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THE INFLUENCE OF WATERSHED DEVELOPMENT ON THE EUTROPHICATION OF SHALLOW LAKES: A MODELING APPROACH APPLIED TO LAKE BALATON

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PREFACE

One of the principal projects of the Task on Environmental Quality Control and Management in IIASA's Resources and Environment Area is a case study of eutrophication management for Lake Balaton, Hungary. The case study is a collaborative project involving a number of scientists from several Hungarian institutions and IIASA (for details see WP-80-187 and WP-81-108).

As part of the case study, different lake ecological models and water quality management models are under development, serving both to improve our scientific understanding and to solve real-life problems. Generally the water quality of the lake is directly related to nutrient loads, which in turn are the result of different kinds of human activities and natural processes in the watershed. Consequently, as was done in this study, the water quality can be directly related to the development of the watershed. With historical data for the lake and its region, valuable conclusions can be drawn on the past development of artificial eutrophication and future trends can also be analysed to some extent. A remarkable advantage of the approach presented here lies in its simplicity.

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ABSTRACT

A multiregional, multicriteria watershed development model is presented as a way of describing the eutrophication processes in shallow lakes on an annual basis. Its application to Lake Balaton is illustrated. The simulation and forecasting of eutrophication in the lake, which depend on different watershed development activities, is discussed for the period 1981-85.

The formulation of the model rests on the fact that a close connection exists between the eutrophication of a shallow lake and the development of its watersheds which generate nutrient loading. A multicriteria utility function is used to describe watershed development. The applications of the model to Lake Balaton are presented; they are based on the regionalization of the Balaton basin into eleven regional units (four waterbodies and seven watersheds).

Watershed development needs are assessed for the various watersheds of the Balaton basin, for the period 1930-1980. The eutrophication indicated by a moving summer average of chlorophyll-a for each of the four basins of the lake depends on the level of watershed development in the corresponding or contributing watershed, their geometric character and the eutrophication in the preceding basin. The spatial distribution of the water quality within basins is not considered. The model parameters are elaborated by regression analysis.

The simulation of eutrophication is based on three development variations for each watershed for 1981-85, namely a strong, a medium and a zero growth variation. Using different combinations of the specific watershed variations, more than 30 spatial lake protection strategies and their effects on eutrophication were simulated on an annual time scale. The average uncertainty of the simulated eutrophication values for the whole lake is ±23%.

With the help of this simulation, the spatial efficiency of the comprehensive control actions in the watershed has been measured. The forecast of eutrophication by 1985 is given by the most realistic watershed development strategy.

One of the more important recommendations is that the most efficient development management, i.e., control strategy from the viewpoint of the whole lake, is the very one which concentrates all of the limited, available control efforts in the next five years on the Zala watershed, which is the largest source of nutrient loading. This suggestion is based on the relative efficiency figures of the protection measures taken for the various watersheds and calculated by the model. To illustrate the use of the model for evaluating the effectiveness of different management actions and lake protection policies, the possible effects of the Kis-Balaton reservoir on eutrophication are identified. The model can be combined with other models dealing with the Lake Balaton problem and applied to the eutrophication problem of other shallow lakes and man-made storage reservoirs.

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THE INFLUENCE OF WATERSHED DEVELOPMENT ON THE EUTROPHICATION OF SHALLOW LAKES: A MODELING APPROACH APPLIED TO LAKE BALATON

1. INTRODUCTION

The acceleration of eutrophication in Lake Balaton, a shallow lake, is caused by the increasing socio-economic and water resources development--watershed development--in the contributing watersheds, during the last few decades. Artificial eutrophication is the response of the lake-ecosystem to man's interference. However, watershed development, which is *a priori* and spontaneous from the viewpoint of the lake, can be modified by the policy adopted to protect the lake.

The concept of watershed development was originally proposed for river basins outlined by Dávid (1976). The aim of this process is to establish a continuous balance among natural water supplies, socio-economic and environmental requirements and their effects over space, time, quality, quantity and energy aspects on a basin-wide scale during the socio-economic development of the regions. Therefore, it is an increasingly integrated, planned and comprehensive long-term process, the purpose of which is to achieve the optimal use and control of natural water resources. The criteria for optimal use and control basically depend on the constraints of socio-economic growth.

The main elements and features of watershed development, their changing importance during the process, the structure and the ratio of the basic activities depend on the stage of development. For evaluation and modelling of the progress of watershed development, a multicriteria analysis based on a system of indices was proposed by Dávid (1978a). This multicriteria analysis is necessary because of the great number of elements and criteria involved in watershed development.

The integration of the watershed development approach and water quality control has been suggested in Dávid (1978b). When considering the problem of eutrophication in Lake Balaton (Herodek, 1976; van Straten et al., 1979) or other shallow lakes, the idea of applying the watershed development approach to the eutrophication problem seems to be appropriate. Dávid et al. (1979) developed the concept behind this application, which is that the close connection between eutrophication of the lake and man-made watershed development can serve as a basis for modelling eutrophication.

There are then, two basic approaches to modelling the eutrophication problems in shallow lakes (Figure 1). The first approach (A), relates watershed development with nutrient loading which, in turn, affects eutrophication, while the second approach (B), directly connects watershed development to eutrophication. For eutrophication control purposes, both approaches are important.

In the case of (A), the processes have to be described by fairly detailed, structural models. Once developed, such models are extremely useful, in particular for short-term management. However, the construction of reliable models requires a good interdisciplinary knowledge about many physical and other processes. In most situations, additional investigations will be necessary, involving laborious and coordinated data collection programs,--a time-consuming operation. Furthermore, it is difficult and in many cases impossible to collect the historical data.

In the case of approach (B), a direct relation is sought in terms of an integrated, multicriteria empirical model which can be used especially for long-term management of eutrophication. The long-term effects of human activities can be measured and simulated by this approach since the historical time-series of the basic factors needed are usually available from regular statistical data. The development of such a model requires a relatively short time. However, considering the detailed process involved, this approach can only be considered as a rough approximation. The integrated character does not supply information on the actual behavior of the individual processes that may play a role; but it is good for general and regional evaluation.

There is a pressing socio-economic need to control the eutrophication of Lake Balaton, therefore both approaches are necessary to accomplish this goal. The model described and applied in the present paper employs approach (B), while approach (A) is the object of other modelling efforts carried out in the course of the Lake Balaton Case Study. The results of the two approaches can be harmonized in a further step of the research efforts.

According to this conceptual framework and the previous study (Dâvid, et al., 1979), the purpose of this paper is to present a multiregional and multicriteria watershed development model for the description of the long-range eutrophication process in shallow lakes, to show how it is adapted to Lake Balaton and illustrate its application in simulating the eutrophication in the lake, depending on different watershed development activities, for the period 1981-85.

2. MODEL DESCRIPTION

The discrete time watershed development model of the multiannual eutrophication process, in an arbitrary shallow lake, is described in this section.

The model is based on the regionalization of the hydrological system of the lake which is in many respects similar to the watershed of a river basin. Its reaches are the waterbodies, (here a waterbody is meant to be a segment of the lake where the water quality is approximately uniform), which are connected to the watersheds. According to this, the lake is considered to consist of N waterbodies: WB_j, $j = 1,2,\ldots,N$. The water in the lake flows from WB_1 to WB_N. Each WB_j is connected to n_j watersheds (the value of n_j is 1 or 2):

$$WS_{ji},\ i = 1 \text{ or } i = 1,2;\ j = 1,2,\ldots,N.$$

Every WB and WS plays a special role and has a special system of interconnections. They cannot be interchanged or replaced by one another. The waterbodies and watersheds form the regional units of the model, they are connected by hierarchical order, based on the direction of hydrological throughflow. Therefore the basin may be considered a multiregional, hierarchical system.

On the basis of the foregoing, an index $\underline{E}(\underline{l},\underline{j})$ characterizing the annual eutrophication of the waterbody WB_j in year $\underline{l}$ of a multi-annual period can be described as follows:

$$\begin{aligned} &\underline{E}(\underline{l},\underline{j}) = \underline{f}_j\{\underline{M}(\underline{l},\underline{j});\ [\underline{NL}(\underline{l},\underline{j},\underline{i}),\ \underline{i} = 1 \text{ or } \underline{i} = 1,2]; \\ &[\underline{T}(\underline{u}),\ \underline{u} = 1,\dots,\underline{j}];\ [\underline{E}(\lambda;\underline{j}),\ \lambda = l-1,\ l-2,\dots,];\quad (1) \\ &[\underline{E}(\lambda,\underline{u}),\ \lambda = \underline{l},\ \underline{l}-1,\dots,;\ \underline{u} = 1,\dots,\underline{j}-1]\}. \end{aligned}$$

Here $\underline{M}(\underline{l},\underline{j})$ characterizes meteorologically WB_j and the adjacent watersheds WS_{ji} in year $\underline{l}$; $\underline{NL}(\underline{l},\underline{j},\underline{i})$ is the annual nutrient loading coming from WS_{ji} in year $\underline{l}$; the indices $\{\underline{T}(\underline{u})\}$ geometrically characterize WB_j and its 'upstream' basins; the indices $\{\underline{E}(\lambda;\underline{j})\}$ indicate the past states of eutrophication in WB_j; the indices $\{\underline{E}(\lambda,\underline{u})\}$ the present and past states of eutrophication in the "upstream" waterbodies. It is noted that an equation of similar structure can be derived from the finite difference form of the differential equation governing algal dynamics.
Then the following assumptions are made:

(i) According to the watershed development concept mentioned in the previous section, the value of $\underline{NL}(\underline{l},\underline{j},\underline{i})$ depends on $\underline{D}(\underline{l},\underline{j},\underline{i})$ and $\underline{H}(\underline{j},\underline{i})$, where $\underline{D}(\underline{l},\underline{j},\underline{i})$ is the watershed development index which indicates the state of socio-economic and water management development on WS_{ji} with respect to their influence on nutrient loading in year $\underline{l}$; $\underline{H}(\underline{j},\underline{i})$ is the natural geographic indicator of WS_{ji}, which is constant in time and indicates the natural role of the watershed WS_{ji} in the multiregional hydrological system. Indicating their role by their product, this connection can be written as

$$\underline{NL}(\underline{l},\underline{j},\underline{i}) = \underline{h}\ [\underline{H}(\underline{j},\underline{i}) \cdot \underline{D}(\underline{l},\underline{j},\underline{i})].$$

(ii) The present state $E(l,j)$ of eutrophication of a basin depends on $E(l-1,j)$, (but not on $E(l-2,j)$, $E(l-3,j)$ etc.), on the present state $E(l,j-1)$ of eutrophication and on the geometrical character $T(j-1)$ of the preceding waterbodies.

On the basis of these assumptions, Eq. (1) can be written in the form

$$E(l,j) = f_j\{M(l,j);\ [H(j,i) \cdot D(l,j,i),\ i = 1,\ n_j];\ T(j);\ T(j-1);\ E(l-1,j);\ E(l,j-1)\}. \tag{3}$$

E and T are looked for in such a form that Eq(3) should be transformed into

$$T(j)\ E(l,j) = f_j\{M(l,j);\ [H(j,i) \cdot D(l,j,i),\ i = 1,\ n_j];\ T(j) \cdot E(l-1,j);\ T(j-1)\ E(l,j-1)\}. \tag{4}$$

Then the following further restrictions are made.

(i) Considering the "random" effect of meteorological factors on the $E(l,j)$ values and our efforts to characterize the long-term, multi-annual eutrophication process, instead of $E(l,j)$ its moving average

$$E^*(l,j) = [E(l-1,j) + 2E(l,j) + E(l+1,j)]/4 \tag{5}$$

is written in Eq(4), and $M(l,j)$ is omitted. According to the sense,

$$\begin{aligned} E^*(1,j) &= [2E(1,j) + E(2,j)]/3 \\ \text{and} \qquad & \\ E^*(L,j) &= [E(L-1,j) + 2E(L,j)]/3 \end{aligned} \tag{6}$$

in case of the first and the last (L-th) year of the time period. Physically E and thus E^* can be determined on the basis of the annual and summer average and peak of such indicators of eutrophication as chlorophyll-a, phytoplankton production, biomass and individual count. E^* can be considered as the eutrophication index of the multi-annual eutrophication process.

(ii) The waterbody's geometrical index $\underline{T}(j)$ can be determined by the consideration of the surface area of the waterbody, the average depth and the average volume of water in it.

(iii) The watershed development index is considered in the form

$$\underline{D}(\underline{l},\underline{j},\underline{i}) = \underline{g}\{[\underline{F}_p^n(\underline{l},\underline{j},\underline{i})];\ [\underline{F}_q^d(\underline{l},\underline{j},\underline{i})];\ [\underline{F}_r^w(\underline{l},\underline{j},\underline{i})]\} \quad , \tag{7}$$

where $\underline{F}_p^n(\underline{l},\underline{j},\underline{i})$, $\underline{F}_q^d(\underline{l},\underline{j},\underline{i})$ and $\underline{F}_r^w(\underline{l},\underline{j},\underline{i})$ are, respectively, the $\underline{p}$-th natural, the $\underline{q}$-th regional development and the $\underline{r}$-th water management basic factor in the watershed WS_{ji} influencing the nutrient loading in year $\underline{l}$. The aim of the introduction of the watershed development index is to express in an integrated form the level of regional and water management activities on the watershed in time influencing the nutrient loading coming from there. In this sense, the watershed development index can be viewed as a multiattribute utility function. According to the multicriteria utility theory (Keeney and Raiffa, 1976), it can be written as

$$\underline{D}(\underline{l},\underline{j},\underline{i}) = \sum_{\underline{k}=1}^{\underline{K}} \underline{w}_k \underline{I}_k(\underline{l},\underline{j},\underline{i}) \quad , \tag{8}$$

where the $\underline{I}_k$'s are indicator or criterion indices each of which expresses a watershed development criterion influencing nutrient loading and has to be composed from the basic factors, the $\underline{w}_k$'s are weighting factors constant in time and space, furthermore $\sum_{k=1}^{\underline{K}} \underline{w}_k = 1$. All of the $\underline{I}_k$'s are dimensionless; most of them are time-dependent, are manageable partly short- and partly long-term and express possible--small or great--influence on nutrient loading; they are simple functions of the basic factors with a specific meaning.

To get $\underline{I}_k$ in a dimensionless form, a transformation is applied as follows:

$$\underline{I}_k = \frac{\underline{I}_k^1 - \underline{I}_{0,k}^1}{I_{100,k}^1 - \underline{I}_{0,k}^1} \cdot 100 \quad , \tag{9}$$

where $\underline{I}_{0,k}^1 \geq 0$ and $\underline{I}_{100,k}^1$ mean the lowest and highest possible values of $\underline{I}_k^1$ during the watershed development process and where $\underline{I}_k^1$ is a composition of the basic $\underline{F}$ factors in their original dimensions. The minimum value $\underline{I}_{0,k}^1$ refers to the natural or initial stage of development, to the nutrient loading without any human influence, the maximum value $\underline{I}_{100,k}^1$ to a maximal stage of development, to a maximal human influence. They can be calculated on the basis of the actual and historical values and on the expected development conditions of the indices $\underline{I}_k^1$. The interval $[\underline{I}_{0,k}^1, \underline{I}_{100,k}^1]$ indicates the possible range of $\underline{I}_k^1$ during the watershed development. In other words, it is a scale to measure the utility of the criterion. The definition of $\underline{I}_k$ in Eq.(9) implies that

$$0 \leq \underline{I}_k \leq 100 \quad , \tag{10}$$

where $\underline{I}_k = 0$ means no influence on nutrient loading, $\underline{I}_k = 100$ a maximal one. Then the following reasonable constraint is made: a higher index value should express a higher effect on nutrient loading. In certain cases, the composition of factors leads to an index $\underline{I}_k^*$ whose increase indicates a decreasing effect on nutrient loading. In these cases the transformation

$$\underline{I}_k = 1 - \underline{I}_k^* \tag{11}$$

is required.

