservoir of 75 km^2 surface area (volume 10^7 m^3) will be constructed. This is practically equivalent to the re-establishment of a former marshland, that has been drained in the past century. The idea is that this marshland will act as a preliminary settling pond for the Zala River prior to discharge into the lake. In addition, emphasis will be put on keeping a high reed stand in the reservoir in order to remove dissolved phosphorus fractions from the water as well. Although the plan is rather costly a Kis-Balaton reservoir could be very instrumental in reducing the pollution loads from the main tributary to the lake, provided that sufficient environmental conditions can be maintained, such as shallow depth, limited water level fluctuations (to protect the reed) and a sufficient dissolved oxygen concentration. To assure the latter condition sewage treatment should not be ignored in the Zala watershed.

A third management alternative, with direct applicability, would be the (partial) dredging of the lake's sediment deposits, most notably in the Keszthely basin. However, such an operation is expensive and should only be considered in connection with other protective measures, and only if more close research has indicated a significant delay in response to nutrient input reductions due to the sediment buffering, as discussed before.

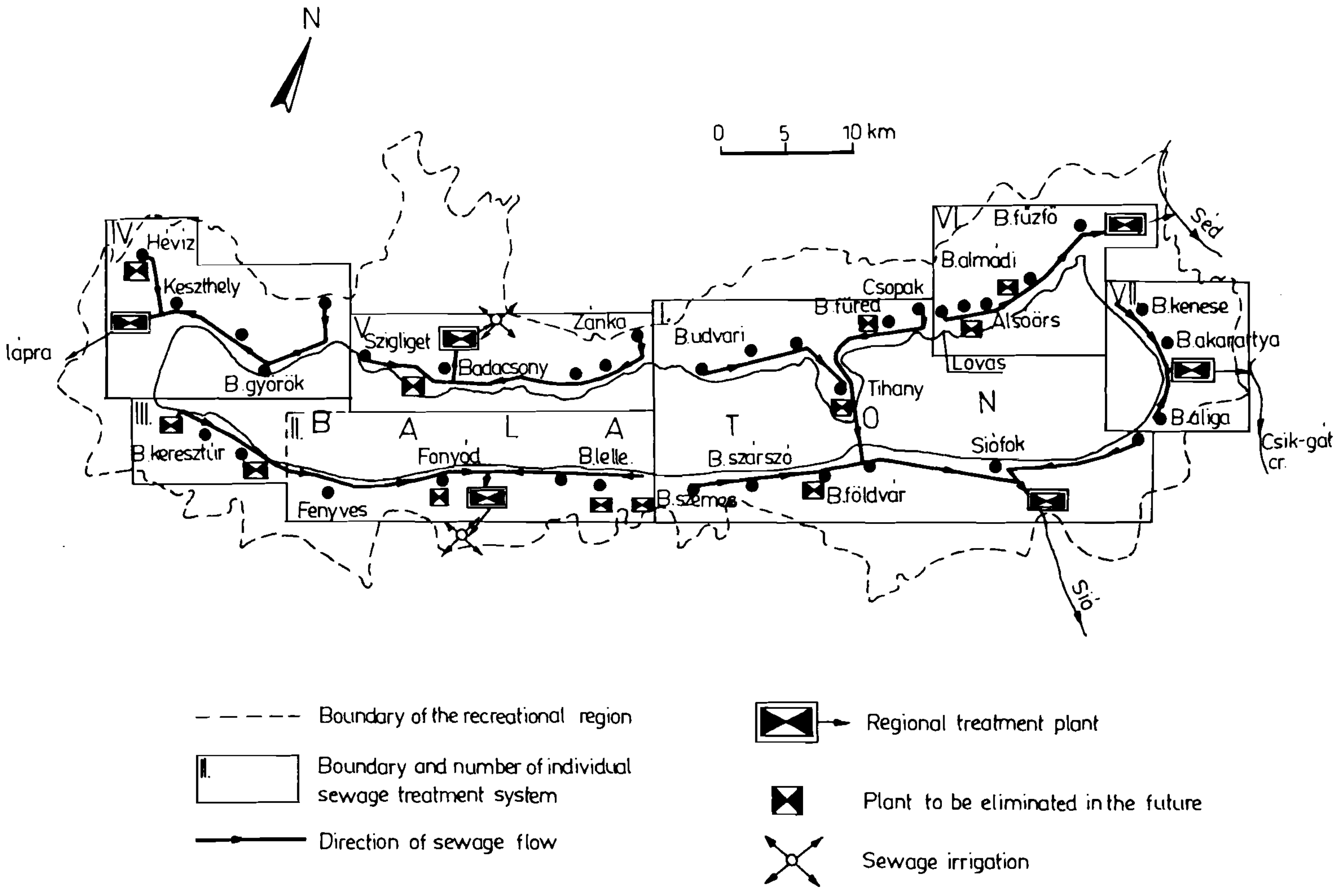


Figure 34. Long term sewage disposal concept of the Balaton region.

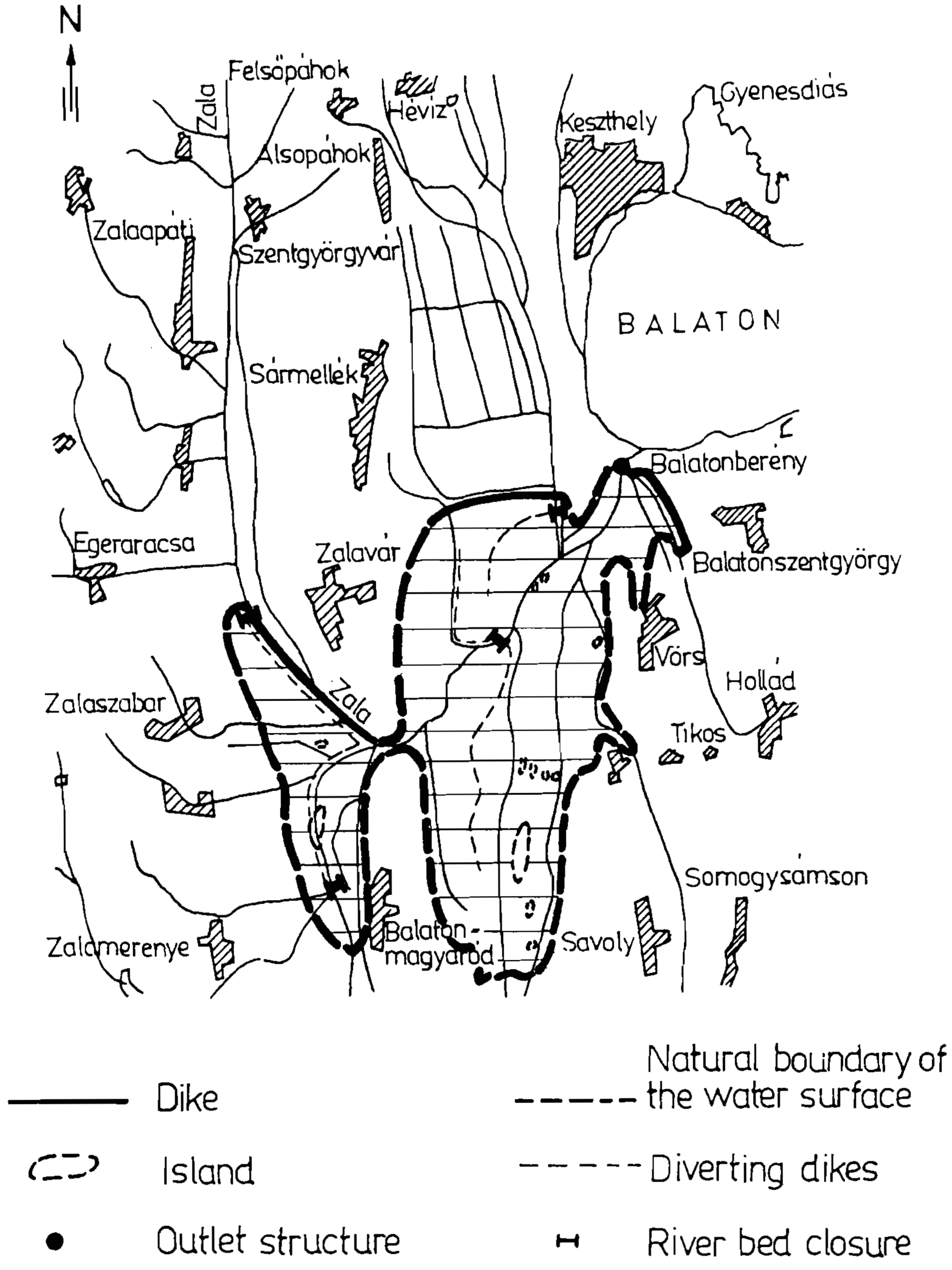


Figure 35. Design plan for Kis-Balaton reservoir (after Lotz, 1976).

A fourth group of management alternatives comprises of different protection measures in the watershed. In many cases the complexity of the processes involved presently inhibits the quantitative assessment of effectiveness. To this category belong the following:

-- Control of fertilizer application, especially in the nearshore areas (more intensive supervision, avoidance of over uses, consideration of right time of application).
-- Erosion control by changed land cultivation techniques, such as terracing or contour tillage, or by construction of erosion retention dams.
-- Appropriate treatment or disposal of solid wastes, especially sewage treatment sludge and septic tank sludge.
-- Treatment and/or land-disposal of liquid manure from large scale livestock breeding.

Finally a category of management possibilities remains of various character. Some of these are side-effects from measures proposed for other reasons than lake eutrophication abatement.

-- Storage reservoirs constructed for irrigation purposes can be effective in retention of phosphorus too (similar to the Kis-Balaton project).
-- Measures aimed at a better level regulation could have a side effect on water quality as well, because of the changes in flushing regime. However, these effects will probably be small given the long retention times prevailing in the majority of the lake.
-- Some negative effects have been attributed to the erection of shore protection structures, with the argument that the natural beachy shore was instrumental in removing floating debris and dead organic material from the lake.
-- Maintenance and protection of reed stands as filter of phosphorus from discharges from the shore (discussed before).
-- In-stream removal of nutrients from smaller tributaries (under investigation at present).
-- The introduction of herbivorous fish as a biological alternative is perhaps less advisable for a large lake as the Balaton, because it can have unpredictable and irreversible adverse effects on the ecology of the lake.

This overview of possible control options concludes this chapter and this report. We have tried to summarize the knowledge available needed for the development of mathematical models, not only for scientific satisfaction but also, eventually, as tool in the prediction of the lake's responses to future human activities. Here systems analysis techniques in a strict, rather technical sense find their application. The other, indispensable step towards a type of management model is the evaluation of the economical, social, legal and institutional aspects of different control alternatives. Linking the two steps together is the task of systems analysis in a broader sense, a challenge for the future in the case of Lake Balaton.

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APPENDIXES

Appendix A. Some characteristics of the Balaton water system and the sub-catchment areas (after Baranyi, 1975).

Stream and watershed (1)	Area km^2 (2)	Length of stream km (3)	Length of basin km (4)	Elevations	
				max. m.A.s. (5)	min. (6)
1. ZALA					
1.1 At the city of Zalaegerszeg	464,8	52,4	45,2	322	150
1.2 Between Zalaegerszeg and Zalaapáti	1063,2	52,7	52,9	388	108
1.3 Between the source and Zalaapáti	1528,0	115,1	98,1	388	108
1.4 Between Zalaapáti and the mouth	1092,8	23,7	22,8	445	105
1.5 Between the source and the mouth	2621,8	138,8	120,9	445	105
2. STREAMS ON THE NORTHERN SUBWATERSHED					
2.1 Lesence creek	100,5			445	105
2.2 Világos creek	53,1	8,9	8,8	324	105
2.3 Kétöles-árok	9,6			152	105
2.4 Tapolca creek	49,5	10,2	10,1	316	105
2.5 Egerviz	365,6	32,0	30,1	610	105
2.6 Burnoti creek	82,2	9,2	8,7	447	105
2.7 Csorszai creek	21,2	7,6	7,4	250	105
2.8 Örvényesi-séd	19,9	8,1	7,6	416	105
2.9 Tavi-séd	14,4	8,6	8,0	816	105
2.10 Séd	16,7	9,6	8,6	430	105
2.11 Arácsi creek	13,5	5,4	5,1	441	105
2.12 Csopaki-séd	14,2	4,8	4,2	426	105
2.13 Lovasi-séd	44,0	4,3	6,9	374	105
2.14 Vörösberényi-séd	10,8	5,3	4,9	320	105
2.15 Füzfoi-séd	4,9	1,3	1,2	262	105
3. STREAMS ON THE SOUTHERN SUBWATERSHED					
3.1 Balatonszéplaki-árok	18,7	6,9	5,8	222	105
3.2 Endrédi creek	23,0	6,8	6,5	267	105

Appendix A. (Continued.)

Stream and watershed (1)	Area km² (2)	Length of stream km (3)	Length of basin km (4)	Elevations max. m.A.s. (5)	 min. (6)
3.3 Koroshegyi-séd	36,8	9,8	9,4	317	105
3.4 Tetves creek	94,1	25,1	23,8	302	105
3.5 Nagymetszés	87,8	18,0	17,3	293	105
3.6 Balatonboglári-határárok	58,8	15,7	14,9	301	105
3.7 Keleti-Bozót	250,9	43,8	34,2	258	105
3.8 Nyugati-Övcsatorna	604,5	49,6	47,6	237	105
4. BALATON AND THE SHORELINE	1152,7			816	105
5. TOTAL BALATON CATCHMENT	5774,5			816	105

Appendix B. Characteristics of the watershed and its development (David et al., 1979).

I. Natural factors.

Factor Code	Description	Unit	WS1	WS23 (WS2+WS3)	WS45 (WS4+WS5)	WS67 (WS6+WS7)
F_1	lake area connected to WS	km^2	40	140	190	230
F_2	ground surface area of WS	km^2	2750	1650	530	250
F_3	the distance of the average elevation of WS and WB above sea level	m	65	70	75	95
F_4	distance between the areal gravity center of the WS and the connected WB	km	30	12	6	4
F_5	average slope of arable land of WS	%	11	7	8	10
F_6	average yearly precipitation	mm	750	710	660	650
F_7	maximum precipitation for one day	mm	70	52	51	53
F_8	average number of dry days in a year	days	293	281	277	275
F_9	total length of water courses	km	1410	704	212	104
F_{10}	length of rivers	km	40	-	-	-
F_{11}	potential water resources (multi-annual average runoff)	$\frac{10^6 m^3}{year}$	600	280	100	20
F_{12}	average volume of water in the lake's WB connected with the watersheds	$10^6 m^3$	80	410	600	810

Appendix B. (Continued.)

II. Regional (socio-economic) development factors.

Factor Code	Description	Unit	WS1	WS23	WS45	WS67
F_{13}	number of constant population	10^3 head	180	100	80	60
F_{14}	number of population working in industry	10^3 head	23	16	5	8
F_{15}	number of population working in agriculture	10^3 head	26	20	6	3
F_{16}	visitor's day	10^3 head x day	1200	860	1500	2000
F_{17}	number of settlements	settlements	180	93	25	10
F_{18}	number of industrial plants	plants	140	90	18	40
F_{19}	number of large animal farms	farms	10	7	4	2
F_{20}	arable land	km^2	1700	1140	250	90
F_{21}	vineyards and orchards	km^2	146	110	54	28
F_{22}	forest land	km^2	710	330	210	80
F_{23}	urbanized area	km^2	170	100	40	70
F_{24}	number of standard (full-grown) animals	10^3 head	70	16	10	4
F_{25}	total amount of fertilizers used in equivalents P_2O_5	$\frac{10^3 t}{year}$	37	23	7	3
F_{26}	length of motoring (paved) roads	km	980	220	110	100

Appendix B. (Continued.)

