HYDRODYNAMICAL ASPECTS OF THE EUTROPHICATION MODELLING IN THE CASE OF LAKE BALATON

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PREFACE

Since April 1978 a collaborative study has been underway between IIASA and the Coordination Council for the Environmental Research on Lake Balaton of the Hungarian Academy of Sciences. This study is aimed at the development and investigation of the threat of the lake's increasing eutrophication. Principal elements of the study are the identification of the dominant nutrient sources, the investigation of the dominant modes of nutrient transport from the watershed to the lake, and the study of the effects of the nutrient inputs on the water quality of the lakes with the help of water quality models.

This collaborative paper deals with the modelling of water movement as part of the water quality modelling element of the project. The paper summarizes the special hydrodynamical features of the lake, analyzes the relevance in connection with eutrophication and sets out scenarios for further work on those hydrodynamical aspects that are important for a better understanding of the lake's quality development.

The work reported in this paper was prepared by the author during a short stay at IIASA. It is recognized that it constitutes only the first step in a continuing effort. We would therefore appreciate any comments, remarks, or suggestions by our readers that could help to better shape future activities in this field.

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1. INTRODUCTION

Most of the eutrophication models assume that there is a spatial homogeneity in space and only the change of the process with time has to be considered. The equations are ordinary differential ones (generally non-linear) but involve many uncertainties because of the unsatisfactory knowledge on the biological processes and lack of consistent data.

In spite of these difficulties often the spatial variations may not be neglected and transport processes (mainly in presence of larger pollutant sources) has to be taken into consideration (see e.g. Halfon and Lam, 1978, 1978; Lam and Jaquet, 1976; Parker, 1978; George and Heaney, 1978). Spatial changes may be caused not only by transport processes inside water. The entrainment (or settling) and variation of extinction due to wind action may play an important role, too. These factors influence the formation of eutrophication process in space, however they probably cause changes mainly with time.

Taking into account the aforementioned aspects the influence of wind action, flow pattern, transport processes, entrainment, extinction, etc. often has to be involved into an ecological model on a more precise manner than it is usual. The whole model will become naturally more complicated. However the higher complexity does not necessarily require a better understanding and description of the biological and chemical processes. When using some type of grids in the course of the numerical solution of the more dimensional problem, the kinetic equations will remain the same separately for all the boxes (grid elements).

Whether it is worthwhile to use a more complex model it depends on the special problem treated. The purpose of this report is to discuss this question for Lake Balaton.

In the next two chapters the knowledge available about air, water and sediment motion will be presented. The fourth chapter considers the possibilities of modelling in the light of the results available. The question of the use of three-dimensional hydrodynamical model available at IIASA will be discussed here, too. The last chapter includes recommendations concerning future work on this field.

2. ORIGIN OF INFORMATION AVAILABLE

In the last 10-15 years with the setting up of a measurement network system for the whole lake intensive examinations were elaborated. These measurements involved the following (Fig. 1, Muszkalay and Starosolszky, 1964; Muszkalay, 1973; Hamvas, 1967).

2.1 WIND MEASUREMENTS

The wind data (hourly or three times a day) are registered at seven stations:

Siófok
Szemes
Szemes, middle-point in the cross section
Akali
Máriafürdő[x]
Nemesvita[x]
Keszthely

2.2 WATER MOTION

2.2.1 Water Level Measurements (hourly data)

The stations are as follows:

Kenese
Siófok
Alsóörs
Tihany

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[x] Irregular measurements.

Szemes
Szemes, middle-point
Akali
Fonyód
Badacsony
Keszthely
Máriafürdő[x]
Balatonberény[x]
Mouth of river Zala[x]
Györök[x]
Szigliget[x]

2.2.2 Wave Measurements (three times daily, having five minutes duration)

Siófok
Tihany
Szemes

2.2.3 Velocity Measurements

Siófok[x]
Tihany (four points in a vertical, regularly)
Szemes, middle-point[x]
Mouth of river Zala[x,xx]

2.2.4 Examination on a Combined Air-Water Physical Model (Györke, 1975)

The area of Lake Balaton realized on model is illustrated on Fig. 1.a. The scales are the following:

Continental area $\lambda = 1000$, undistorted
Lake (Froude model) $\lambda_h = 1000$, horizontally
$\lambda_v = 50$, vertically.

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[x] Irregular measurements.

[xx] The measurements do not characterize the lake relations.

The air motion in the model was produced by 18 fans capable of regulating the wind parameters both in space and time (the range of air velocity was 7-13 ms^{-1}). Only the western part of the lake was built up in the model defining the right side boundary by the nodal zone of the longitudinal seiche[x]. Examining the wind data of more years six basic wind types were determined. A year long run on the model consisted of putting together these basic winds having different durations and frequencies but resulting the total yearly energy input by the air.

2.2.5 Sediment Motion

a) Erosion measurements were performed in 9 cross sections (Fig. 1.d, yearly data are available).

b) The movement of traced bottom sediment were examined on 6 places (special measurements).

c) Daily suspended solids measurements[xx] were made in some of the cross sections mentioned in point a).

d) Combined bottom sediment and suspended solids measurements were elaborated in 14 points (see the area in Fig. 1.d) between 1969-71[xxx] (Györke, 1975). The purpose of these measurements was to examine in nature the effect of wind on sediment motion. Thus in each occasion three measurements were made

I. before setting up the wind (background level in water and sediment);
II. during storm (W = 20-30 kmh^{-1});
III. 12 hours after abating the storm.

Four samples were taken from each vertical from the water.

e) Sediment motion was studied also on the physical model.

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[x] Validity of open boundary condition is not exactly proved. Furthermore some uncertainties exist in scaling rules as well.

[xx] Not continued at present.

[xxx] Yearly 1-2 measurements.

3. CHARACTERIZATION OF THE MOTION OF AIR, WATER AND SEDIMENT

3.1 WIND CONDITIONS ALONG THE LAKE

In the case of Lake Balaton the frontal winds are the most important having a duration of 12-36 hours, and an average direction N, NNW. The mountains surrounding the northern shore of the lake influence very expressively the wind conditions (see later). From the point of view of sediment (and probably water) motion, air movements having a velocity larger than 10 km h^{-1} play a role. As an average the number of days having such type of wind is 100 in a year (wind direction between WNW and ENE).

When characterizing a wind the most important parameters are the absolute value (W) and direction (α) of the wind, the duration (t) and fetch (F). Approximately the energy of wave motion induced by the wind

$$E \sim W^2 ,$$

and similarly the shear stress at the free surface

$$\tau \sim W^2 .$$

However, from the point of view of erosion and entrainment from the bottom the duration is also important. Thus it was found by Györke (1975), that the parameter

$$W^2 \cdot t$$

is decisive.[x] When considering a certain time period (e.g. a year), one can sum the values $W^2 \cdot t$ in each direction

$$\sum W^2 \cdot t$$

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[x] For the characterization of entrainment process the product $W^2 \cdot t \cdot F$ could be also applied involving the role of fetch. Another usual parameter is $W \cdot t$.

and form a resultant $\bar{R}$ given by $|\bar{R}|$ and α_R.

Without going into detailed discussions the following yearly averaged values will be presented for six stations (Table 1, see Fig. 1 and a more detailed map) (Györke, 1975). Considering the data three properties have to be underlined:

a) $|\bar{R}|$ has a decreasing tendency[x] from Siófok to Keszthely showing the origin of silting the Keszthely Bay (see later);

b) $|\bar{R}|$ is small on the northern part of the lake (Akali, Szigliget) because of the special configurations of the terrain;

c) due to the presence of the mountains there is an extremely large change in α (order of magnitude $20 - 50^{\circ}$).

Conclusions

a) the prevailing wind direction is N, NW; however the spatial variation above the lake is large;

b) erosion will take place near the southern shore;

c) the danger of silting is the largest in Bay Keszthely.

3.2 WATER MOTIONS

The global motion (flow, waves, seiches, etc.) in the lake is influenced mainly by the following factors:

the direction of the wind is approximately perpendicular to the longitudinal axis of the lake;

irregular mountains;

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[x] Inside $\Sigma W^2 \cdot t$ Σt was approximately constant along the lake.

presence of peninsula Tihany;
non-steady wind conditions;
large wave height as compared to the water depth.

3.2.1 Results Gained from Site Measurements

Some typical data are as follows:

a) maximum longitudinal difference in water level 1.0 m;

b) maximum transversal difference in water level at Szemes 0.4 m (the free surface is curved);

c) maximum velocity at Tihany 1.4 ms^{-1}

d) range of the velocity at Tihany 0.2 to-0.4 ms^{-1} (negative value indicates flow towards Keszthely);

e) range of the velocity inside Keszthely Bay 0.1 to 0.2 ms^{-1};

f) duration of seiche 0.2 - 24.0^h; as an average value 5.5h can be given in longitudinal, while 0.9 h in transversal direction for the western basin.

