MATHEMATICAL MODELS FOR MANAGEMENT OF EUTROPHIED LAKES

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Abstract
Anthropogenic eutrophication is a global process of aquatic ecosystem degradation that takes place for the most lakes in the Europe and other developed continents. It creates a lot of ecological and economical problems for lakes and their watershed. Integrated approach to rehabilitation of eutrophied aquatic ecosystems has been proposed. It consists of simultaneous application of two groups of protective measures. First one is a reducing of nutrient load from catchment area. Second one is withdrawal of the nutrient from water body directly and a limitation of aquatic ecosystem productivity. The proposed approach requires to choice optimal set of de-eutrophication technologies taking into account their costs. It is complex problem that has been solved on the basis of simulation and expert assessment methods. Integrated mathematical model (STOOKS3-model) has been developed and used as a base of simulation method. STOOKS3-model is a set of interacted mathematical models which includes model of nutrient load from catchment area (Z-model); model of water body water quality (C-model) for ; Model of eco-technologies and their cost assessment (U/E-model). Z-model is used for estimation of structure and value of nutrient load on water body. C-model destined to evaluation of desired level of nutrient load and assessment of ecological efficiency of eco-technologies. U/E-model is intended to selecting of optimal sets of de-eutrophication technologies. Proposed approach has been successfully tested on the six pilot lakes in Northern Europe.

Introduction

Eutrophication of water bodies is global worldwide process of aquatic ecosystem degradation. At present time the trophic level of the most European lakes is very high. According to classification of water bodies (1) trophic levels could be describes as an intervening ones between oligotrophic and eutrophic levels for Northern Europe, between mezotrophic and polytrophic levels for Central Europe and between eutrophic and gypertrophic levels for Southern Europe. The problem extends to coastal seas and rivers. Main indicator of eutrophication is a huge biomass of algae: blue-green in summer and autumn, diatomic and green in spring. During calm weather several algae bloom-forming species can raise to the water surface to form scum. This may look like paint, jelly or flock. Scum may be blue-green, greyish-green, greenish-brown, or even reddish-brown. This phenomenon is known as water bloom.

The main reason of eutrophication is excess of nutrients in the water of lakes. The nutrients enter in the water body from the watershed, and by nutrient recycling from the bottom deposits. Research of the influence of phosphorus on lakes has shown that it is an important factor for lake eutrophication, and nitrogen is the second one for highly eutrophied lakes (2). Simultaneously, the following hydrological features of a lake play a very important role in the lake eutrophication process: inflow and outflow of rivers, lake's depth and surface area and their ratio, configuration of lake, transparency and suspended solid concentration, etc. Climatic conditions are very important, too: air and water temperature, precipitation and evaporation, wind, etc.

The purpose of all remediation techniques and rehabilitation measures is to prevent abundant autochthonic biomass accumulation and correspondingly following self-pollution by means of decreasing primary production and increasing decomposition (respiration) in order to regain ecological balance in water ecosystem. The goal can be reached by means of nutrient content reduction, illumination decrease, water flow turbidity increase and changing the relationship between production and respiration. Every abovementioned action has its own parameters of regulation and control techniques, which can be exerted as well directly on given water bodies, as on associated drainage basins. The principal methodological problem is to develop a strategy for selecting the most efficient technology, or a set of technologies, for each group of water bodies: lakes, rivers, reservoirs, coastal zones of seas. This strategy must be based on quantitative evaluations and forecast of the effectiveness of different actions in reference to the general indicators of eutrophication and related to water quality indices, and also be applicable to various kinds of water bodies.

Methods

Integrated approach to rehabilitation of eutrophied aquatic ecosystems consists in simultaneous application of two groups of protective measures:

- reducing nutrients and other polluting matters input from drainage basins;
- extracting nutrients directly from the water body and restricting the productivity of the aquatic ecosystem.