According to the above considerations,

$$0 \leq \underline{D}(\underline{l},\underline{j},\underline{i}) \leq 100 \quad , \tag{12}$$

and $\underline{D}$ changes in time parallel with nutrient loading. This implies that $\underline{D}$ can decrease in time if $\underline{NL}$ decreases.

Let the relative ground surface area of WS_{ji} as a percentage of the total watershed area of the basin now be taken for the natural geographical indicator $\underline{H}(\underline{j},\underline{i})$ of the watershed. Based on this and considering the product in Eq.(2), the integrated watershed development indices corresponding to WB_j can be calculated as follows.

$$D^*(l,j) = \sum_{i=1}^{n_j} H(j,i) \cdot D(l,j,i). \tag{13}$$

(iv) The function f_j in Eq.(4) is looked for among the linear functions.

On the basis of the above considerations, Eq.(4) is transformed into

$$T(j)E^*(l,j) = a_j + b_j D^*(l,j) + c_j T(j-1)E^*(l,j-1) + d_j T(j)E^*(l-1,j) \quad , \tag{14}$$

which is the general form of the multiregional and multicriteria model of multi-annual eutrophication processes in shallow lakes based on the watershed development concept and on discrete time steps.

This model involves input parameters $L, N, n_j, H(j,i), K, T(j)$, w_k and input variables $E(l,j)$ for $l \leq L$ and $F_k(l,j,i)$. After the calculation of the variables $E^*(l,j)$ for $l \leq L$ and $D^*(l,j)$ the calibration procedure follows: the parameters a_j, b_j, c_j, d_j are determined, $E^*(l,j)$ is estimated for $l \leq L$, and the best estimate is determined. As final output the values of $E^*(l,j)$ for $l > L$ are produced.

The watershed development index can also be calculated in the following way. The $I_k(l,j,i)$'s are standardized to

$$J_k(l,j,i) = \frac{I_k(l,j,i)\dfrac{SI_k(j)}{Ln_j}}{\sqrt{\dfrac{Ln_j \sum\limits_{i=1}^{n_j} \sum\limits_{l=1}^{L} I_k^2(l,j,i) - SI_k^2(j)}{Ln_j(Ln_j-1)}}} \tag{15}$$

where

$$SI_k(j) = \sum_{i=1}^{n_j} \sum_{l=1}^{L} I_k(l,j,i) \quad , \tag{16}$$

SI_k/Ln_j are respectively the dominator on the right side of Eq.(15) are the mean respective standard deviation of $I_k(l,j,i)$ for fixed j. Then for each j a factor analysis of the $J_k(l,j,i)$'s is performed. Let $FJ_k(l,j)$ denote the value of the k-th factor for j ($k = 1,2,\ldots,K_j$) in year l and $\hat{E}_k(l,j)$ the estimate calculated by writing $FJ_k(l,j)$ instead of $D^*(l,j)$ in Eq.(14).

Let

$$S^*_{jk} = \frac{\sum_{I=1}^{L} [E^*(l,j)-\hat{E}_k(l,j)]^2/L}{\sum_{I=1}^{L} E^{*\prime}(l,j)/L} \cdot 100 \quad , \tag{17}$$

and

$$w^*_{jk} = \frac{1/S^*_{jk}}{\sum_{k=1}^{K_j} 1/S^*_{jk}} \tag{18}$$

and S^*_j be the error percentage corresponding to

$$\sum_{k=1}^{K_j} w^*_{jk}\, FJ_k(l,j) \tag{19}$$

(the better the estimation which FJ_k gives in itself, the larger is its weight). The natural geographic indicator can be improved by taking into account such quantities as the difference of the average elevation of the watershed and the corresponding waterbody, the distance between the areal gravity center of the watershed and the corresponding waterbody, the average slope of arable land, the average precipitation of several years, the total length of water courses, etc.

For determination of the best parameters and for comparison of various combinations, the following error calculation can be used.

$$\underline{S}_j = \frac{\sqrt{\sum\limits_{\underline{l}=1}^{\underline{L}} [\underline{E}^*(\underline{l},\underline{j})-\hat{\underline{E}}(\underline{l},\underline{j})]^2/\underline{L}}}{\sum\limits_{\underline{l}=1}^{\underline{L}} \underline{E}^*(\underline{l},\underline{j})/\underline{L}} \cdot 100 \quad , \qquad (20)$$

where $\hat{E}(l,j)$ is estimated by the model.

3. APPLICATION OF THE MODEL TO LAKE BALATON

The specification of Eq.(14) for Lake Balaton is described in this chapter. The basis of this specification is the regionalization of the hydrological system of the lake.

In keeping with the regionalization described in the previous section, the lake is considered to consist of $N = 4$ waterbodies: Keszthely Bay (WB_1), Szigliget Basin (WB_2), Szemes Basin (WB_3) and Siófok Basin (WB_4), as proposed by Baranyi (1974). The Keszthely Bay is connected to one watershed (WS_{11}), while the others are connected to two watersheds on each side: WS_{21}:WS_{22}:WS_{31}:WS_{32}: WS_{41}:WS_{42}: (Figure 2). Therefore, the Balaton basin may be considered a multiregional, and with respect to the waterbody, also a hierarchical system. There are eleven regional units (four waterbodies and seven watersheds) which are connected by hierarchical order, based on the direction of water flow. According to this hierarchical character, four basin levels (B_j) are considered, all of them at the outflow section of the corresponding waterbodies. This multiregional, hierarchical system of the Balaton basin is shown in Figure 3. Also, the regions covered by the separate watershed and waterbody modelling efforts according to approach A are indicated. Some natural characteristics of the Balaton basin according to the proposed regionalization are listed in Table 1. The relative figures given in the last two columns of the table indicate the difference in natural loading in the individual hierarchical levels.

Considering the described regionalization, for the specification of Eq. (14) there are two main tasks, namely the construction of the watershed development index and the selection of model options. On the basis of these, the specified form of the model is developed.

3.1 Construction of the Watershed Development Index

One of the most important tasks of specification is the careful construction of the watershed development index.

According to Eq.(7), the description of watershed development is based on the basic development factors. From the basic factors characterizing the stage of regional development of a watershed, 50 development factors were selected which in some way could be of importance with respect to nutrient loadings. They include 12 natural, 14 regional development and 24 water management factors. Their nomination and description are listed in Appendix 1. The natural factors are considered to be constant in time, while the others are time-dependent. Their values were determined for each of the seven watersheds in 1930, 1940, 1950, 1955, 1960, 1965, 1970, 1975 and 1978 by the help of water management experts of these regions. The values of the selected factors for 1930 and 1978 are also presented in Appendix 1 to indicate the first and final values of these time series. The set of years which were determined for the factors, was selected according to the characteristics of the development process.

The selected basic factors have three functions: 1) most of them are direct elements of the indicator indices for watershed development; 2) some of them provide a basis for computing the indices involved in the previous group; 3) a few are not yet directly used, but presented in order to provide an overview of the features of the watershed development process which might possibly appear in the future.

On the basis of these selected factors, a system of indicator indices as development criteria was created. The $k = 25$ indicator indices (I_k) defined are presented in Appendix 2, together with their composition as well as a description of its effects on nutrient loading. The indices (I_k')s are presented with their original dimensions. It should be noted that there is no a priori relationship between the number of factors and the number of indices, as is perhaps suggested by the incidental ratio of 2 in this application. Typically, there is a conflict between the wish for more detailed criteria and the availability of the data needed in such detailed criteria. Therefore, a reasonable balance should be found. For the present application, reasoned judgment drawing upon personal experience has been the basis of the selection of the 25 criteria listed. As soon as more information on their relationship with the nutrient loading are available, slight changes to decrease their number might be desirable.

The composition of the indicator indices from the basic factors can be done in many ways. In practice the composition was guided by the wish to separate the various watershed development processes as much as possible in order to make the influence of management decisions transparent. As a result, 20 out of 25 indices are manageable on the short- or long-term. The remaining five (I_1-I_5) express natural factors which can hardly be influenced, but they have been included because of significant effects on nutrient loadings. These effects are considered in the construction of the weighting system which is discussed below. The indicator indices include--among others--the tourist loading, the specific fertilizer use, the density of motoring roads, the amount of used water infiltrated into the soil, the ratio of population served by waterworks and sewage canals, the untreated part of the sewage water, the urbanized part of the watershed, etc.

The actual value of the 25 criteria for the previously mentioned 9 years between 1930 and 1978 were calculated in two steps. First, the physical values of these watershed development criteria were calculated according to their algorithms listed in Appendix 2, using the data of the appropriate basic factors from Appendix 1. These physical values, also for 1930 and 1978, are presented in Appendix 3. As an illustration, the time series of tourist loading and the ratio of untreated sewage discharge for the seven watersheds are presented in Figures 4 and 5, respectively. For comparison, the time series of the summer average of chlorophyll-a are also indicated in the figures. Some of the I_k'-s increase over time and space, but some of them have changing character over time and space. The time-series of indicator indices were used for the construction of the weighting system.

The lower and upper limits of the criteria scale as intervals needed for the normalization of the criteria according to Eq.(9) are listed in Table 2. The development of this scaling was based on the historical range of the indices and a subjective judgment of their future development.

Next, as a second step, the normalized, dimensionless value of each of the criteria was calculated according to Eq.(9), using the data of Table 2 and Appendix 3. The results, the normalized values of the indicator indices as watershed development criteria for the seven watershed units form the basis of the calculation of the watershed development index.

To express the different influences of indicator indices on nutrient loading according to Eq.(8), there is a need to develop a system of weighting factors for the selected indicator indices. We assume that the weighting system is constant for all regional units and in time.

The formulation of the weighting system has been done in two steps. First, a system of weighting factors was developed by a multicriteria analysis of the time-series of indicator indices between 1930-1978. Then the control of this weighting system was done by comparing it with a number of weighting systems based on the practical knowledge of aspects in the field.

The multicriteria analysis of long-term time-series of indicator indices was based on the six selected criteria listed in Appendix 4. They express the changing character of the trend in the time-series, the spatial differences of time-series among the watershed units, the effects of the indicator indices on eutrophication and the manageability of the activity involved in the index. Each criteria has three classifications with 1,2 and 3 points. The scale with 3 points indicates a stronger weight than the one with 1 point. Based on these criteria and their classification, the multicriteria evaluation of time-series of indicator indices is presented in Appendix 5. The evaluation can be followed in case of I_8 and I_{18}, the time-series of which are shown in Figures 4 and 5, respectively. Summarizing the points for each I_k (ΣP)

and taking the second power of this sums $(\Sigma P)^2$, the value of weighting factors was calculated as the ratio of $(\Sigma P)^2$ and the total sum of $(\Sigma P)^2$. These figures are given in Appendix 5. As a result of this analysis, the weighting system for the indicator indices, developed by the long-term time-series analysis of indicator indices is presented in Table 4.

This weighting system was controlled by a comparison of other weighting systems. They involved five individual systems given by experts on basis of their practical knowledge (Dâvid et al., 1979), and five other systems constructed with the help of mathematical statistics and different geographic characteristics of the basin. Furthermore the uniform weighting as a basis for comparison was also taken into account. The ratio of the maximum and minimum weighting factors in the different weighting systems varied between 1-10. Altogether there were 12 weighting systems in the comparison. The comparison was done by a correlation analysis between the watershed development indices calculated by the individual weighting system and different eutrophication indices for two years, 1965 and 1975.

According to this correlation analysis, the following conclusions were reached: the best correlation ($r = 0,77-0,78$) were found by two systems, namely the one developed on a multicriteria basis and another one constructed with the help of mathematical statistics and geographic characteristics. But the differences in the correlation was small, about 10%, for the other systems as well. This means that the construction of the watershed development index is not very sensitive to the weighting system as a whole in case of 25 indicator indices. This conclusion is appropriate because 25 is quite a large number in a unit system of indices. As we decrease the number of indices, this sensitivity might increase. The weakness of sensitivity is explained also by the factor analysis described in the next chapter.

Considering the long-range character of the problem, the weighting system presented in Table 4 was selected for the construction of the watershed development index. In this system, the ratio of maximum and minimum w_k values is more than five, which means that the weighting makes quite a large difference among the indicator indices.

Using the selected weighting system, the watershed development indices, the $D(l,j,i)$ values were calculated by Eq. (8) for the seven watersheds and for the selected years (Table 5). The D values for 1980 were estimated by a trend analysis of the previous values. The time series of the watershed development index of the watersheds are presented in Figure 6 with the values of chlorophyll-a. The shape of the curves indicates the appropriateness of the basic assumption of this approach.

3.2 Selection of the Model Options

Let us take the relative ground surface area of the watershed WS_{ji} as a percentage of the total watershed area of the basin for the natural geographical indicator $H(j,i)$, and calculate the watershed development index $D(l,j,i)$ according to the previous chapter, the integrated watershed development index $D^*(l,j)$ according to Eq. (13). For determining those waterbody geographical index $T(j)$ and eutrophication index $E(l,j)$ which are the best with respect to the error percentage (20), $7 \times 4 \times 3 = 84$ $\{T^p, E^{qr}\}$ combinations were compared. T^1 was the relative average volume of water, $T^2 = \sqrt{T^1}$, T^3 the relative surface area of the waterbody, $T^4 = \sqrt{T^3}$, T^5 the square root of the average depth of the waterbody multiplied by T^3, $T^6 = \sqrt{T^5}$, and $T^7(j) \equiv 1$. E^{qr} was the yearly average ($q = 1$), the summer average ($q = 2$), the yearly maximum ($q = 3$) and the summer maximum ($q = 4$) of chlorophyll-a ($r = 1$), phytoplankton biomass ($r = 2$) and chlorophyll-a modified by a regression on phytoplankton biomass ($r = 3$). The comparison of the various combination of these indices led to the result of chlorophyll-a measurement of Tôth (1980) $T(j) \equiv 1$. This latter result indicates that $E(l,j)$ is primarily determined by the processes within the waterbody and by its geographical conditions. $E(l,j)$ is the result of the eutrophication processes in the waterbody. In these calculations $L = 8$, $l = 1$ was the year 1973,...,$l = 8$ was the year 1980. With the above $T(j)$, thus actually without the waterbody geographical index, Eq. (14) has the form

$$E^*(l,j) = a_j + b_j \cdot D^*(l,j) + c_j \cdot E^*(l,j-1) + d_j \cdot E^*(l-1,j) \quad . \tag{21}$$

The values of the summer average of chlorophyll-a as the optimal eutrophication index and its moving average $E^*(l,j)$ for the mentioned 8 years are given in Table 6 (in mg/m^3).