Analyzing the data of five years Muszkalay (1966) got the following relationships for the longitudinal slope (defined on the basis of maximum water level difference between Kenese and Keszthely)

$$I = 0.038\ t^{1/4}\ (W_r - 2.8) \qquad [\mathrm{cm\ km^{-1}}]\ ,$$

where $W_r = W \cdot \cos\alpha$ the longitudinal component of the wind velocity vector ($\alpha < 22.5^o$) $[ms^{-1}]$, and t, the duration of wind [h]; $t < 12h$.

If

$\alpha > 22.5^o$ (nearer to transversal wind direction),

$$I = 0.0105\ t^{1/4}(W_r + 13.5) - 0.16\ .$$

No close correlation exists between wind data and transversal slope, but the latter one may be three or four times larger than the longitudinal slope.

The velocity at Tihany is defined by the longitudinal slope between Alsóörs and Szemes, and approximately the

$$v = 500 \sqrt{i} - 0.5 \qquad [ms^{-1}]^{x}$$

estimation can be given (Muszkalay, 1973, i[-]). According to the measurements the flow has the same direction along the whole depth (showing towards Keszthely or Kenese) and the water is often streaming opposite to the wind.

Considering seiche motions, slopes and waves in most of the cases the longitudinal slope is quite small while the transversal one is much larger. Longitudinal seiches are important to which transversal seiches will be superimposed. The wave motion is of shallow water in character. The height of the wave depends on the parameters of the wind (W, α, t, F), on turbulence, depth and interferences. All these effects may sometimes cause the water level to be 1.5 m higher than the static one.

The square mean value of wave height was approximated by Muszkalay (1973) by the equation

$$H = a(W_a - 2)^{0.725} \quad [m],$$

where "a" depends on α, F, h $a = 0.05 - 0.12$; $W_a[ms^{-1}]$ is an hourly average value previous to the occurrence of H_{max}. The formula is valid in the vicinity of Szemes.

Some extreme examples about the global variation of water level are given in Fig. 2-6. (Muszkalay and Starosolszky, 1964.)

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[x] 1.0 m below the free surface

3.2.2 Results of the Physical Model (Györke, 1975)

Here mainly the mixing of fresh Zala water in the lake will be considered.

a) If no wind is acting the largest part of fresh Zala water remains in the bay (Fig.7)[x]. During outflow in the Sió canal an intensive motion can be observed towards Szigliget.

b) In case of steady state wind conditions (Fig. 8) a complicated three-dimensional flow pattern will be gained. The motion of the layer near to the free surface corresponds to the wind direction. However, the largest part of fresh Zala water will be transported in the lower layer in an opposite direction. This motion is induced by waves and transversal slope, and causes sediment (originated mainly from river Zala) motion in the same direction. The motion near the bottom is directed towards North. The mixing between the two bays (Keszthely and Szigliget) is small.

c) During increasing winds an inflow can be observed into Bay Keszthely while the effect of decaying wind is just opposite. However, due to the quicker damping of waves in Bay Keszthely the outflow is smaller (see Fig. 9, transient conditions).

Conclusions

a) Due to the complicated geometrical, topographical and wind conditions the flow is expressively of three-dimensional in character;

b) In the cross section Tihany the flow is a longitudinal one having high velocities. The peninsula Tihany divides the lake into two areas;

c) A complicated mixed seiche motion is formed in the

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[x] Naturally the outflow from the bay is equal to the inflow.

lake. The transversal slope of the free surface is generally much larger than the longitudinal one. The height of waves is very large compared to the water depth. This fact causes erosion (and probably intensive entrainment from the bottom) in the southern part of the lake.

d) Different zones are formed in the lake having more or less independent circulations. The two bays (Keszthely and Szigliget) belong to this category, also. The largest portion of fresh Zala water (and the suspended solids and nutrients connected to it) remains in Bay Keszthely (incomplete mixing).

3.3 SEDIMENT MOTIONS

Sediment transport is mainly affected by the motion of air and water. Its general features correspond to the expected ones on the basis of the previous chapters.

3.3.1 Results of In Situ Measurements

Analyzing the water balance of Lake Balaton Szesztay (1969) estimated the rate of silting as 0.54 mm/year. However the largest part of the lake seems to be in equilibrium from this point of view and first of all Bay Keszthely is endangered. Here the special conditions of the bay and the sediment quantity transported from other sections of the lake play an important role.

Erosion and entrainment are intensive near the southern shore line. This is illustrated on Fig. 10, where the yearly development of erosion and the change during four months long observation period is also given. The figure involves wind and suspended solids (SS) concentration data, too. Due to wind action the suspended solids concentration may increase from 20 - 30 gm^{-3} to 200 gm^{-3} (in extreme cases to 4-500 gm^{-3}).

As the figure shows a correlation exists between wind and SS data. The direction of wind has an important role, the largest entrainment rates can be found in the case of winds normal to the southern shore line.

The special measurements mentioned in 2.2.5.d, served an interesting picture about the entrainment and sediment motion. The SS concentration distribution was uniform along verticals in all the cases. The background value and the concentration belonging to period III (Section 2.2.5) varied between 20 and 40 gm^{-3}. During storm (period II) values between 100-200 gm^{-3} were observed near the southern shore line and in the middle part of lake. In the vicinity of northern shore line only negligible variations could be found compared to the background level. This fact illustrates clearly the variation of entrainment from the bottom sediment (being influenced by the change in fetch, wave heights, turbulence, etc.).

The particle size distribution was also determined for SS and bottom sediment. The pattern is the expected one on the southern shore having coarser fraction and a larger mean particle size in the bottom sediment (150 - 200 and 20 -30 μm, resp.). However on the northern part of the lake the bottom sediment contains smaller particles (mean size 5-10 μm) than the water (20-30 μm).

This fact illustrates that there is a sediment transport associated with water in northern direction.

The bottom sediment motion (see 2.2.5.b) shows a similarly unfavorable picture from the point of view of Bay Keszthely, the motion is directed in most of the cases towards the bay (Fig. 11).

3.3.2 Results of the Physical Model

The transport of suspended solids generally follows the water motion (see 3.2.2). Thus the water will become "oversaturated" in Bay Keszthely which leads later to deposition and silting. The duration of winds having directions different from the prevailing one is relatively short thus the sediment cannot leave the bay. Shortly speaking, the bay is working as a trap.

The deposition pattern of Zala sediment after two years long simulation period may be seen on Fig. 12. Worthwhile to mention that in the vicinity of Zala mouth no deposition takes place due to wave motion and intensive flows.

Accordingly the model results sediment can be transported also from Bay Szigliget into Bay Keszthely.

Conclusions

a) Near the southern shore line an intensive entrainment takes place;

b) The entrained sediment is transported towards the northern shore where later deposition will occur;

c) The bay is working as a trap;

d) No deposition can be observed near the Zala mouth due to wave and flow actions.

4. APPLICABILITY OF A HYDRODYNAMIC-TRANSPORT MODEL FOR LAKE BALATON

From the previous chapters one can realize that the flow pattern, seiches, waves, sediment motions and wind conditions are of very complicated nature in Lake Balaton. Concerning modelling activity both aspects mentioned in Chapter 1-- transport processes and exchange at the bottom layer -- play an important role (see Harleman and Vasiliev, 1978, too). The results presented here showed that the fresh water of

Zala river (containing sediments, nutrients, etc.) would not be mixed completely inside the lake. Due to this fact and the special properties of Bay Keszthely transport processes may influence strongly the degree of eutrophication (which shows a decreasing tendency in East-West direction, Harleman and Vasiliev, 1978). The importance of entrainment from the bottom was discussed in Section 3.3.1 and illustrated on Figs. 11 and 12. Though the results were gained for bottom sediments and suspended solids a similar effect may be expected concerning particulate phosphorus. Due to wind action interstitial water may be stirred up, too. In this way the soluble phosphorus will also be influenced. Consequently neither the second aspects of hydrodynamical modelling may be neglected.

In the light of the aforementioned aspects the modelling of the effect of wind induced flows can be classified according to Fig. 13. Here distinction has to be made whether the model serves for simulation of real situations or for better understanding of the process considered.

4.1 INFLUENCE OF WIND INDUCED FLOWS ON THE TRANSPORT PROCESS (MODEL A)

4.1.1 Basically here a combined hydrodynamic-transport model has to be used consisting of boxes (e.g. grid elements). In the transport model the kinetic equations of nutrients, algae, etc. has to be built in (Halfon and Lam, 1978, 1978), thus the total model will have more boxes and compartments. This type of model can be classified according to Table 2 depending on the number of spatial dimensions and assumptions made on time dependence.

From the table it appears that for Lake Balaton (for purpose A) only the application of model types III, V and VI seems to be feasible. However the use of models V and VI requires large and fast computers.The execution time is in case VI at best real time/50 (Lam, 1978, personal communication) and enormous quantity of data has to be handled when applying the model for real situations. These models help in better understanding of the process. On this field the application of models already existing is proposed (Vasiliev and Kvon, 1977; Halfon and Lam, 1978; Durham and Butler, 1976).