III. Water management factors.

Factor Code	Description	Unit	WS1	WS23	WS45	WS67
F_{27}	total official fresh water demand	$\frac{10^6 m^3}{year}$	31	51	32	28
F_{28}	total actual water use	$\frac{10^6 m^3}{year}$	23	34	20	19
F_{29}	actual domestic water use	$\frac{10^6 m^3}{year}$	10	15	10	9
F_{30}	actual industrial water use	$\frac{10^6 m^3}{year}$	4	7	2	3
F_{31}	actual irrigation water use	$\frac{10^6 m^3}{year}$	4	8	6	6
F_{32}	actual water use of animal farming	$\frac{10^6 m^3}{year}$	5	4	2	1
F_{33}	water use with drinking water quality	$\frac{10^6 m^3}{year}$	9	8	5	4
F_{34}	amount of consumed water	$\frac{10^6 m^3}{year}$	6	16	13	11
F_{35}	amount of reused water	$\frac{10^6 m^3}{year}$	3	5	1	1
F_{36}	amount of water import from outside the watershed	$\frac{10^6 m^3}{year}$	8	-	-	-
F_{37}	amount of water export to outside the basin	$\frac{10^6 m^3}{year}$	-	-	-	7
F_{38}	underground water resources taken out	$\frac{10^6 m^3}{year}$	14	10	8	4

Appendix B. (Continued.)

III. Water management factors. (Continued.)

Factor Code	Description	Unit	WS1	WS23	WS45	WS67
F_{39}	peak actual water use in August	m^3/s	1.0	1.9	1.0	1.2
F_{40}	irrigation water use in August	m^3/s	0.6	1.2	0.7	0.8
F_{41}	total effluent discharge collected by sewage works	$\frac{10^6 m^3}{year}$	8	8	5	6
F_{42}	treated effluent discharge from F_{41}	$\frac{10^6 m^3}{year}$	4.0	1.0	0.5	0.5
F_{43}	existing storage capacity	$10^6 m^3$	6.0	10.0	3.5	0.5
F_{44}	number of reservoirs (and fish ponds)	reservoir (fish ponds)	5 (4)	6 (12)	1 (2)	1 (2)
F_{45}	number of population supplied with waterworks	10^3 head	74	59	56	45
F_{46}	number of population supplied with sewage works	10^3 head	30	29	30	25
F_{47}	irrigated area	km^2	18	25	20	21
F_{48}	drainage area	km^2	160	75	5	-
F_{49}	length of beaches used for recreation	km	20	15	20	25
F_{50}	number of existing water right licenses for water use and waterworks	licenses	550	1100	750	350

Appendix C. Long term monthly river inflow and inter-basin throughflow for the four Balaton basins.

a) Calculated tributary inflows of the different Balaton basins. (Long term monthly average values in 10^6 m^3/month.)

	Basin			
Month	1 Keszthely	2 Szigliget	3 Szemes	4 Siófok
I.	26,27	15,73	5,096	2,37
II.	34,44	21,23	6,87	3,19
III.	44,30	26,52	8,59	3,99
IV.	32,91	19,70	6,38	2,96
V.	25,32	15,16	4,91	2,35
VI.	25,32	15,16	4,91	2,35
VII.	21,52	12,87	4,17	1,94
VIII.	16,45	9,85	3,18	1,49
IX.	15,50	9,27	2,99	1,40
X.	16,13	9,66	3,12	1,46
XI.	23,73	14,21	4,59	2,13
XII.	25,0	14,96	4,83	2,26

b) Calculated outflows from the different Balaton basins into the downstream basins.* (Monthly average values calculated on the basis of water balances in 10^6 m^3/month.)

I.	25,45	38,16	39,35	36,9
II.	33,39	46,84	43,65	34,53
III.	41,5	57,5	52,55	39,89
IV.	31,51	45,87	45,36	39,86
V.	24,51	36,65	37,66	34,82
VI.	23,75	33,01	30,02	23,28
VII.	20,53	29,86	28,98	24,99
VIII.	16,26	25,39	27,63	27,98
IX.	15,6	25,32	28,8	30,95
X.	16,44	27,25	31,8	35,12
XI.	23,01	34,48	35,5	33,3
XII.	24,7	38,65	42,12	42,7

*Outflows from the Siófok basin are equal to the outlet through the Siófok gate.

Appendix D. IIASA data base.

The main data for Lake Balaton are stored in a computerized data base at IIASA. This appendix presents an abstract of the data in graphical form. Numerical values can be made available on request (in writing to IIASA, REN Area, indicating the intentional use).

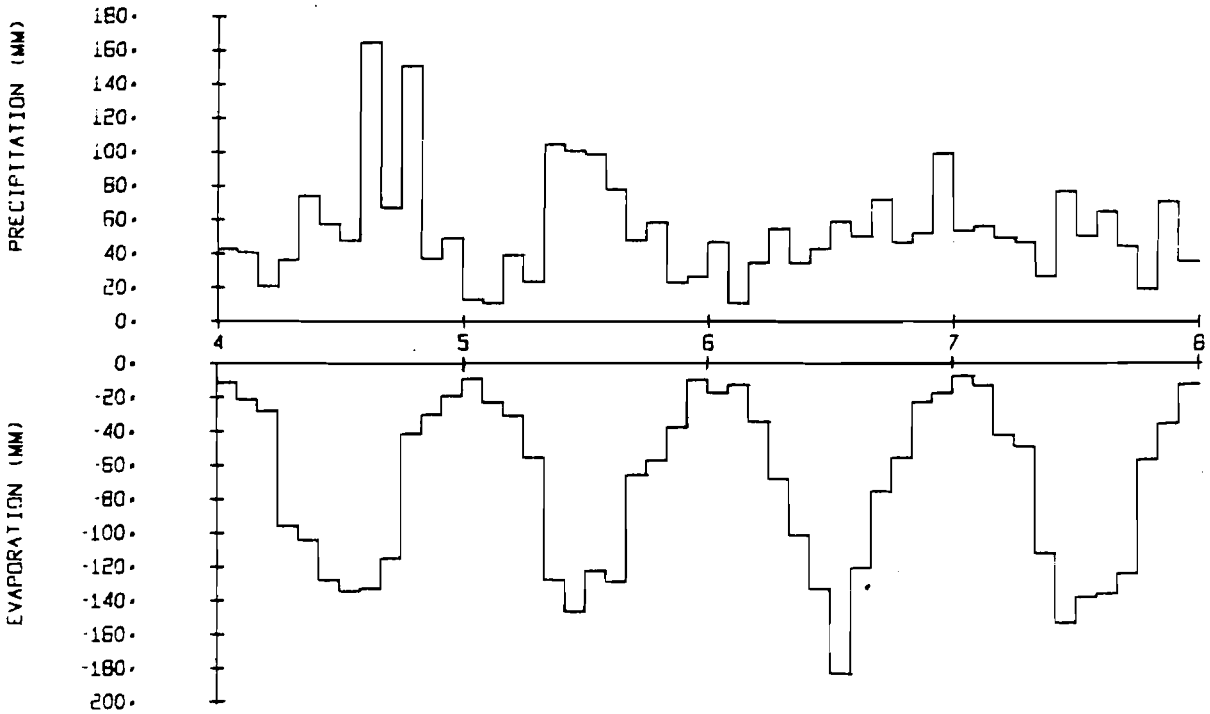
-- Waterbalance data. Monthly totals for precipitation, evaporation, inflow and outflow in mm (source: J. Urbán. VITUKI)
-- 10-day means for temperature, day sum of global radiation and daily mean wind (obtained from 8 readings per day) at Siofok (source: VITUKI)
-- River Zala discharge, total-P load, ortho-P load and suspended solids load (source: Joó, West Transdanubian Water Authority)
-- Basinwise averages for chlorophyll-a, secchi-disk depth, suspended solids, various phosphorus fractions and various nitrogen fractions. Basinwise averaging performed at IIASA from more-point observations.

Chlorophyll-a data from different sources: x L. Tóth (VITUKI), o F. Tóth (Transdanubian Water Authority)

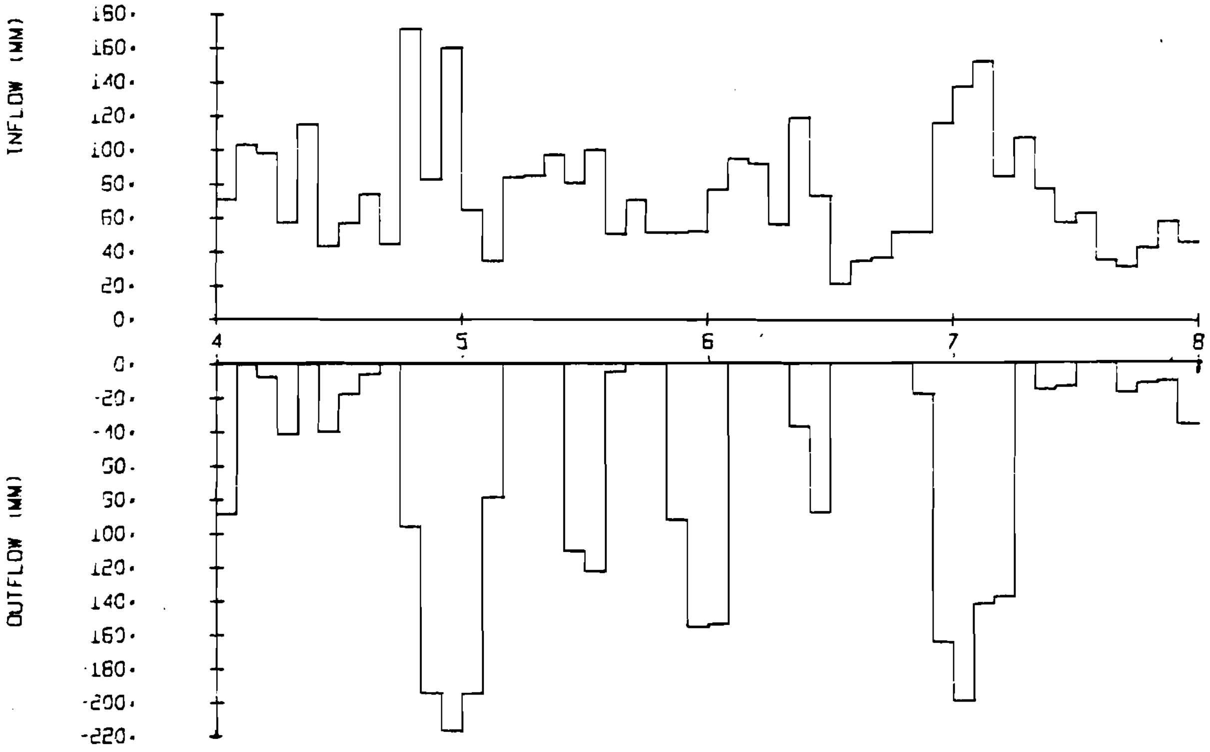
Key:

TP :	total P	; directly measured
TDP:	total dissolved P	; directly measured
PO4:	ortho-P	; directly measured
DOP:	dissolved organic P	; calculated as TDP-PO4
TPP:	total particulate P	; calculated as TP-TDP
POP:	particulate organic P	; calculated as TPP-PIP
PIP:	particulate inorganic P	; directly measured
TKN:	total Kjeldahl N	; directly measured
DKN:	dissolved Kjeldahl N	; directly measured
PDN:	particulate (organic) N	; calculated as TKN-DKN
NO3:	nitrate	; directly measured

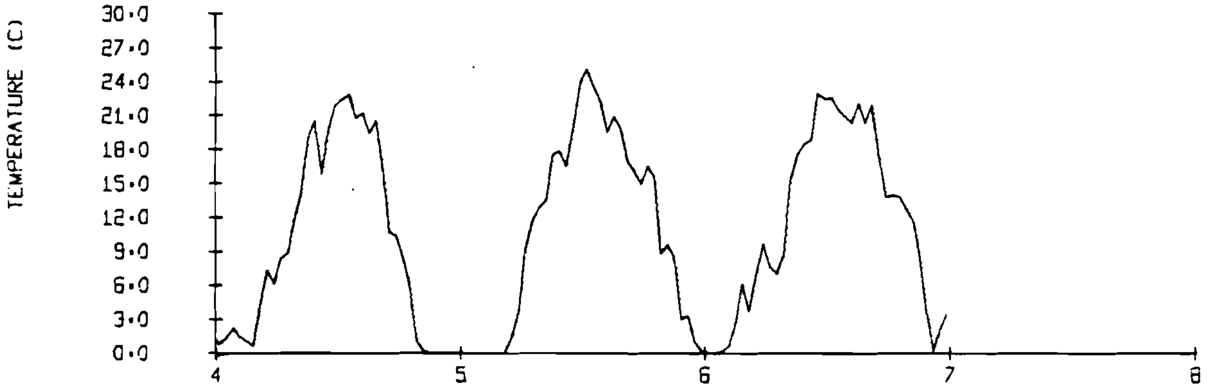
Note: the timescale on the axis is in years since 1st. of January 1970, i.e. the line section between mark 4 and 5 is 1975, etc.



