A WATERSHED DEVELOPMENT APPROACH TO THE EUTROPHICATION PROBLEM OF LAKE BALATON

(A Multiregional and Multicriteria Model)

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PREFACE

This report is one of the results of the collaboration in the framework of IIASA's Lake Balaton Case Study between the Hungarian Balaton Eutrophication Modelers Group (BEM) and IIASA's Resources and Environment Area task on Models for Environmental Quality Control and Management. The approach to the eutrophication management problem of Lake Balaton proposed in this report is an attempt to bypass the detailed modelling of watershed and waterbody processes, constituting the other line of research pursued in the Balaton Case Study. As such, it takes a special place in the spectrum of modelling activities around Lake Balaton, deserving attention precisely because of its different angle of attack.

The work for this report was done during several short visits of the Hungarian authors to IIASA. It is obvious that the results, though promising, are of intermediate nature. Let the reader therefore not hesitate to convey to the authors any critical remarks and comments he might have, in the interest of further development of this research.

ABSTRACT

The approach to long-term management of the eutrophication of a lake proposed in this paper is based on the hypothesis that a close relation exists between the human activity in the watershed and the degree of eutrophication in the adjacent waterbody. The method builds on the watershed development approach applied earlier to water resources planning.

To test the basic hypothesis and to investigate the relationship in quantitative form an application to the eutrophication problem of Lake Balaton has been attempted. For this purpose the Balaton catchment was separated into regional units with differing degrees of development. In view of the main water transport direction in Lake Balaton, the adjacent waterbodies can be considered as a hierarchical system. For this multiregional, hierarchical system a model was formulated in which the effects of the relevant watershed development factors and natural factors on the nutrient loading from the watershed are expressed in one condensed watershed development figure. Comparison of the development figure for various time instants and various regions with historical and spatial data for the degree of eutrophication should then allow the specification of the relation in a numerical form.

The actual application presented in this paper is of preliminary nature because data for the existing level of watershed development (1975-76) were available only. A system of 25 nutrient loading effecting watershed development criteria was designed on the basis of 50 development and natural factors selected from available statistical data. The 25 criteria were then composed into a development indicator for the four watershed regions using 7 alternative weighting systems. The results were compared with 3 alternative eutrophication indices derived

from phytoplankton biomass data. The model relationship was analyzed by means of correlation analysis, and a tentative assessment was made of the sensitivity to weighting system and eutrophication index.

The first numerical results support the idea behind the basic hypothesis of the watershed development approach. The quantitative results agree with subjective opinions on the present situation in the Balaton region. The overall conclusion is that it is worthwhile to pursue the line of research of this report as a perspective tool in the simulation of the effects of long-term watershed development policies on the eutrophication of the lake. The collection of the necessary historical data for this purpose is highly recommended.

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1. INTRODUCTION

The eutrophication of Lake Balaton in Hungary, a relatively large (600 km^2), shallow (3.5 m average depth) lake, with a watershed of 5180 km^2 (Figure 1), has considerably accelerated since the 1960's. Socio-economic development on the watershed and subsequent harmful phenomena affecting the lake-ecosystem must be held responsible for this acceleration. To analyze this process, predict its later course and determine the steps required to protect the water quality in future, it is desirable to investigate the eutrophication problem of the lake not only from the physical, chemical and biological point of view, but also from the point of view of watershed development.

The concept of river basin (watershed) development as a process was outlined by David (1976). The aim of this process is to establish a continuous balance among natural water supplies and socio-economic and environmental requirements over space, time, quality, quantity and energy aspects on a basin-wide scale during the socio-economic development. 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.

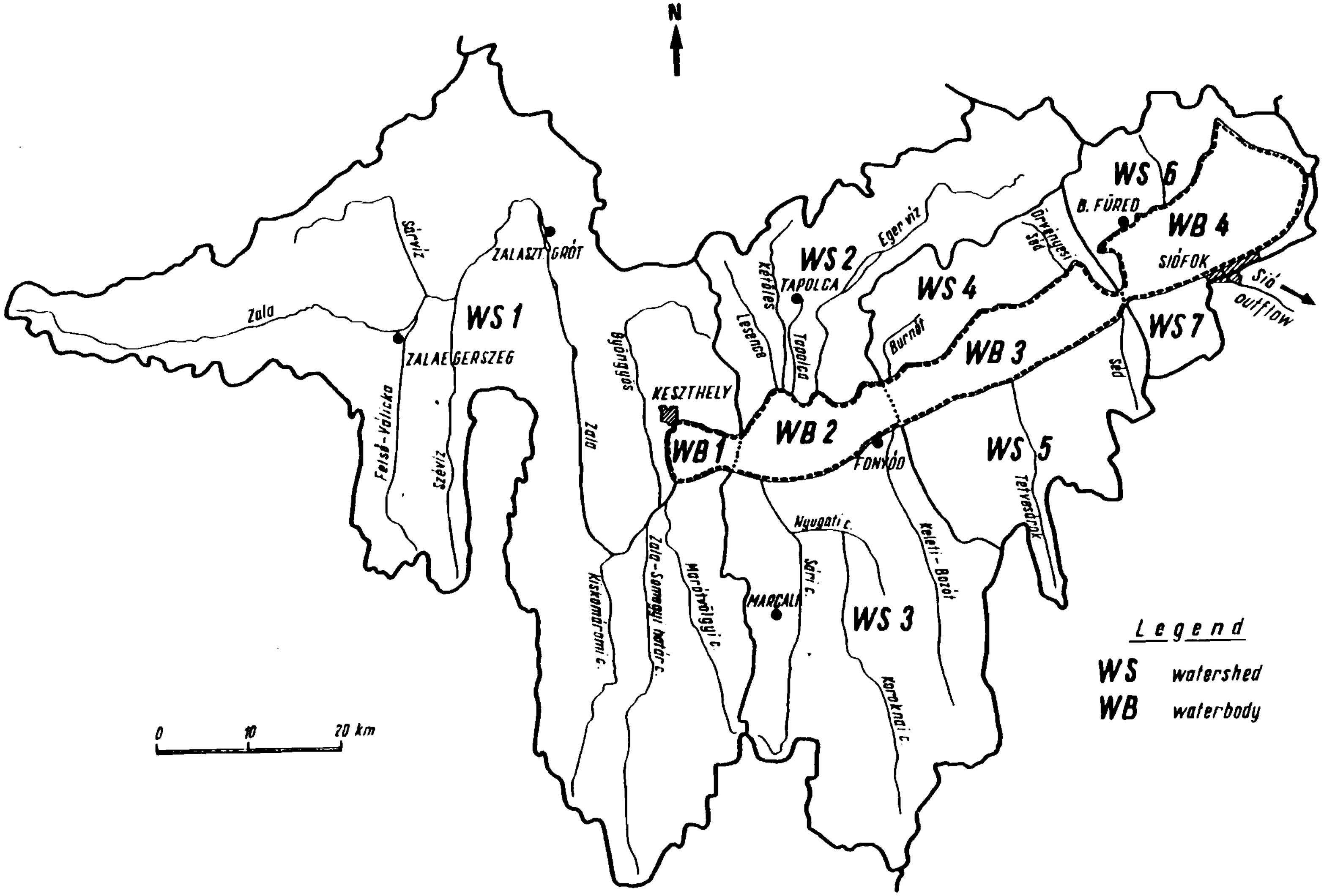

Figure 1. Regionalization of the Balaton Basin.

From the perspective of water resources management, the development process of the watershed can be divided into three consecutive periods: (I) a natural, (II) a developing, and (III) a fully developed phase.