The first group of measures, directed on reducing the input of nutrients from the basin, will be denoted as Um-technologies, and the second one, directed on the nutrient input from inside the water body and decreasing the biomass of phyto-plankton, as Un-technologies or the management (3). The first path is traditional, but on advanced stages of eutrophication it quite often turns out to be inefficient compared to applied efforts. This happens because internal processes able to support eutrophication take the key role, although external load was drastically reduced.

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In this manner, there are strong grounds for believing that the most efficient approach can be reached as a sum of both technology groups:

$$Uert = [Um + Un], \tag{2.1}$$

where Uert is an ecological rehabilitation technology for a eutrophied water body. It should be noted that a selection of such management technology should be combined with minimal costs:

$$S(Um, Un) \rightarrow \min, \tag{2.2}$$

where S is a technology application cost. Water quality indices shall not exceed permissible standard:

$$Cj < Cjs(U, Zj), \tag{2.3}$$

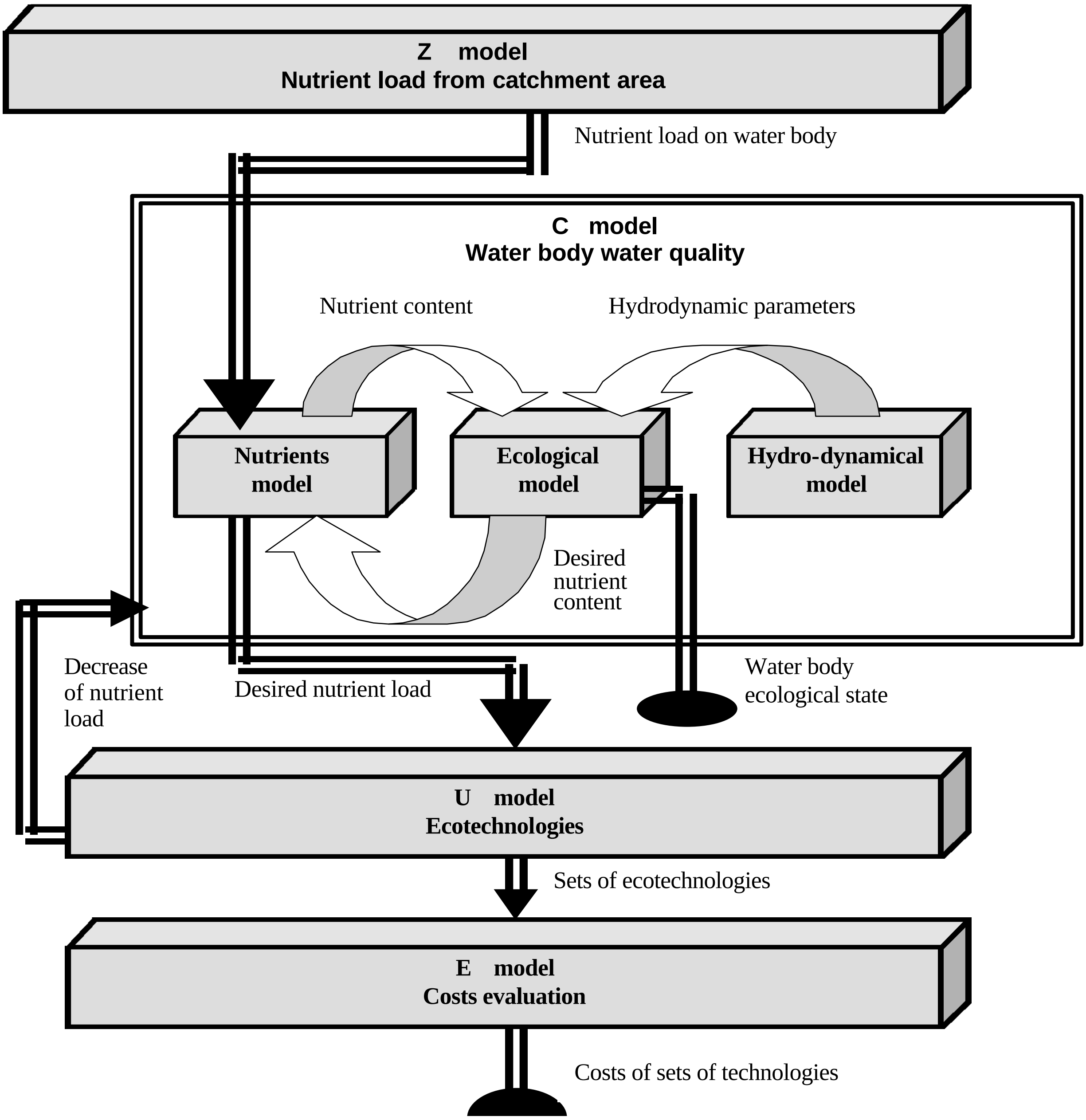
where Cj is concentration; j is water quality index; Cjs is water quality standard value; U is a type of management, and Zj is pollution load.