Because of the shallow character of the lake complete mixing may be assumed along verticals. Thus the three-dimensional treatment of the problem would be required mainly because of the three-dimensional pattern of the flow, not directly because of the transport process. This means if one has the correct flow pattern and uses a two-dimensional horizontal transport model including depth integrated values quite feasible results may be gained (see Table 2; naturally the appearance of dispersion[x] may cause uncertainties. However, its effect is not large if the concentration is equalized sufficiently along depth).

Thus for practical purposes model type III (Table 2) may be proposed (involving a second model for the estimation of exchange in bottom layer, see later). Its applicability will depend mainly on the fact how correct is HDM 2 (Table 2) concerning the depth averaged velocities. In the course of selecting the solution technique or model type available primary attention has to be paid to the strong variation of wind velocity in space and short execution time of the computer program.

For illustrating the possible effect of change in wind direction see Figs. 14 and 15 (Durham and Butler, 1976), which show solutions for Lake Erie at 40 ft depth below the surface, for two different wind directions, having a deviation

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[x] It has to be emphasized that dispersion includes here the contribution of non-uniformities along a vertical (but not on the whole cross section) to the transport, only.

$\Delta\alpha = 22.5^{o}$. The order of magnitude of $\Delta\alpha$ is the same or larger for Lake Balaton. The two cases naturally may not be compared correctly because along Lake Balaton variable deviations can be found among different points in space at the same time influencing the circulation pattern.

Naturally it is possible that the model will not produce satisfactory results because of neglecting vertical circulations and consequently the transport of Zala water will be fundamentally different from the real one (Fig. 8, keep in mind that the surface water layer moves according to the wind direction, but the fresh water of Zala including sediments, nutrients, etc. in the opposite one). It is proposed to adopt an existing model or to develop a low effort first order approach in order not to waste time with a full and comprehensive development since the starting assumption may not be correct. The attempt has to be followed by testing simple situations for Lake Balaton.

In possession of encouraging results detailed verification may be based on water level and water quality data, results of the physical model and on future measurements (velocity, nutrients, etc.). As a first step the kinetic submodel can be calibrated by assuming spatial homogeneity (Table 2, I, Lam and Jaquet, 1976).

From many points of view it might become desired to divide the whole lake into subregions (saving computer time, etc.). It has to be emphasized that the two bays (Keszthely and Szigliget) must not be separated with respect to hydrodynamical aspects. Boundaries of further subregions can be located e.g. at Szemes and Tihany.

If only a given area of the lake will be considered an open boundary condition has to be defined. The structure of the hydrodynamical model has to guarantee some flexibilities in this respect (e.g. it has to allow the description of water level along the open boundary. Other possibilities are often very uncertain, see Horwood and Bedwell, 1978).

4.1.2 Possibility for Use of Three-Dimensional Steady State Hydrodynamical Model Available at IIASA

The model was developed and applied for Lake Erie by Durham and Butler, 1976. Basically the mixed analytical-numerical method of Gedney (1971) was used in the frame of which first the integrated stream function will be computed from a two-dimensional Poisson equation using over-relaxation technique followed by the derivation of the depth integrated velocities. The third velocity component together with the vertical distributions of horizontal components and pressure will be gained afterwards from analytical expressions. Although application of the model might cause some smaller difficulties in the case of Lake Balaton (i.e. definition of open boundary condition if not the whole lake is considered; the shallowness of lake; the assumption of constant wind directions; the neglection of water level change due to wind action in some places in the course of the derivation of governing equations, see Gedney, 1971, etc.) it would serve some very useful results for better understanding of flow pattern at least under steady state conditions.

However unfortunately the program may not be used at present at IIASA. The reasons are as follows.

a) Very large one-, and two-dimensional blocks are defined. Accordingly a computer having at least 300 Kbyte memorie is required (rough estimation). Thus the model may not be applied on PDP11 computer available at IIASA.

b) The program is not flexible, it was fitted to the special problem of Lake Erie. Thus the number of grid points is fixed causing the large memorie requirement mentioned. All the "DO" cycles correspond to the number of points used (122 and 40 respectively).

c) Some smaller parts of the program restrict also the general application (specific constant values built in the program, etc.).

d) Actually the program was not accessible on computer during the visit.

Considering the whole question the following propositions can be given.

a) Efforts have to be made to apply a larger computer (e.g. IBM at Pisa). However reorganization, generalization and adoptation work have to be performed in this case, as well.

b) An attempt has to be taken to decrease drastically the number of grid points and to adopt the model on PDP11.

The main advantage in use of the program would lie in the comparison of the results of a three- and a two-dimensional model and would serve for judging the applicability of the second one at least under steady state conditions.

4.2 INFLUENCE OF WIND INDUCED FLOWS ON THE INTERACTION AT THE BOTTOM LAYER (Model B, Fig. 13)

The effect of this type of exchange due to physical action is many-sided (see earlier, too):

a) Sediments and particulate phosphorous will be reentrained from the bottom layer (at a different rate in space) and later deposited again on other parts of the lake;

b) Soluble phosphorous content of the interstitial water will be also removed;

c) Extinction will vary.

The importance of these effects are different, e.g., if the soluble reactive phosphorous plays the decisive role, if the particulate phosphorous is stable enough and if the soluble phosphorous content of interstitial water precipitates quickly after resuspension, the change in extiction will be the capital issue. A decision in this field can only be made after some basic and in situ experiments suggested already on the Tihany meeting. These aspects will influence the question whether it is necessary to apply a more detailed transport equation for the bottom layer or not.

From the point of view of interaction the following parameters are the most important:

a) wind data (absolute value, direction, fetch, duration, time dependence);

b) bottom friction and kinetic energy available at bottom layer (Harleman and Vasiliev, 1978);

c) density difference between water and sediment;

d) type of sediment and suspended solids (particle distribution, shape of particles, cohesive or non-cohesive properties, etc.);

e) the way how phosphorous fractions are bound to the sediment.

Connected to point b), the origin of kinetic energy or bottom shear is important. Thus turbulence, seiches and wave motions may play different roles (in the latter case the bottom orbital velocity has to be taken into consideration, see Lam and Jaquet, 1976). This fact causes differences in modelling of the interaction process.

Suggestions for modelling are as follows.

a) One can use the parameter estimation technique (see Jolánkai and Szöllősi-Nagy, 1978). This method does not give an insight concerning the nature of the process but it is a useful tool in practice.

b) Regression models can be applied for extinction and entrainment on the basis of wind (absolute value and direction), water level, suspended solids and phosphorous (soluble and particulate) time series belonging to different locations. Additional measurements are needed, however the data presented on Figs. 10 and 11 can be used for a first guess at present.

c) The shear stress, kinetic energy, wave motion, the parameters $W \cdot t$, $W^2 \cdot t$, $W^2 \cdot t \cdot F$ (see Section 3.1) may be involved into the process.

d) Model type IV (Table 2) can be used by fitting to measured data.

e) A special simplified model can be developed for estimating the effect of waves (Lam and Jaquet, 1976), or the available turbulent kinetic energy at the interface (see for stratified flow, Hansen, 1978).

5. RECOMMENDATIONS

On the basis of previous chapters and discussions continued in IIASA the following recommendations may be given for future work on the problem discussed in the report.

5.1 MEASUREMENTS

a) It is proposed to perform some quality measurements (e.g. phosphorous) to get a better guess on the importance of spatial variations (within bays; water and bottom sediments have to be involved).

b) Measurements are required for the estimation of extinction and entrainment (see Section 4.2). At least daily but during some storms more frequent samples are needed (both on suspended solids and phosphorous fractions, water and bottom sediment).

c) Velocity measurements would help a lot.

d) The conduction of some basic experiments (or collection of results available) is proposed connected to the interactions at the bottom, to the phosphorous resuspension, precipitation, etc.

5.2 MODELLING ACTIVITY

a) A horizontally two-dimensional unsteady hydrodynamical model coupled to a transport (diffusion-advection) model involving sinks, sources and kinetic equations of different compartments is recommended for practical application. The model has to be capable of taking into consideration the variation of wind in space and time furthermore for definition of open boundary conditions.

b) For judging quickly the applicability of such type of model there is an urgent need to compare at least the results of a steady state three- and two-dimensional hydrodynamical model available for Lake Balaton. Concerning the three-dimensional model an effort has to be made for reorganizing and adopting the model of Durham and Butler, e.g. in Pisa, or by reducing the number of grid points on PDP11.

c) For better understanding of the process attempts have to be made for usage of an unsteady three-dimensional hydrodynamical model available elsewhere (model of Vasiliev and Kvon, or Simon's model used e.g. by Halfon and Lam).

d) A separate model has to be developed for estimation of interaction processes at the bottom. Here the use of parameter estimation technique, regression models, vertically two-dimensional hydrodynamical model or other special models seems to be feasible. This model will serve as a submodel for the model mentioned in point a).

e) It is proposed to use a computer which allows a very dense accessibility.

f) Recommended, too, to join together all the aspects mentioned in the report as closely as possible.

g) Intensive work is required for the preparation of input data (bottom configuration, wind, etc.) taking into account the actual situations.