In *period I* there is no significant human interference in the watershed; the quantity and quality of water resources are virtually conform to natural conditions, and fluctuate with them. In *period II*, deliberate human interference is restricted to that of a local and regional character and expands step by step to basin-wide dimensions. Under its influence, the natural runoff system gradually changes and becomes more regulated. Multipurpose integrated water projects and growing systems are constructed with increasingly large capacities. The usable water resources, the importance of water demand control, the amount of sewage effluent, the number of point and non-point sewage sources, and the extent of sewage treatment, etc., also increase according to the socio-economic and environmental conditions. The deterioration of the water quality has begun and induces the development of water quality control. Finally, *period III* is that of total regulation of the watershed, where the redistribution of completely regulated water resources among users and the prevention of water damages, etc., are continuously undertaken by the fully developed, basin-wide and controlled multipurpose water resources system as a unit.

The main elements and features of watershed development and their changing importance during the process have been characterized by David (1978 a). The structure and the ratio of the basic activities also 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 David (1978 b). This multicriteria analysis is needed because of the great number of elements and criteria involved in watershed development. Based on this proposition, the Institute for Water Management (1979) in Budapest evaluated the progress of watershed development in the river basin (main watersheds) of Hungary. According to this investigation, the river basin of Lake Balaton presently is in the first phase of *period*

II of development and relatively less developed than some other river basins of the country.

The integration of the watershed development approach and water quality control has been proposed previously by David (1978 a). The problem of the eutrophication of Lake Balaton seems to provide a suitable example for analysis within this framework.

The present ratio of the degree of eutrophication in the lake is estimated to be roughly 8:4:2:1 for the Keszthely, the Szigliget, the Szemes and Siofok Basins, respectively. The data of the adjacent watershed areas show a similar ratio, suggesting a close relation between degree of eutrophication and the connected watershed. Such marked differences in eutrophication were not observed in the early 1950's (Herodek, 1976), when the watersheds were in the natural (I) phase of development. Therefore, the eutrophication should be considered as the result of the regional and water management development process on the watershed during the last 20-30 years. The similarity in both space and time qualitatively suggests that the idea of applying the watershed development approach to the eutrophication problem is appropriate.

The degree of development of the watersheds is different, and so is the water quality in the adjacent waterbodies. Therefore, the following basic hypothesis is made: *there is a close connection between eutrophication of the lake and the human-made watershed development.*

The purpose of the present paper is to outline the multiregional and multicriteria model for long-term control of eutrophication in Lake Balaton, based on the watershed development approach, and to present the preliminary application of the model to the present stage of watershed development. The model purposely parallels the family of models on eutrophication of Lake Balaton, the detailed structural modelling on nutrient loading and the models of eutrophication processes of the waterbody. Together with these models, it can form a system of supplementary models on Balaton eutrophication.

The paper is organized in the following way. In the next chapter the description of the model is presented. Next, the preliminary application of the model is discussed. Finally, the results of the preliminary application and the conclusions of the applied approach are summarized.

2. WATERSHED DEVELOPMENT MODEL FOR EUTROPHICATION CONTROL

In this chapter, the concept and the composition of the watershed development model is outlined and its capability for long-term eutrophication control is described.

2.1 Approaches to Eutrophication Modelling

As can be seen in Figure 2, there are two basic approaches to modelling the eutrophication problems at Lake Balaton. The first approach indicated by (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 control. 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 values of the various types of data involved.

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 control 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

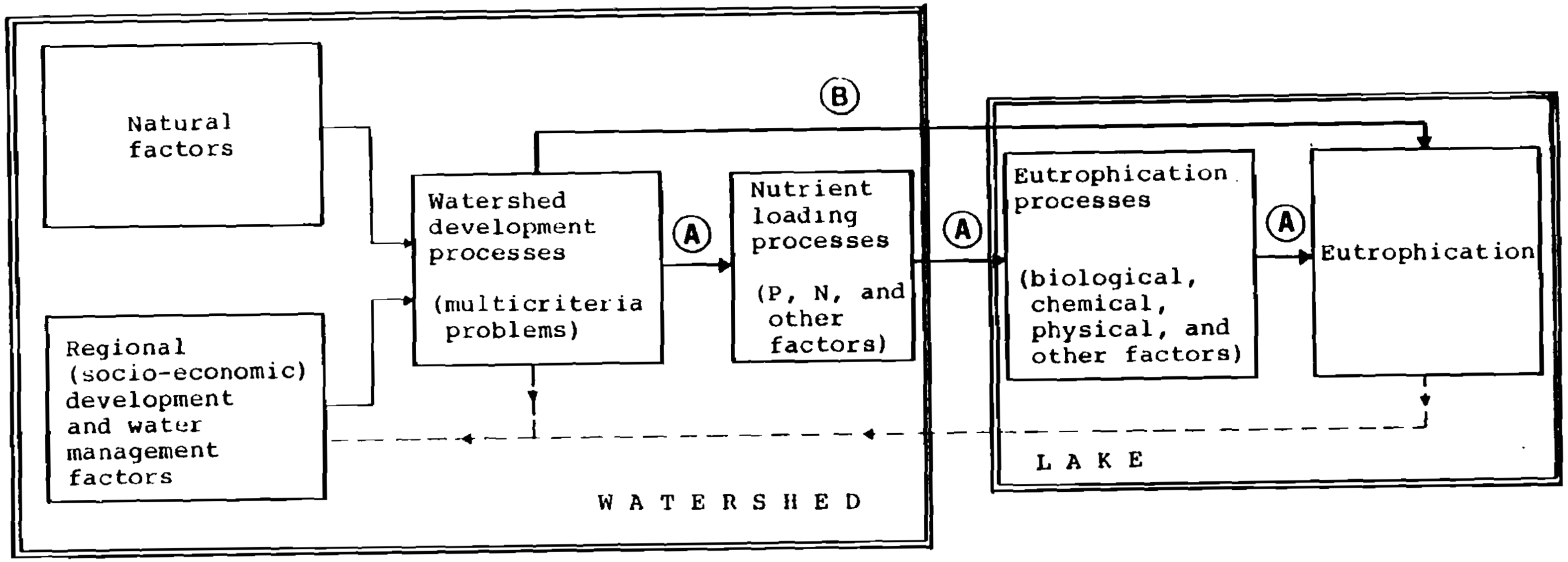

Figure 2. Approaches (A and B) to the modelling of the eutrophication problem.

relatively short time. However, considering the detailed processes involved, this approach can only be considered as a rough approximation. The integrated character does not supply information on the actual behaviour of the individual watershed and waterbody processes that may play a role.

There is a pressing socio-economic need to control the eutrophication of Lake Balaton, and both approaches are necessary to accomplish this goal. The model described in the present paper employs approach (B), while approach (A) is the object of other modelling efforts conducted by the BEM (Balaton Eutrophication Modelling) project.

2.2 Regionalization of the Balaton Basin

The area considered in this approach involves not only the lake itself, but also its watersheds. Lake Balaton and its watersheds form a unit river basin, which we propose should be called the Balaton Basin. This name can express that the lake itself is an inseparable part of the basin. As the water flows through the lake from west to east, the lake itself can be considered as a special "river". (The lake surface is approximately ten percent of the basin area.) Its reaches are the waterbodies, which are connected to the watersheds. A regionalization of the basin is proposed (Figure 1), in which four waterbodies after Baranyi (1974) and seven watersheds should be considered. The four waterbodies, which have previously been mentioned, are Keszthely Bay, and the Szigliget, Szemes and Siofok Basins. Keszthely Bay is connected to one watershed, while the others are connected to two watersheds on each side. Because of the direction of the flow in the Balaton Basin and geographical and economical factors, every waterbody and watershed plays a special role and has a special system of connections. They cannot be interchanged or replaced by one another.