The factor analysis performed for the alternative calculation of the watershed development index resulted for $j = 1$ in 2 factors, for each of the other j's in 4 factors ($K_1 = 2$, $K_2 = K_3 = K_4 = 4$). This result is in good harmony with the weak sensitivity of the weighting system mentioned earlier. The corresponding error percentages S_j^* turned out to be only little smaller than the S_j's. For that reason and with the purpose of maintaining the physical content of the watershed development index, at length the original construction of $D(l,j,i)$ was kept. For similar reasons and purposes, the original natural geographical indicator $H(j,i)$, i.e. the ratio of the ground surface area of WS_{ji} in the total watershed area of the basin was also kept. Its value for WS_{11}, WS_{21}, $WS_{22}, \ldots, WS_{42}$ is in turn 0.515, 0.185, 0.126, 0.061, 0.053, 0.022 and 0.038. The values of the corresponding D^* are listed in Table 7 for the period 1973-80.

Then the following problem was investigated: is it possible to reduce the number of parameters in the system of equation (21)? Trials were made in two directions. First, an attempt was made to make some parameters zero. It turned out that--presumably because of the definition of $E^*(l,j)$--the assumption $d_j = 0$ increases the error percentages S_j only to a small extent (in keeping with $c_1 = 0$.) Second, an attempt was made to model more than one watershed with the same system of parameters. It turned out that $a_2 = a_3 = a_4$, $b_2 = b_3 = b_4$ and $c_2 = c_3 = c_4$ can be assumed. Thus the system of Eq.(21) was transformed into the following:

$$\begin{aligned} E^*(l,1) &= a_1 + b_1 D^*(l,1) \quad , \\ E^*(l,j) &= a_2 + b_2 \cdot D^*(l,j) + c_2 \cdot E^*(l,j) \, , \quad j = 2,3,4 \quad . \end{aligned} \tag{22}$$

The parameter values are the following:

$$\begin{aligned} a_1 &= -215.26, \quad & b_1 &= 16.76, & & \\ a_2 &= -4.47, \quad & b_2 &= 1.29, \quad & c_2 &= 0.50 \end{aligned} \tag{23}$$

Then the specified model of multi-annual eutrophication processes in Lake Balaton is the following:

$$\underline{E}^*(\underline{1},1) = -215.26 + 16.76 \cdot \underline{D}^*(\underline{1},1)$$

and

$$\underline{E}^*(\underline{1},\underline{j}) = -4.47 + 1.29 \cdot \underline{D}^*(1,j) + 0.50\ \underline{E}^*(\underline{1},\underline{j}-1),\ \underline{j} = 2,3,4 \quad . \tag{24}$$

Multiplying $\underline{b}_2$ resp. $\underline{c}_2$ by the standard deviation of $\underline{D}^*(\underline{1},\underline{j})$ resp. $\underline{E}^*(\underline{1},\underline{j}-1)$ calculated for $\underline{j} > 1$, one gets 3.34 resp. 4.71. These numbers roughly show that the eutrophication index of WB_j $(\underline{j} > 1)$ depends on the eutrophication index of WB_{j-1} $4.71/3.34 = 1.41$ times as much as on the development index of the adjacent watersheds. The estimated values $\hat{\underline{E}}(\underline{1},\underline{j})$ corresponding to the above parameters according to Eq.(22) are given in Table 8. The error percentages $\underline{S}_j$ calculated according to Eq.(20) are 8.5, 10.1, 27.2, 35.8 for $WB_1,\ldots,WB_4$, resp. Their average is 22.6.

An obvious constraint for the time domain of the validity of Eq.(24) is that $\underline{E}^*(\underline{1},\underline{j})$ should be positive. A sufficient condition is that $\underline{D}^*(\underline{1},1) > 12.84$ and $\underline{D}^*(\underline{1},\underline{j}) > 0.29$ for $j = 2,3,4$. The first inequality is equivalent to $\underline{D}(\underline{1},1,1) > 24.93$, which holds only from the year 1969. Thus Eq.(24) has a limited past validity (which is in good harmony with Figure 6). It does not hold, of course, for Eq.(21).

4. SIMULATION OF EUTROPHICATION FOR 1981-85

The application of the specified model Eq.(24) for the simulation of eutrophication between 1981-85 is presented in this section. This is a possible application, because the model has obviously some predictive capacity. The matter at issue is that the expected turn of watershed development can be pretty well forecast and this makes it possible to predict the future trend of eutrophication assuming the future validity of the basic conditions of the model specification.

The simulation of the eutrophication in the lake is based on three watershed development variations all of which are the result of various human activities on the corresponding watersheds. In case of the strong growth rate variation indicated by 3, the increase of the watershed development index ($\underline{D}$) follows the previous trend between 1981-85 too. It assumes that there will be practically no effective lake protection policy to decrease the nutrient loading. On the other hand there is a zero growth rate variation indicating by 1 which assumes such an effective lake protection policy that the watershed development index ($\underline{D}$) could be constant at the 1980s level. It means that the results of positive and negative measures and efforts on the control of nutrient loading will be balanced. Finally there is a medium growth rate variation indicated by 2, which assumes that the lake protection policy will be gradually more and more effective and therefore it involves a decreasing growth rate of $\underline{D}$. Considering the real conditions of decision making and implementation of lake protection measures, it is not yet feasible to assume a decrease in $\underline{D}$ between 1981-85. Therefore a variation like this has not yet been considered. It would be feasible in a later period. The watershed development indices for the seven watersheds calculated according to these variations are presented in Table 9. The respective $\underline{D}^*$ values are also presented there.

Based on these growth rate variations of $\underline{D}$, various lake protection strategies can be constructed according to the spatial distribution of these variations over the watersheds (WS_{ji}). Thirty-three lake protection strategies listed in Table 10 were developed. There are three pure strategies (No.1, No.14 and No.25), when the same growth rate variation is applied for all of the seven watersheds (variation 3, 2 and 1, respectively). They are uniform development strategies. The other strategies are combined ones in which different growth rate variations are connected to the individual watersheds.

By the application of Eq.(24), the response of the waterbodies of the lake can simulate these lake protection strategies. The response is expressed by the $\underline{E}^*$ values.

The simulation results of the pure strategies are listed in Table 9 and they are presented in Figure 7 which is an extension of Figure 6 to the simulated five year period. The development of $\underline{D}$ values according to the growth rate variations and the development of E^* values corresponding to the pure strategies are indicated in the figure. In case of strategy No.1, which is the most serious, the lake eutrophication index which is the average of the same indices in the waterbodies will increase with 78% by 1985, in comparison with the level of 1980. In case of strategy No.14 and No.25 the same values are 46 and 5%, respectively. The last figure indicates that a small increase of $\underline{E}^*$ can occur as a response to the increase of $\underline{D}$ from 1979 to 1980. This delay can be calculated by the moving average $\underline{E}^*$.

The effectiveness of various strategies is measured by the percentage of decrease of the lake average eutrophication index compared to its value produced by strategy No.1. These values of effectiveness are also listed in Table 10.

For illustration of the simulation results, the time series of variables of two important strategies (No.6 and No.26) are presented in Figures 7 and 8 indicated by strong, dark lines. The spatial distribution of the watershed development and eutrophication process in the Balaton basin according to the same strategies are shown schematically in Figures 9 and 10, respectively. Based on these representations, an evaluation can be made of the simulation results.

5. EVALUATION OF RESULTS

In this section the results of simulation are discussed and evaluated, and the main conclusions of the modelling work are presented.

5.1 Discussion of Results

On the basis of the application of the specified model for the simulation of the eutrophication process between 1981-85, the following results have been obtained.

(i) If we consider the pure strategies, the three years' average values of summer average of chlorophyll-a in 1985 will be between 60.5-35.0; 39.2-27.5; 20.8-13.0 and 9.5-5.5 mg/m^3 in the respective waterbodies, starting from WB_1. It indicates that the same increase of watershed development in the various watersheds results in the greatest eutrophication in WB_1.

(ii) The evaluation of the pure strategies furthermore indicates that the difference between the maximum and minimum values of simulated eutrophication indices according to the various pure strategies is the largest in the first basin and its value decreases towards the eastern end of the lake ($WB_2 \ldots WB_4$) (see Figure 7). The smallest is in WB_4. The values in 1985 are 25.5, 11.7, 7.8, 4.0 mg/m^3 respectively, and their ratio is 6.4:3:2:1. This ratio indicates the chance and certainty of lake protection measures in the various watersheds connected to the waterbodies. This difference can be narrowed to the greatest extent if measures are taken in WS_{11}. Moreover, this indicates the effectiveness of our measures in connection with the waterbodies.

(iii) Based on the previous results, the effectiveness of the combined strategies can be evaluated. First let us consider and compare the strategies No.6 and No.26 (see Figures 7-10). In case of strategy No.6 a clear increase is shown in WS_{11}, while in the other six watersheds there is none. It means that we concentrate our efforts on WS_{21}, WS_{22}, ... WS_{42}, but no effective measures will be taken in WS_{11}. The result of this strategy, as can be seen in Figure 7, is that the eutrophication in WB_2, WB_3 and WB_4 will be only a little bit less than eutrophication in case of the worst strategy (No.1). Therefore the effectiveness of this strategy is very poor, only 6% (see Table 10). It means that we can make a lot of effort to reduce the nutrient loading in six watersheds, but the effectiveness of these measures is very poor because of the hierarchical character and the loading conditions of the system. We make these efforts in the wrong place.

On the contrary, in case of strategy No.26, we concentrate our efforts only on one watershed, namely to WS_{11} (growth rate variation is zero). In parallel it is assumed that there are no effective measures in all of the other watersheds (strong growth-rate variation is applied). The result can be seen in Figure 8. In WB_1 we reach the minimum value of eutrophication and in the other waterbodies the eutrophication is near to the minimum values. The effectiveness of this strategy is 33%.

Further results can be seen by comparing other strategies. These comparisons clearly indicate the importance of the regional distribution of the lake protection measures in this hierarchical eutrophication system, because the effectiveness of measures depends on their applied spatial distribution to a very great extent (see Table 10).

(iv) According to the simulated strategies, the relative efficiency of protection measures involved in the values of D^* and taken on the various watersheds connected to the waterbodies has to be determined. The calculation is presented in Table 11. Four strategies were selected for this calculation. As can be seen from the table, the efficiency of the same volume of protection measures to decrease eutrophication is 6.2 times greater in WS_{11} than in WS_{41}-WS_{42}. The corresponding values are 1.7 and 1.1 for WS_{21}-WS_{22} and for WS_{31}-WS_{32}, respectively. These figures are in good harmonization with the ratio mentioned in point (ii) of this section.

(v) Considering the results of the simulation and the present activities on lake protection, strategy No.14 can be considered as a possible version of the forecast of eutrophication in the lake by 1985. It means that the values of E^* will be 50, 33, 17, 7 mg/m^3 for the waterbodies starting from WB_1. It indicates a smaller growth rate of eutrophication than previously noted, according to the effects of the intensification of lake protection measures. But it should be mentioned that if the measures will be concentrated to a greater extent on WS_{11}, then the efficiency of the investments can be increased and better conditions can be achieved.

(vi) With the watershed development index, the specified model can be used to evaluate the effectiveness of different management actions and lake protection policies. As an illustration of this, an evaluation has been made of the effectiveness of the Kis-Balaton reservoir. The capacity of the projected reservoir will be 100.10^6 m^3. It will be located at the end of Zala river in WS_{11}. The effectiveness of the reservoir can be measured by the decrease in the watershed development index and according to this, by the decrease of the eutrophication index in the waterbodies. Let us assume that with the 1980 watershed development index only one action will be taken, i.e., the construction of this reservoir, and that there will be no protection or pollution activity. In this case, the construction of the reservoir will influence the 9 indicator indices listed in Table 12, while the other 16 will remain unchanged. Eight indices from the nine decrease, and only one increases. In case of I_{18} and I_{19} this change is large, at I_{22} it is medium, while at the others it is small. The value of change expressed in per cent of the value for 1980 of I_k', is calculated and estimated depending on the availability of the required data. For example, in case of I_{19}, it is calculated, but for I_7 it is estimated. The 9 indices involve the hydrological, environmental, social, regional economic and technical effects of this protection investment. According to the listed per cent values of I_k', the $\Delta I_k'$ and the modified I_k' values were calculated. Similarly the dimensionless I_k, the modified I_k and ΔI_k values were determined. Then with the aid of w_k values the $\Delta I_k w_k$ values were calculated and their sum, the net balance of the reservoir is $\Delta D = -2,0$, which means that the reservoir will decrease the watershed development index by 2.0 points (Table 12). According to this, D^* is -1.03 and therefore the modified D^* is 13.87 compared to the 1980s level.

The estimation of effectiveness of the Kis-Balaton reservoir then can be calculated by Equation 24. The results of this calculation are presented for the four WB-s in Table 13. As can be seen in it, the Kis-Balaton reservoir can decrease the 1980s level of eutrophication expressed by E^* by 45,4 40,0 26,4 and 39,2% for WB_1 . . . . . . WB_4, respectively. As an index to measure its reliability, the average error of this calculation is ±23%. Considering that the reservoir with full capacity will start to operate 8-10 years later, and the watershed development will increase slightly, these relative effectiveness values might be smaller. Therefore, it is recommended that the Kis-Balaton reservoir be completed as early as possible.

The above methods can be used to evaluate the effectiveness of all other protection policies, measures, management strategies, individual investments, etc. By this approach the comprehensive effects of such activities, for example, the development of sewage treatment plants can be estimated in the watersheds as a unit, hierarchical system.

5.2 Conclusions and Recommendations

(1) The specified model is able to describe the relationship between the eutrophication and the nutrient oriented watershed development on a multi-annual and multiregional basis by the consideration of a multicriteria utility function of watershed development. The eutrophication process of shallow lakes, like Lake Balaton, can be characterized by the model. Furthermore the model is able to simulate the various lake protection policies, strategies, investments, projects, etc. and to measure and to compare their effectiveness. It is proposed that the effects of the various projects and other measures planned for the next five year period be estimated by the model, as a decision analysis aid.

(2) According to the results of simulation and forecasting, it is proposed to concentrate all of our limited, available control efforts and resources on the Zala watershed in the next five years.

(3) It is proposed to utilize the calculated relative efficiency figures of the protection measures implemented in the various watersheds relating to the socio-economic, regional development and water management planning processes of the region. For example, if the location of a sewage treatment plant with a certain capacity has to be determined, locating it in the Zala watershed could be about 6 times more efficient than placing it in WS_{41} or WS_{42} from the viewpoint of the whole lake.

(4) Considering that the results of this modeling work harmonize well with the physical considerations of experts and with the results of other research scientists [e.g., the nutrient loading values determined by Jolánkai, Somlyódy (1981)], it is proposed that the results of this research work be integrated with that of other Lake Balaton modelers.

(5) Considering the fifty years' long time series of Balaton basin development and eutrophication, it is proposed to study the development in the past and the delays between these processes in the various regions. It gives some information regarding the intensification of control works.