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FIGURES AND TABLES

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Table 1. Average values characterizing wind conditions for 1970.

Table 2. Classification of combined hydrodynamic-transport models.

	Siófok	Szemes	Máriafürdő	Keszthely	Akali	Szigliget
$\lvert\bar{R}\rvert$	$1{,}8.10^6$	$1{,}0.10^6$	$0{,}95.10^6$	$0{,}64.10^6$	$0{,}5.10^6$	$0{,}61.10^6$
α_R	302^o	307^o	267^o	288^o	321^o	297^o

$\lvert\bar{R}\rvert$ $[km^2\ h^{-1}]$

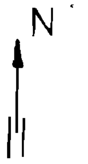
α_R is measured counterclockwise from the axis x (W-E, direction $N \equiv 270^o$)

Table 1. Average values characterizing wind conditions for 1970 (Györke, 1975)

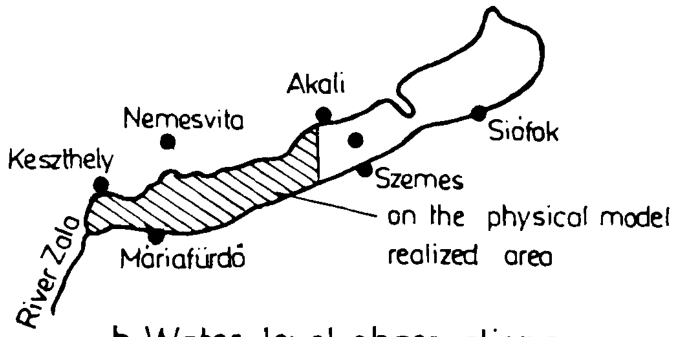
NUMBER OF DIMENSIONS	TIME DEPENDENT?	
0 I	YES	There is no transport in space, homogeneity is assumed.
HDM 1 + TM 1 II	YES	In-and outflows of cells will be gained. Because of the complexity of the present problem, not applicable.
HDM 2 + TM 2 (horizontally) III	YES	Vertical currents neglected. Possible way for application.
HDM 2 (+ TM 2) (vertically) IV	YES	Horizontal currents neglected. Proposed to be used for purpose B.
HDM 3 (+ TM 2 or 3) V	NO	Mainly for better understanding. Steady state wind conditions.
HDM 3 (+ TM 2 or 3) VI	YES	Mainly for better understanding.

Note: HDM indicates hydrodynamical model
TM indicates transport model including kinetic processes, sinks and sources.

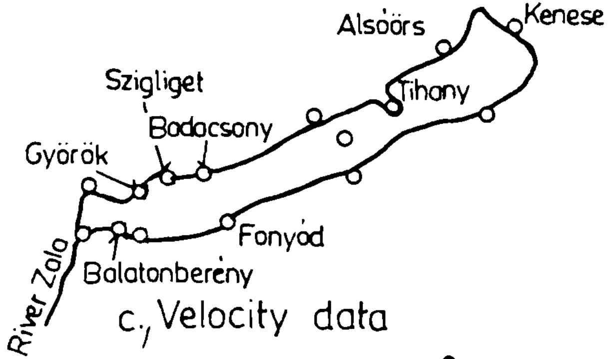
Table 2. Classification of combined hydrodynamic-transport models.



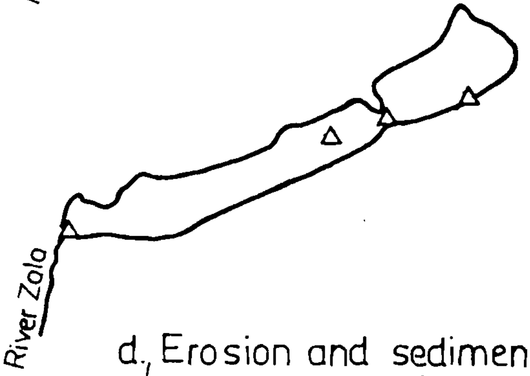
a., Wind data



b., Water level observations



c., Velocity data



d., Erosion and sediment measurements

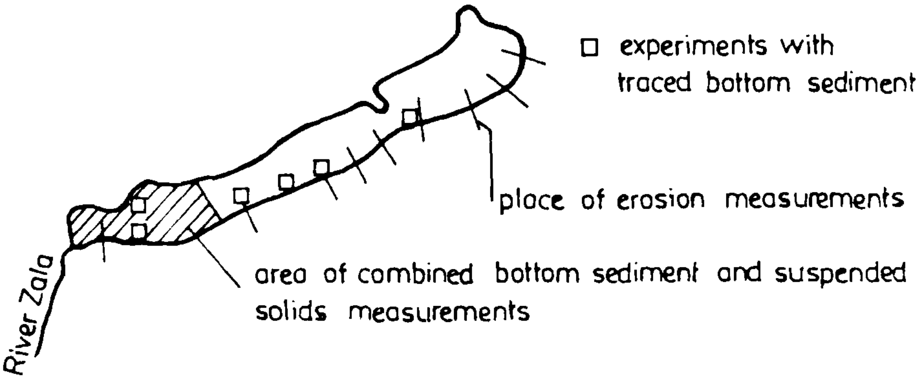


Fig.1. Measurement network on LAKE BALATON

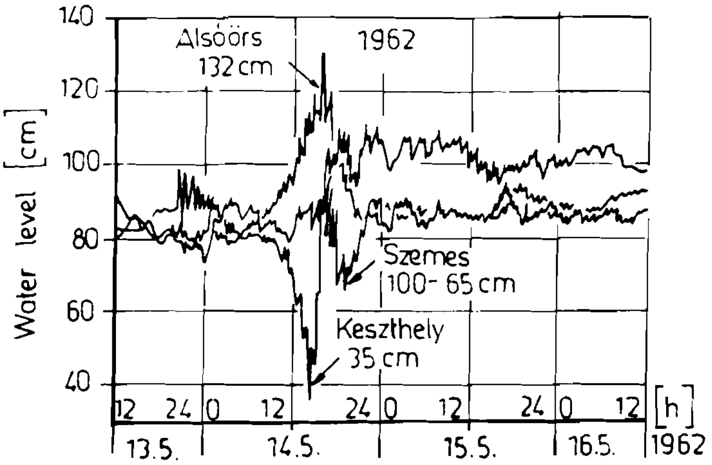


Fig. 2. Longitudinal oscillations
(Muszkalay and Starasolszky, 1964)

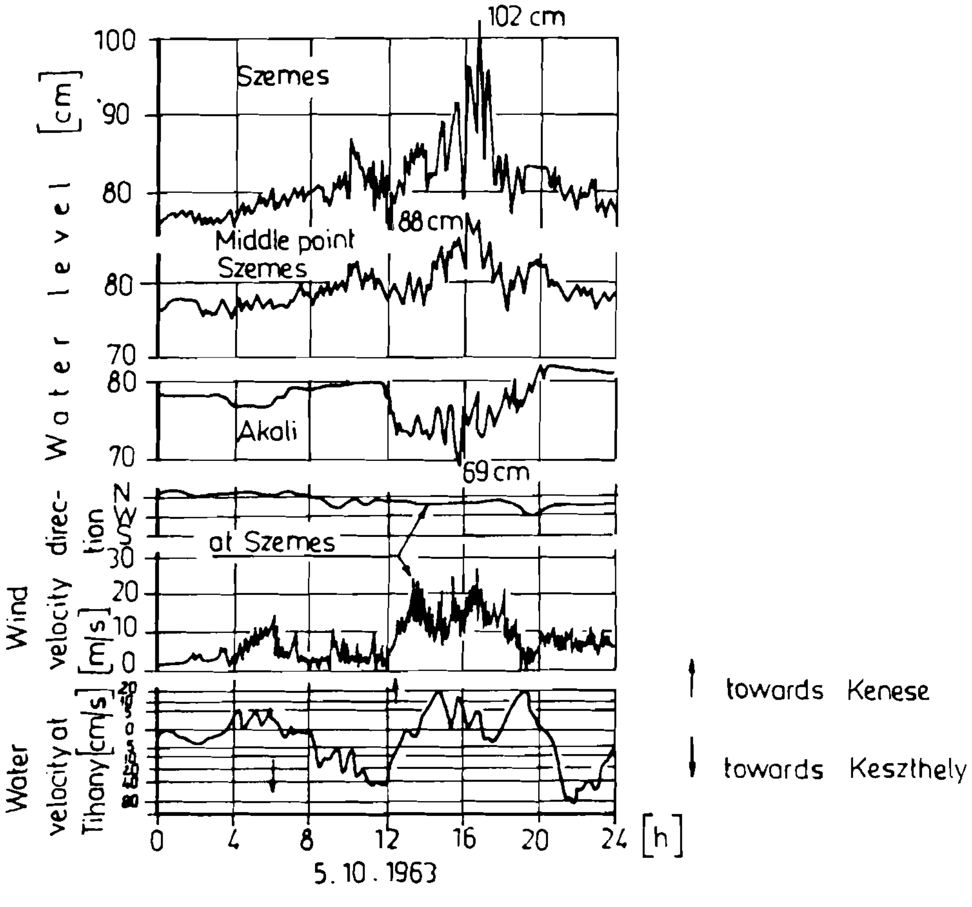


Fig. 3. Transversal oscillatios
(Muszkalay and Starasolszky, 1964)