MONTHLY WATERBALANCE



MONTHLY WATERBALANCE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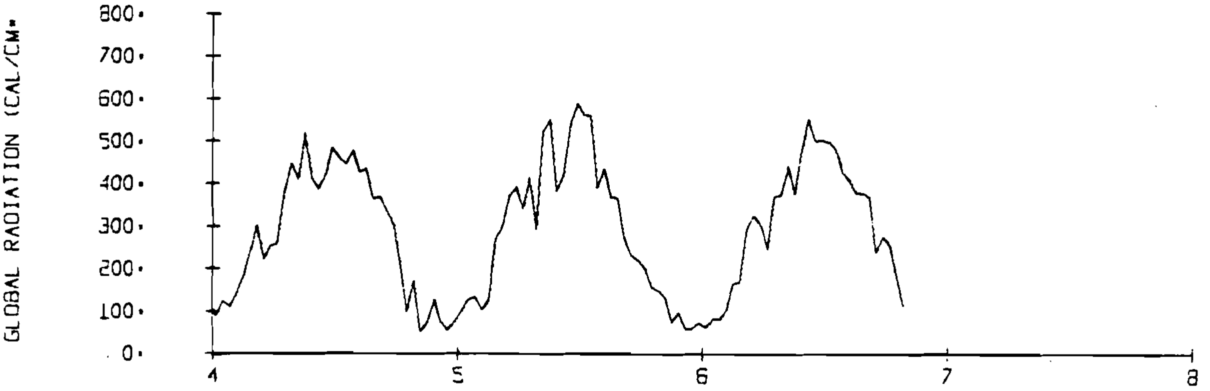
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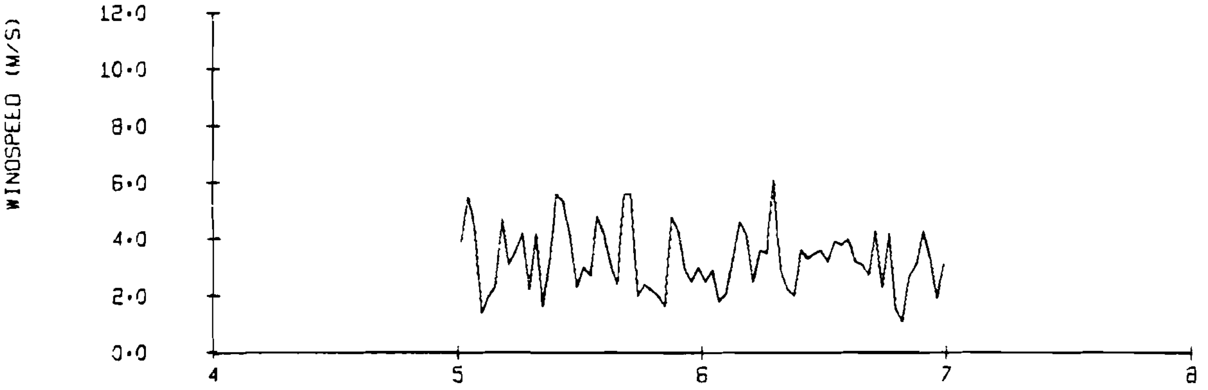
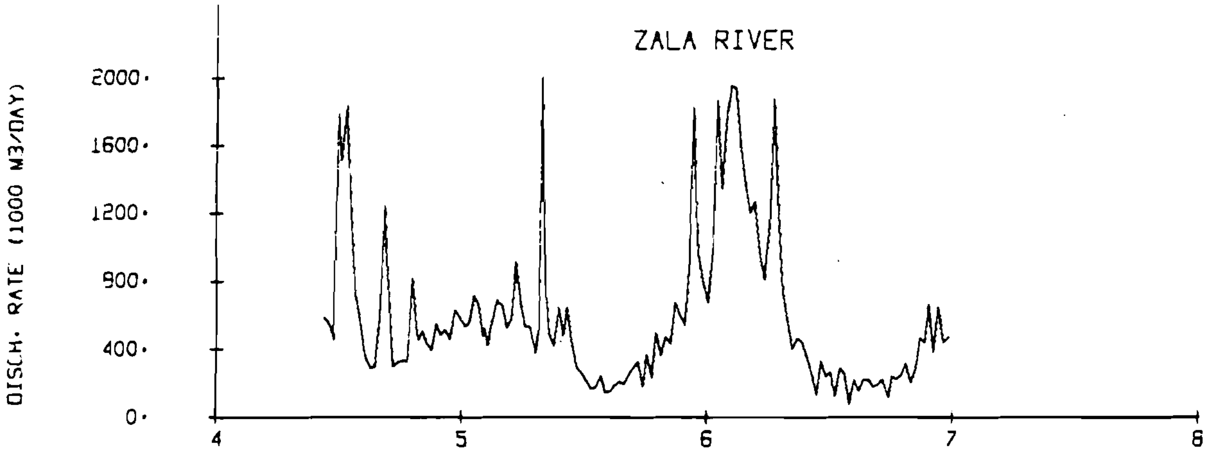

10-DAY MEAN WIND (SIOFOK)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DISCH. RATE (1000 M3/DAY)
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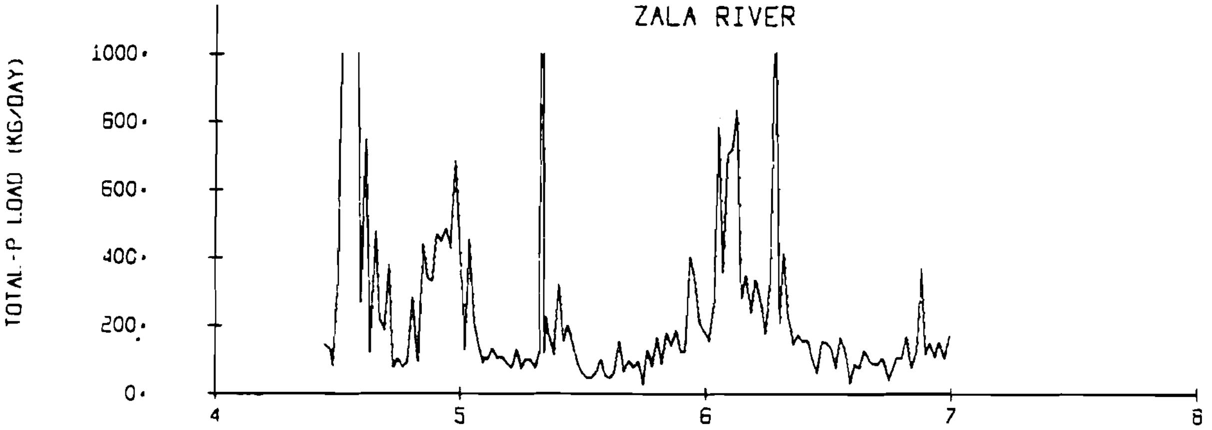
1600
1200
800
400
0
4
5
6
7
8


ZALA RIVER
TOTAL-P LOAD (KG/DAY)
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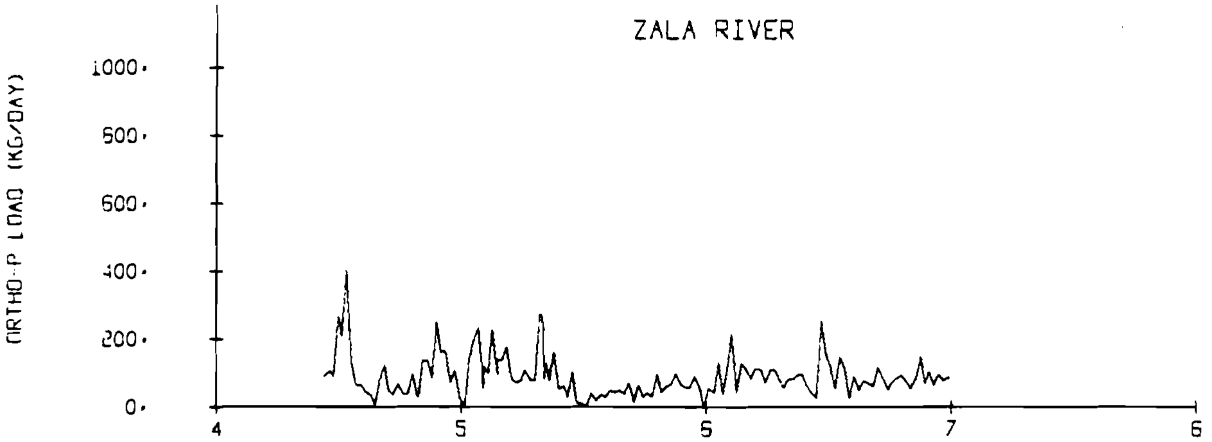
600
400
200
0
4
5
6
7
8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ORTHO-P LOAD (KG/DAY)
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800
600
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200
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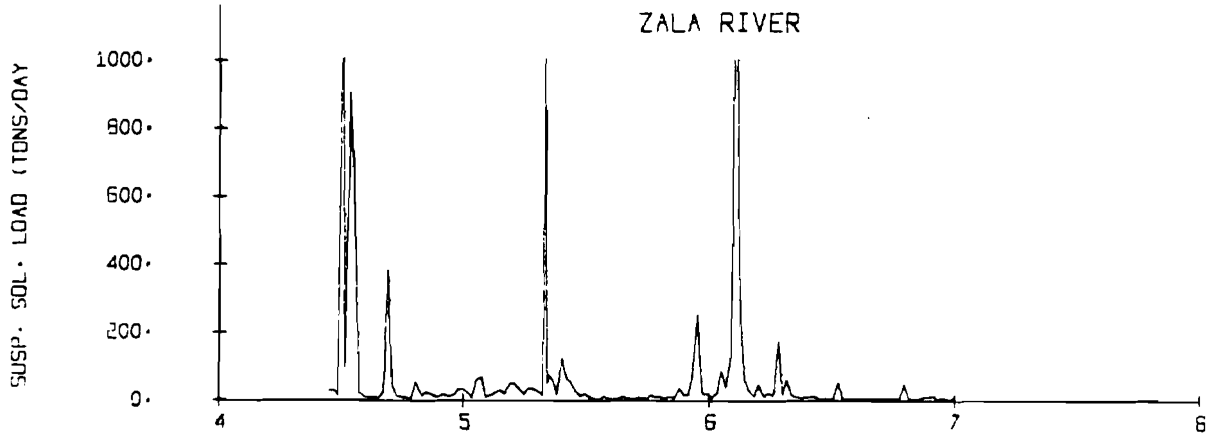
ZALA RIVER
SUSP. SOL. LOAD (TONS/DAY)
1000
800
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400
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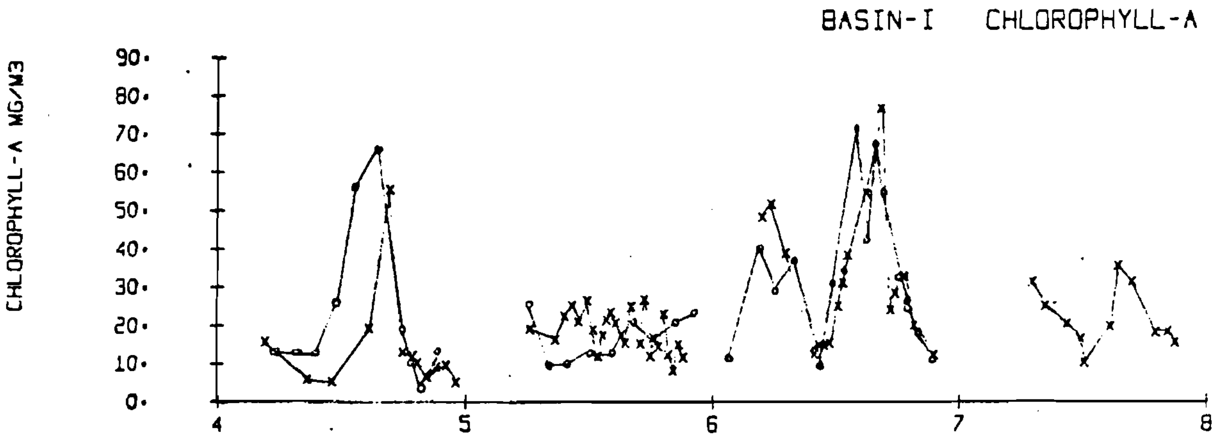
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CHLOROPHYLL-A MG/M3
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4
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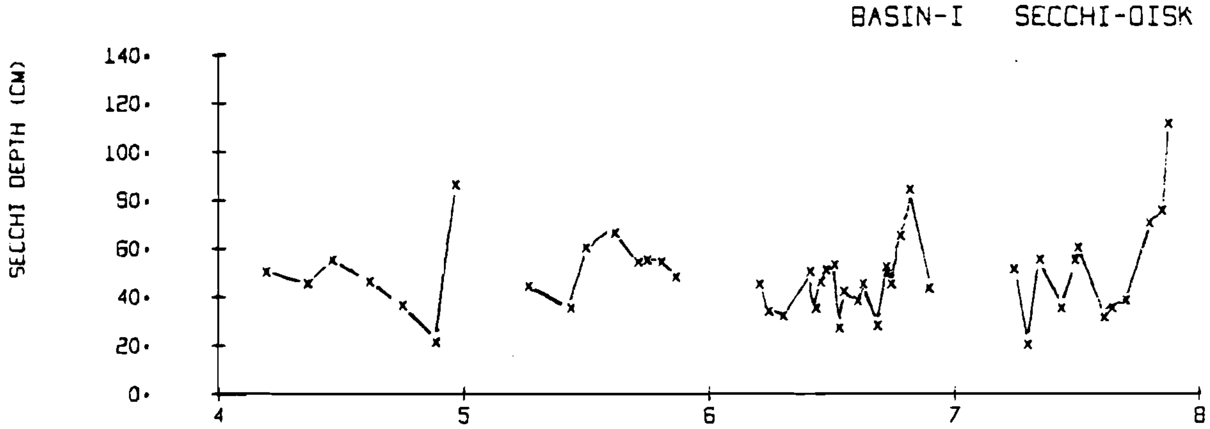
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SECCHI DEPTH (CM)
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120
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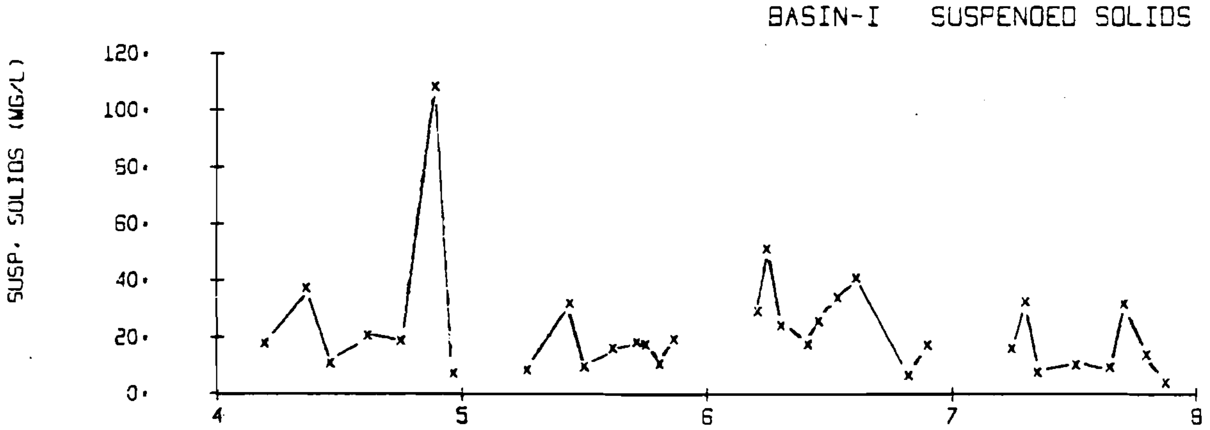
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SUSP. SOLIDS (MG/L)
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80
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40
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6
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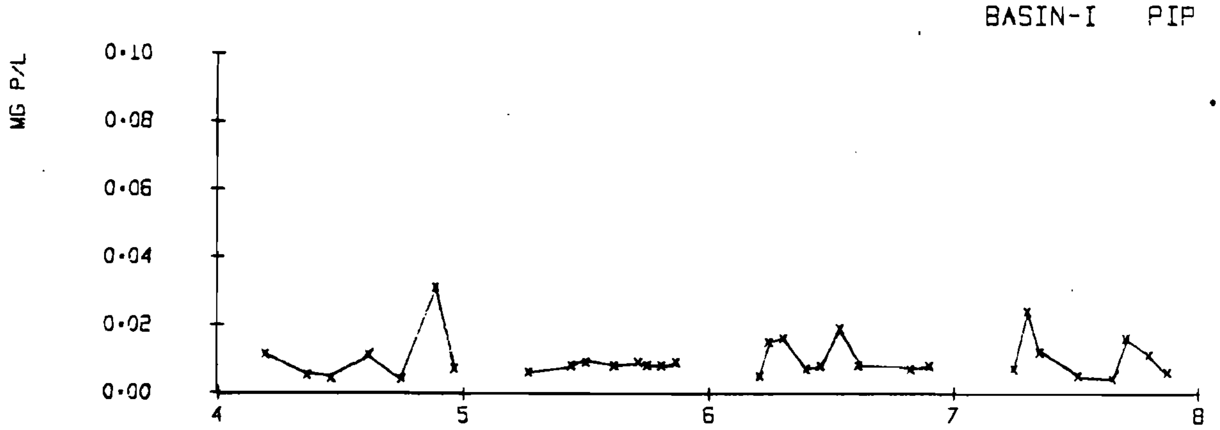
8