Therefore, *the Balaton Basin could be considered as a multiregional, and with respect to the waterbody, also as 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 general description of the multiregional, hierarchical system of the Balaton Basin is given by

$$B = (\bigcup_{j=1}^{4} WB_j) \cup (\bigcup_{i=1}^{7} WS_i) \quad , \tag{1}$$

where B denotes the total Balaton Basin, WB_j denotes the j-th waterbody, and WS_i - with i=i(j) - denotes the i-th watershed. As a result of the hierarchical description, 1 implies

$$B_j = B_{j-1} \cup WB_j \cup (\bigcup_{i(j)} WS_i) \; , \tag{2}$$

where B_j denotes the j-th level of Balaton Basin.

The outflow of the first level is at the eastern edge of Keszthely Bay, the outflow of the fourth level and of the whole Balaton Basin is at Siofok.

2.3 Description of the Model

The formulation of the watershed development model for eutrophication control of Lake Balaton is based on the following basic assumptions:

1. the increase of eutrophication in the lake is the result of the regional water management development process in the watershed;
2. the lake and its watersheds form a unit hydrological basin, which is considered as a multiregional, hierarchical system composed of eleven watershed and waterbody units, and in which the direction of water flow should be followed and is unchangeable;

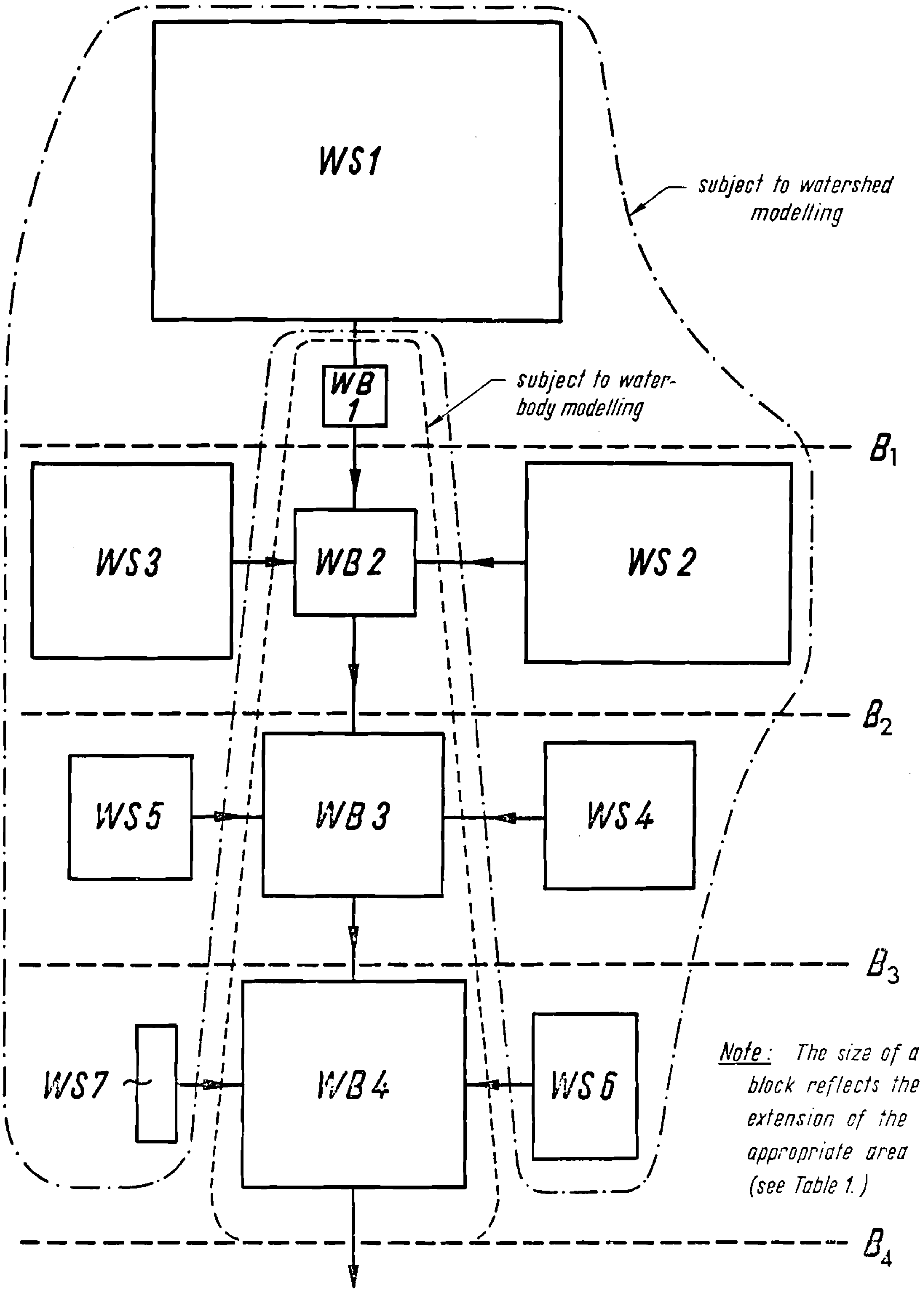

Figure 3. The multiregional, hierarchical system of the Balaton Basin.

Table 1. Some natural characteristics of 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 loading per unit water volume
		Watershed	Lake surface (Water body)	Total			
		km^2			$10^6 m^3$	%	m^2/m^3
SEPARATE	B1	2750	40	2790	80	1.4	34.4
	B2-B1	1650	140	1790	410	7.8	4.0
	B3-B2	530	190	720	600	26.4	0.9
	B4-B3	250	230	480	810	47.9	0.3
Balaton Basin		5180	600	5780	1900	10.4	2.7
CUMULATIVE	B1	2750	40	2790	80	1.4	34.4
	B2	4400	180	4580	490	3.9	9.0
	B3	4930	370	5300	1090	7.0	4.5
	B4 (total Balaton Basin	5180	600	4780	1900	10.4	2.7

3. the regional (watershed) units can be in a different stage of watershed development.

Using the above assumptions, the degree of eutrophication (ET) on B_j level can be described as follows:

$$ET(B_j,t) = ff\left[ET(B_{j-1},t) \quad ; \quad \sum_{i(j)} NL(WS_i,t) \quad ; \quad \Delta ET(WB_j,t)\right] \quad , \tag{3}$$

where $ET(B_j,t)$ and $ET(B_{j-1},t)$ denote the eutrophication on the j-th and j-1th level in (discrete) time t, $NL(WS_i,t)$ denotes the nutrient loading coming from the i-th watershed connected to WB_j in time t, and $\Delta ET(WB_j,t)$ denotes the change of eutrophication in WB_j in time t, according to the processes in the waterbody. Since we want to characterize the eutrophication as a long-range process, the time variable t is considered in years. Since the year as a time scale is in the same order of magnitude as the flow time, and since the model primarily addresses long-term phenomena, possible time delays between input and output are not taken into consideration.

According to our modelling approach, we consider the change of eutrophication caused by the processes in the waterbody as a black box, so that Equation 3 can be transformed as follows:

$$ET(B_j,t) = g\left[ET(B_{j-1},t) \quad ; \quad \sum_{i(j)} NL(WS_i,t)\right] \quad , \tag{4}$$

Using our basic hypothesis, the nutrient loading coming from the i-th watershed can be described in the following form

$$NL(WS_i,t) = k\left[F_{n\mu}(WS_i,t) \quad ; \quad F_{d\nu}(WS_i,t) \quad ; \quad F_{w\rho}(WS_i,t)\right] \tag{5}$$

if $\mu = 1,2,\ldots M \quad \nu = 1,2,\ldots N \quad \rho = 1,2,\ldots R$, where $F_{n\mu}$, $F_{d\upsilon}$ and $F_{w\rho}$ are the μ-th natural, the υ-th regional development and the ρ-th water management basic factors in the watershed influencing the nutrient loading, all in time t.