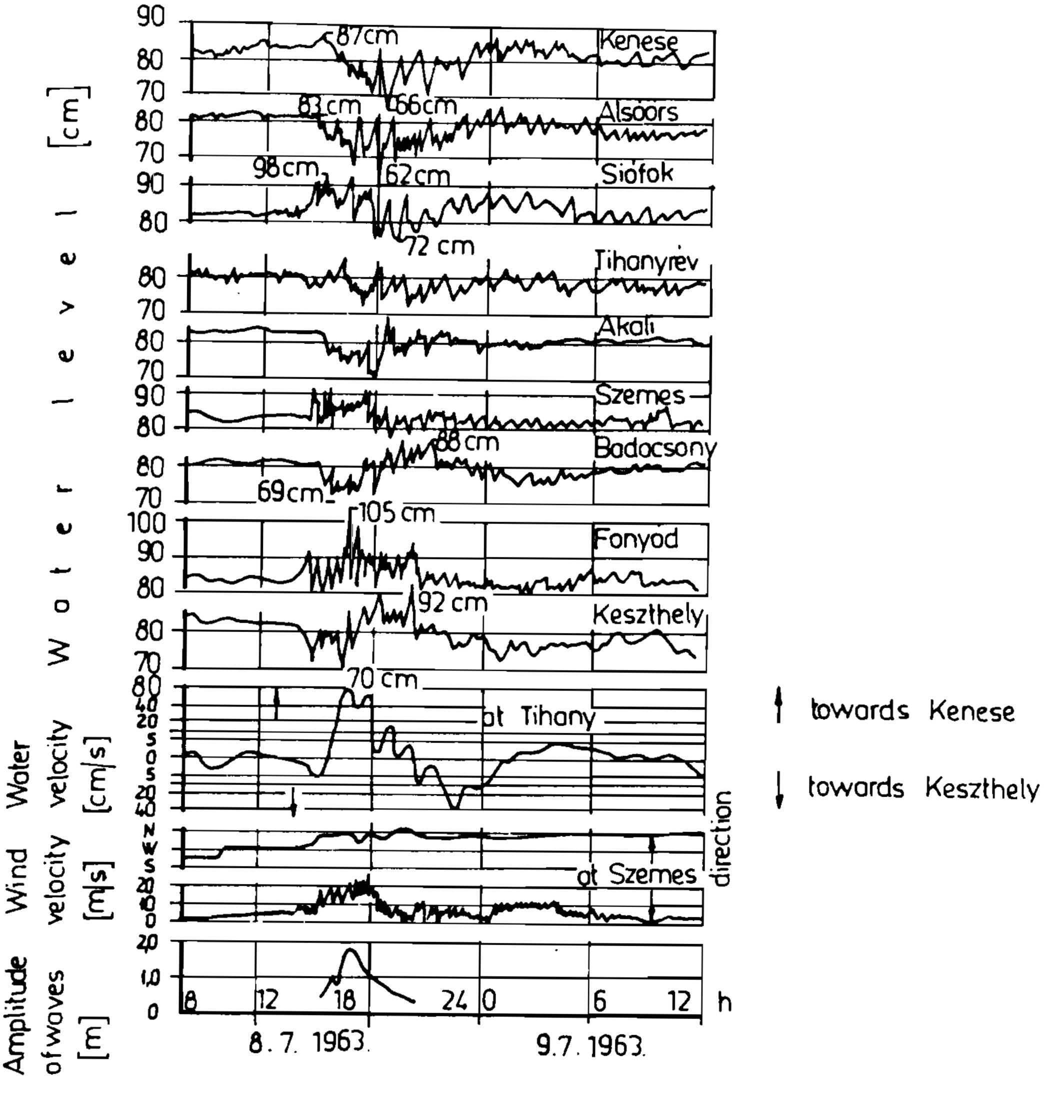


Fig. 4. Superimposed motions (Muszkalay and Starasolszky, 1964)

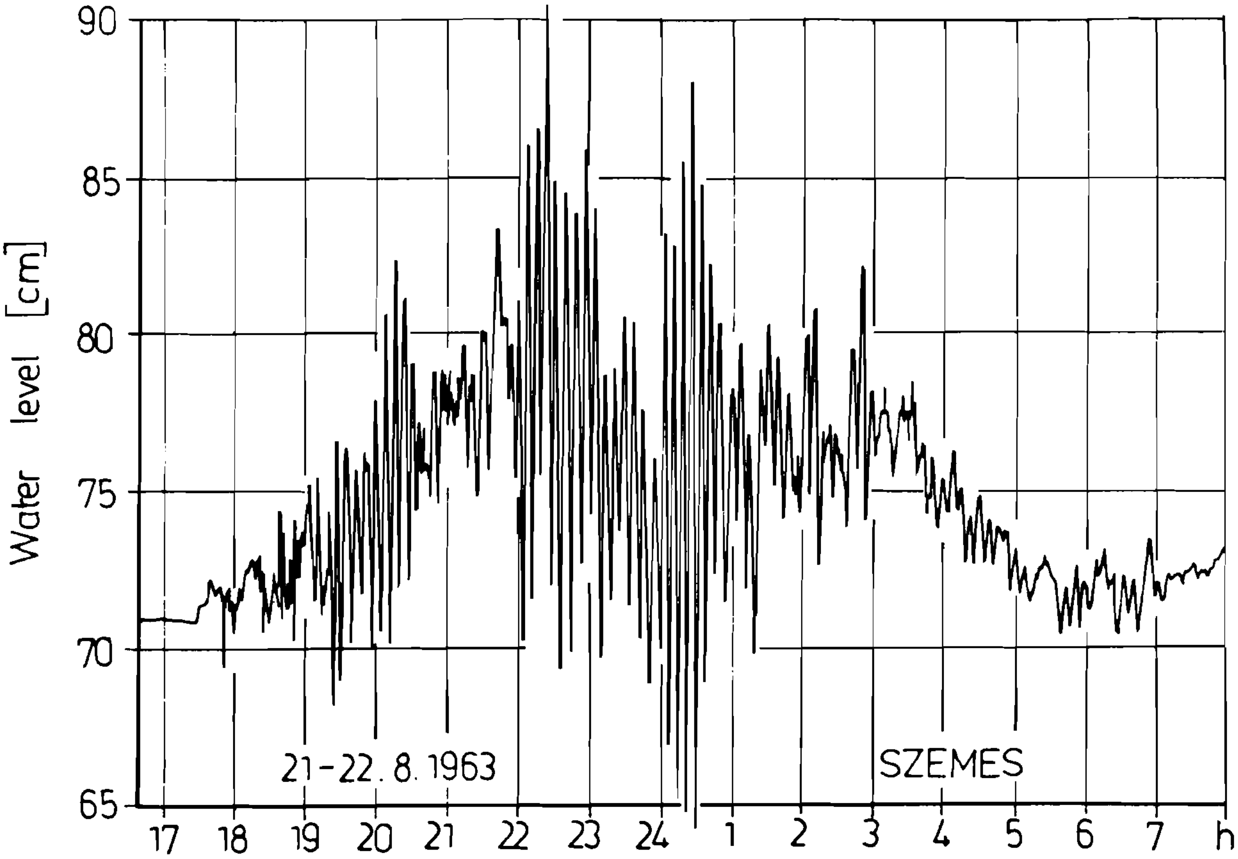


Fig. 5. Short term oscillation
(Muszkaloy and Starasolszky, 1964)

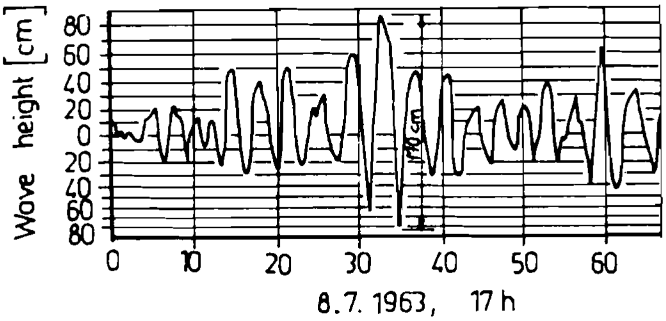


Fig. 6. Wave picture
(Muszkalay and Starasolszky, 1964)