BASIN-I PIP
MG P/L
0.10
0.08
0.06
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0.02
0.00
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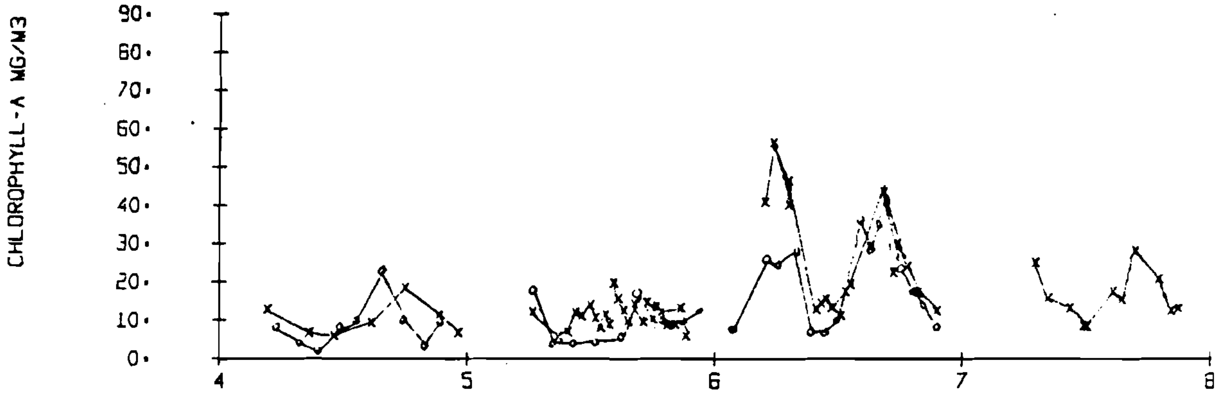
5
6
7
8

BASIN-II CHLOROPHYLL-A



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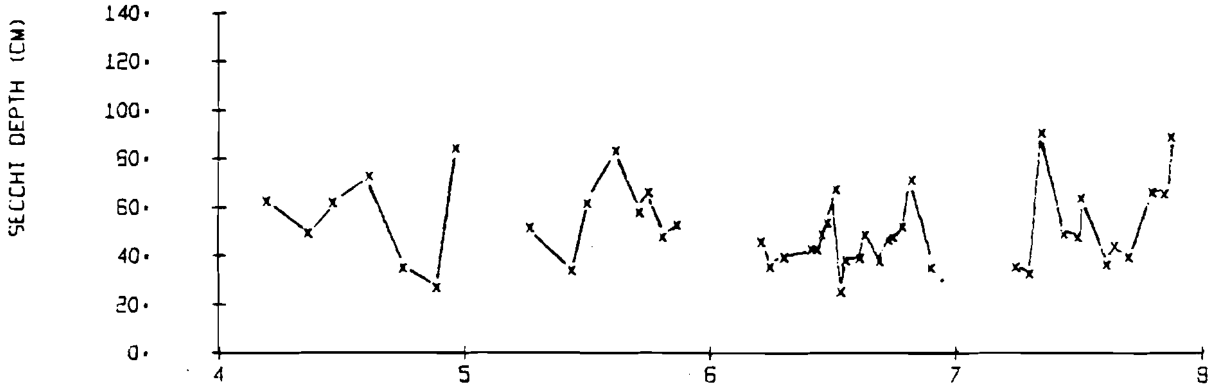

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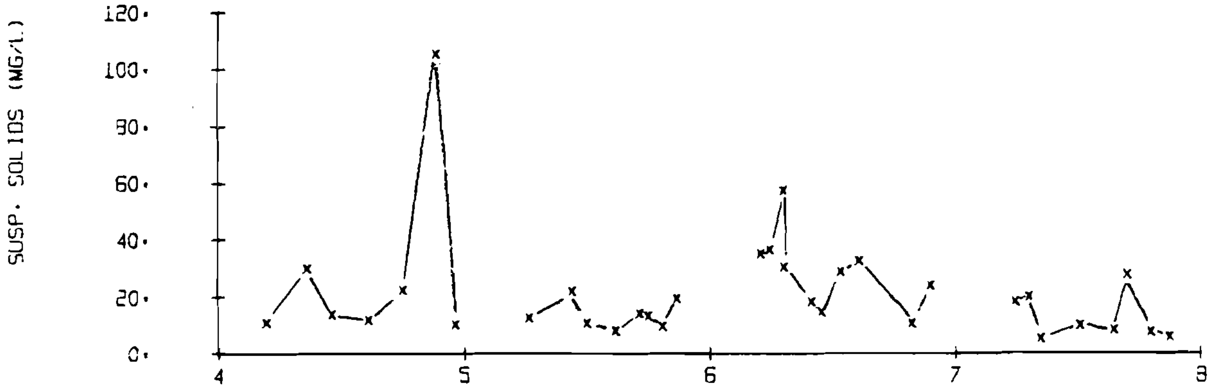
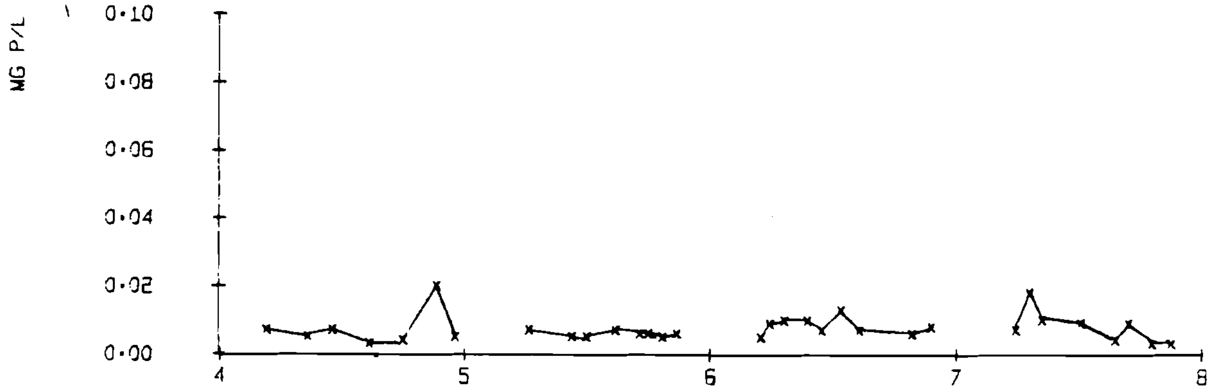
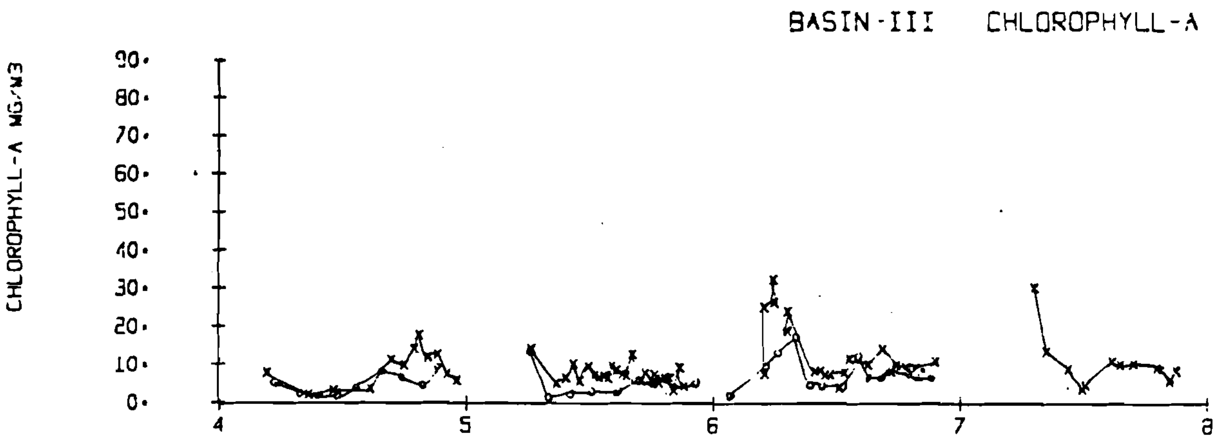