According to the watershed development approach Equation 5 can be transformed into the following form by grouping the basic factors

$$NL(WS_i,t) = h\left[D_i(F_{n\mu}, F_{d\nu}, F_{w\rho},t) \quad ; \quad H_i(F_{n\mu})\right] , \qquad (6)$$

where D_i is the stage of watershed development of the i-th watershed and H_i is the indicator of the natural character of WS_i. Here D_i, called the development figure, indicates the state of the regional and water management development with respect to their influence on nutrient loading in time t. D_i depends on a large number of different kinds of basic factors. It is assumed that H_i is constant in time; it indicates the natural role of i-th watershed in the multiregional hydrological basin system and depends on some constant natural factors.

The aim of the introduction of the development figure is to express in integrated form the level of regional and water management activities on the watershed in time t, which influence the nutrient loading coming from there. In this sense the development figure can be viewed as a multiattribute utility function (Keeney, Raiffa, 1976). Therefore, according to the multicriteria utility theory, it can be written as

$$D_i(F_{n\mu}, F_{d\nu}, F_{w\rho},t) = \sum_{k=1}^{K} W_k \cdot I_k(WS_i,t) \quad , \qquad (7)$$

where I_k is the k-th indicator or criterion index to express a watershed development criterion influencing nutrient loading in time t. It has to be composed from the basic factors F. W_k is the weighting factor of I_k. It is assumed that W_k is constant in time and $\sum_{k=1}^{K} W_k = 1$. All of the I_k criteria are dimensionless; most of them are time-dependent, partly short and partly long-term manageable; they express possible influence on nutrient loading; they are simple functions of the basic factors with an apparent meaning and their increase implies the increase of nutrient loading.

To get I_k in a dimensionless form, a transformation is applied as follows

$$I_k = \frac{I_k^1 - I_{0,k}^1}{I_{100,k}^1 - I_{0,k}^1} \cdot 100 \quad , \tag{8}$$

where $I_{0,k}^1 \geq 0$ and $I_{100,k}^1$ mean the lowest and highest possible values of I_k^1 during the watershed development process and where I_k^1 is a composition of the basic F factors in their original dimensions. The minimum value $I_{0,k}^1$ refers to the natural stage of development, to the nutrient loading without any human influence, the maximum value $I_{100,k}^1$ 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 I_k^1. The interval $\left[I_{0,k}^1, I_{100,k}^1\right]$ indicates the possible range of I_k^1 during the watershed development. In other words, it is a scale to measure the utility of the criterion. The definition of I_k in Equation 8 implies that

$$0 \leq I_k \leq 100 \quad , \tag{10}$$

where $I_k = 0$ means no influence on nutrient loading, $I_k = 100$ a maximal one.

In certain cases, the composition of F factors leads to an index I_k^*, whose increase indicates decreasing effect on nutrient loading. In these cases the transformation

$$I_k = 1 - I_k^* \tag{11}$$

is suggested, in order to match the convention that a higher index value expresses a higher effect on nutrient loading.

According to the above constraints it also follows that

$$0 \leq D_i \leq 100 \quad , \qquad (12)$$

where D_i changes in time parallel with the development of the watershed as far as it affects the nutrient loading from the watershed. This implies that the value of D_i can decrease in time if the nutrient loading decreases.

With respect to the natural character of watersheds, we assume that Equation 6 can be rewritten as

$$NL(WS_i,t) = h\left[H_i D_i\right] \quad . \qquad (13)$$

In other words, the nutrient loading is a function of the product of the natural watershed factor (in practice mainly based on the watershed area) and the development figure. The term $H_i D_i$ is thus the nutrient loading indicator of WS_i, denoted by $nl(WS_i,t)$. For the entire water basin the H_i can be normalized to fulfill the constraint $\sum_{i=1}^{7} H_i = 1$, so that H expresses the weight to be assigned to the watershed development figure of each basin due to its natural character.

Given Equation 13 and the definition Equation (7) the basic relation expressed by Equation 4 can be formulated in terms of the criteria indexes and H_i as

$$ET(B_j,t) = f\left[ET(B_{j-1},t) \quad ; \sum_{i(j)} H_i \sum_{k=1}^{k} W_k I_k(WS_i,t)\right] \qquad (14)$$

where $i = 1,2...7$, $j = 1,...4$ and $k = 1,2...K$.

This equation describes the dynamic multiregional and multicriteria form of the watershed development model for the eutrophication control in Lake Balaton.

Assuming that the numerical form of the function can be determined by regression analysis, considering historical data series, the model can be used for the simulation of different long-term watershed development policies and therefore for the simulation of their effects on eutrophication. In other words, with the help of this model different long-term eutrophication control measures or policies can be simulated and evaluated on a multicriteria basis.

Further work is oriented to the development of the physical content and numerical form of the model.

3. PRELIMINARY APPLICATION OF THE MODEL

In this chapter the preliminary application of the model is discussed for the present level of watershed development. The aim of this preliminary application is to develop the concrete, physical system of variables and to find the numerical form of connections involved in the model for one specific point in time. Based on this, the applicability of the watershed development approach is evaluated and the preliminary results are presented.

In light of the present availability of data, this first numerical application of the model is performed with watershed development data of the year 1975 and eutrophication data of the year 1976. The combination of the data from both years is acceptable in this preliminary stage, because on the one hand the values of the basic factors are changing slowly, and on the other hand, the regional and water management development should in any case, precede changes in eutrophication.

3.1 Determination of Input Variables

According to Equation 14, the following input variables should be composed and formalized: regional units, basic factors and watershed development criteria (indicator indices), the system of their weighting factors, natural watershed indicators and eutrophication factors.

3.1.1 Regional Units

The present availability of watershed data did not allow the analysis of the full set of watersheds according to Figure 3. Instead, the two watersheds adjacent to a single waterbody were combined into one watershed for this preliminary application. Thus, a system of four waterbodies and four watersheds results for the time being.

According to the previous notations, the regional units considered are the following (see Figure 1 and Figure 3):

WB 1, WB 2, WB 3, WB 4; j = 1,2,3,4.
WS 1, WS 23(WS 2 + WS 3), WS 45 (WS 4 + WS 5),
WS 67(WS 6 + WS 7); i = 1,23,45,67.

Therefore, the multiregional model in this case is composed of eight regional units.

3.1.2 Watershed Development Criteria

From the basic factors characterizing the stage of regional development of a watershed, 50 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, description and values for 1975 by regional watershed unit are listed in Table 2. Note that these presented values are only preliminary, as they were estimated from larger and different territorial units.

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

On the basis of these selected factors a system of watershed development criteria (indicator indices) was composed. The 25 criteria defined are presented in Table 3, together with a verbal description of each criterion as well as a description of its effects on nutrient loading. 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.

Table 2. Basic factors for indicating watershed development and their impact on nutrient loading (data for 1975).

I. Natural factors.

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

Table 2 (contd..)

II. Regional (socio-economic) development factors.

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

Table 2. (contd..)

III. Water management factors.

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

Table 2. (contd..)

III. Water management factors. (Continued.)

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

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 and data are available, slight changes 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 21 out of 25 criteria are manageable on the short or long term. The remaining four (J_2-J_5) express natural factors which can hardly be influenced, but they have been included because of significant effects on nutrient loadings.