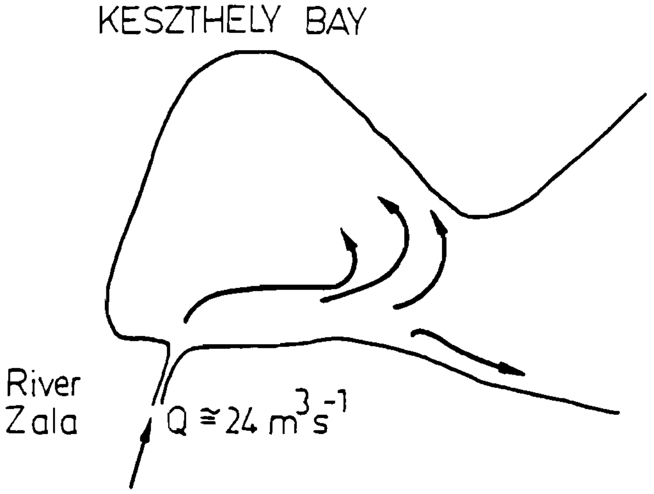


Fig.7. Motion of fresh Zala water, W = 0

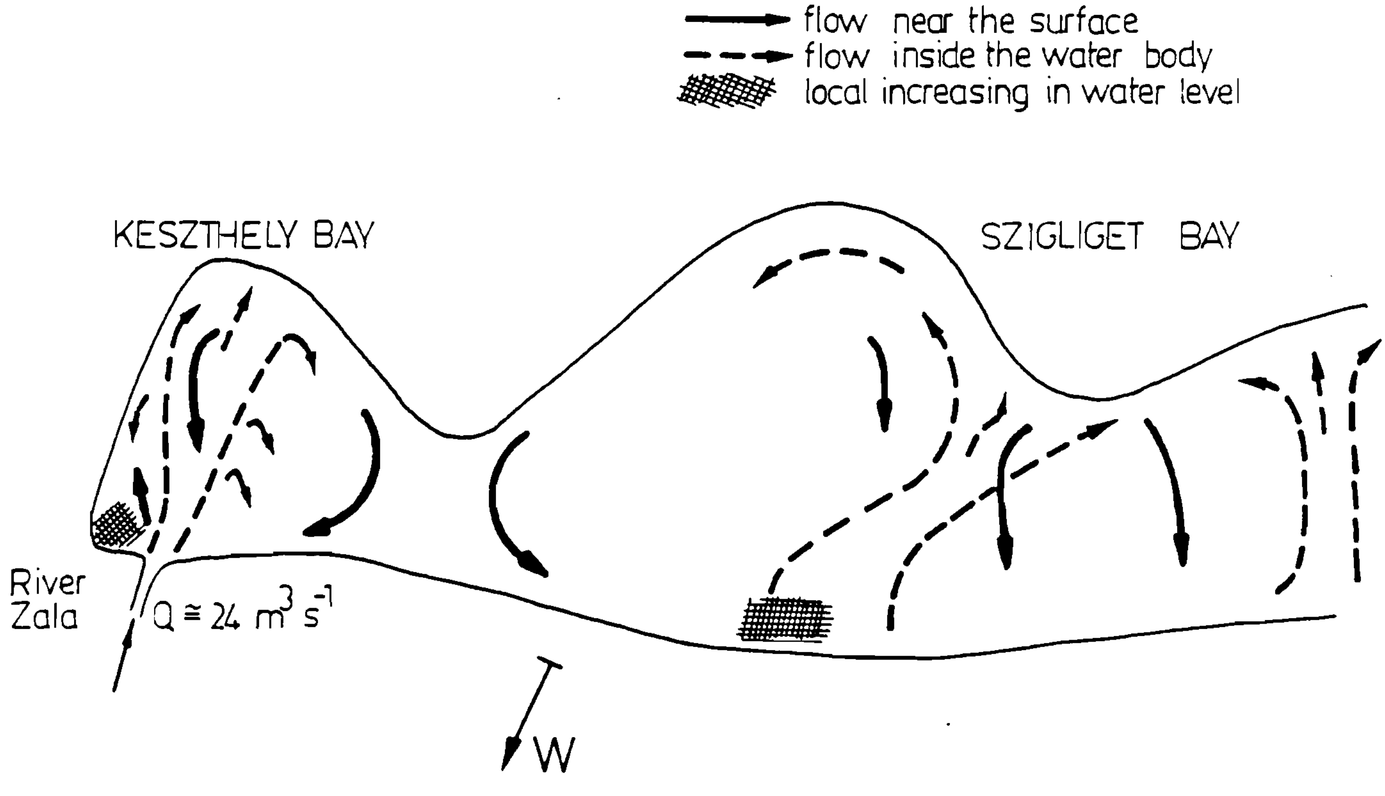


Fig. 8. Wind induced flows; $W \approx 31\ km\,h^{-1}$ direction NNE at Máriafürdö