BASIN-II PIP

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CHLOROPHYLL-A MG/M3
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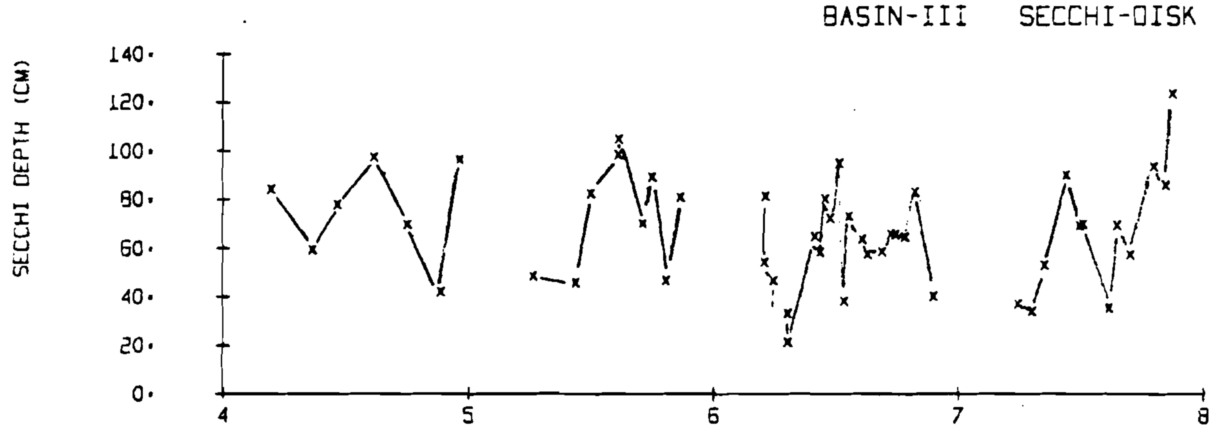
BASIN-III SECCHI-DISK
SECCHI DEPTH (CM)
140·
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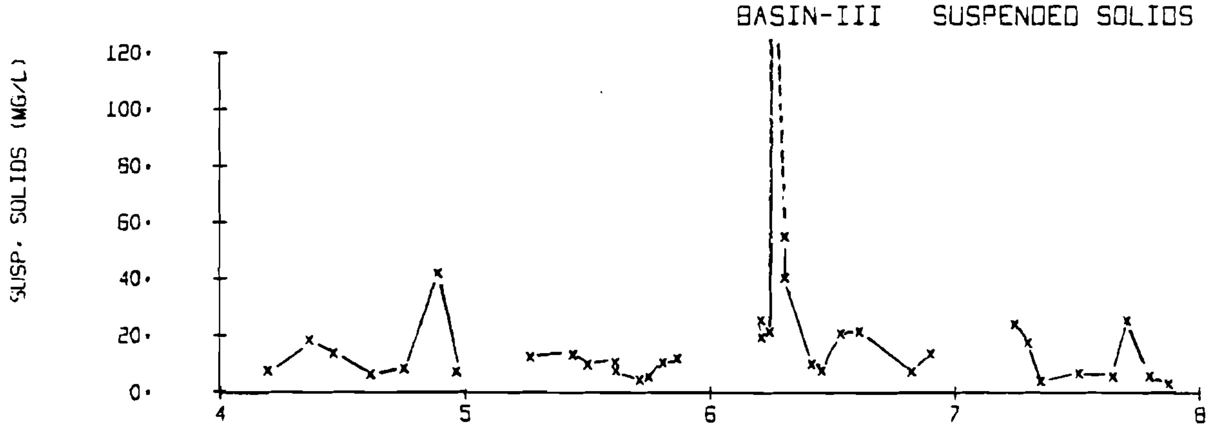
BASIN-III SUSPENDED SOLIDS
SUSP. SOLIDS (MG/L)
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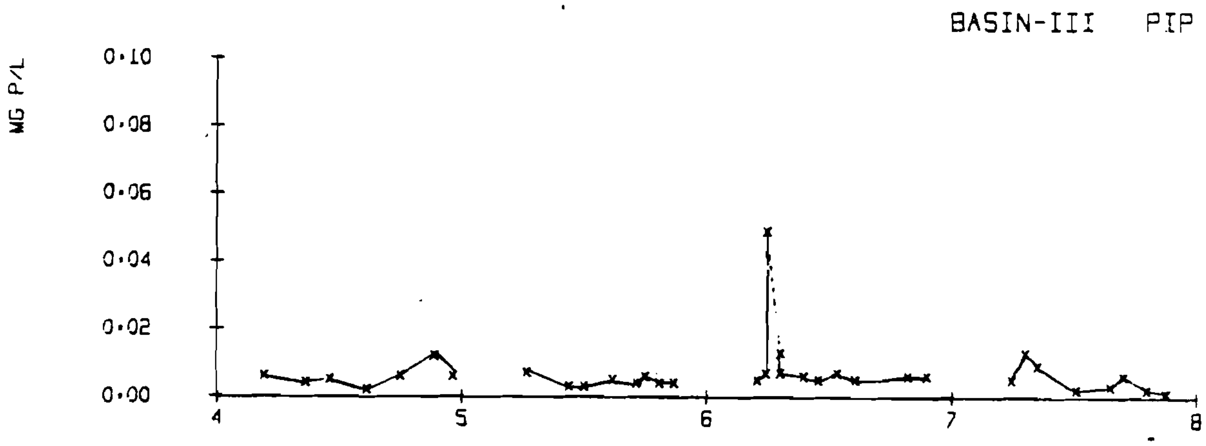
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MG P/L
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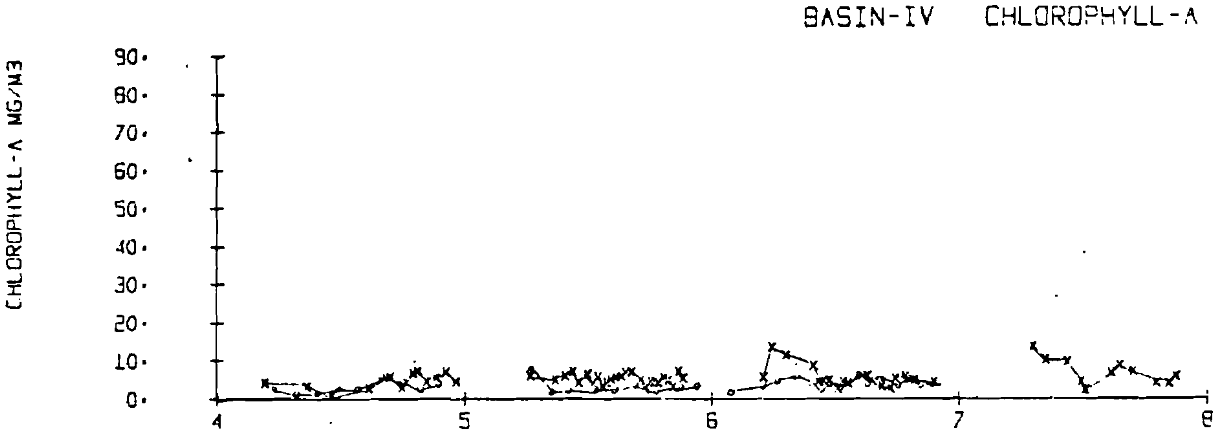
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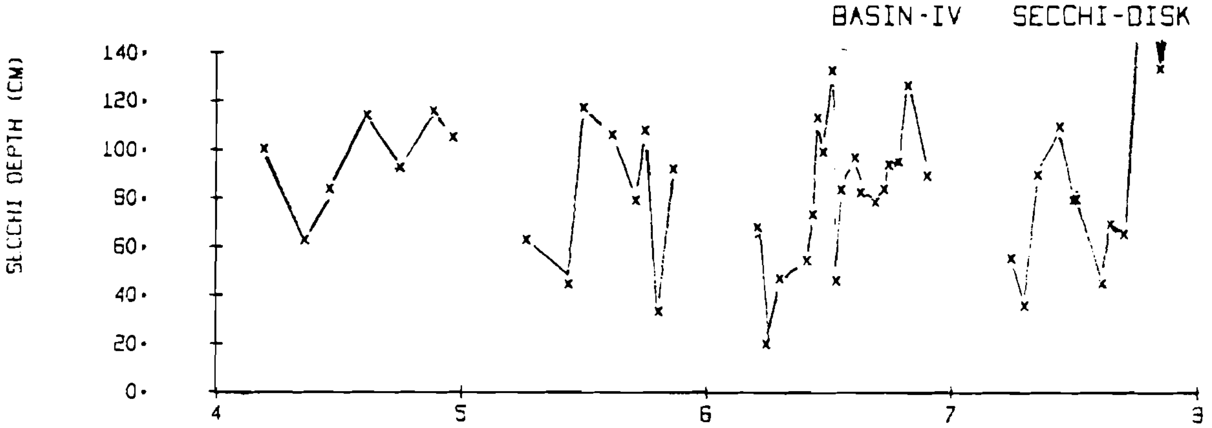
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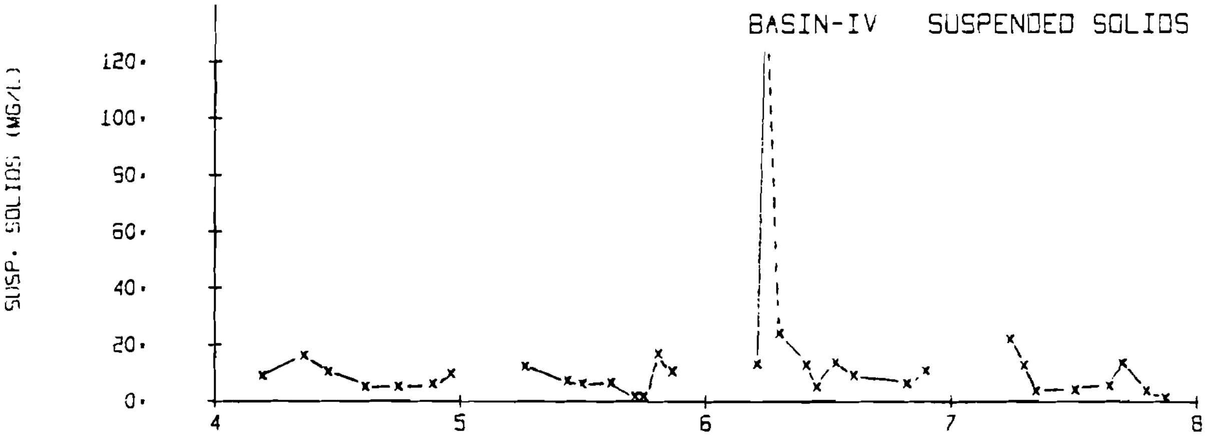
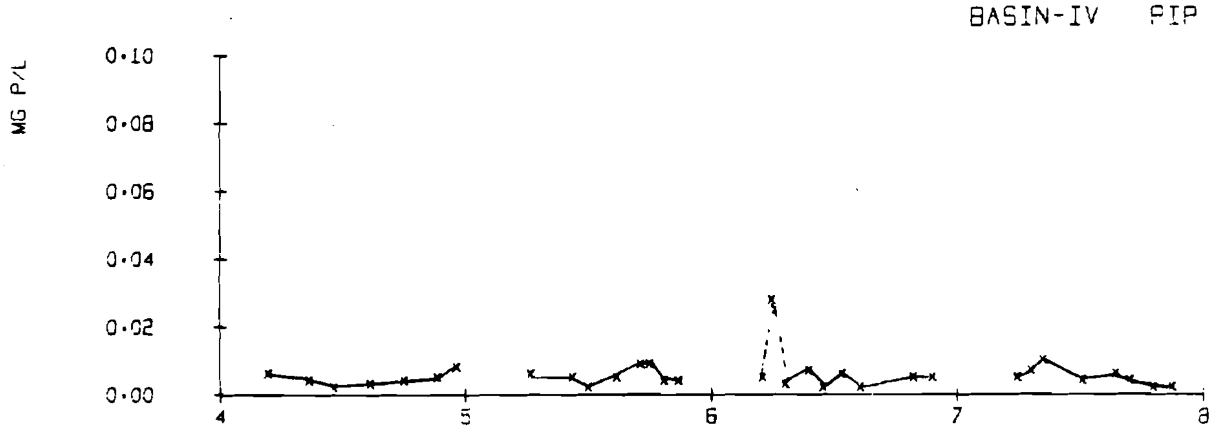
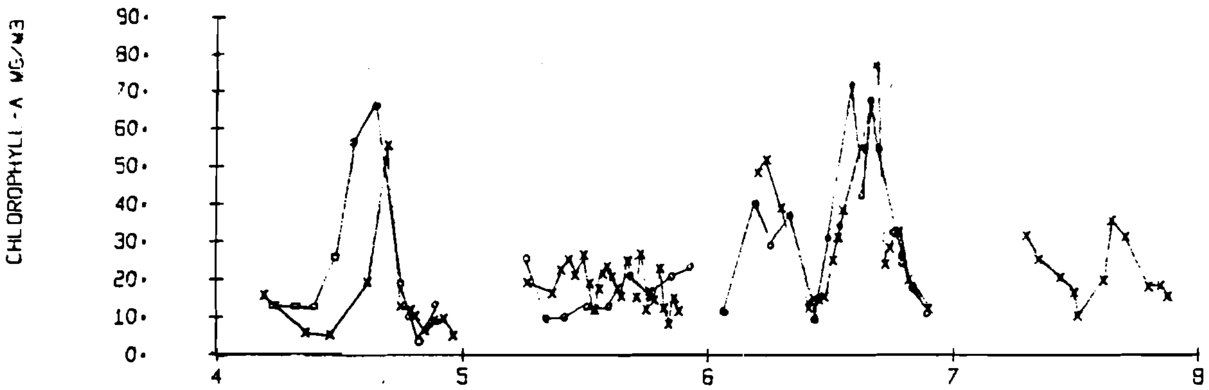
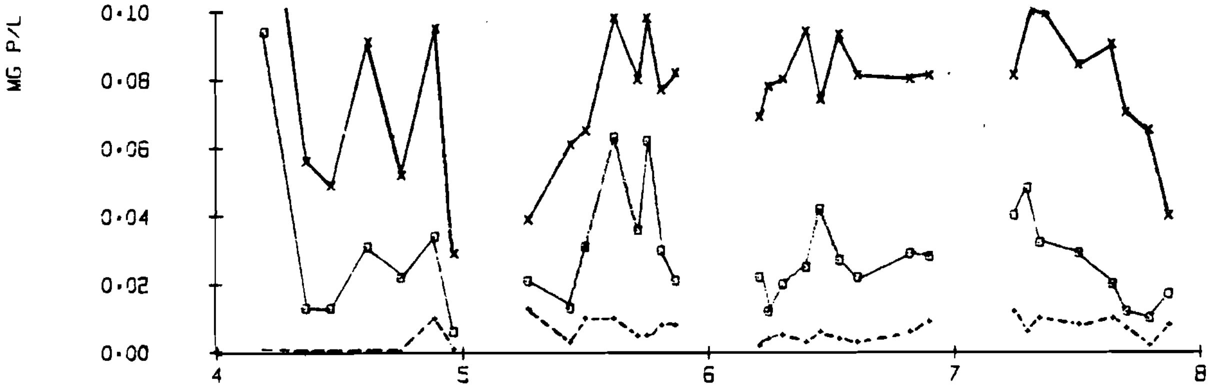
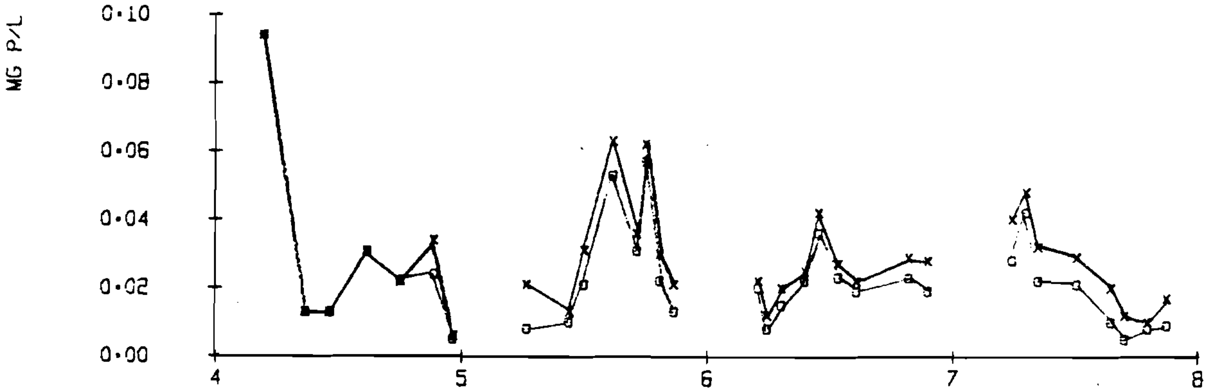
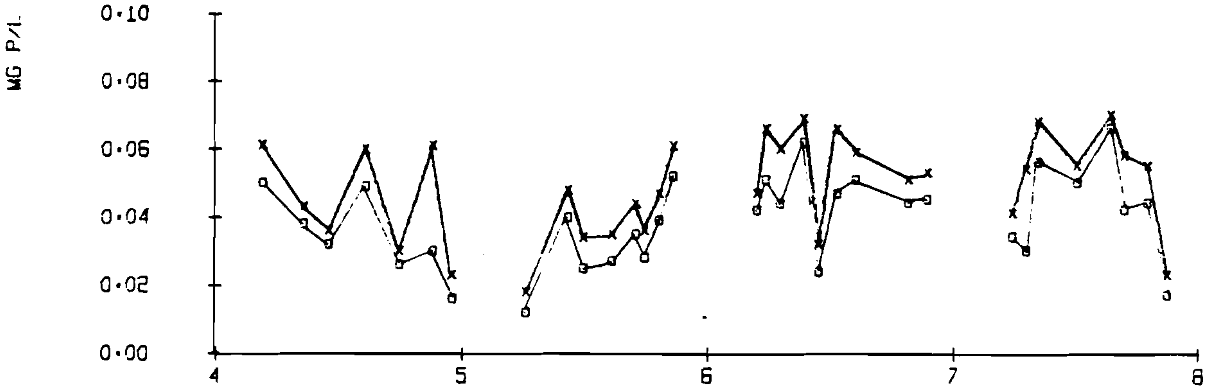

BASIN-IV SUSPENDED SOLIDS

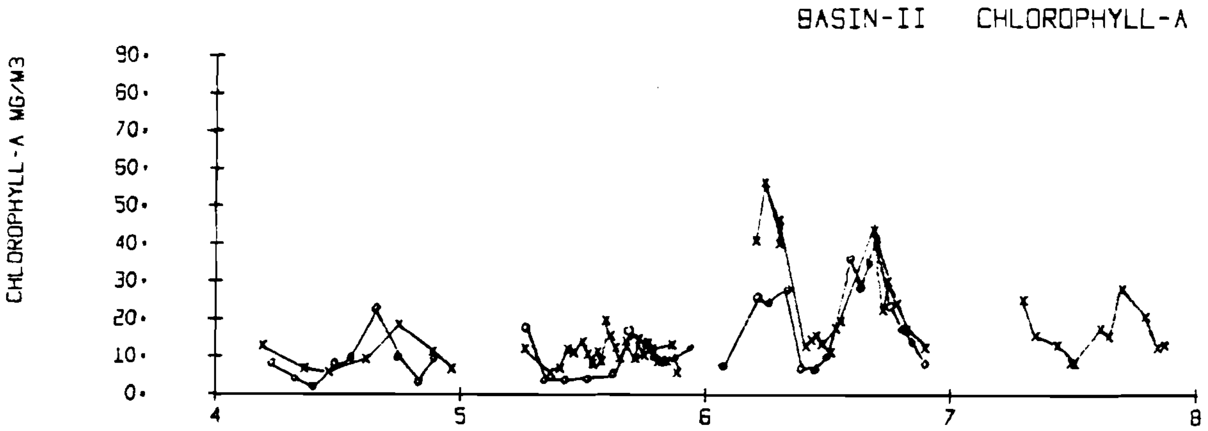

BASIN-IV PIP

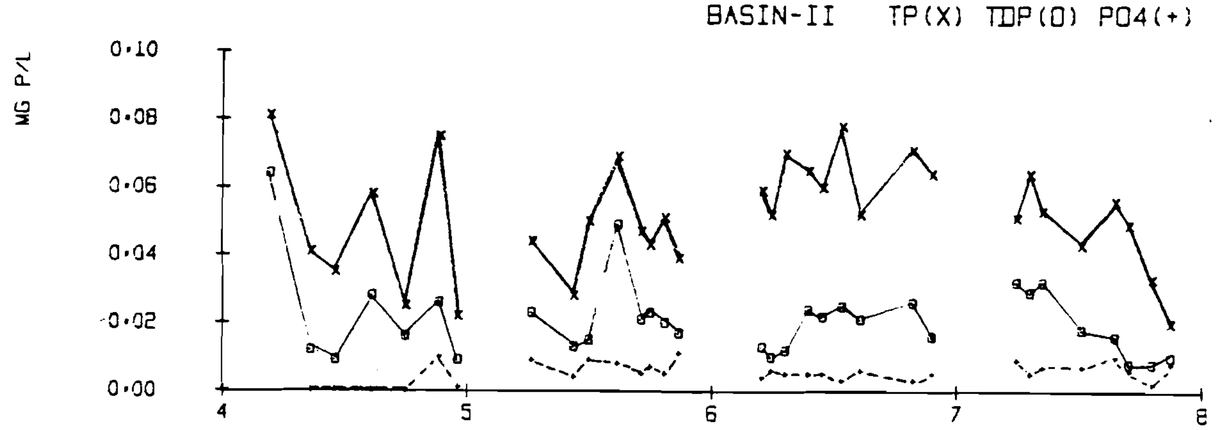

BASIN-I CHLOROPHYLL-A

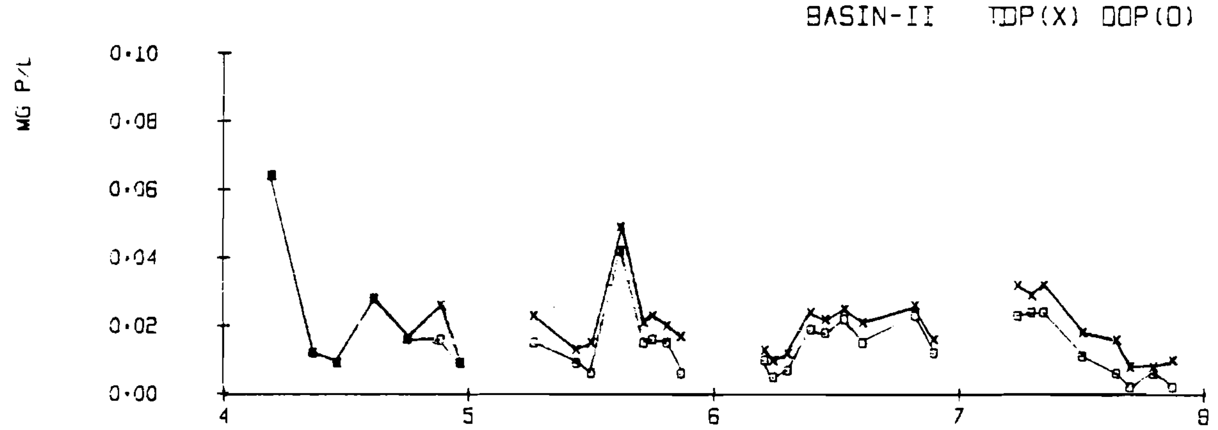

BASIN-I TP(X) TDP(O) PO4(+)