The actual values of the 25 criteria for 1975 were calculated in two steps. First, the physical values of these watershed development criteria were calculated according to their algorithms listed in Table 3, using the data of the appropriate basic factors from Table 2. These physical values are presented in Table 4. This table also contains the lower and upper limits of the criteria scale, the limits being needed for the normalization of the criteria (Chapter 2.3). The development of this scaling was based both on the actual present range of the criteria and a subjective judgement of their historical and future development.

Next, as a second step, the normalized, dimensionless value of each of the criteria was calculated according to Equation 8, and using the data of Table 4. The results, the normalized values of watershed development criteria for the four watershed units, are listed in Table 5.

3.1.3 Weighting Systems

To express the different influences of the watershed development criteria on nutrient loading according to Equation 7, there is a need to develop a system of weighting factors for the selected criteria. We assume that the weighting system is constant for all regional units.

Table 3. The watershed development criteria (indicator indices).

Note: According to Eq. 8 J_k denotes the normalized, dimensionless, while J_k' denotes the original (physical) form of the k-th criterion or indicator index.

Criteria Code	Name of the criteria	Composition and description of J_k'	Unit of J_k'	Description of the effects of J_k' on nutrient loading
J_1	Population density	$J_1' = F_{13}/F_2$ $\frac{\text{number of constant population}}{\text{area of WS}}$	$\frac{\text{head}}{\text{km}^2}$	higher value indicates higher effects (more water demand, more sewage water and regional development, etc.)
J_2	quantity distribution of precipitation	$J_2' = F_7/F_6$ $\frac{\text{max. one day precipitation}}{\text{average yearly precipitation}}$	$\frac{\text{mm}}{\text{mm}}$	higher value indicates more wash out from the soil, more erosion
J_3	time distribution of precipitation	$J_3' = 1 \frac{365 - F_8}{F_8}$ $1 - \frac{\text{number of wet days}}{\text{number of dry days}}$	$\frac{\text{day}}{\text{day}}$	higher value indicates less uniform distribution of rainfall which is worse for wash out, water demand, water management control, causes more erosion, etc.
J_4	density of natural water courses	$J_4' = F_9/F_2$ $\frac{\text{length of water courses}}{\text{area of WS}}$	$\frac{\text{m}}{\text{km}^2}$	higher value indicates more erosion, more possibilities to collect and transfer both point and non-point sources
J_5	natural energy potential of WS	$J_5' = F_3/F_4$ average slope of the surface of WS	o/oo	higher value indicates more erosion, more runoff, shorter collection time, etc.

Table 3 (contd..)

Criteria Code	Name of the criteria	Composition and description of J'_k	Unit of J'_k	Description of the effects of J'_k on nutrient loading
J_6	population ratio involved in industry	$J'_6 = F_{14}/F_{13}$ $\frac{\text{population in industry}}{\text{constant population}}$	$\frac{\text{head}}{\text{head}}$	higher value indicates greater importance of industry, therefore more ecological problems, more water demand, more sewage water, more demand for recreation, etc.
J_7	population ratio involved in agriculture	$J'_7 = F_{15}/F_{13}$ $\frac{\text{population in agriculture}}{\text{constant population}}$	$\frac{\text{head}}{\text{head}}$	higher value indicates greater importance of agriculture, more non-point sources, fertilizer and chemical use, etc.
J_8	visitor (tourist) loading	$J'_8 = F_{16}/F_{13}$ $\frac{\text{visitor's day}}{\text{constant population}}$	$\frac{\text{visitor day}}{\text{head}}$	higher value indicates more NL to the WS and the WB, more need for infrastructure, more non-constant population, etc.
J_9	density of possible point sources	$J'_9 = (F_{17} + F_{18} + F_{19})/F_2$ (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.
J_{10}	ratio of arable and forest land use	$J'_{10} = F_{20}/F_{22}$ arable/forest land	$\frac{\text{km}^2}{\text{km}^2}$	higher value indicates more non-point nutrient loadings more erosion, more run-off, etc.
J_{11}	urbanized part of the WS	$J'_{11} = F_{23}/F_2$ $\frac{\text{urbanized area}}{\text{area of WS}}$	$\frac{\text{km}^2}{\text{km}^2}$	higher value indicates more sewage water, more infiltration to the soil, more urban runoff, shorter collection time, etc.

Table 3 (contd..)

Criteria Code	Name of the Criteria	Composition and description of J'_k	Unit of J'_k	Description of the effects of J'_k on nutrient loading
J_{12}	ratio of vineyards and orchards	$J'_{12} = F_{21}/F_{20}$ $\frac{\text{area of vineyards and orch.}}{\text{arable land}}$	$\frac{km^2}{km^2}$	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.
J_{13}	fertilizer use	$J'_{13} = F_{25}/F_{20}$ $\frac{\text{total amount of used fertilizer}}{\text{arable land}}$	kg/year/km^2	higher value indicates more nutrient loadings
J_{14}	density of animal population	$J'_{14} = F_{24}/F_2$ $\frac{\text{number of standard animals}}{\text{area of WS}}$	$\frac{\text{head}}{km^2}$	higher value indicates more NL (more sewage water, more pasture land use, more water demand, etc.)
J_{15}	density of motoring roads	$J'_{15} = F_{26}/F_2$ $\frac{\text{length of motoring roads}}{\text{area of WS}}$	$\frac{m}{km^2}$	higher value indicates more regional development, more traffic, more tourists, more non-point traffic and agricultural sources
J_{16}	use of potential water resources	$J'_{16} = F_{28}/F_{11}$ $\frac{\text{total actual water use}}{\text{potential water resources}}$	$\frac{m^3}{m^3}$	higher value indicates more use of natural resources, more regional development, more water management activities

Table 3 (contd..)

Criteria Code	Name of the Criteria	Composition and description of J'_k	Unit of J'_k	Description of the effects of the J'_k on nutrient loading
J_{17}	used water infiltrated into the soil	$J'_{17} = [F_{28}-(F_{34}+F_{35}+F_{41})]/F_2$ 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.
J_{18}	ratio of untreated sewage discharge	$J'_{18} = 1 - F_{42}/F_{41}$ $1-\frac{\text{treated effluent discharge}}{\text{total effluent discharge}}$	$\frac{m^3}{m^3}$	higher value indicates more NL.
J_{19}	ratio of unregulated runoff	$J'_{19} = 1 - F_{43}/F_{11}$ $1-\frac{\text{existing storage capacity}}{\text{potential water resources}}$	year	higher value indicates more nutrient loading, because less water can be stored before getting to Balaton
J_{20}	ratio of population supplied with drinking water works	$J'_{20} = F_{45}/F_{13}$ $\frac{\text{population supplied with d.w.w.}}{\text{number of constant population}}$	$\frac{\text{head}}{\text{head}}$	higher value indicates greater development, more water demand, more sewage effluents, etc.
J_{21}	ratio of population supplied with sewage works	$J'_{21} = F_{46}/F_{13}$ $\frac{\text{population supp. with s.w.}}{\text{number of constant population}}$	$\frac{\text{head}}{\text{head}}$	higher value indicates more sewage water facilities, than more nutrient loading.

Table 3 (contd..)