(6) Based on the evaluation of the present results, further development of the model is proposed. In keeping with the results of the factor analysis conducted by the authors, it is possible to decrease the number of I_k indices. Using the nutrient loading estimate of Jolânkai, Somlyôdy (1981), it is possible to determine Eq. (2) in a numerical form for the past couple of years. From this then an effort can be made to estimate the historical time-series of the nutrient loading. Furthermore, by the application of remote sensing to evaluate the spatial distribution of water quality in the lake, the characterization of the eutrophication index can be developed.

(7) In light of the eutrophication problems in many other shallow reservoirs, it is proposed that this model and this methodology be used for the protection of those waterbodies as well.

(8) Considering the interdisciplinary character of the model it is proposed to use it in other fields of activity, for example in the planning of regional development.

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Table 1. Some natural characteristics of the Balaton basin

Hierarchical level		Area			Volume of water in the lake (at average water level)	Ratio of water body's area and the total area	Natural ground surface area per unit water volume
		Watershed	Lake surface (Water body)	Total			
			km^2		$10^6 m^3$	%	m^2/m^3
SEPARATE	B_1	2700	40	2740	90	1,5	30,0
	$B_2 - B_1$	1630	136	1766	480	7,7	3,4
	$B_3 - B_2$	600	188	788	540	23,9	1,1
	$B_4 - B_3$	315	231	546	815	42,3	0,4
Balaton Basin		5245	595	5840	1925	10,2	2,7
CUMULATIVE	B_1	2700	40	2740	90	1,5	30,0
	B_2	4330	176	4506	570	3,9	7,6
	B_3	4930	364	5294	1110	6,9	4,4
	B_4 (total Balaton basin)	5245	595	5840	1925	10,2	2,7

Table 2. Interval of indicator indices

Index code	Unit	Scale with limits	
		lower, $I^1_{0,k}$	upper $I^1_{100,k}$
I_1	% x mm	0	18
I_2	1	0,03	0,20
I_3	1	0	1
I_4	m/km^2	100	800
I_5	‰	0	40
I_6	1	0	0,5
I_7	1	0,4	0,95
I_8	visitor day/head	0	100
I_9	sources/100 km^2	0	100
I_{10}	1	0,4	8
I_{11}	1	0	0,5
I_{12}	1	0	0,6
I_{13}	kg/ha/year	0	800
I_{14}	head/km^2	0	500
I_{15}	m/km^2	0	3000
I_{16}	1	0	4
I_{17}	$m^3/yr/km^2$	0	25000
I_{18}	1	0	1
I_{19}	1	0,2	1
I_{20}	1	0	1

Table 2. (contd.)

Interval of indicator indices

Index code	Unit	Scale with limits	
		lower, $l^{1}_{o,k}$	upper $l^{1}_{loo,k}$
I_{21}	1	o	1
I_{22}	1	o	1
I_{23}	head/km^2	lo	4oo
I_{24}	works/km^2	o	6
I_{25}	$m/lo^6\ m^3$	o	15o

Table 3. Variability of indicator indices over time

Type of variability over time	Code of indicator indices
constant	I_1, I_2, I_3, I_4, I_5
strong, quick	I_6, I_7, I_8, I_{13}, I_{15}, I_{16}, I_{17}, I_{18}, I_{2o}, I_{21},I_{22},I_{24},I_{25}
slight, slow	I_9, I_{1o}, I_{11}, I_{12}, I_{14}, I_{19}, I_{23}

Table 4. The weighting system

Code of indicator index	Value of weighting factors w_k	
I_1	o,o33	
I_2	o,o23	
I_3	o,o18	
I_4	o,o18	
I_5	o,o23	
I_6	o,o28	
I_7	o,o38	
I_8	o,o74	max.
I_9	o,o51	
I_{1o}	o,o14	min.
I_{11}	o,o28	
I_{12}	o,o28	
I_{13}	o,o74	max.
I_{14}	o,o28	
I_{15}	o,o51	
I_{16}	o,o58	
I_{17}	o,o51	
I_{18}	o,o51	
I_{19}	o,o28	
I_{2o}	o,o45	
I_{21}	o,o51	
I_{22}	o,o38	
I_{23}	o,o33	
I_{24}	o,o58	
I_{25}	o,o58	
	1,ooo	

Table 5. Watershed development indices

Years	Values of D (1, j, i)						
	WS_{11}	WS_{21}	WS_{22}	WS_{31}	WS_{32}	WS_{41}	WS_{42}
1930	13,28	15,19	11,23	17,78	13,90	13,66	14,16
1940	13,96	15,99	11,66	18,46	14,06	14,84	16,23
1950	15,20	16,32	12,04	19,24	14,44	15,34	19,70
1955	20,40	17,48	12,43	20,66	14,95	16,10	22,80
1960	21,90	19,16	18,49	23,14	15,55	20,62	26,32
1965	23,46	22,30	20,46	26,75	17,67	33,33	33,70
1970	25,08	27,23	23,39	30,43	20,35	36,89	39,75
1975	26,79	27,28	23,56	33,98	24,44	41,96	43,02
1978	28,10	29,90	23,95	35,83	26,27	45,52	42,09
1980	29,00	31,60	24,20	37,00	27,50	47,80	43,50

Table 6.

The summer average of chlorosphyll-a and its moving average

(in mg/m^3)

WB	1		2		3		4	
year	E	E*	E	E*	E	E*	E	E*
1973	12.7	13.0	7.3	7.0	4.2	3.9	2.6	2.7
1974	13.7	13.1	6.4	7.4	3.3	3.5	2.9	2.4
1975	12.2	14.5	9.7	10.1	3.4	4.6	1.3	2.7
1976	19.8	19.8	14.7	14.8	8.3	7.0	5.2	3.9
1977	27.5	23.8	20.1	17.3	8.1	8.1	3.8	4.7
1978	20.4	28.8	14.3	22.8	7.7	9.2	5.9	5.3
1979	46.8	34.5	42.3	19.5	13.2	11.0	5.4	5.4
1980	23.8	31.5	18.9	26.0	9.9	11.0	4.9	5.1

Table 7.

The integrated watershed development indices

WB	1	2	3	4
year	D*			
1973	13.4	8.0	3.2	2.5
1974	13.6	8.0	3.3	2.5
1975	13.8	8.0	3.4	2.6
1976	14.0	8.2	3.4	2.6
1977	14.2	8.4	3.5	2.6
1978	14.5	8.5	3.6	2.6
1979	14.7	8.7	3.6	2.7
1980	14.9	8.9	3.7	2.7

Table 8.

The estimated eutrophication indices

WB	1	2	3	4
year	$\hat{E}$			
1973	10.1	12.4	3.2	0.7
1974	13.1	12.4	3.5	0.5
1975	16.0	13.1	4.9	1.1
1976	19.6	16.0	7.4	2.4
1977	23.5	18.3	8.8	2.9
1978	27.3	21.0	11.6	3.5
1979	31.2	24.1	15.1	4.5
1980	35.1	22.8	13.8	4.5

Table 9.

The numerical data of simulation

Indices and their growth rate variations (grv)			WB1	WB2		WB3		WB4	
			WS_{11}	WS_{21}	WS_{22}	WS_{31}	WS_{32}	WS_{41}	WS_{42}
Watershed development index, D, %	1980		29,0	31,6	24,2	37,0	27,5	47,8	43,5
	1985	Zero (1) grv	29,0	31,6	24,2	37,0	27,5	47,8	43,5
		Medium (2) grv	30,7	35,0	24,4	39,5	29,5	52,5	44,0
		Strong (3) grv	32,0	37,0	25,3	40,5	31,5	54,5	46,5
geographical indicator, H(j,i)			0,515	0,185	0,126	0,061	0,053	0,022	0,038
Integrated watershed development index, D*, %	1980		14,9	8,9		3,7		2,7	
	1985	Zero (1)	14,9	8,9		3,7		2,7	
		Medium (2)	15,8	9,5		4,0		2,8	
		Strong (3)	16,5	10,0		4,1		3,0	
Eutrophication index, E*, mg/m³	1980		31,5	26,0		11,0		5,1	
	1985	Zero (1)	35,0	27,5		13,0		5,5	
		Medium (2)	49,5	32,8		17,0		7,3	
		Strong (3)	60,5	39,2		20,8		9,5	
Differences	D^*_{85}	Strong-Zero	1,6	1,1		0,4		0,3	
	E^*_{85}	Strong-Zero	25,5	11,7		7,8		4,0	

Table 10. Simulated lake protection strategies and their effectiveness

Strategy No.	The applied growth rate variation on the watersheds				Effectiveness (%)
	WS_{11}	WS_{21}-WS_{22}	WS_{31}-WS_{32}	WS_{41}-WS_{42}	
1	3	3	3	3	0
2	2	1	1	1	21
3	1	2	1	1	39
4	1	1	2	1	4o
5	1	1	1	2	4o,5
6	3	1	1	1	6
7	1	3	1	1	38
8	1	1	3	1	39
9	1	1	1	3	4o
1o	2	2	1	1	19
11	1	1	2	2	39
12	3	3	1	1	2,5
13	1	1	3	3	38,5
14	2	2	2	2	18
15	1	2	2	2	38
16	2	1	2	2	19
17	2	2	1	2	19
18	2	2	2	1	18
19	3	2	2	2	2
2o	2	3	2	2	16
21	2	2	3	2	17
22	2	2	2	3	17
23	3	3	2	2	1
24	2	2	3	3	17
25	1	1	1	1	41
26	1	3	3	3	33
27	3	1	3	3	3
28	3	3	1	3	2
29	3	3	3	1	1
3o	2	3	3	3	15,5
31	3	2	3	3	1
32	3	3	2	3	o,5
33	3	3	3	2	o,5

Table 11. Calculation of the relative efficiency of protection measures

Water-sheds WS_{ji}	**Simulated lake protection strategy**		**Effectiveness of the strategy (from Table 10)** %	**Relative effectiveness of** WS_{ji} **connected to** WB_j, %	**Ratio of relative effectiveness** %	Decrease of D* loading of WB_j by the strategy (from Table 9)	**Standardized value of decrease of D* by the smallest**	**Relative efficiency of measures taken on** WS_{ji}
	No.	**Composition**						
1	2	3	4	5	6	7	8=7:0,3	9=5:8
WS_{11}	26	1-3-3-3	33,0	33,0	80	1,6	5,33	6,2
WS_{21}^+	13	1-1-3-3	38,5	5,5	13	1,1	3,67	1,5
WS_{22}								
WS_{31}^+	9	1-1-1-3	40,0	1,5	4	0,4	1,33	1,1
WS_{32}								
WS_{41}^+	25	1-1-1-1	41,0	1,0	3	0,3	1,0	1,0
WS_{42}								
				Total	100	3,4		

Table 12. Estimation of watershed development index in case of the Kis-Balaton reservoir

No.	Influenced indicator index	Change in value of I'_k	Values for WS_{11}							
			I'_k in 198o	$\Delta I'_k$	Modified I'_k	I_k	Modified I_k	ΔI_k	w_k	$\Delta I_k \cdot w_k$
1	I_4	decrease,3,5%	456	-16	44o	51	48,5	-2,5	o,o18	-o,o45
2	I_7	decrease, o,5%	o,78	-o,oo4	o,776	7o	68,3	-1,7	o,o38	-o,o65
3	I_{1o}	decreasa, 3,o%	2,61	-o,o8	2,53	29	28,o	-1,o	o,o14	-o,o14
4	I_{12}	increase, 2,5%	o,o7	+o,oo2	o,o72	11,7	12,o	+o,3	o,o28	+o,oo9
5	I_{13}	decrease, 2,5%	178	-5,o	173	22,5	21,6	-o,9	o,o74	-o,o67
6	I_{18}	decrease, 5o%	o,2	-o,1o	o,1o	2o	1o	-1o,o	o,o51	-o,51o
7	I_{19}	decrease, 34%	o,99	-o,34	o,65	99	56	-43,o	o,o28	-1,2o5
8	I_{22}	decrease, 12%	o,12	-o,o15	o,1o5	12	1o,5	- 1,5	o,o38	-o,o57
9	I_{24}	decrease, 5%	o,58	-o,o3	o,55	1o	9,2	- o,8	o,o58	-o,o46

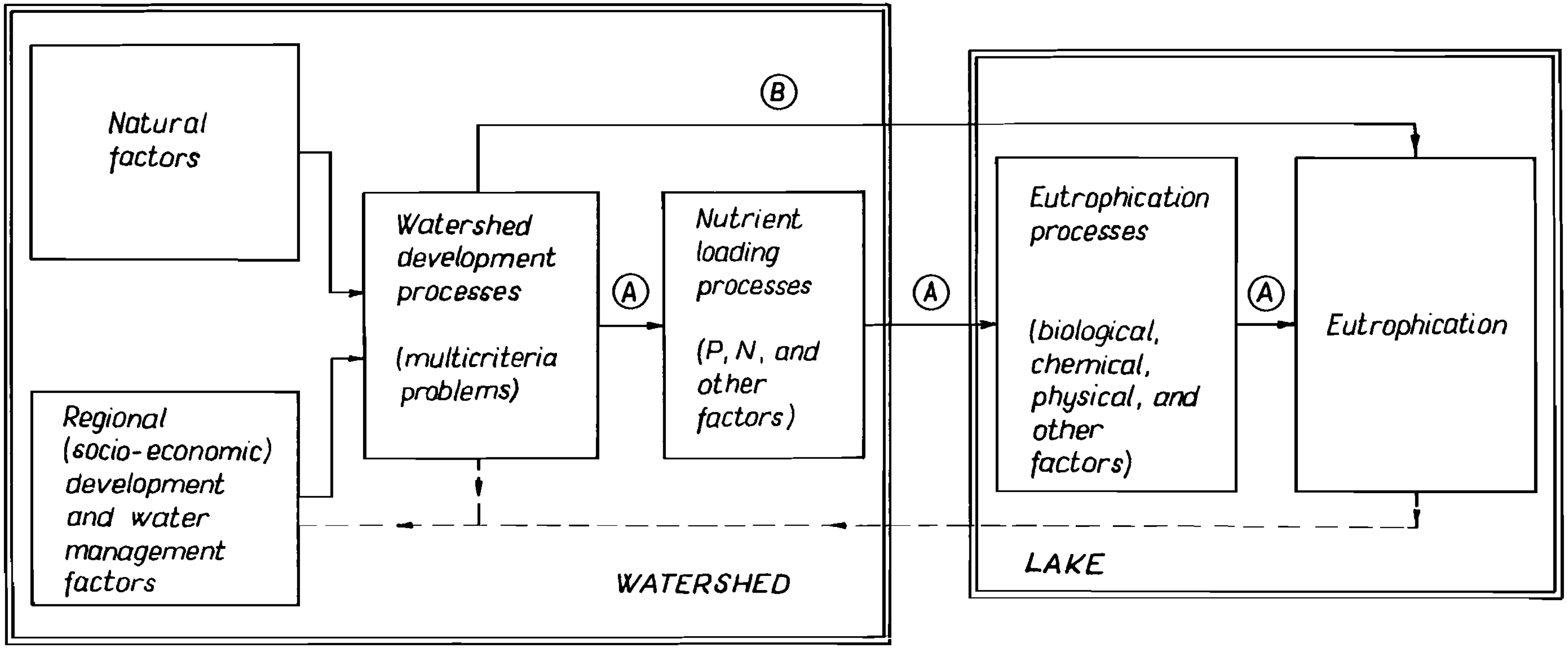
D /198o,1,1/ = 29,o
Δ D = -2,o
Modified D = 27,o