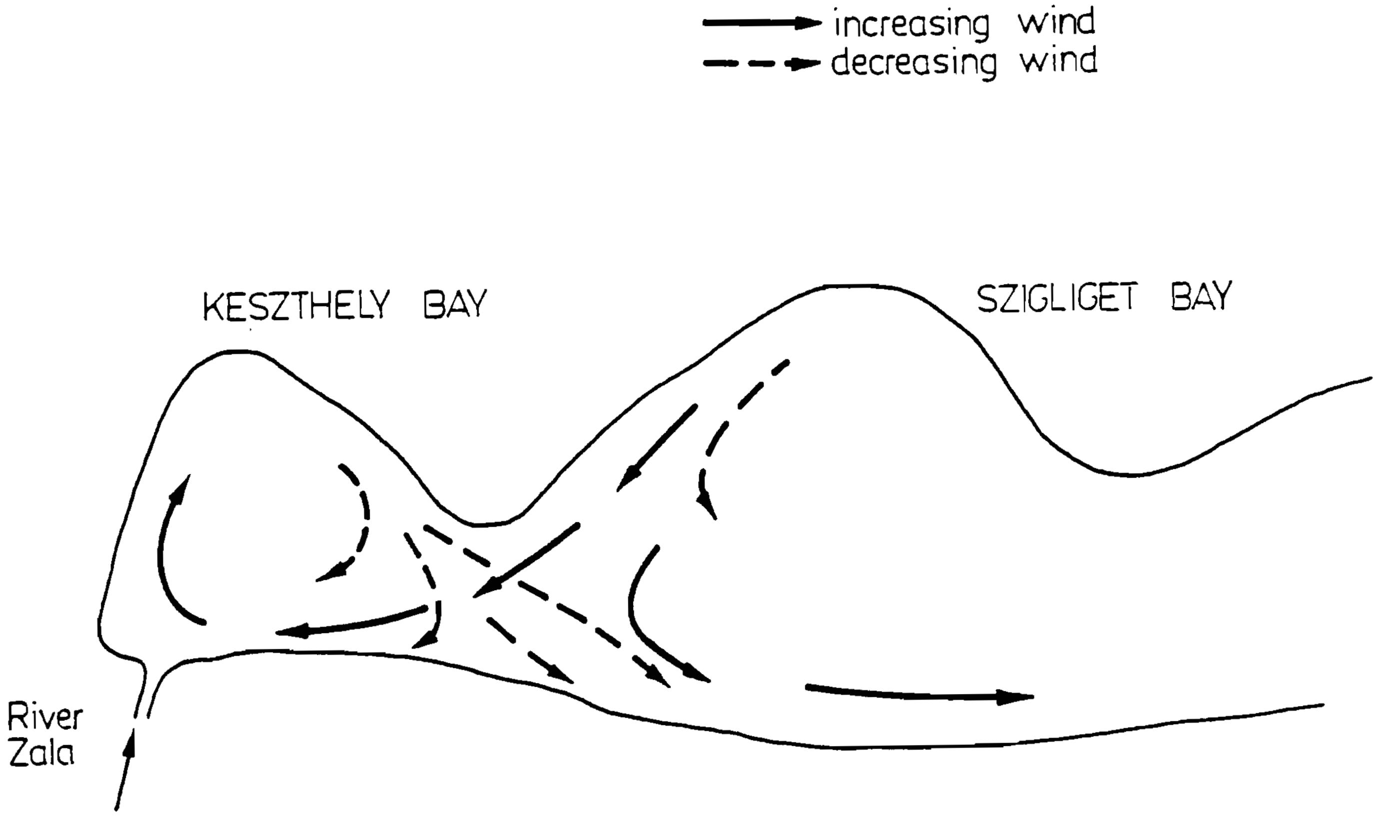


Fig.9. Effect of transient wind conditions

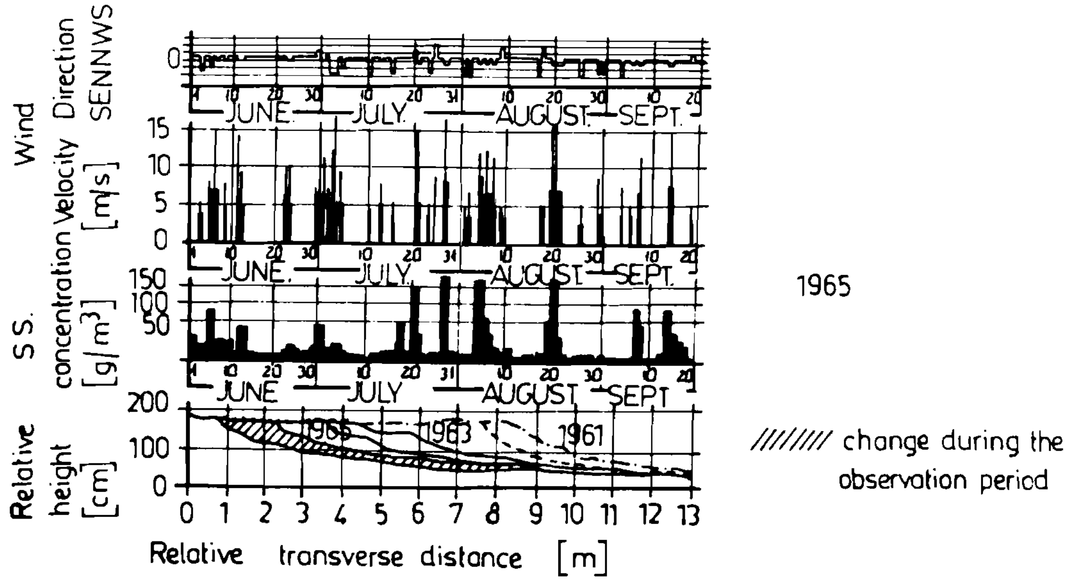


Fig. 10. Erosion suspended solids concentrations and wind data (Hamvas, 1967)

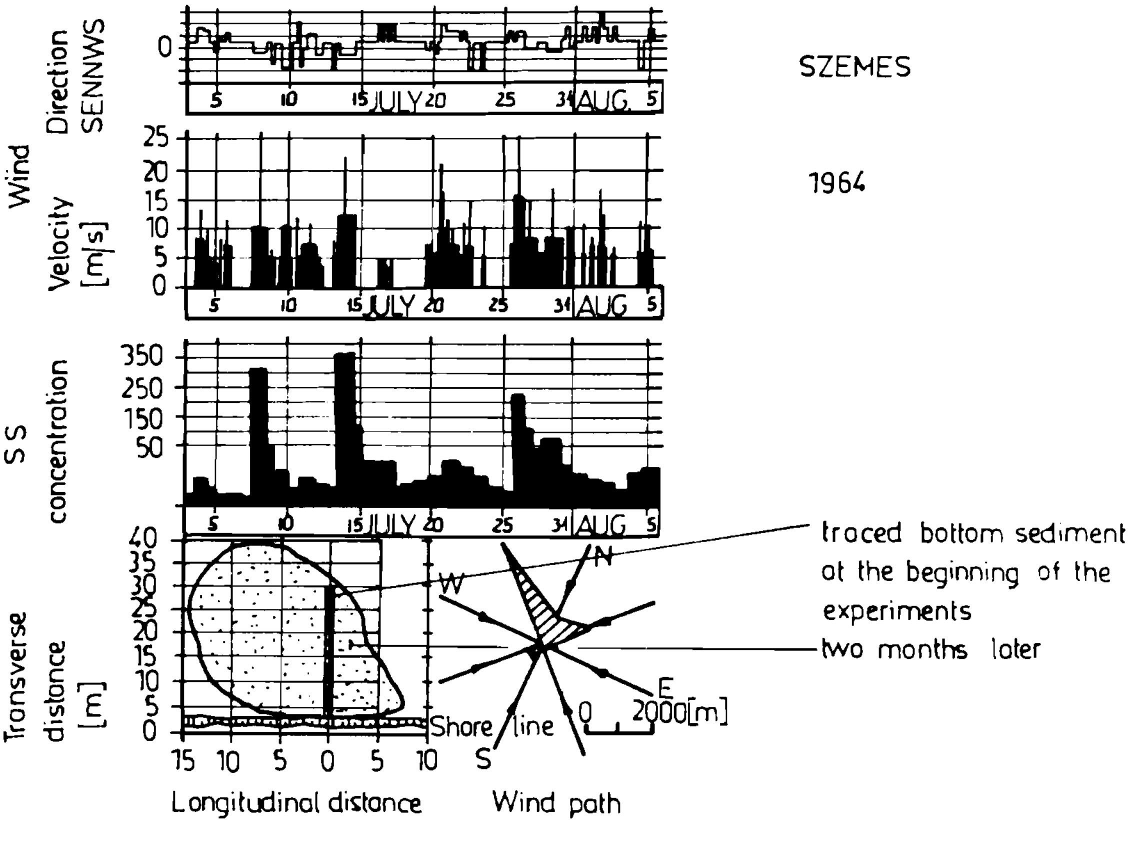


Fig. 11. Suspended solids concentrations and wind data. Motion of traced bottom sediment (Hamvas, 1967)

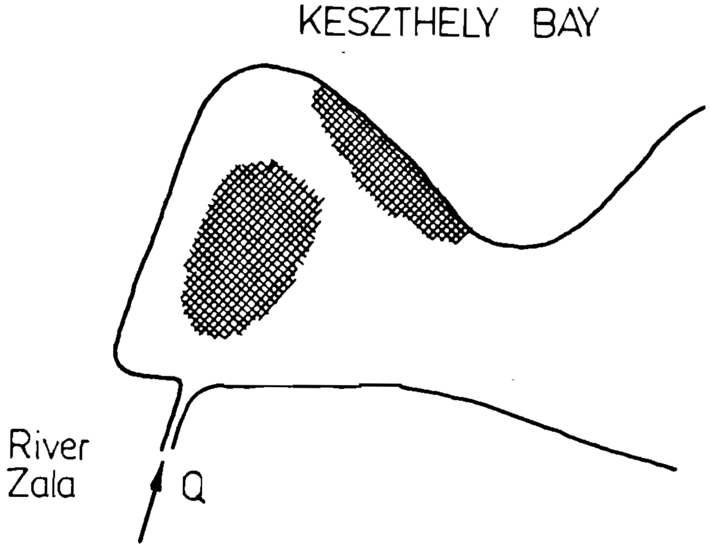
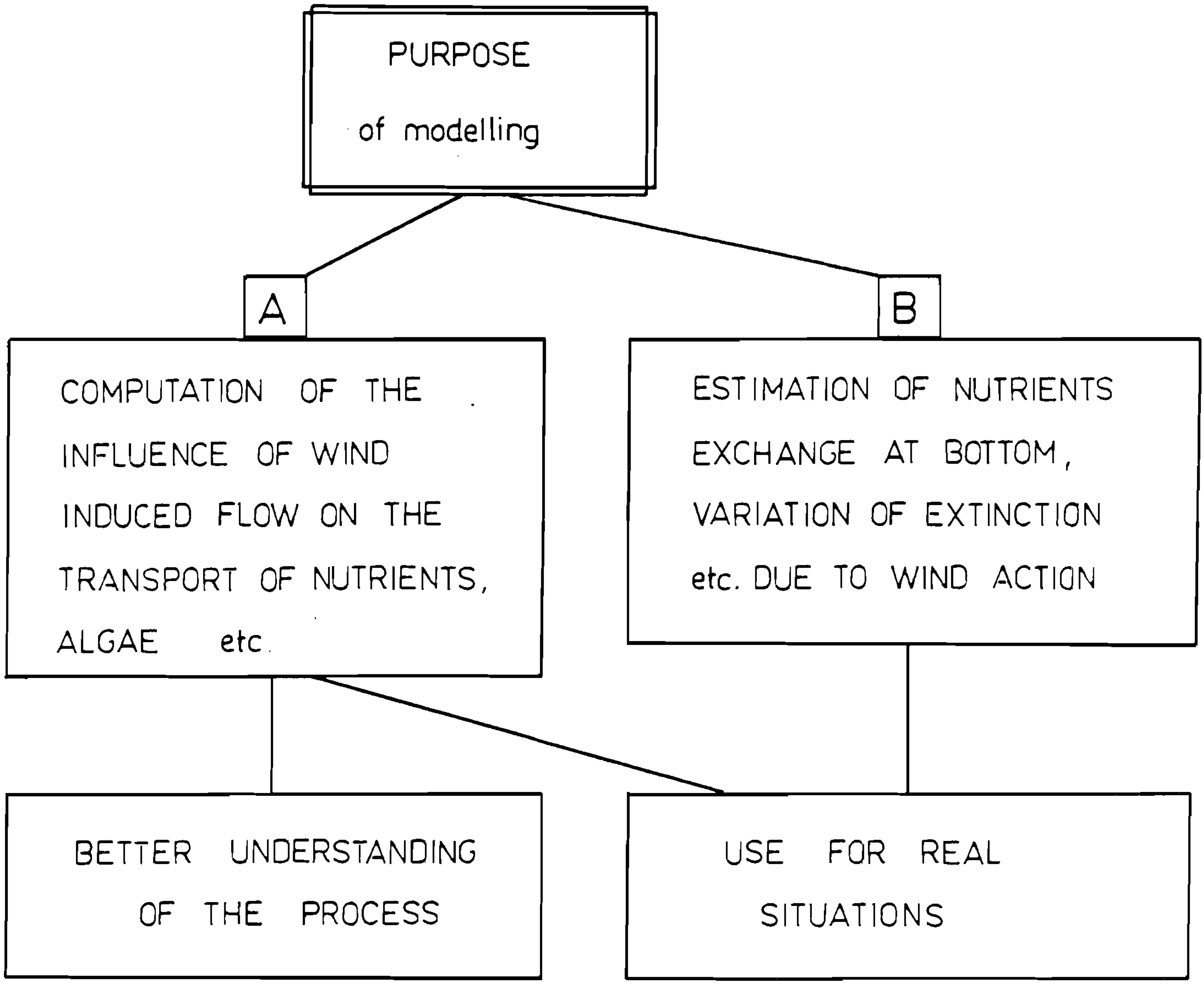