Criteria Code	Name of the Criteria	Composition and description of J'_k	Unit of J'_k	Description of the effects of the J'_k on nutrient loading
J_{22}	ratio of irrigation and drainage	$J'_{22} = (F_{47}+F_{48})/F_{20}$ $\frac{\text{area of irrigation and drainage}}{\text{arable land}}$	$\frac{km^2}{km^2}$	higher value indicates higher cultivation, more wash out possibilities, etc.
J_{23}	erosion potential	$J'_{23} = F_5 \cdot F_7$ slope of arable land x max. one day precipitation	% x mm	higher value indicates more erosion, more wash out from the arable land, thus more NL
J_{24}	density of all water works in the WS	$J'_{24} = F_{50}/F_2$ $\frac{\text{number of water rights}}{\text{area of WS}}$	$\frac{\text{works}}{km^2}$	higher value indicates more regional development, more possible sources of nutrient loading
J_{25}	beach length indicator for direct recreation loading	$J'_{25} = 100 - F_{12}/F_{49}$	$\frac{10^6 m^3}{km}$	higher value indicates more nutrient loading (more visitors, more recreation loading of water)

Table 4. The physical values of watershed development criteria in 1975 and their scales.

Criteria Code	Unit	Physical values of J'_k				Scale with limits	
		WS1	WS23	WS45	WS67	lower, $J'_{0.k}$	upper $J'_{100.k}$
J_1	head/km^2	65	61	151	240	20	300
J_2	1	0.09	0.07	0.08	0.08	0.03	0.15
J_3	1	0.75	0.70	0.68	0.67	0	1
J_4	m/km^2	513	427	400	416	300	600
J_5	%o	2	6	12	24	0	30
J_6	1	0.13	0.16	0.06	0.13	0	0.4
J_7	1	0.14	0.20	0.08	0.05	0	0.4
J_8	visitor day/head	7	9	19	33	0	50
J_9	$\frac{\text{sources}}{100\ \text{km}^2}$	12	12	9	21	0	40
J_{10}	1	2.4	3.5	1.2	1.1	0.5	5
J_{11}	1	0.06	0.06	0.08	0.028	0	0.4

Table 4 (contd..)

Criteria Code	Unit	Physical values of J'_k				Scale with limits	
		WS1	WS23	WS45	WS67	lower, $J'_{0.k}$	upper $J'_{100.k}$
J_{12}	1	9	10	22	31	0	50
J_{13}	kg/ha/yr	217	202	280	333	0	500
J_{14}	head/km^2	25	10	19	16	0	40
J_{15}	m/km^2	356	133	207	400	0	500
J_{16}	1	0.04	0.12	0.20	0.95	0	1
J_{17}	m^3/yr, km^2	2181	3030	1887	4000	0	5000
J_{18}	1	0.50	0.87	0.90	0.92	0	1
J_{19}	year	0.99	0.96	0.96	0.97	0	1
J_{20}	1	0.41	0.59	0.70	0.75	0	1
J_{21}	1	0.17	0.29	0.38	0.42	0	1
J_{22}	1	0.10	0.09	0.01	0.23	0	1
J_{23}	% mm	7.70	3.64	4.08	5.30	2	10
J_{24}	works/km^2	0.2	0.7	1.4	1.4	0	2
J_{25}	10^{6}m^3/km	96	73	70	68	20	99

Table 5. Normalized values of watershed development criteria.

Criteria Code	Normalized values of J_k			
	WS1	WS23	WS45	WS67
J_1	16	15	47	79
J_2	50	33	42	42
J_3	75	70	68	67
J_4	71	42	33	39
J_5	7	20	40	80
J_6	33	40	15	33
J_7	35	50	20	12
J_8	14	18	38	66
J_9	30	30	22	52
J_{10}	42	67	16	13
J_{11}	15	15	20	70
J_{12}	18	20	44	62
J_{13}	43	40	56	67
J_{14}	63	25	48	40
J_{15}	71	27	41	80
J_{16}	4	12	20	95
J_{17}	44	61	38	80
J_{18}	50	87	90	92
J_{19}	99	96	96	97
J_{20}	41	59	70	75
J_{21}	17	29	38	42
J_{22}	20	18	20	46
J_{23}	71	20	26	41
J_{24}	10	35	70	70
J_{25}	96	67	63	61

Because of the lack of exact and structural knowledge on this type of physical weighting, five experts of the BEM team were interviewed, resulting in five separate weighting systems on the basis of the individuals' practical knowledge of the Balaton Basin. The five weighting systems, indicated by SW_{α}, $\alpha = 1,5$, are presented in Table 6. Furthermore, SW_6 was constructed with the help of mathematical statistics, basically by combining the weighting systems that maximized the correlation between the development figure and each of the eutrophication indices (see Chapter 3.15). System 7 in this table indicates the uniform weighting as a basis for comparison.

The use of the alternative weighting systems in the present stage of development of the investigation allows for the evaluation of the sensitivity to the weighting system. This is important since the weighting also will influence the conclusions for control derived from the model. It also makes clear that the model represents a means of combining, in a formalized and explicit way, the subjective judgement of experts in the field.

3.1.4 Watershed Indicators

The H_i indicators used to express the role of the watershed itself in the multiregional hydrological system, are calculated as the ratio of the individual watershed areas to the total. This approximate approach is considered acceptable for this preliminary application, since the site of the watershed is of dominant influence on the absolute value of nutrient loading. Thus, according to the data of Table 1, these indicators are as follows:

	WS 1	WS 23	WS 45	WS 67
H_i	0,53	0,32	0,10	0,05

3.1.5 Eutrophication Indices

In accordance with the suggestions of the biological experts of the BEM team in the Biological Research Institute, Tihany, the phytoplankton biomass was selected to characterize the eutrophication in the watershed development model. The

Table 6. Alternative systems of weighting factors.

Criteria Code	Alternative weighting systems, SW_x x = 1,...7						
	1	2	3	4	5	6	7
	Value of weighting factors (W_k)						
1	0.06	0.06	0.049	0.07	0.06	0.04	0.04
2	0.04	0.02	0.049	0.05	0.04	0.05	0.04
3	0.04	0.01	0.028	0.05	0.04	0.04	0.04
4	0.03	0.04	0.014	0.04	0.04	0.05	0.04
5	0.04	0.05	0.014	0.07	0.06	0.01	0.04
6	0.02	0.02	0.056	0.02	0.03	0.02	0.04
7	0.01	0.04	0.035	0.02	0.02	0.02	0.04
8	0.06	0.05	0.063	0.05	0.04	0.06	0.04
9	0.04	0.06	0.049	0.06	0.06	0.04	0.04
10	0.05	0.04	0.021	0.05	0.05	0.01	0.04
11	0.05	0.03	0.063	0.02	0.03	0.04	0.04
12	0.05	0.05	0.042	0.05	0.04	0.06	0.04
13	0.08	0.06	0.042	0.08	0.06	0.05	0.04
14	0.07	0.06	0.042	0.03	0.02	0.06	0.04
15	0.01	0.01	0.021	0.01	0.02	0.06	0.04
16	0.03	0.03	0.021	0.03	0.03	0.01	0.04
17	0.03	0.02	0.014	0.02	0.03	0.03	0.04
18	0.06	0.05	0.070	0.06	0.06	0.03	0.04
19	0.07	0.04	0.042	0.05	0.05	0.04	0.04
20	0.01	0.04	0.028	0.02	0.03	0.04	0.04
21	0.01	0.05	0.063	0.03	0.05	0.04	0.04
22	0.02	0.02	0.014	0.02	0.02	0.05	0.04
23	0.06	0.05	0.042	0.05	0.03	0.06	0.04
24	0.01	0.04	0.055	0.01	0.03	0.04	0.04
25	0.01	0.06	0.063	0.04	0.05	0.05	0.04
Total	1.00	1.00	1.000	1.00	1.00	1.00	1.00

selection had two criteria: 1) the capability of characterizing the eutrophication in integrated form; 2) the availability of historical data for approximately the last 20-25 years. The phytoplankton biomass as an indicator meets both criteria.