D* /198o,1,1/ = 14,9o
ΔD^* = -1,o3
Modified D* = 13,87

Total -2,oo9
+o,oo9
ΔD = -2,ooo

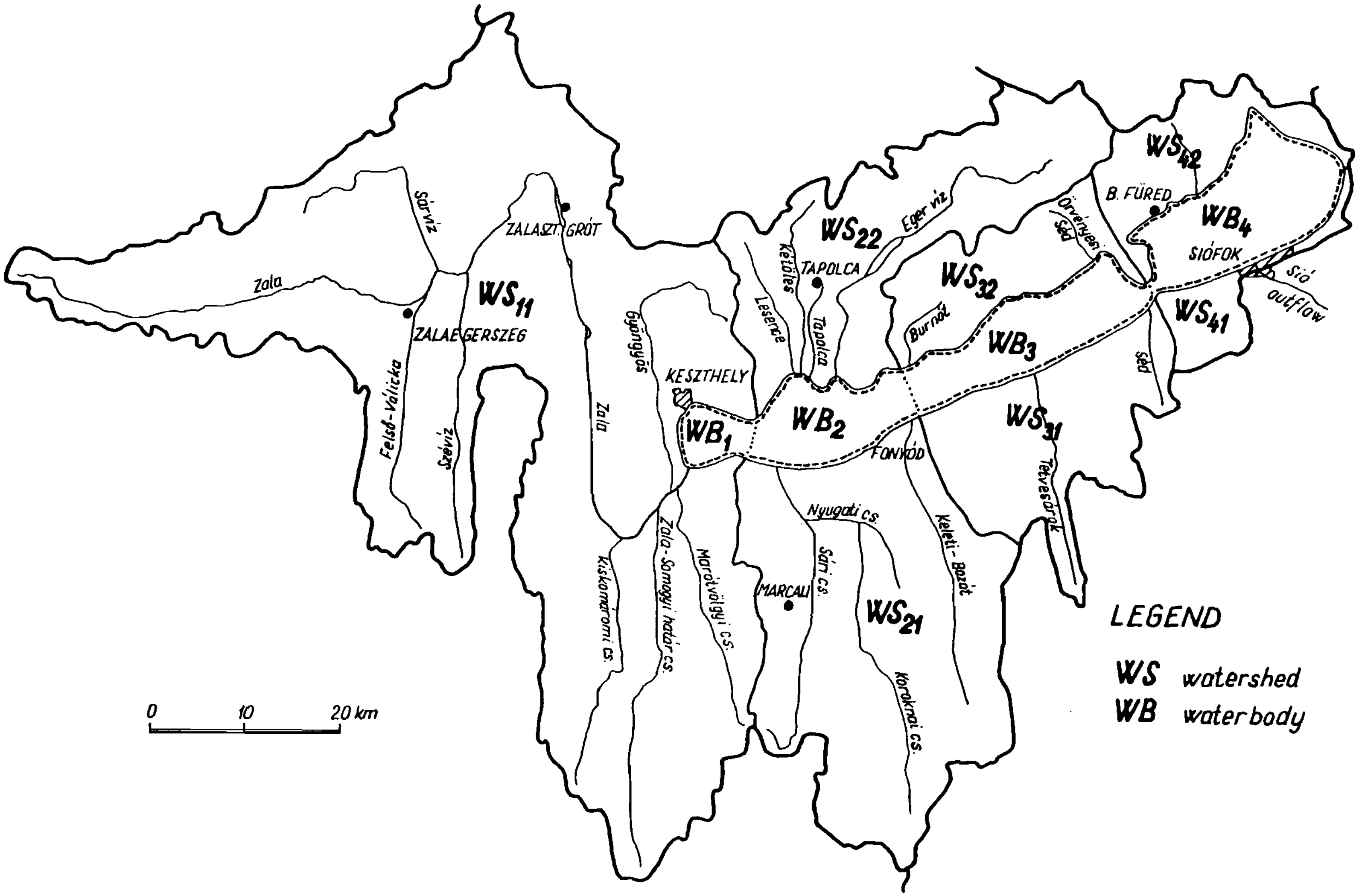
Table 13. Estimation of effectiveness of the Kis-Balaton reservoir on eutrophication

Eutrophication indices	WB_1	WB_2	WB_3	WB_4
E^* in 198o (mg/m^3)	31,5	26,o	11,o	5.1
Modified E^* (mg/m^3) by the reservoir	17,2	15,6	8,1	3,1
ΔE^* (mg/m^3)	14,3	1o,4	2,9	2,o
$\frac{\Delta E^*}{E^*(198o)}$ 1oo (%)	45,4	4o,o	26,4	39,2



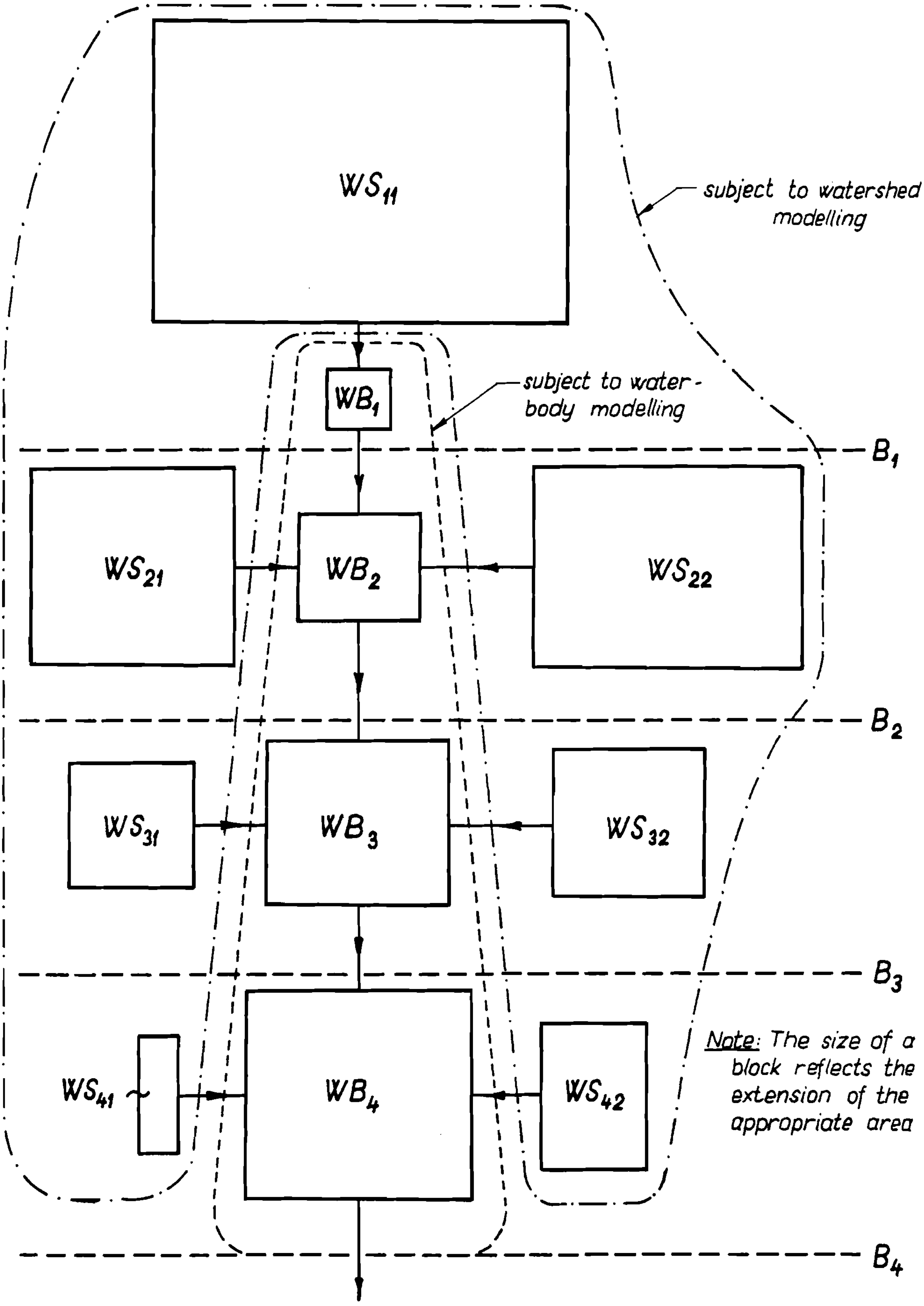
Approaches (A and B) to the modelling of the eutrophication problem

Figure 1.



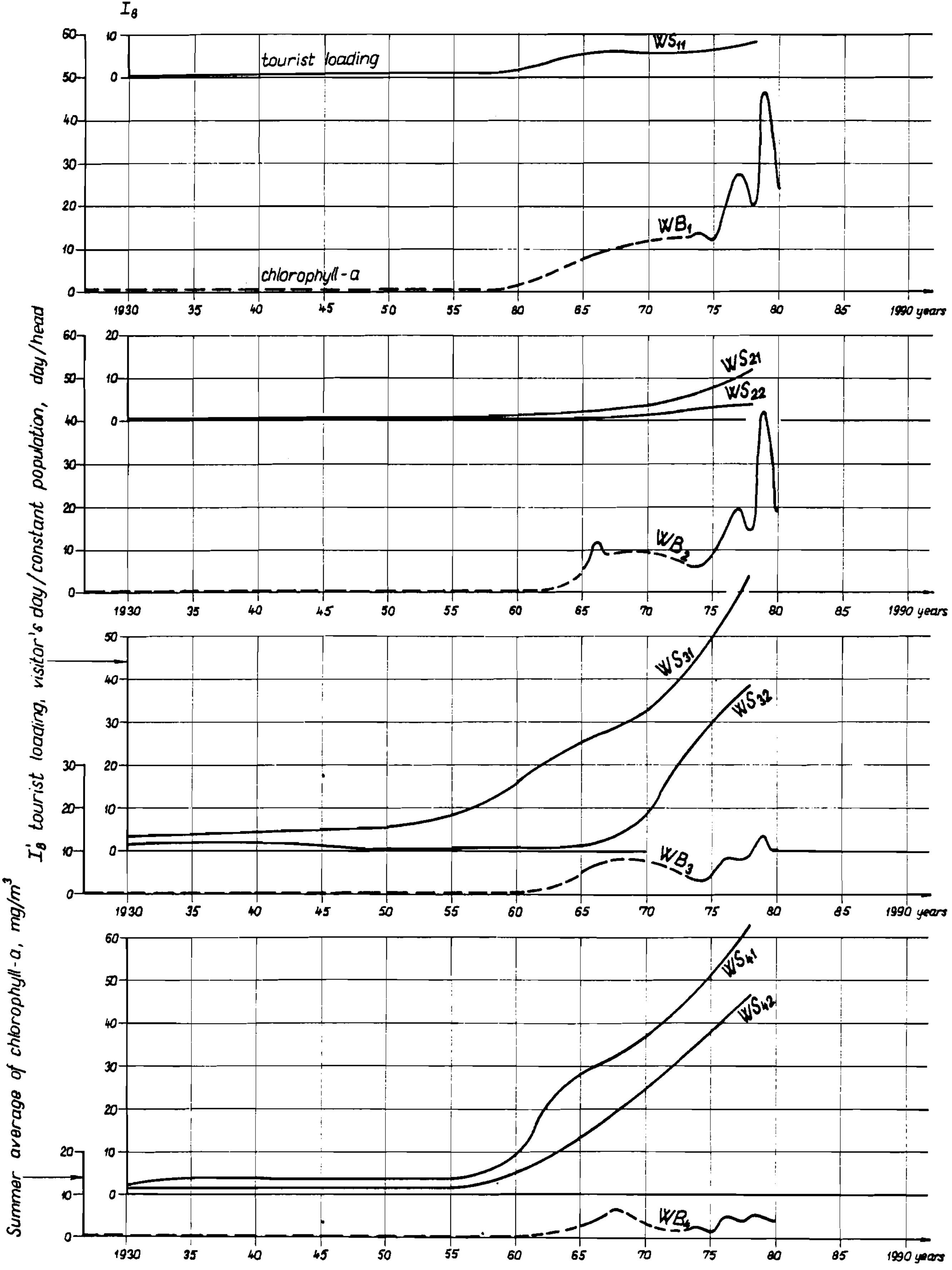
Regionalization of the Balaton basin

Figure 2.



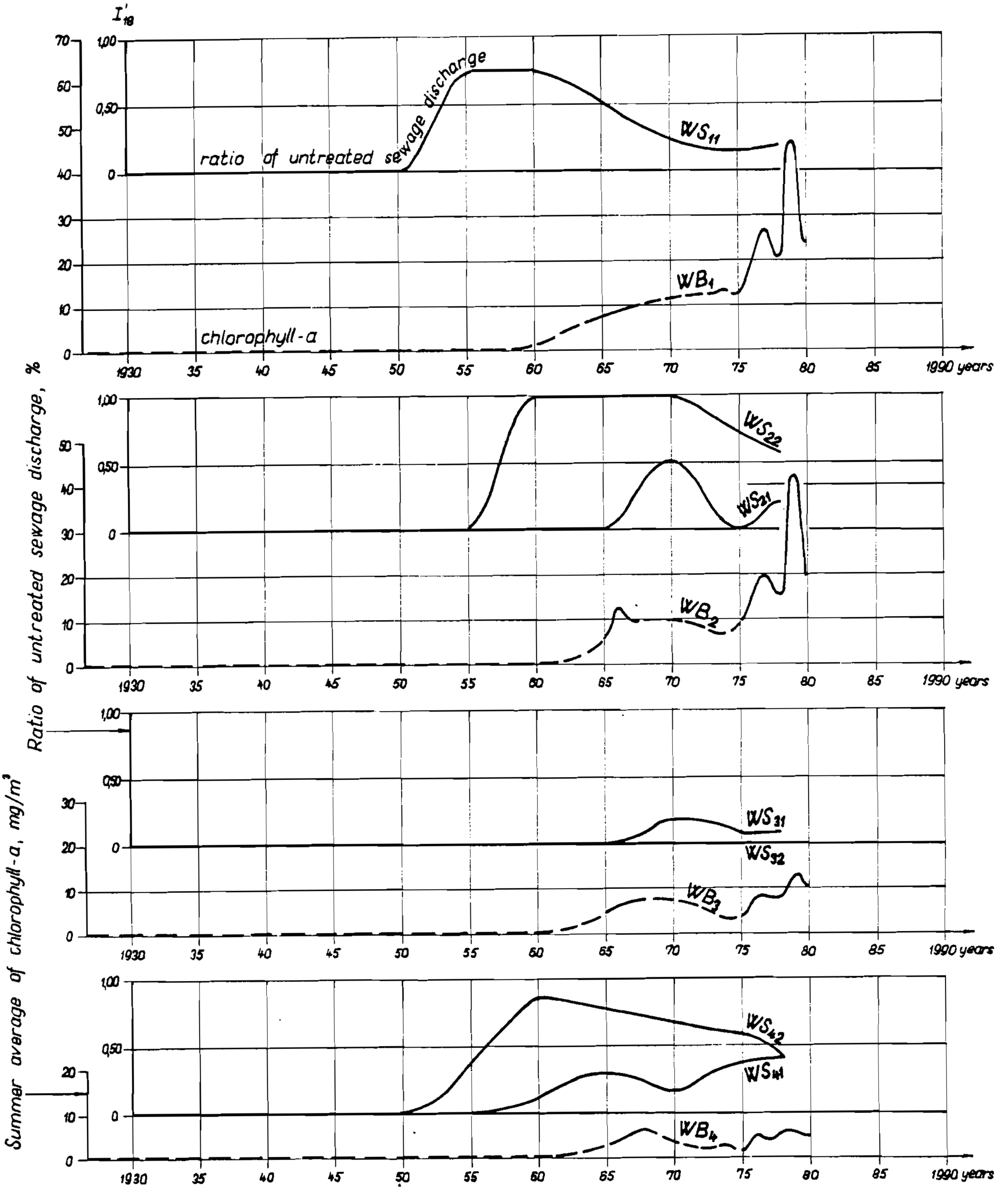
The multiregional, hierarchical system of the Balaton basin

Figure 3.