The proposed approach is intended to be a tool for decision-making. It has to allow creating sets of technologies for de-eutrophication of lakes and reservoirs and estimating their costs and effectiveness. Such a complex problem may be solved based on simulation and expert assessment methods, and it needs an integrated mathematical model as scientific background. In this case, the STOCKS 3 integrated model has been developed. This model is presented as a system of interacted mathematical models: model of nutrient load from the catchment area (Z-model); model of water quality in the water body (C-model); model of eco-technologies (U-model); model for cost assessment of different sets of eco-technologies (E-model). The model links together a set of parameters such as characteristics of the catchment area, nutrient load on water body, content of nutrients, and main water quality indices of the water body (biomass of phytoplankton, BOD, and dissolved oxygen content), parameters of eco-technologies, costs of eco-technologies.. Figure 1 represents the general structure of the model.

Z-model - nutrient load. Anthropogenic eutrophication is a consequence of nutrient input from anthropogenic sources. Therefore, for developing de-eutrophication technologies of water body, it is important to estimate the structure and intensity of natural and anthropogenic nutrient sources. This knowledge enables: to define typological level of water body, that is ecological state, which is defined by natural sources of nutrient load only; to define a way to decrease nutrient load on water bodies by implementing eco-technologies. Because the direct method of measuring all nutrient flows is practically an insoluble task, mathematical modeling is used. The goal of using Z-model is to define the structure of the nutrient load on a water body.

C-model - water quality. The preferred strategy of de-eutrophication is chosen based on modelling of he effects of different management actions on the water body. The water quality model has to allow solving the following series of tasks: to estimate decrease of nutrient load needed to achieve previous trophic levels; to determine typological trophic level; to evaluate ecological results from im-

Figure 1: Structure of STOOKS3 integrated model



plementing different sets of eco-technologies. The water quality model consists of three model blocks: hydrodynamic, nutrient and ecological one. The hydrodynamic features of the modeled water bodies were described using box model. The nutrient model describes nutrient content depending on nutrient load, hydrological characteristics of the water body, and morphometry. The ecological model block describes the water quality taking into account internal and external water exchange in a lake. The major equations of the model are the equations for biomass of phytoplankton, BOD, and dissolved oxygen content, which are based on balance of production and decomposition processes in aquatic ecosystem under the conditions of nutrients limiting. Generally, three main subsystems of the aquatic ecosystem are considered: subsystem of plankton, subsystem of benthos, and subsystem of higher aquatic plants.

U/E-model - technology and costs. The mathematical model of substance material flows and estimation of optimum balance is the first step for creating the mathematical model for optimizing nitrogen and phosphorus load reduction. The reduction of nutrient load, namely nitrogen and phosphorus, is needed to improve the trophic status and to rehabilitate lakes. The level of nutrient load reduction will depend on implemented technology and financial limitations. The optimal technology was chosen based on the results mathematical modeling (U-model), and the minimal costs of solutions for the implemented technology were defined (E-model).