For the characterization of the eutrophication by phytoplankton biomass, the data listed in Table 7, were used (Vörös 1979, and personal communication). These are the results of monthly measurements on phytoplankton biomass. The corresponding sampling points are shown in Figure 4, indicating that all of the four considered waterbodies were sampled in at least one place (see Figure 1 also).

For finding the best eutrophication indicator, three alternative eutrophication indices (ET_β, where $\beta = 1,2,3$) were developed from the data presented in Table 7, as follows:

ET 1 - yearly average
ET 2 - summer maximum
ET 3 - yearly maximum

of phytoplankton biomass. These indicator indices first were calculated for the sampling places, representing the waterbodies. Then, inter- and extrapolating these figures exponentially along the longitudinal section of Lake Balaton, the values of the eutrophication indices ($ET_{\beta j}$) for the outflow points of the waterbodies, e.g. for the four basin levels, were estimated. The complete list of these eutrophication indices are presented in Table 8.

The alternative indices offer another possibility for sensitivity analysis. However, in the subsequent approach, the values from the water basin boundaries have been used, since they reflect in some way the effects of internal processes on the waterbody (considered to be a black box in our approach).

3.2 Indication of Nutrient Loading by Watershed Development

Using the normalized values of watershed development criteria (Table 5), and the different weighting systems (Table 6),

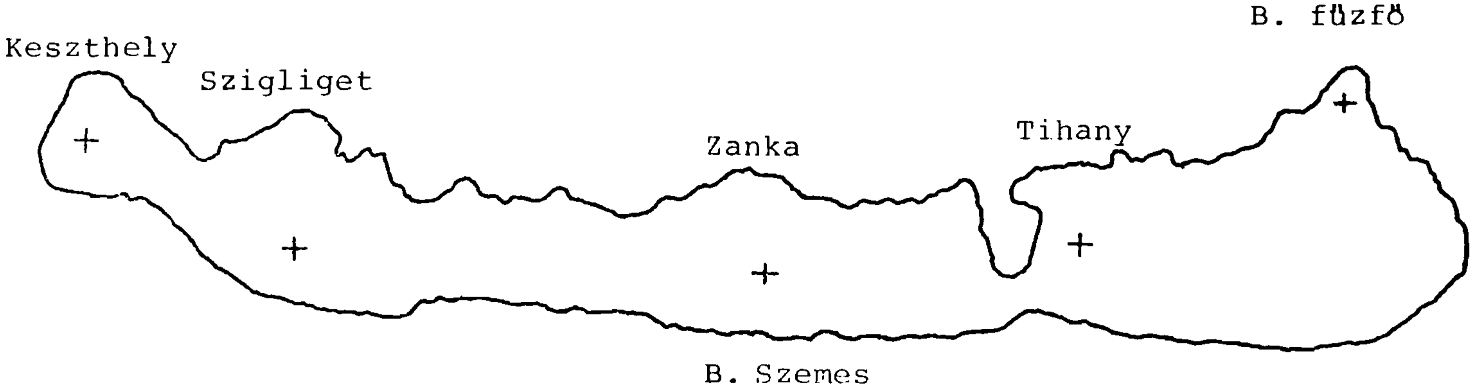

Figure 4. Primary production and biomass measurement sites.

Table 7. Observed data of phytoplankton biomass in Lake Balaton in 1976 (after Lajos Vörös).

Sampling places	Months							
	IV	V	VII	VIII	IX	X	XI	XII
	mg/l net weight							
Keszthely Bay, WB1	12.15	3.55	10.34	11.07	11.38	7.51	2.30	3.38
Szigliget Basin, WB2	7.18	1.77	0.92	5.92	6.82	5.15	1.91	2.69
Szemes-Zanka, WB3	5.88	1.63	1.81	1.88	1.77	1.06	0.83	1.97
Tihany, WB4	5.27	1.63	1.20	2.72	1.93	0.72	0.35	1.12
Füzfü, WB4	6.88	1.97	1.33	2.39	2.00	0.63	0.66	1.29

Table 8. The list of eutrophication indices.

Places	Phytoplankton biomass indices (B)		
	Yearly average ET1	summer max. ET2	yearly max. ET3
	mg/l net weight		
Keszthely Bay, WB1	7.7	11.1	12.2
basin level, B1	6.0	8.5	11.2
Szigliget Basin, WB2	4.1	5.9	7.2
basin level, B2	3.4	5.0	7.9
Szemes-Zanka, WB3	2.0	1.9	5.9
basin level, B3	2.1	2.8	5.4
Tihany, WB4	1.9	2.7	5.3
Füzfo, WB4	2.1	2.4	6.9
basin level, B4	1.5	2.3	4.7

the multicriteria development figures of the different weighting systems ($D_{\alpha i}$) for each of the four watershed units were calculated according to Equation 7. These development figures are presented in Table 9. They measure the "utility" of the watershed for nutrient loading resulting from the level of development in 1975.

Based on the multicriteria development figures, the nutrient loading indicators (nl_{ix}) were computed according to Equation 13, using the watershed indicators (H_i) listed in Section 3.14. They are listed in Table 10. These indicators express the relative contribution to the nutrient loading by the watershed within the multiregional basin system at the established level of development.

Because of the fixed time in the present preliminary application, both the development figures and the nutrient loading indicators basically can only be used for the relative comparison among the watersheds and for the sensitivity analysis of the weighting system. They were considered also as input data in the first step towards the numerical formulation of the basic equation of the watershed development model. Later these data will be used as one point in time in the forthcoming dynamic investigations.

3.3 Numerical Approach to the Basic Relationship

In view of the fixed time level in this first application a numerical analysis of the basic relationship of Equation 14 was aimed only at the investigation whether the assumed relation among the variables ET, D and H exists or not. To achieve this goal a multiple correlation analysis (Kendall and Stuart, 1966) was done using the previously presented input data.

According to Equation 14, the eutrophication of the outflow section of a given waterbody depends on the development figure and the natural character of the adjacent watershed, and furthermore, on the eutrophication of the outflow section of the previous waterbody. Therefore, considering $i = j$ in the present application, let us denote by $ET_{\beta j}$ the β-th type eutrophication index at the outflow section of the j-th waterbody, e.g. at the j-th basin level, by $D_{\alpha j}$ the development figure of the watershed

Table 9. Development figures (D_i) Unit %.

Watersheds	Systems of weighting (x)						
	SW1	SW2	SW3	SW4	SW5	SW6	SW7
WS1	42.8	47.5	41.4	43.4	41.9	42.7	42.0
WS23	38.6	39.1	40.2	40.7	41.5	38.4	39.8
WS45	43.7	44.5	45.6	45.4	45.1	45.4	43.1
WS67	59.8	59.7	60.3	61.6	61.3	62.4	60.0

Table 10. Nutrient loading indicators (nl_i).