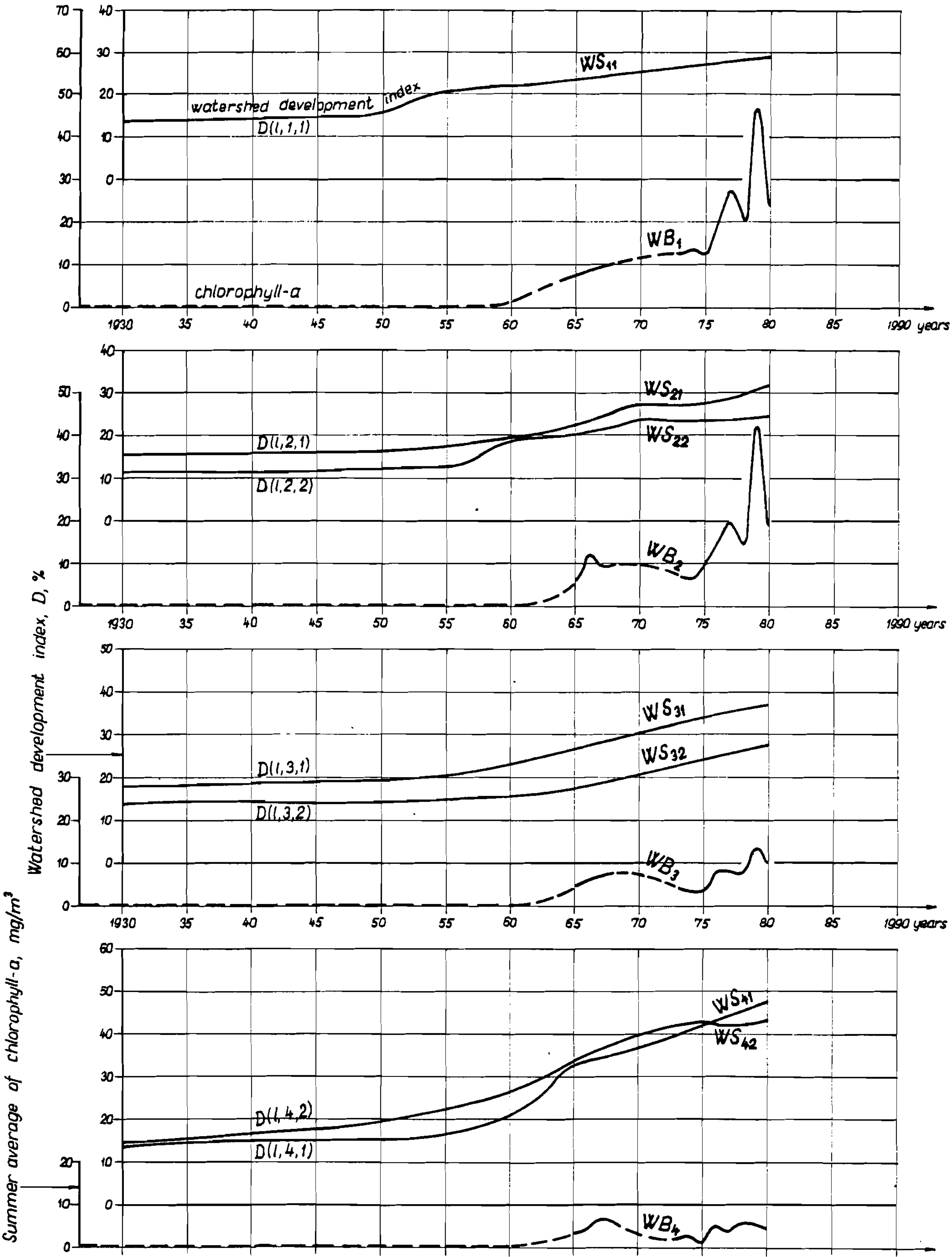
The time series of tourist loading

Figure 4.



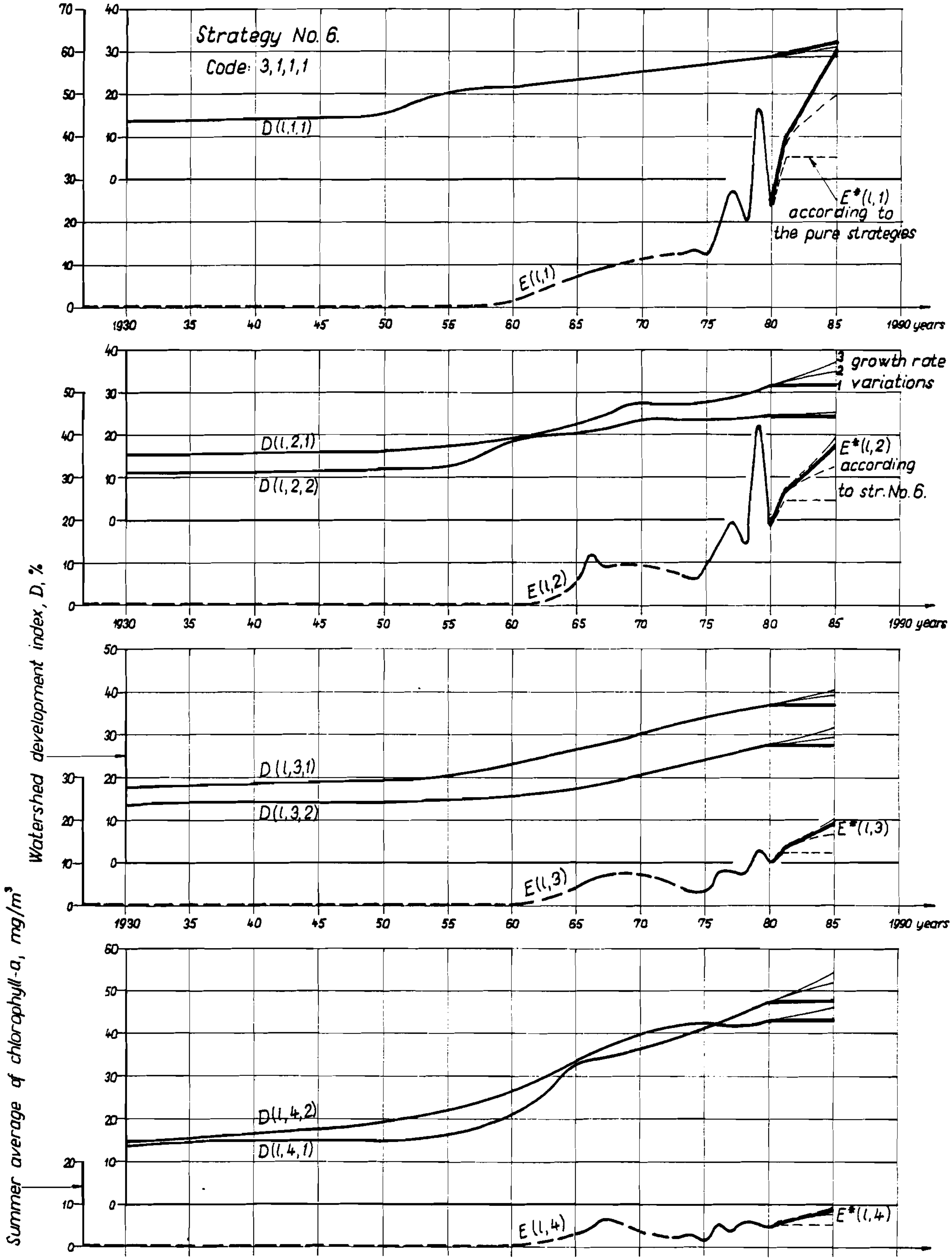
The time series of the ratio of untreated sewage discharge

Figure 5.



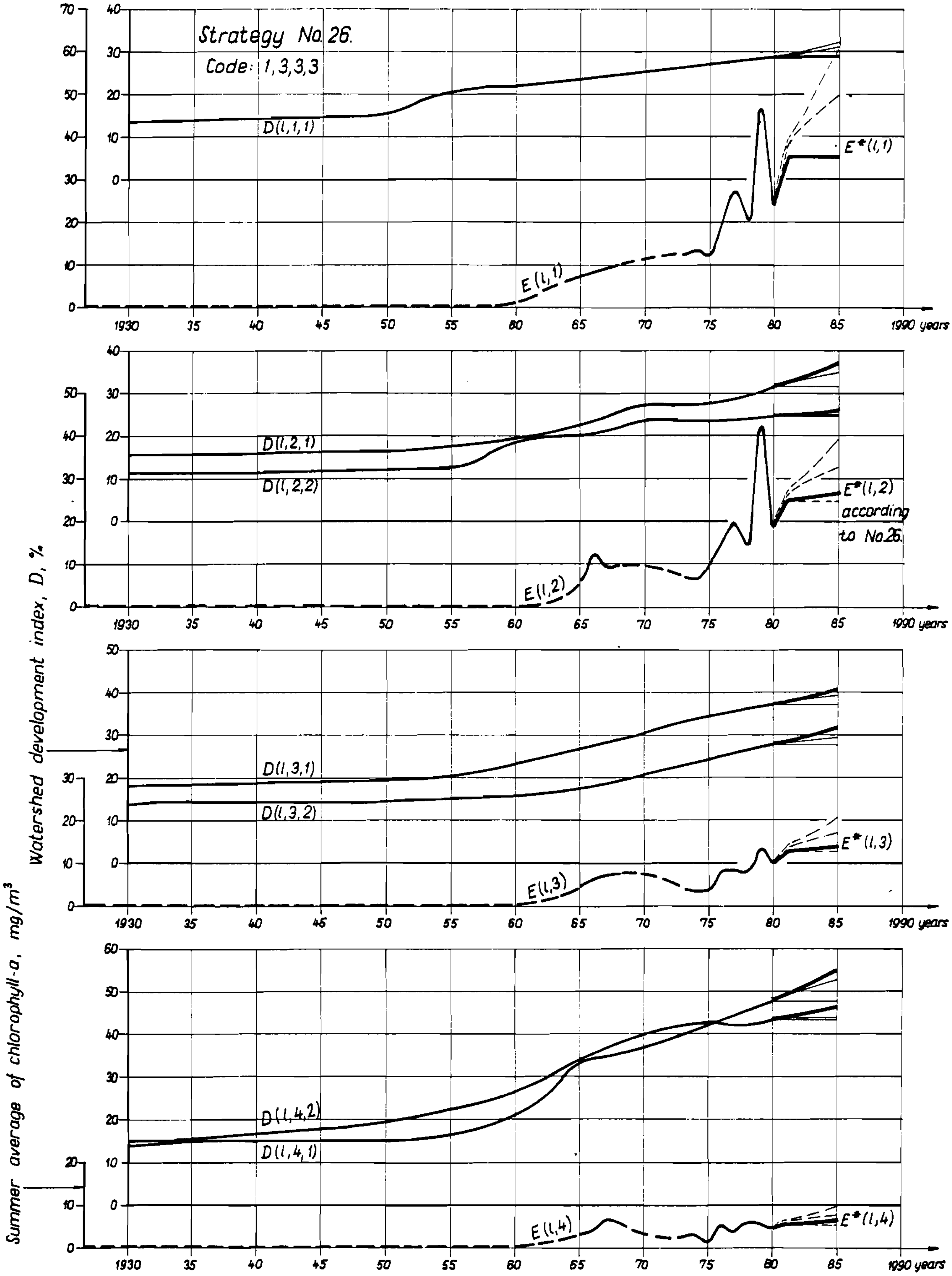
The time series of the watershed development index

Figure 6.



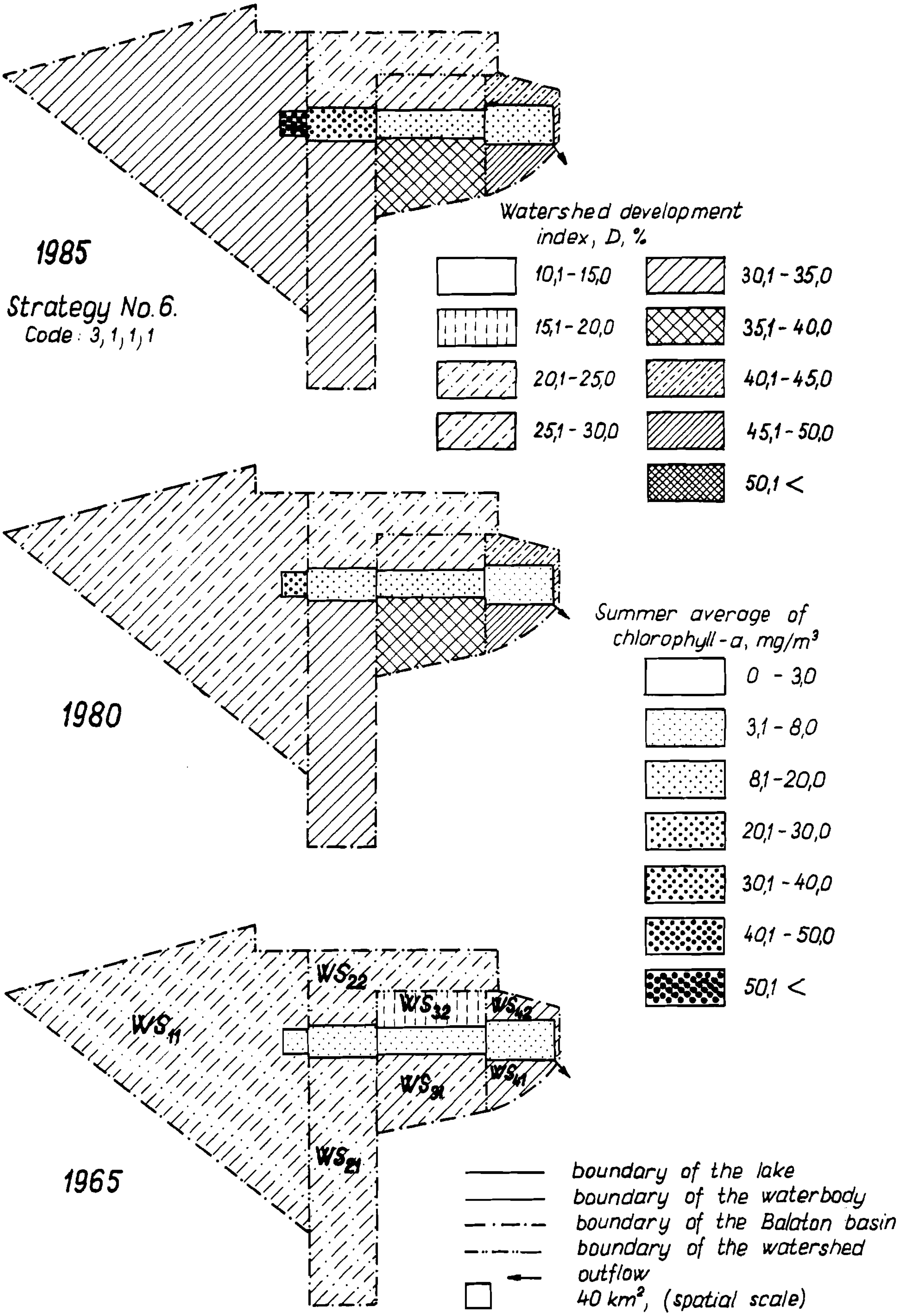
Simulation of strategy No. 6.