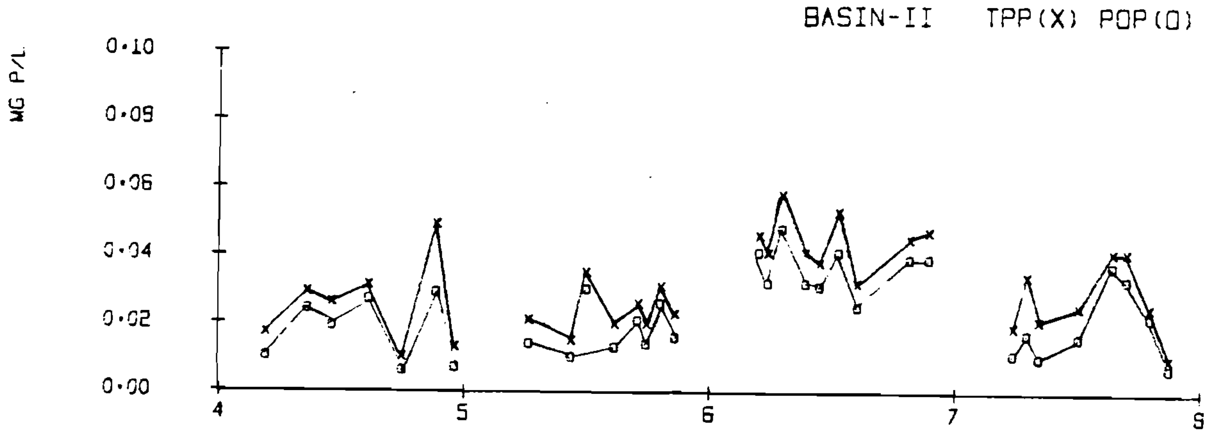

BASIN-I TDP(X) DOP(O)

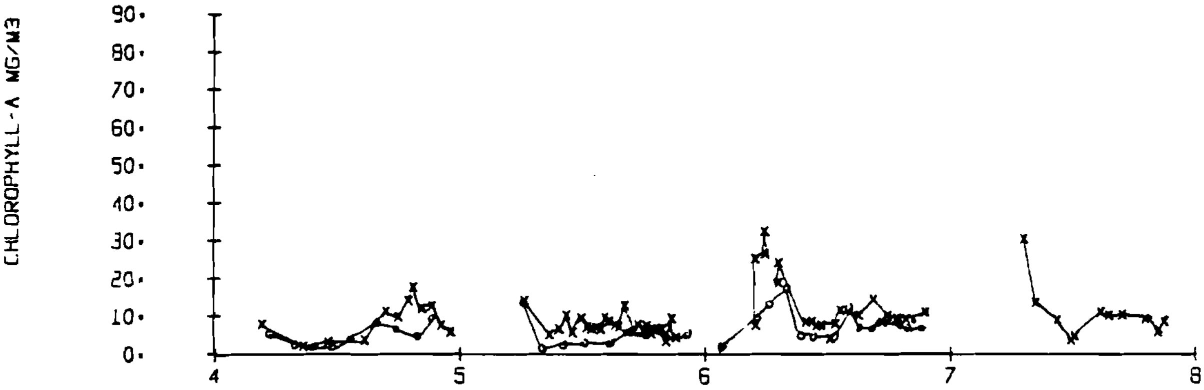

BASIN-I TPP(X) POP(O)

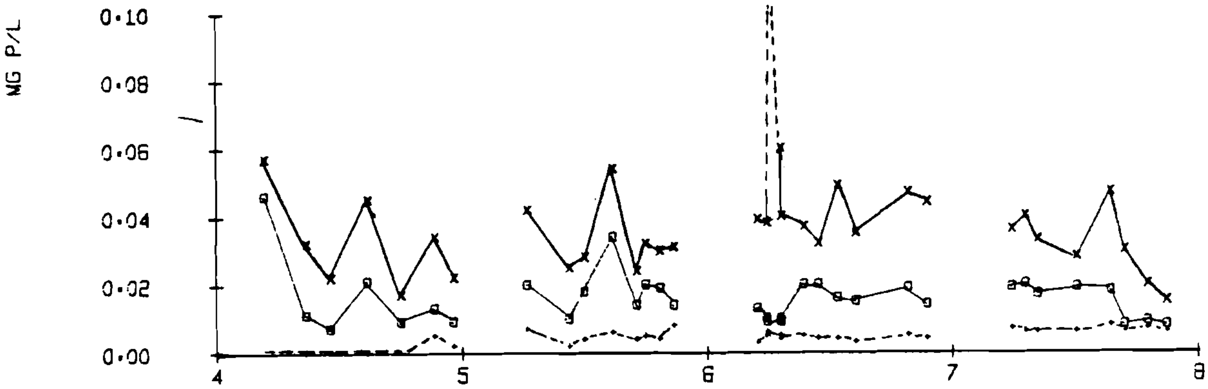

BASIN-II CHLOROPHYLL-A
CHLOROPHYLL-A MG/M3
90·
80·
70·
60·
50·
40·
30·
20·
10·
0·
4
5
6
7
8

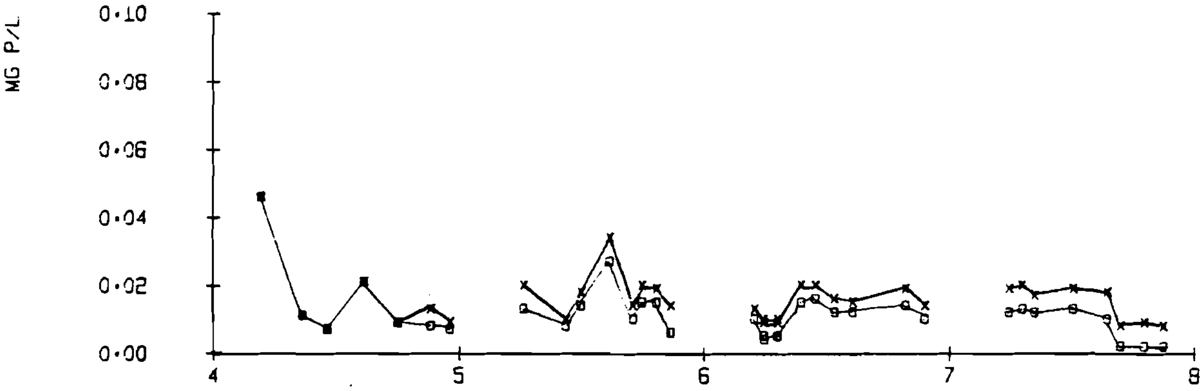

BASIN-II TP(X) TDP(O) PO4(+)
MG P/L
0·10
0·08
0·06
0·04
0·02
0·00
4
5
6
7
8

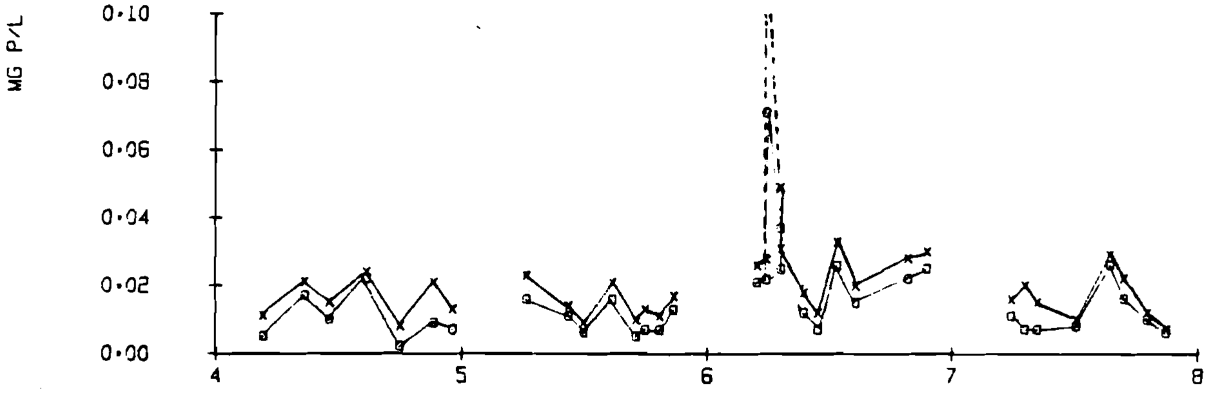

BASIN-II TDP(X) DOP(O)
MG P/L
0·10
0·08
0·06
0·04
0·02
0·00
4
5
6
7
8

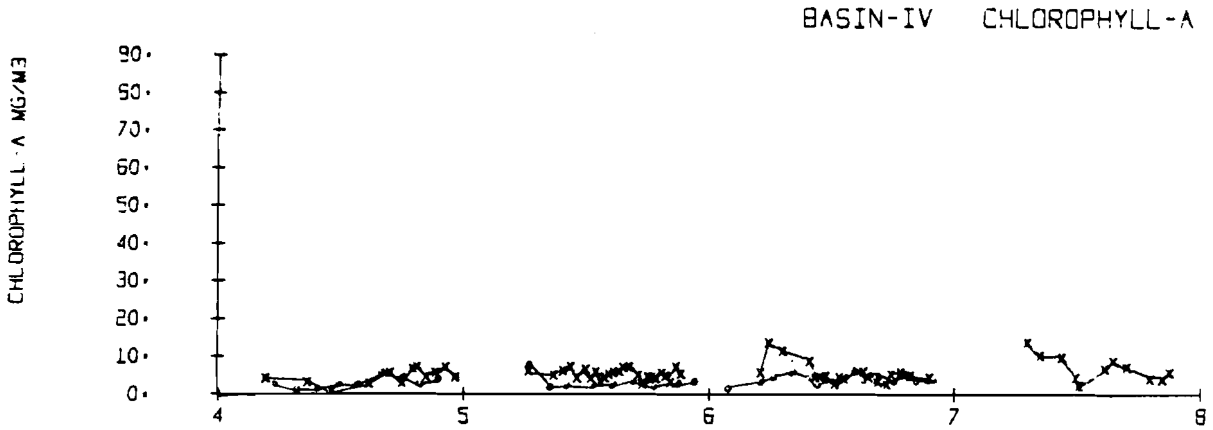

BASIN-II TPP(X) POP(O)
MG P/L
0·10
0·08
0·06
0·04
0·02
0·00
4
5
6
7
8

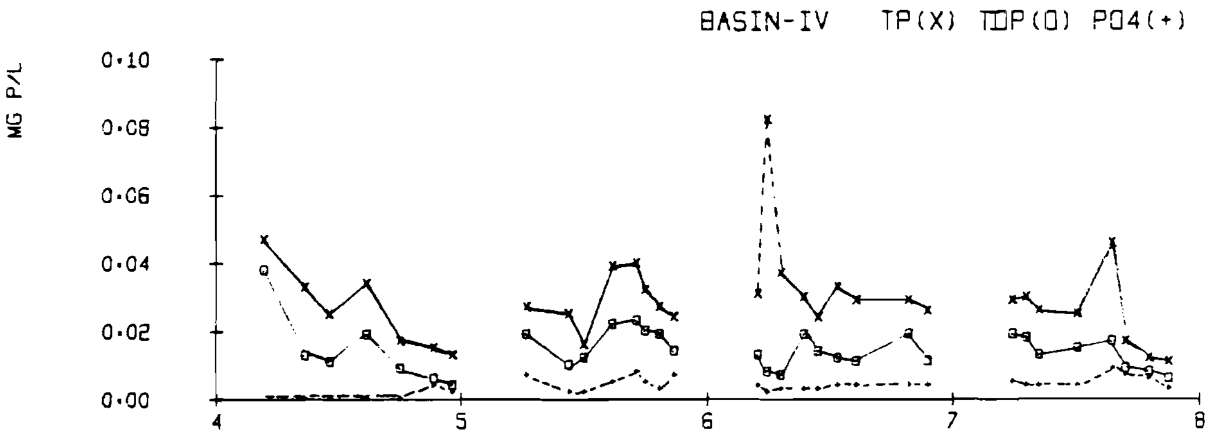

BASIN-III CHLOROPHYLL-A

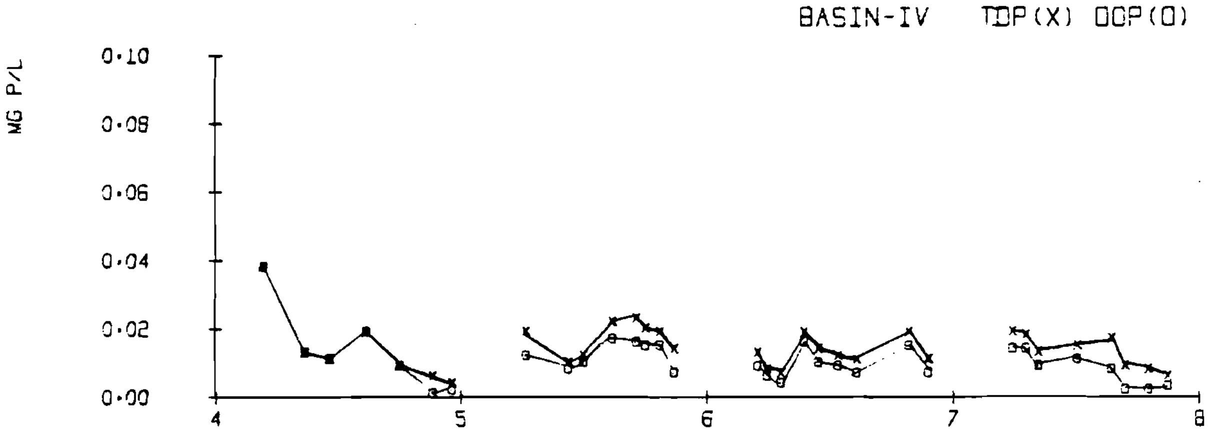

BASIN-III TP(X) TDP(O) PO4(+)$

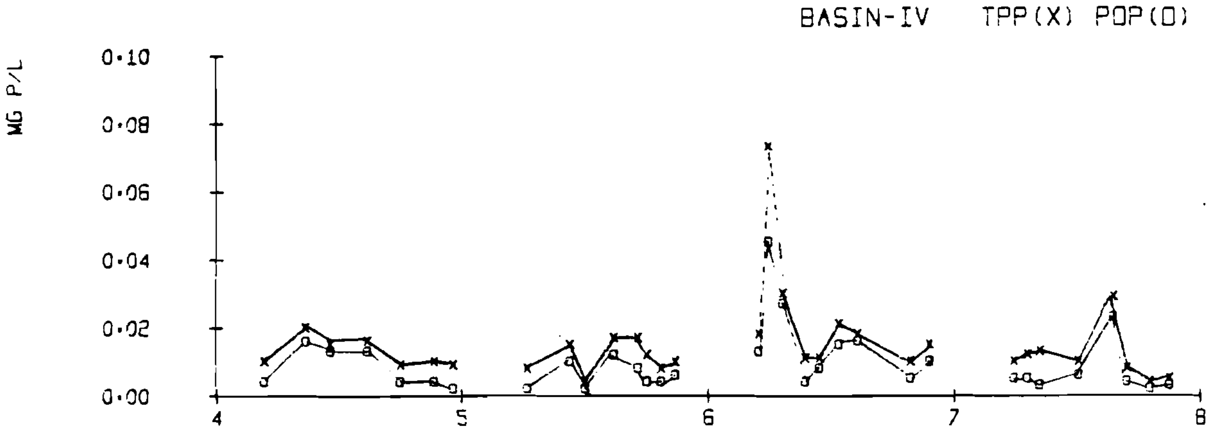

BASIN-III TDP(X) DOP(O)