Watersheds	Systems of weighting (x)						
	SW1	SW2	SW3	SW4	SW5	SW6	SW7
WS1	22.7	22.0	21.9	23.0	22.2	22.6	22.2
WS23	12.3	12.5	12.9	13.0	13.3	12.3	12.7
WS45	4.4	4.5	4.6	4.5	4.5	4.5	4.3
WS67	3.0	3.0	3.0	3.1	3.1	3.1	3.0

connected to the j-th waterbody calculated under the α-th weighting system and by H_j, the value of the watershed indicator connected to the j-th waterbody. Obviously, according to the character of the multiregional system, it is assumed that $ET_{\beta o} = 0$. For fixed β and α, let the numbers a_1, b_2, and c_3 be determined by

$$\sum_{j=1}^{4} \left[ET_{\beta j} - (a_1 ET_{\beta, j-1} + b_2 D_{\alpha j} + c_3 H_j) \right]^2 = \text{minimum} \ . \quad (15)$$

In order to reduce the dominant effect of the natural watershed indicator (essentially the watershed area) a transformation is applied according to

$$ET'_{\beta j} = \begin{cases} ET_{\beta j} - C_3 H_j \quad ; & \text{if } j = 1,\ldots 4 \quad ; \\ 0 \text{ if } j = 0 \quad ; & \end{cases} \quad (16)$$

Now define

$$X_{\beta\alpha j} = a\,ET_{\beta,j-1} + b\ D_{\alpha j} \quad (17)$$

then equation (15) can be restated as

$$\sum_{j=1}^{4} \left[ET'_{\beta j} - X_{\beta\alpha j} \right]^2 = \text{minimum} \quad . \quad (18)$$

The coefficients a, b and c can be found by partial differentiation, equation to zero and solving for the resulting system of linear equations.

For fixed β and α, let us denote by σ the multiple correlation coefficient between $ET'_{\beta j}$ on the one hand, and on the other hand $ET'_{\beta,j-1}$ and $D_{\alpha j}$; then σ is the (ordinary) correlation coefficient of $ET'_{\beta j}$ and $X_{\beta\alpha j}$ (see Equations 17-18).

For fixed eutrophication indices the effectiveness of the various weighting systems was characterized by the correlation coefficients σ, which reflect the connection of $ET_{\beta j}$ with $ET_{\beta,j-1}$ and $D_{\alpha j}$, cleaned of the effect of H_j.

The values of the correlation coefficient σ calculated according to the described method, are listed in Table 11. For the calculation, the eutrophication indices of the basin levels listed in Table 8, and the development figures listed in Table 9, were used.

As shown by Table 11, the results of this first numerical investigation indicate the very strong, practical functional connection among the basic variables of this approach.

4. EVALUATION OF RESULTS

In this chapter, first the results of the preliminary application of the model are discussed and evaluated, then the main conclusions of the modelling work are presented.

4.1 Discussion of Results

On the basis of the preliminary application of the model, the following results have been obtained.

1. Based on the correlation analysis performed for the present (1975-76) level of watershed development, it can be stated that the basic assumption of the multiregional and multicriteria dynamic watershed development model hypothesizing a close connection between eutrophication and human watershed development, is underlined by the first numerical results. It also means that approach (B) to eutrophication modelling (see Chapter 2.1) is feasible. Furthermore, it justifies the necessity of regionalization of the Balaton Basin according to the developed solution.
2. A high correlation was found between eutrophication and development figure. The correlation was highest if the algal summer maximum biomass was used as a measure of eutrophication (between 0.94 and 0.99 depending on the weighting system). Also a high correlation was found with the yearly average (0.90-0.97). The relation between development figure and

Table 11. Correlation coefficient (σ)

Eutrophication indices (β)	Systems of weighting (x)						
	SW1 x=1	SW2 x=2	SW3 x=3	SW4 x=4	SW5 x=5	SW6 x=6	SW7 x=7
yearly average $\beta = 1$	0.901	0.947	0.970	0.947	0.951	0.951	0.934
summer maximum $\beta = 2$	0.941	0.982	0.990	0.977	0.979	0.977	0.965
yearly maximum $\beta = 3$	0.788	0.826	0.824	0.807	0.775	0.848	0.783

yearly maximum is less pronounced, although they are still correlated.

A comparison of the results for the 7 weighting systems used allows for a preliminary analysis of the sensitivity of the method to the weighting. From Table 11 it can be seen that correlation is strong irrespective of the weighting system. However, on the whole, the uniform weighting provides slightly lower correlations, which suggests the need for weighting. Furthermore, it should be realized that, with one single point in time, a rigid sensitivity test is not possible.

Table 9 indicates that the differences in development, according to the weighting systems, are not very large among the watersheds. Relatively large differences would have been needed to detect the sensitivity to the weighting of the different indices. Consequently, the choice of the most suitable weighting system and eutrophication index can be performed only later when time-series are available. Nevertheless, the above preliminary results can not only provide guidelines for the further analysis of eutrophication control, but can also help to direct a concentrated course of action to the most important measures.

3. Evaluating the present level of development of the watersheds, as expressed by the development figures in Table 9, it can be stated that watershed 67 is at the highest level, about 60% of watershed development, as far as it effects nutrient loading. The watershed with the next highest level of watershed development is WS 45, with about 45%, then WS 1 with about 42-45%, and finally WS 23 with about 40%.

   The last two watersheds can be considered virtually on the same level of development, whereas WS 45 is about 10% more developed and WS 67 is about 50% more developed. This ranking corresponds with the general opinion of the water management and regional development experts.

But with the help of the multicriteria development figure, we can also measure in numerical terms the differences among the regional units.

4. Based on the development figures, the nutrient loading indicators express the normalized nutrient loading coming from the watersheds as part of the whole multiregional basin system. Therefore, the data of Table 10 show that if the nutrient loading for WS 67 is 3 units, then it is 4.5 units, 12.5-13.0 units and 22.0-23.0 units for WS 45, WS 23 and WS 1, respectively. It means that the ratio of the nutrient loading among the four watersheds connnected to the waterbodies can be estimated as 7.5: 4.3: 1.5: 1. The differences with the ratio of the natural watershed area, which is 11: 6.6: 2.1: 1 express the effect of the watershed development on nutrient loading of the lake. At about the same level of development in WS 1 and WS 23 (40%) different estimates of the contribution to the lake's pollution occur (50% from WS 1; 30% from WS 23). Similarly, the role of the highest developed regions (WS 45 and especially WS 67) in the whole Balaton system is smaller because of the natural location of these areas in the multiregional hierarchical system ("downstream").

These preliminary results, especially the ratio of nutrient loading, can be used to estimate the actual amount of nutrient loading for the whole lake if a value for just one of the four waterbodies or watersheds is available. Furthermore, these results underline the weight of the natural hydrological character in the system, and provide direction to where we have to concentrate the eutrophication control efforts so as to use the available economic resources in a most effective way.

It should be stressed that the methods for calculation of the watershed indicator (H_i) and of the nutrient loading indicator (nl_i) from the development figure are preliminary and should be further developed, having once obtained more historical data.

5. Considering the composition of the multicriteria development figure, the selected system of criteria seems appropriate for characterizing the long-term watershed development as indicated by the impact on nutrient loading.

4.2 Conclusions and Recommendations

1. The outlined multiregional and multicriteria dynamic watershed development approach can be considered as an essential element of the decision analysis in the long-range control of the eutrophication in Lake Balaton. Therefore, it is recommended that a numerical and detailed form of this model be developed, under consideration of the preliminary results of the present application.
2. It is recommended that the historical data needed for the evaluation of the time patterns of development figure and eutrophication indices be collected, on the basis of the finalized system of criteria. This should be done for the seven watershed units separately. In possession of these data, one should apply the present methodology for the analysis of the time series, and in general, of the watershed development process.
3. Using the proposed dynamic multiregional and multicriteria watershed development model, different long-term watershed development policies and their effects on eutrophication can be simulated. These can serve as a basis for decisions on control actions.
4. Based on the numerical results of the present preliminary application, one should, in the case of limited monetary resources, concentrate the control actions as soon as possible to watersheds 1 and 23. By doing this, the most effective application of the economic resources available for eutrophication control can be achieved.

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