The ecological state of water bodies is defined by two groups of interacting factors: natural and anthropogenic. Natural factors, in the first place natural sources of nutrient load and sediment storage, cause natural eutrophication process, which takes a long time (thousands of years). Anthropogenic pressure changes the trend of development and speeds up the eutrophication process substantially. *The typological trophic level* has been interpreted as a level defined by natural factors only. For calculating typological trophic levels, it is necessary: to determine the level of natural nutrient load using Z-model; to calculate values of main water quality indices using C-model; to determine the trophic level of water body according to classification of water bodies (1).

The role of bottom deposits requires a special discussion. Accumulation of bottom deposits and their content result from the influence of both natural and anthropogenic factors. Moreover, at present time effective technologies exist for sediment dredging. Therefore, the question sounds: "Does the influence of bottom deposits belong to the natural or the anthropogenic part of nutrient load?" Taking into account that there is no conventional point of view to this problem, two typological levels were defined for each water body:

- Typological level #*1* - the influence of bottom deposits excluded from natural load;
- Typological level #*2* - the influence of bottom deposits included in natural load.

Results

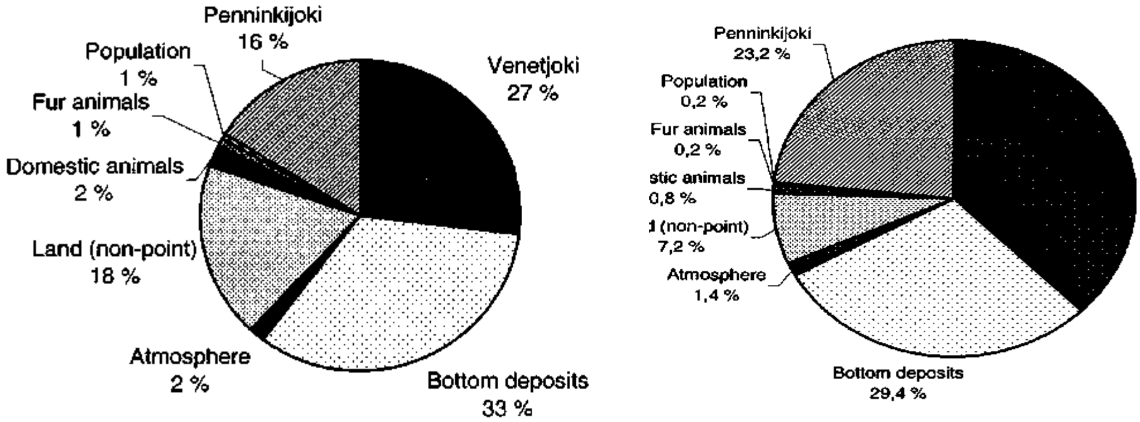
The proposed approach was applied in practice in full scale for two Finnish and two Swedish pilot areas. Below the results for the Lake Halsuanjarvi presented as an example.