Figure 7.



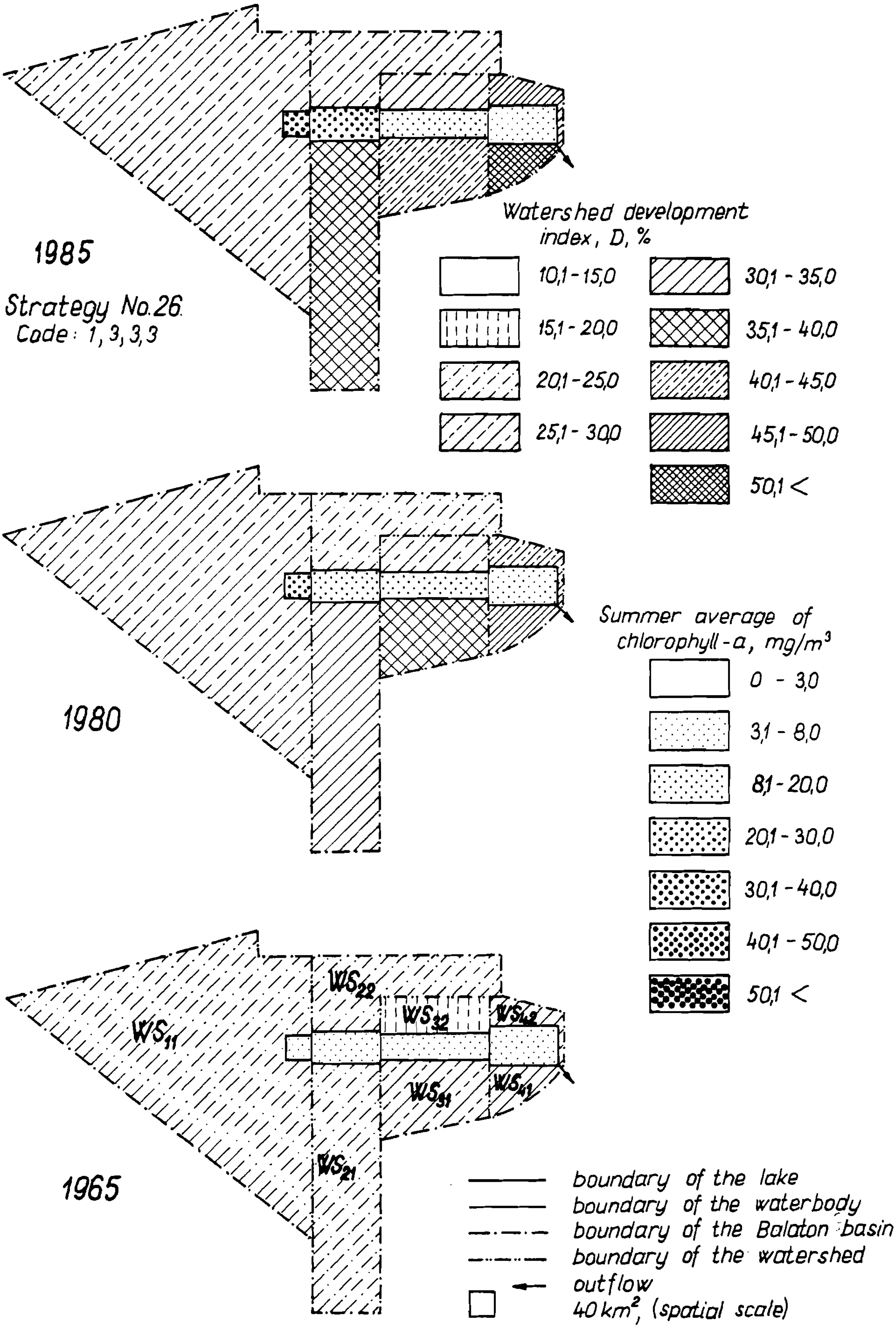
Simulation of strategy No. 26.

Figure 8.



The eutrophication process in the Balaton basin according to strategy No. 6.

Figure 9.



The eutrophication process in the Balaton basin according to strategy No. 26.

Figure 10.

Appendix 1.

Selected development factors for indicating watershed development and their impacts on nutrient loading

I. Natural factors (considered to be constant in time)

Factor code	Description	Unit	Values of factors WS_{11}	WS_{21}	WS_{22}	WS_{31}	WS_{32}	WS_{41}	WS_{42}
F_1	lake area connected to WS	km^2	40	136		188		231	
F_2	ground surface area of WS	km^2	2700	970	660	320	280	115	200
F_3	the distance of the average elevation of WS and WB above sea level	m	80	35	160	40	110	40	100
F_4	distance between the areal gravity center of the WS and the connected WB	km	25	18	12	7	5	3	4
F_5	average slope of arable land of WS	%	12	4	7	4	5	2	3
F_6	average yearly precipitation	mm	745	680	708	650	680	600	610
F_7	maximum precipitation for one day	mm	130	101	78	74	109	63	73
F_8	average number of dry days in a year	days	232	271	277	272	277	274	279
F_9	total length of water courses	km	1230	680	150	137	75	35	50
F_{10}	length of rivers	km	40	0	0	0	0	5	0
F_{11}	potential water resources (multiannual average runoff)	$10^6 m^3$/year	300	80	70	25	30	10	15
F_{12}	average volume of water in the lake's WB connected with the watersheds	$10^6 m^3$	90	480		540		815	

Appendix 1. (contd.)

II. Regional (socio-economic) development factors

(data for 1930 and 1978)

Factor code	Description	Unit	years	Values of factors						
				WS_{11}	WS_{21}	WS_{22}	WS_{31}	WS_{32}	WS_{41}	WS_{42}
F_{13}	number of constant population	10^3 head	1930	202	55	36	21	15	13	16
			1978	209	55	39	25	11	27	38
F_{14}	number of population working in industry	10^3 head	1930	8	2	2,8	1,0	0,9	1,1	1,1
			1978	37	8	2,8	3,0	0,3	2,0	9,2
F_{15}	number of population working in agriculture	10^3 head	1930	110	19,0	12,4	7,0	4,5	3,6	4,4
			1978	45	10,0	4,2	4,0	0,8	5,5	5,1
F_{16}	visitor's day	10^3 head x day	1930	50	15	5	69	16	30	25
			1978	1700	655	151	1593	420	1695	1750
F_{17}	number of settlements	settlements	1930	195	48	31	22	29	7	14
			1978	177	48	27	22	9	4	8
F_{18}	number of industrial plants	plants	1930	50	2	20	2	3	3	3
			1978	190	14	57	10	19	75	40
F_{19}	number of large animal farms	farms	1930	0	0	2	0	0	0	1
			1978	16	15	8	2	3	1	3
F_{20}	arable land	km^2	1930	1908	722	359	218	165	72	109
			1978	1800	625	282	192	144	60	87
F_{21}	vineyards and orchards	km^2	1930	150	21	32	10	28	4	20
			1978	125	23	32	16	28	11	25
F_{22}	forest land	km^2	1930	610	128	194	38	57	11	40
			1978	690	189	206	57	72	16	44
F_{23}	urbanized area	km^2	1930	160	75	15	36	12	12	28
			1978	180	75	22	36	16,5	26,5	37,5

Appendix 1 . (contd.)

Factor code	Description	Unit	years	Values of factors						
				WS_{11}	WS_{21}	WS_{22}	WS_{31}	WS_{32}	WS_{41}	WS_{42}
F_{24}	number of standard (full-grown) animals	10^3 head	1930	94	32	12,2	9,0	6,1	3,9	6,6
			1978	75	23	12,9	7,0	7,0	4,8	8,0
F_{25}	total amount of fertilizers used in equivalents P_2O_5	$\frac{10^3 t}{year}$	1930	1	0	0	0	0	0	0
			1978	32	15	6,1	7	3,1	1,7	2,1
F_{26}	length of motoring (paved) roads	km	1930	10	130	20	70	30	30	30
			1978	1150	226	216	110	140	235	228
F_{27}	total official fresh water demand	$\frac{10^6 m^3}{year}$	1930	6,3	10,8	0,4	8,5	0,2	0,5	0,5
			1978	44,2	31,3	11,0	16,2	4,0	18,0	22,0
F_{28}	total actual water use	$\frac{10^6 m^3}{year}$	1930	4,4	10,3	0,33	8,1	0,15	0,33	0,33
			1978	32,4	26,1	7,0	11,1	1,8	10,3	17,8
F_{29}	actual domestic water use	$\frac{10^6 m^3}{year}$	1930	3,1	0,8	0,1	0,4	0,1	0,2	0,2
			1978	12,2	4,0	3,8	2,2	1,0	6,1	4,5
F_{30}	actual industrial water use	$\frac{10^6 m^3}{year}$	1930	0,2	0,1	0,01	0,1	0,01	0,01	0,01
			1978	8,8	0,5	0,5	0,4	0,2	0,9	9,5
F_{31}	actual water use for irrigation and fish ponds	$\frac{10^6 m^3}{year}$	1930	0,5	9,0	0,1	7,4	0	0,1	0
			1978	9,3	20,5	1,52	8,0	0,26	2,78	3,35
F_{32}	actual water use for animal farming	$\frac{10^6 m^3}{year}$	1930	0,6	0,4	0,1	0,2	0,0	0,0	0,1
			1978	2,1	1,1	0,9	0,5	0,3	0,3	0,2
F_{33}	water use with drinking water quality	$\frac{10^6 m^3}{year}$	1930	3,7	1,3	0,2	0,7	0,1	0,2	0,3
			1978	18,3	5,6	5,0	3,1	1,4	6,6	5,1
F_{34}	amount of consumed water	$\frac{10^6 m^3}{year}$	1930	4,1	2,9	0,3	2,0	0,1	0,2	0,2
			1978	18,4	13,4	4,5	3,4	1,5	5,1	5,4
F_{35}	amount of reused water	$\frac{10^6 m^3}{year}$	1930	0	0	0	0	0	0	0
			1978	2,3	0	0	0	0	0	5,0

Appendix 1. (contd.)

Factor code	Description	Unit	years	Values of factors						
				WS_{11}	WS_{21}	WS_{22}	WS_{31}	WS_{32}	WS_{41}	WS_{42}
F_{36}	amount of water import from outside the watershed	1o^{6}m^3/year	193o	o	o	o	o	o	o	o
			1978	4,2	1,6	o	1,o	o	o	o
F_{37}	amount of water export to outside the basin	1o^{6}m^3/year	193o	o	o	o	o	o	o	o
			1978	o	o,6	87,6	o	o	o	7,4
F_{38}	underground water resources taken out	1o^{6}m^3/year	193o	4,o	1,3	o,o9	o,7	o,o5	o,o6	o,o7
			1978	15,2	4,o	157,7	1,6	o,6	3,6	3,6
F_{39}	peak actual water use in August	m^3/s	193o	o,12	o,6	o,o1	o,5	o,o1	o,o1	o,o1
			1978	1,21	2,o	o,65	o,8	o,4	2,3	2,8
F_{4o}	irrigation water use in August	m^3/s	193o	o	o	o	o	o	o	o
			1978	o,5	1,o	o,35	o,1	o,1	o,8	o,7
F_{41}	total effluent discharge collected by sewage works	1o^{6}m^3/year	193o	o,1	o	o	o,1	o	o,1	o,1
			1978	6,5	1,o	1,6	1,3	o,1	4,1	4,8
F_{42}	treated effluent discharge from F_{41}	1o^{6}m^3/year	193o	o,1	o	o	o,1	o	o,1	o,1
			1978	5,2	o,8	o,7	1,2	o,1	2,5	2,9
F_{43}	existing storage capacity	1o^{6}m^3	193o	o	o	o,4	o	o	o,2	o
			1978	2,o	1,o	2,5	o,3	o,1	o,8	o
F_{44}	number of reservoirs (and fish ponds)	reservoir (fish ponds)	193o	o/15/	o/61/	o/4/	o/13/	o/o/	o/5/	o/o/
			1978	8/9/	11/88/	2/8/	3/16/	1/o/	3/8/	o/o/
F_{45}	number of constant population supplied with waterworks	1o^{3}head	193o	7	1	o	1	o	o	o
			1978	126	46	24	19	6	2o	3o
F_{46}	number of constant population supplied with sewage works	1o^{3}head	193o	1	o	o	1	o	o,5	o,5
			1978	66	9	9,4	2	o,5	9,7	8,8
F_{47}	irrigated area	km^2	193o	o	o	o	o	o	o	o
			1978	36	1,9	1o,1	o,2	1,7	18,6	22,3

Appendix 1. (contd.)

Factor	Description	Unit	years	Values of factors						
				WS 11	WS 21	WS 22	WS 31	WS 32	WS 41	WS 42
F_{48}	drainage area	km^2	193o 1978	67 179	1o9 1o9	o o	24,7 24,7	o o	o o	o o
F_{49}	length of beaches used for recreation	km	193o 1978	o,5 6,o	1,o 2o,o	o,1 2,2	1,o 29,o	o,3 11,o	o,3 18,o	o,6 18,4
F_{5o}	number of existing water right licenses for water use and waterworks	licenses	193o 1978	425 1556	7o 277	32 26o	23 1o5	28 38o	7 455	2o 475

Appendix 2.

List and description of indicator indices

Note: I_k denotes the normalized, dimensionless, while I'_k denotes the original (physical) form of the k-th indicator index.