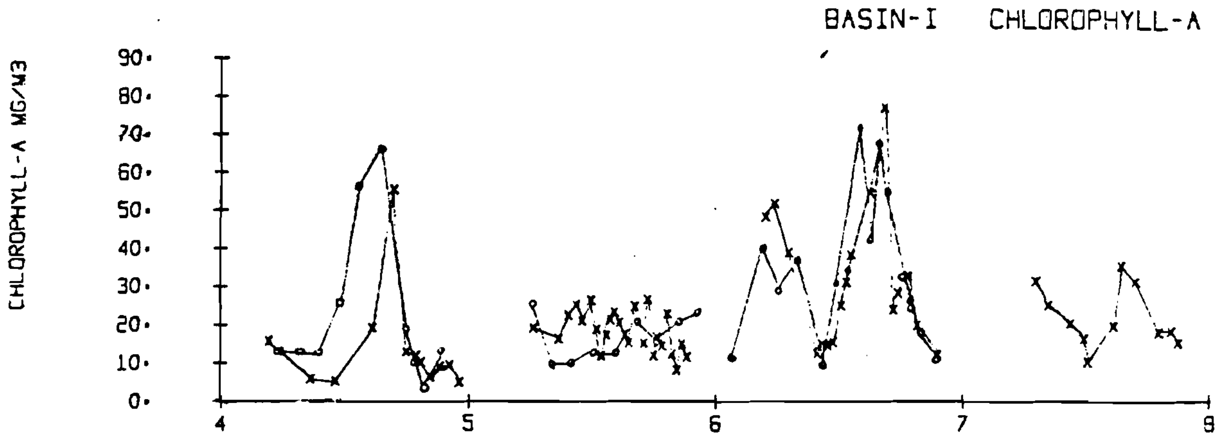

BASIN-III TPP(X) POP(O)