Fig.12. Deposition of Zala-sediment after two years long simulation period



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(hydrodynamical aspects)

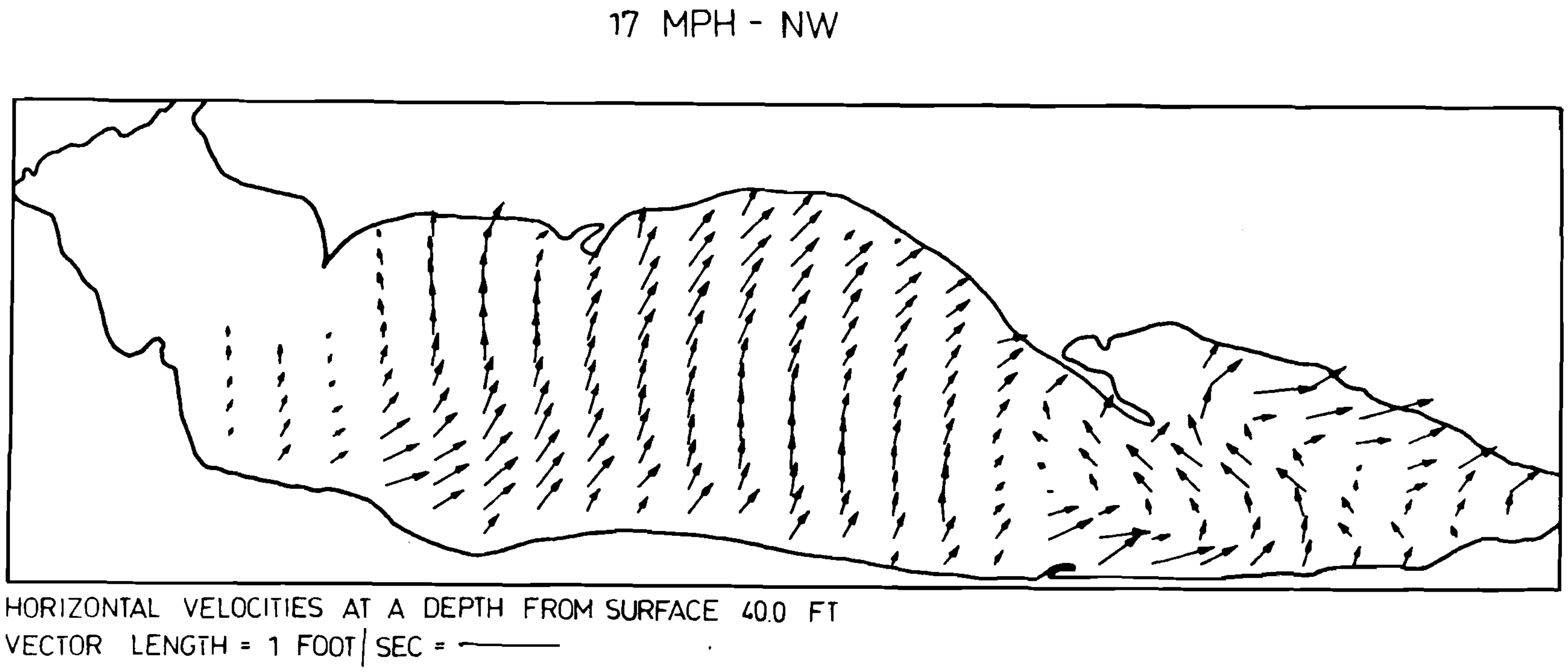

Fig.14. Velocity pattern for Lake Erie, wind direction NW (Durham and Butler, 1976)

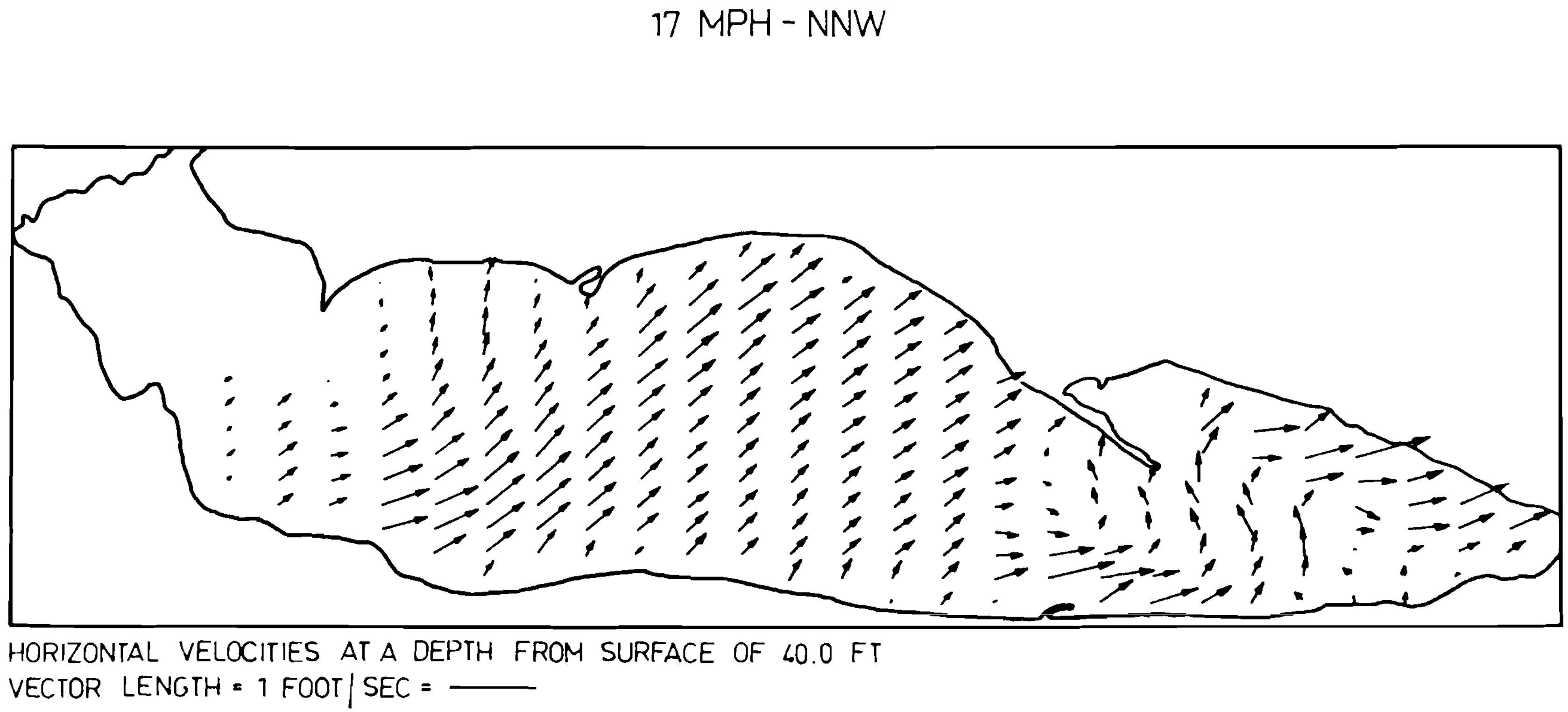

Fig. 15. Velocity pattern for Lake Erie, wind direction NNW (Durham and Butler, 1976)