Index Code	Name of the index (criteria)	Composition and description of I'_k	Unit of I'_k	Description of effects of I'_k on nutrient loading
I_1	erosion potential	$I'_1 = F_5 \cdot F_7$ slope of arable land x max. one day precipitation	%xmm	higher value indicates more erosion, more wash out from arable land, thus more NL
I_2	quantity distribution of precipitation	$I'_2 = F_7/F_6$ $\frac{\text{max. one day precipitation}}{\text{average yearly precipitation}}$	$\frac{\text{mm}}{\text{mm}}$	higher value indicates more wash out from the soil, more erosion
I_3	time distribution of precipitation	$I'_3 = 1 - \frac{365 - F_8}{F_8}$ $1 - \frac{\text{number of wet days}}{\text{number of dry days}}$	$\frac{\text{day}}{\text{day}}$	higher value indicates less uniform distribution of rainfall which is worse for wash out, water demand, water management control, causes more erosion, etc.
I_4	density of natural water courses	$I'_4 = F_9/F_2$ $\frac{\text{length of water courses}}{\text{area of WS}}$	$\frac{\text{m}}{\text{km}^2}$	higher value indicates more erosion, more possibilities to collect and transfer both point and non-point sources
I_5	natural energy potential of WS	$I'_5 = F_3/F_4$ average slope of the surface of WS	o/oo	higher value indicates more erosion, more runoff, shorter collection time, etc.

Appendix 2. (contd.)

Index Code	Name of the index (criteria)	Composition and description of I'_k	Unit of	Description of effects of I'_k on nutrient loading
I_6	population ratio involved in industry	$I'_6 = F_{14}/F_{13}$ $\frac{\text{population in industry}}{\text{constant population}}$	$\frac{\text{head}}{\text{head}}$	higher value indicates greater importance of industry, therefore more ecological problems, more water demand, more sewage water, more demand for recreation, etc.
I_7	population ratio involved in agriculture	$I'_7 = 1 - F_{15} / F_{13}$ $1 - \frac{\text{population in agriculture}}{\text{constant population}}$	$\frac{\text{head}}{\text{head}}$	higher value indicates an increase of efficiency in agricultural production, more non-point sources, fertitilizer and chemical use, etc.
I_8	visitor (tourist) loading	$I'_8 = F_{16}/F_{13}$ $\frac{\text{visitor's day}}{\text{constant population}}$	$\frac{\text{visitor day}}{\text{head}}$	higher value indicates more NL to the WS and the WB, more need for infrastructure, more non-constant population, etc.
I_9	density of possible point sources	$I'_9 = (F_{17} + F_{18} + F_{19})/F_2$ (settlements, industrial plants, animal farms) over area of WS	$\frac{\text{sources}}{100\text{km}^2}$	higher value indicates more point sources, more NL, more need for treatment facilities, etc.
I_{10}	ratio of arable and forest land use	$I'_{10} = F_{20}/F_{22}$ arable/forest land	$\frac{\text{km}^2}{\text{km}^2}$	higher value indicates more non-point nutrient loadings more erosion, more runoff, etc.
I_{11}	urbanized part of the WS	$I'_{11} = F_{23}/F_2$ $\frac{\text{urbanized area}}{\text{area of WS}}$	$\frac{\text{km}^2}{\text{km}^2}$	higher value indicates more sewage water, more infiltration to the soil, more urban runoff, shorter collection time, etc.

Appendix 2. (contd.)

Index Code	Name of the index (criteria)	Composition and description of I'_k	Unit of I'_k	Description of effects of I'_k on nutrient loading
I_{12}	ratio of vineyards and orchards	$I'_{12} = F_{21}/F_{20}$ $\frac{\text{area of vineyards and orch.}}{\text{arable land}}$	$\frac{km^2}{km^2}$	vineyards and orchards indicate the most dangerous type of agricultural land use from the point of view of erosion because of the higher fertilizer use and higher slopes; higher value indicates more erosion.
I_{13}	fertilizer use	$I'_{13} = F_{25}/F_{20}$ $\frac{\text{total amount of used fertilizer}}{\text{arable land}}$	kg/year/ha	higher value indicates more nutrient loadings
I_{14}	density of animal population	$I'_{14} = F_{24}/F_2$ $\frac{\text{number of standard animals}}{\text{area of WS}}$	$\frac{head}{km^2}$	higher value indicates more NL (more sewage water, more pasture land use, more water demand, etc.)
I_{15}	density of motoring roads	$I'_{15} = F_{26}/F_2$ $\frac{\text{length of motoring roads}}{\text{area of WS}}$	$\frac{m}{km^2}$	higher value indicates more regional development, more traffic, more tourists, more point and non-point pollution sources
I_{16}	use of available water resources	$I'_{16} = \frac{F_{28}}{F_{11}+F_{38}+F_{36}-F_{37}}$ $\frac{\text{total actual water use}}{\text{available water resources}}$	$\frac{m^3}{m^3}$	higher value indicates more use of natural resources, more regional development, more water management activities

Appendix 2. (contd.)

Index Code	Name of the index (criteria)	Composition and description of I'_k	Unit of	Description of effects of I'_k on nutrient loading
I_{17}	used water infiltrated into the soil	$I'_{17} = [F_{28} - (F_{34} + F_{35} + F_{41})]/F_2$ total actual water use minus the sum of consumed, reused, and collected sewage water over area of WS	m^3/year/km^2	higher value indicates more sewage water infiltration to the soil, which has a long-range NL effect, deterioration of soil and groundwater, etc.
I_{18}	ratio of untreated sewage discharge	$I'_{18} = 1 - F_{42}/F_{41}$ $1 - \frac{\text{treated effluent discharge}}{\text{total effluent discharge}}$	$\frac{m^3}{m^3}$	higher value indicates more NL.
I_{19}	ratio of unregulated runoff	$I'_{19} = 1 - F_{43}/F_{11}$ $1 - \frac{\text{existing storage capacity}}{\text{potential water resources}}$	$\frac{m^3}{m^3}$	higher value indicates more nutrient loading, because less water can be stored before getting to Balaton
I_{20}	ratio of population supplied with drinking water works	$I'_{20} = F_{45}/F_{13}$ $\frac{\text{constant population supplied with d.w.w.}}{\text{number of constant population}}$	$\frac{\text{head}}{\text{head}}$	higher value indicates greater development, more water demand, more sewage effluents, etc.
I_{21}	ratio of population supplied with sewage works	$I'_{21} = F_{46}/F_{13}$ $\frac{\text{constant populstion supplied with d.w.w.}}{\text{number of constant population}}$	$\frac{\text{head}}{\text{head}}$	higher value indicates more sewage water facilities, than more nutrient loading.

Appendix 2. (contd.)

Index Code	Name of the index (criteria)	Composition and description of I'_k	Unit of I'_k	Description of effects of I'_k on nutrient loading
I_{22}	ratio of irrigation and drainage	$I'_{22} = (F_{47}+F_{48})/F_{20}$ $\frac{\text{area of irrigation and drainage}}{\text{arable land}}$	$\frac{km^2}{km^2}$	higher value indicates higher cultivation, more wash out possibilities, etc.
I_{23}	Population density	$I'_{23} = F_{13}/F_2$ $\frac{\text{number of constant population}}{\text{areas of WS}}$	$\frac{head}{km^2}$	higher value indicates higher effects (more water demand, more sewage water and regional development, etc.)
I_{24}	density of all water works in the WS	$I'_{24} = F_{50}/F_2$ $\frac{\text{number of water rights}}{\text{area of WS}}$	$\frac{works}{km^2}$	higher value indicates more regional development, more possible sources of nutrient loading
I_{25}	beach length indicator for direct recreation loading	$I'_{25} = \frac{F_{49}}{F_{12}}$	$\frac{m}{10^6 m^3}$	higher value indicates more nutrient loading (more visitors, more recreation loading of water)

Appendix 3.

Physical values of indicator indices for 1930 and 1978

Index code	Unit	years	Physical values of I'_k						
			WS_{11}	WS_{21}	WS_{22}	WS_{31}	WS_{32}	WS_{41}	WS_{42}
I_1	%xmm		15,60	4,04	5,46	2,96	5,45	1,26	2.19
I_2	$\frac{mm}{mm}$	C	0,17	0,15	0,11	0,11	0,16	0,10	0,12
I_3	$\frac{day}{day}$	C	0,43	0,65	0,68	0,66	0,68	0,67	0,69
I_4	$\frac{m}{km^2}$	C	455,6	701,0	227,3	428,1	267,9	304,4	250,0
I_5	$^0/oo$	C	3,20	1,94	13,33	5,71	22,00	13,33	25,00
I_6	$\frac{head}{head}$	1930	0,04	0,04	0,08	0,05	0,06	0,08	0,07
		1978	0,18	0,15	0,07	0,12	0,03	0,07	0,24
I_7	$\frac{head}{head}$	1930	0,46	0,65	0,66	0,67	0,70	0,72	0,73
		1978	0,78	0,82	0,89	0,84	0,93	0,80	0,87
I_8	visitor day/head	1930	0,25	0,27	0,14	3,29	1,07	2,31	1,56
		1978	8,13	11,91	3,87	63,72	38,18	62,78	45,05
I_9.	$\frac{sources}{km^2}$	1930	9,07	5,15	8,03	7,50	11,43	8,7	9,00
		1978	14,19	7,94	13,94	10,63	11,07	69,57	25,50
I_{10}	$\frac{km^2}{km^2}$	1930	3,13	5,64	1,85	5,74	2,89	6,55	2,72
		1978	2,61	3,31	1,37	3,37	2,00	3,75	1,98
I_{11}	$\frac{km^2}{km^2}$	1930	0,06	0,08	0,02	0,11	0,04	0,10	0,14
		1978	0,07	0,08	0,03	0,11	0,06	0,23	0,19
I_{12}	$\frac{km^2}{km^2}$	1930	0,08	0,03	0,09	0,05	0,17	0,06	0,18
		1978	0,07	0,04	0,11	0,08	0,19	0,18	0,29

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Appendix 3. (contd.)

Index code	Unit	years	Physical values of I'_k						
			WS_{11}	WS_{21}	WS_{22}	WS_{31}	WS_{32}	WS_{41}	WS_{42}
I_{13}	kg/ha/ /year	1930	5,2	0	0	0	0	0	0
		1978	178	240	216	365	215	283	241
I_{14}	$\frac{head}{km^2}$	1930	34,8	33,0	18,5	28,1	21,8	33,9	33,0
		1978	27,8	23,8	19,6	21,9	25,0	41,7	40,0
I_{15}	$\frac{m}{km^2}$	1930	3,7	134,0	30,3	218,8	107,1	260,9	150,0
		1978	425,9	233,0	327,3	343,8	500,0	2043,5	1140,0
I_{16}	$\frac{m^3}{m^3}$	1930	0,01	0,13	0,00	0,32	0,00	0,03	0,02
		1978	0,10	0,31	0,05	0,40	0,06	0,76	1,59
I_{17}	m^3/year/ /km^2	1930	74	7618	30	18750	143	261	150
		1978	1926	12061	1363	20000	714	9565	13000
I_{18}	$\frac{m^3}{m^3}$	1930	0	0	0	0	0	0	0
		1978	0,2	0,2	0,56	0,08	0	0,39	0,40
I_{19}	$\frac{m^3}{m^3}$	1930	1,00	1,00	0,99	1,00	1,00	0,98	1,00
		1978	0,99	0,99	0,96	0,99	1,00	0,92	1,00
I_{20}	$\frac{head}{head}$	1930	0,03	0,02	0,00	0,05	0,00	0,00	0,00
		1978	0,60	0,84	0,62	0,76	0,55	0,74	0,79
I_{21}	$\frac{head}{head}$	1930	0,00	0,00	0,00	0,05	0,00	0,04	0,03
		1978	0,32	0,16	0,24	0,08	0,05	0,36	0,23
I_{22}	$\frac{km^2}{km^2}$	1930	0,04	0,15	0,00	0,11	0,00	0,00	0,00
		1978	0,12	0,18	0,04	0,13	0,01	0,31	0,26

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Appendix 3. (contd.)

Index code	Unit	years	Physical values of I'_k						
			WS_{11}	WS_{21}	WS_{22}	WS_{31}	WS_{32}	WS_{41}	WS_{42}
I_{23}	$\frac{\text{head}}{\text{km}^2}$	1930	74,8	56,7	54,6	65,6	53,6	113,0	80,0
		1978	77,4	56,7	59,1	78,1	39,3	234,8	190,0
I_{24}	$\frac{\text{works}}{\text{km}^2}$	1930	0,16	0,07	0,05	0,07	0,10	0,06	0,10
		1978	0,58	0,29	0,39	0,33	1,36	3,96	2,38
I_{25}	$\frac{\text{m}}{10^6\text{m}^3}$	1930	5,6	4,2	0,4	3,7	1,1	0,7	1,5
		1978	66,7	83,3	9,2	107,4	40,8	44,2	45,2

Appendix 4.

List and scales of evaluation criteria for weighting

Criteria		Scales (points)		
Code	Nomination	1	2	3
A	Interval of changing	constant	small	large
B	Type of changing	uniform	slight breaking	strong breaking
C	Direction of changing	decreasing	uniform	increasing
D	Differences among watersheds	uniform	medium	strong
E	Effect on eutrophication	small	medium	strong
F	Manageability	no	slowly	quickly

Appendix 5.

Multicriteria evaluation of weighting factors

Code of indicator indices I_k	Evaluation criteria						points ΣP (A-F)	$(\Sigma P)^2$	%	Value of w_k
	A	B	C	D	E	F				
	points									
1	1	1	2	3	3	2	12	144	3,3	o,o33
2	1	1	2	3	2	1	lo	loo	2,3	o,o23
3	1	1	2	2	2	1	9	81	1,8	o,o18
4	1	1	2	3	1	1	9	81	1,8	o,o18
5	1	1	2	3	2	1	lo	loo	2,3	o,o23
6	3	1	3	1	1	2	11	121	2,8	o,o28
7	3	2	3	1	2	2	13	169	3,8	o,o38
8	3	3	3	3	3	3	18	324	7,4	o,o74
9	2	2	3	3	3	2	15	225	5,1	o,o51
lo	2	1	1	1	1	2	8	64	1,4	o,o14
11	2	1	3	1	2	2	11	121	2,8	o,o28
12	2	1	2	2	2	2	11	121	2,8	o,o28
13	3	3	3	3	3	3	18	324	7,4	o,o74
14	2	1	2	2	1	3	11	121	2,8	o,o28
15	3	2	3	3	2	2	15	225	5,1	o,o51
16	3	2	3	3	2	3	16	256	5,8	o,o58
17	3	2	2	3	2	3	15	225	5,1	o,o51
18	3	2	2	2	3	3	15	225	5,1	o,o51
19	2	2	1	1	2	3	11	121	2,8	o,o28
2o	3	3	3	2	1	2	14	196	4,5	o,o45
21	3	3	3	2	2	2	15	225	5,1	o,o51
22	3	1	3	3	1	2	13	169	3,8	o,o38
23	2	1	3	2	2	2	12	144	3,3	o,o33
24	3	3	3	3	2	2	16	256	5,8	o,o58
25	3	3	3	2	3	2	16	256	5,8	o,o58
							Total	4395	loo,o	1,ooo