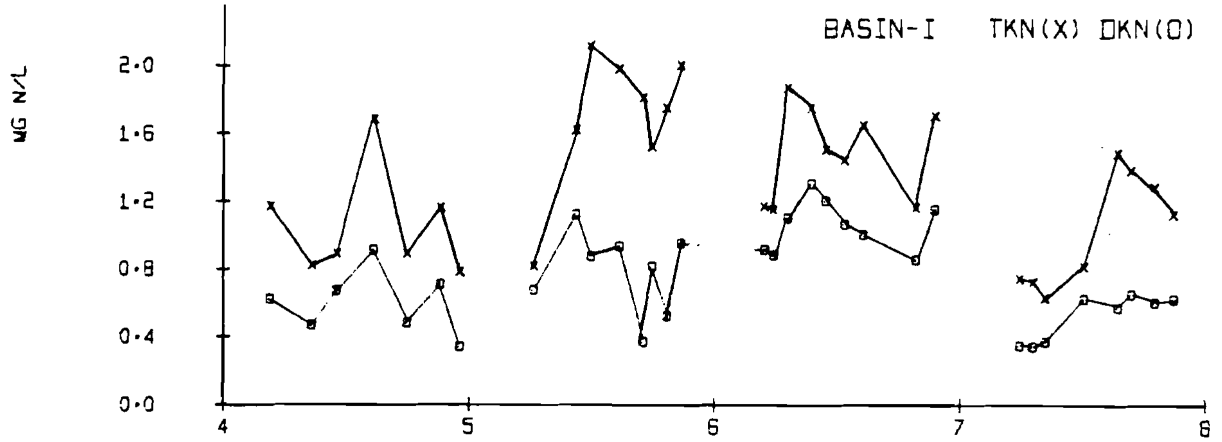

BASIN-IV CHLOROPHYLL-A
CHLOROPHYLL-A MG/M3
90·
80·
70·
60·
50·
40·
30·
20·
10·
0·
4
5
6
7
8

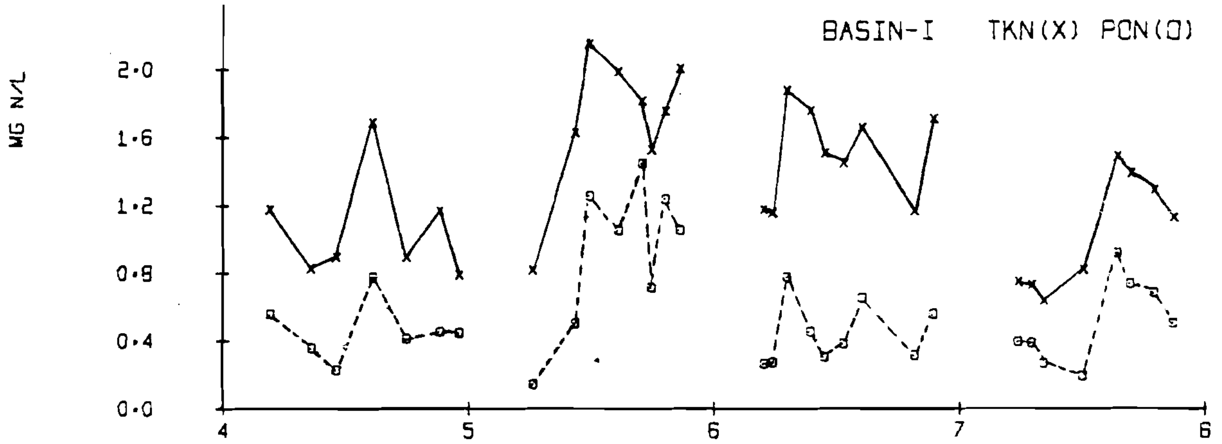

BASIN-IV TP(X) TDP(O) PO4(+)
MG P/L
0·10
0·08
0·06
0·04
0·02
0·00
4
5
6
7
8

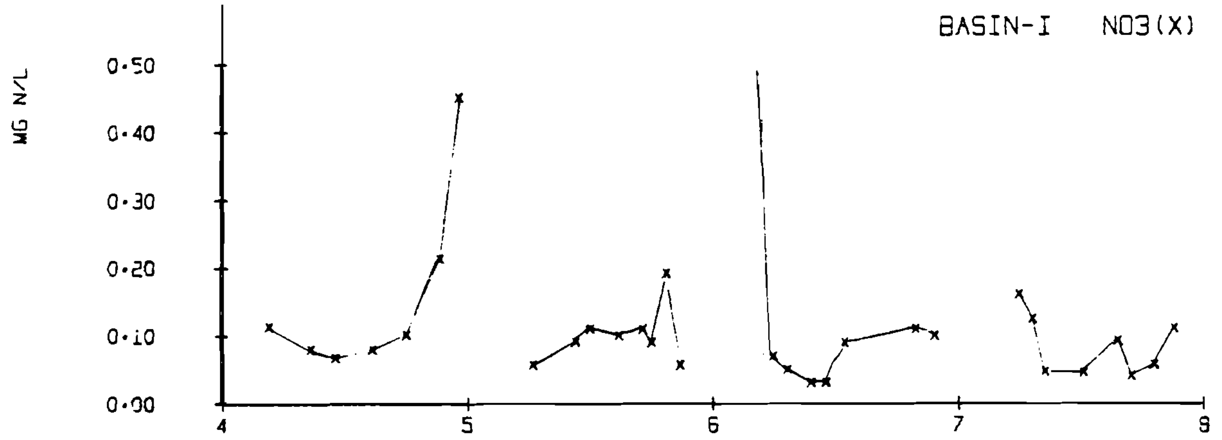

BASIN-IV TDP(X) DOP(O)
MG P/L
0·10
0·08
0·06
0·04
0·02
0·00
4
5
6
7
8

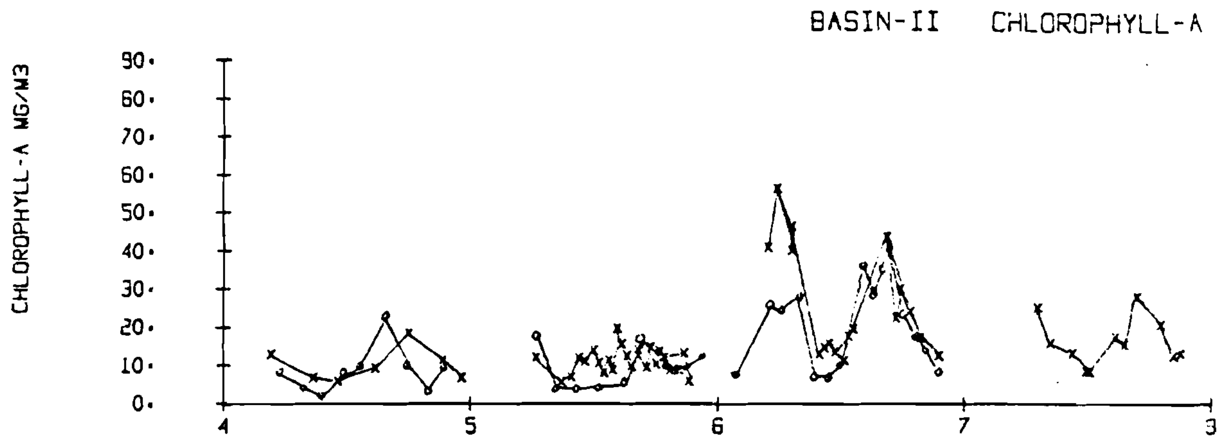

BASIN-IV TPP(X) POP(O)
MG P/L
0·10
0·08
0·06
0·04
0·02
0·00
4
5
6
7
8


BASIN-I CHLOROPHYLL-A
CHLOROPHYLL-A MG/M3
90·
80·
70·
60·
50·
40·
30·
20·
10·
0·
4
5
6
7
8

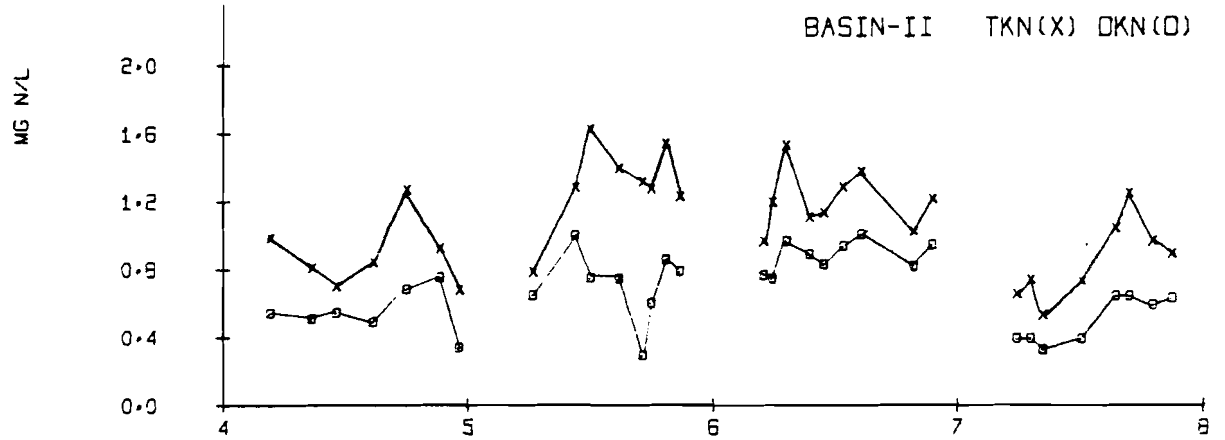

BASIN-I TKN(X) DKN(O)
MG N/L
2·0
1·6
1·2
0·8
0·4
0·0
4
5
6
7
8


BASIN-I TKN(X) PON(O)
MG N/L
2·0
1·6
1·2
0·8
0·4
0·0
4
5
6
7
8

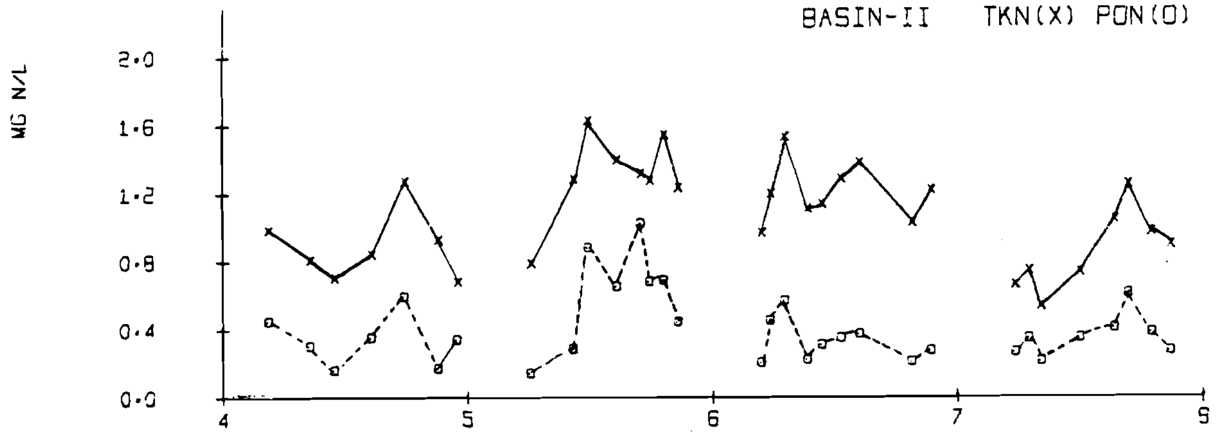

BASIN-I NO3(X)
MG N/L
0·50
0·40
0·30
0·20
0·10
0·00
4
5
6
7
8



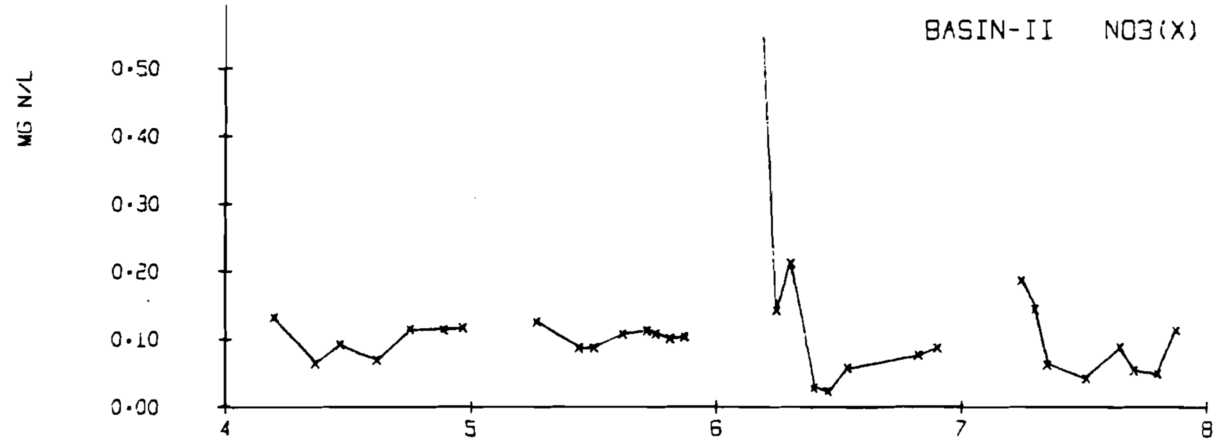
BASIN-II CHLOROPHYLL-A



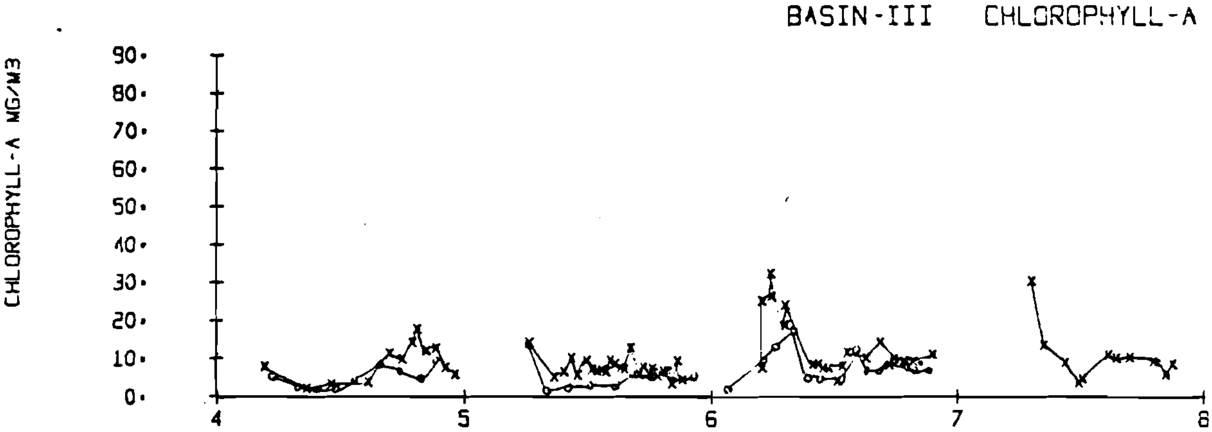
BASIN-II TKN(X) DKN(O)

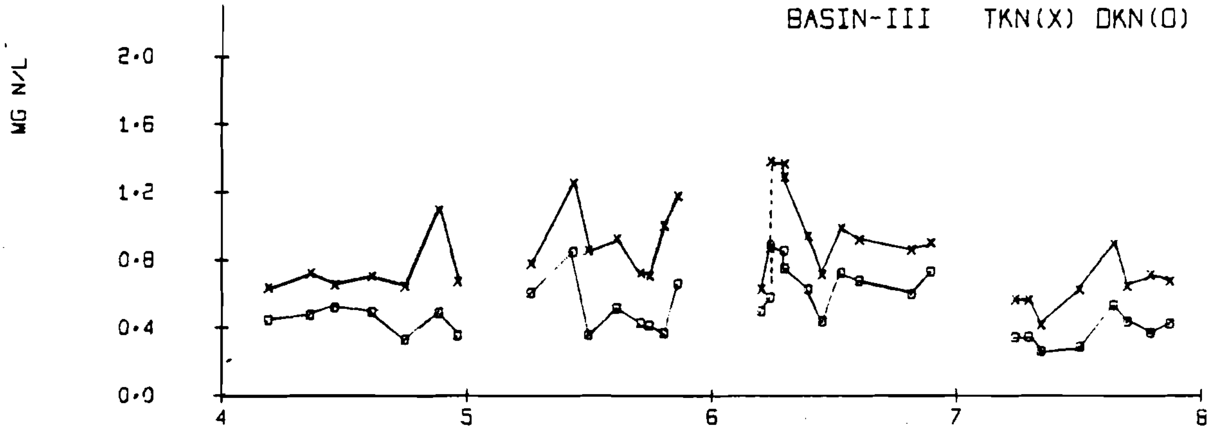


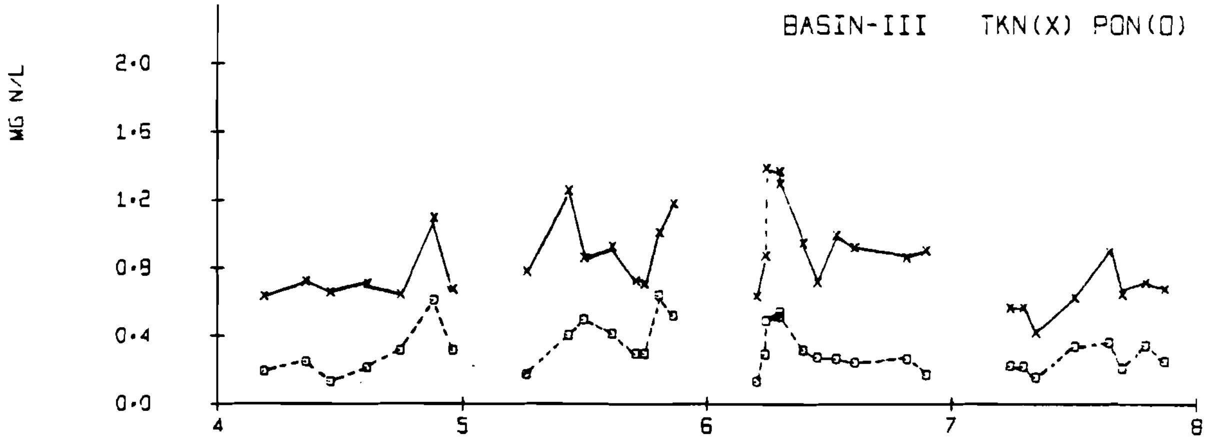
BASIN-II TKN(X) PON(O)

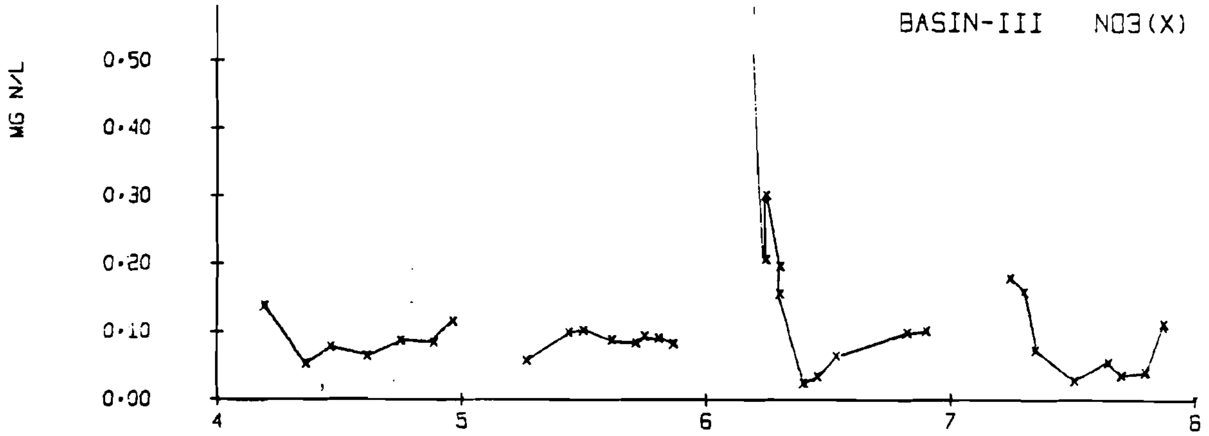


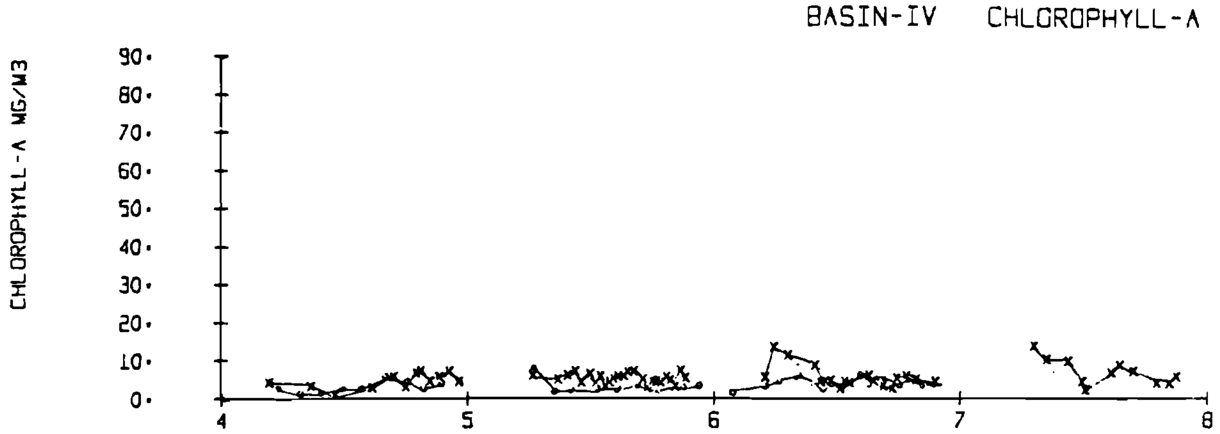
BASIN-II NO3(X)


BASIN-III CHLOROPHYLL-A
CHLOROPHYLL-A MG/M3
90
80
70
60
50
40
30
20
10
0
4
5
6
7
8

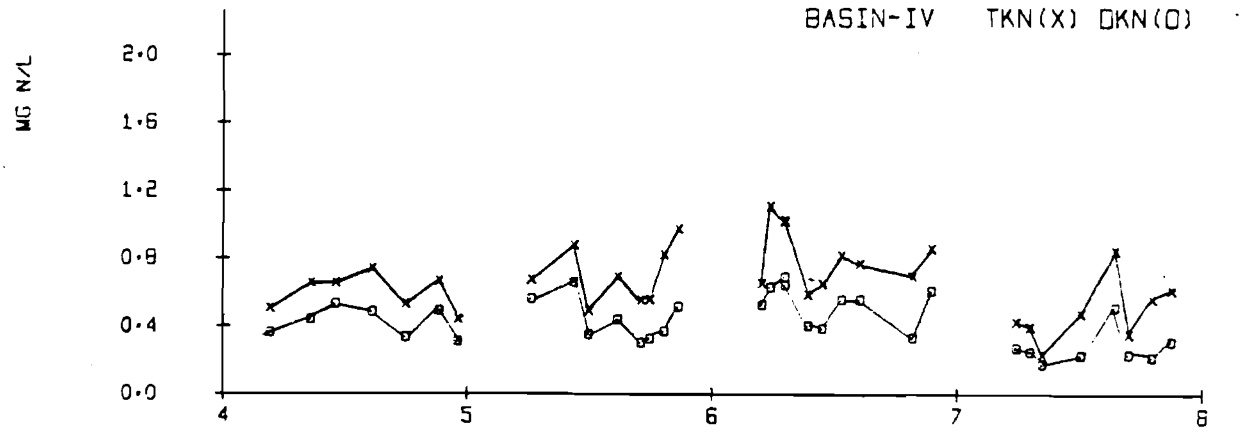

BASIN-III TKN(X) DKN(O)
MG N/L
2.0
1.6
1.2
0.8
0.4
0.0
4
5
6
7
8


BASIN-III TKN(X) PON(O)
MG N/L
2.0
1.6
1.2
0.8
0.4
0.0
4
5
6
7
8

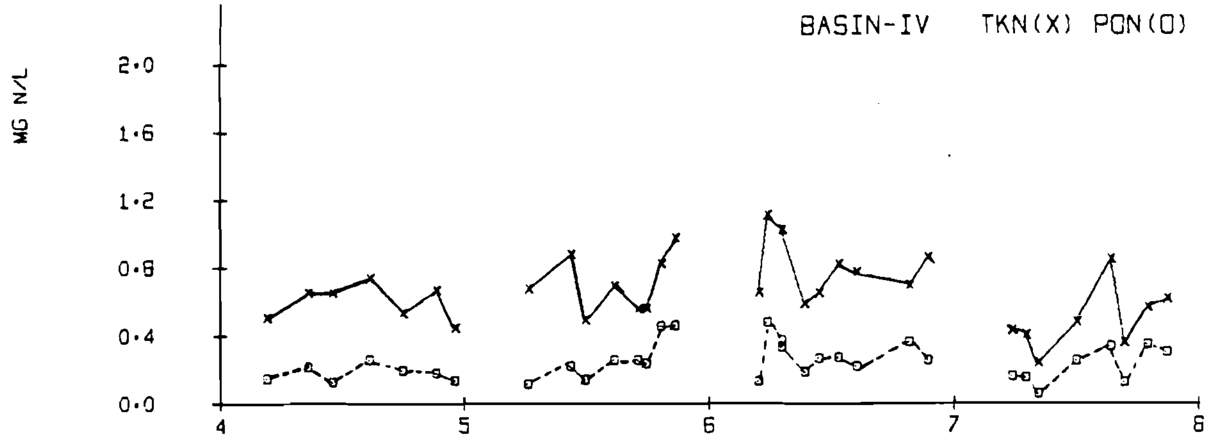

BASIN-III NO3(X)
MG N/L
0.50
0.40
0.30
0.20
0.10
0.00
4
5
6
7
8



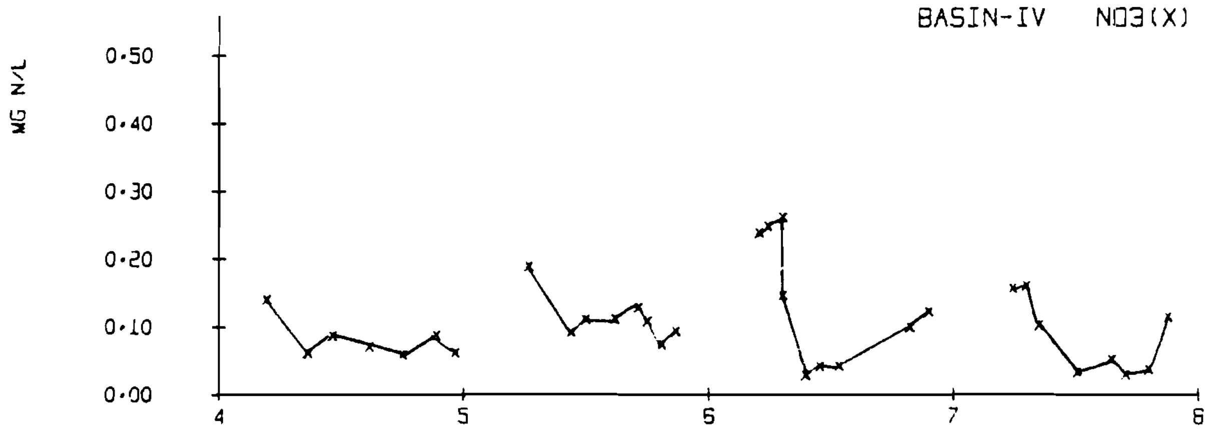
BASIN-IV CHLOROPHYLL-A



BASIN-IV TKN(X) DKN(O)



BASIN-IV TKN(X) PON(O)



BASIN-IV NO3(X)