The Lake Halsuanjarvi is located in Western Finland at 63° of northern latitudeand 24° ofwestern longitude, on a distance of about 80 km from the coast of the Gulf of Bothnia. This region is characterized by a semi-continental climate with cold winter and warm summer. The Lake Halsuanjarvi has mainly recreation use with a camping site located at the south-west shore of the lake. The shape of Lake Halsuanjarvi is quite near to round. Average depth, volume, and surface area are approximately 1.2 m, 0.009 km^3, and 7.7 km^2, respectively. Two rivers flow into the lake: Venetjoki and Penninkijoki. Venetjoki with an average flow rate of about 3.5 m^3/s outflows from the Venetjarvi reservoir. Penninkijoki has an average flow rate of about 3.1 m^3/s. Besides, a discharge of about 0.3 m^3/s enters the lake through small streams and runoff from lake's own catchment area. The River Halsuanjoki, with average flow rate about 6.9 m^3/s, flows out from the lake. Initial data for calculating the inflow and outflow of nutrients by rivers have been calculated based on a restricted set of field data, which was delivered by West Finland Regional Environment Centre. Field data about the outflow through the River Halsuanjoki are not available due to the lack of sampling points. Consequently, the water quality in Halsuanjoki was supposed to coincide with the water quality in the lake. In addition, the patterns of land use in the catchment area were analyzed. This included vast amount of information about agriculture (field area, crops etc.), cattle (e.g. amount of different animals), housing and the treatment of waste water, forestry etc. This information was used to analyse the proportions of nutrient load caused by individual factors. The results from nutrient load calculations are presented in Figure 2. The two major incoming rivers, Penninkijoki and Venetjoki were considered as point loading using available observation data from these rivers. Land represents the non-point load from the lake's own catchment area. The study on the hydrodynamic properties of the Lake Halsuanjarvi gave basis to consider the lake as one mixing box.

The two typological levels for the Lake Halsuanjarvi, corresponding to natural sources of nutrient load only, were defined. Typological level #1 corresponds to the situation, where bottom deposits are considered as anthropogenic load. In the case of typological level #2, bottom deposits are considered as a natural source of nutrients. In these calculations, phosphorus was used as a limited nutrient based on previous analysis. The results from calculating the typological levels and their comparison with the current situation are shown in Figure 3.

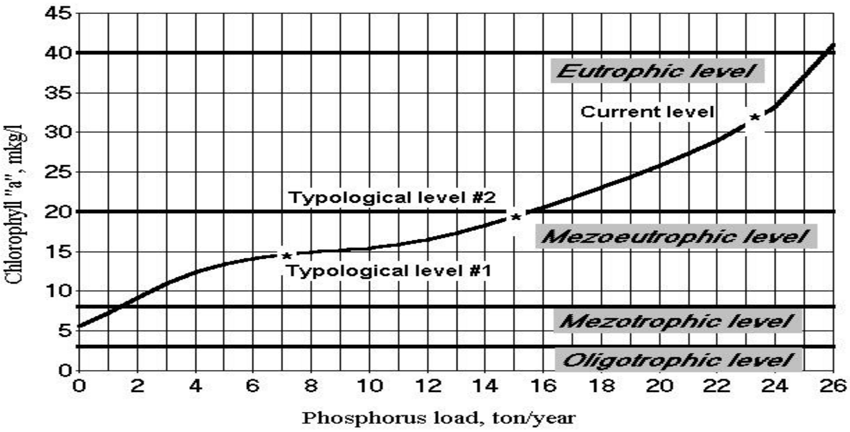
Considering the existing nutrient flows and their importance in the nutrient balance of the lake, a set of technologies was considered: floating straw mat for the incoming rivers to withdraw nutrients; dredging of sediment; constructed wetlands ('bioplato') on the shores of the lake, for cattle and fur

Figure 2: Phosphorus (a) and nitrogen (b) load on the lake



(a) (b)

Figure 3: Influence of phosphorus load on trophic level



animal farms, for scattered housing; precipitation of nutrients by chemicals directly in the lake; application of straw technology in the lake to prevent algae growth. All these technologies were analyzed using U/E-models and estimations of costs corresponding to the selected technologies. These calculations allowed to get a preliminary estimation about the effectiveness of different technologies and related to their use costs. For final recommendations, further and more detailed studies are required. Especially this is true for the real specific costs of each technology, which were estimated very roughly.

Discussion

The results gave a new, more profound understanding about the reasons behind the current state of the lakes. Based on these results it will be easier to plan the future activities targeted on improving the state of the lakes. The modeling results help to understand the significant role of different sources of nutrients. The demonstrated method also allows estimating the effectiveness of different technologies for lake rehabilitation. Detailed calculations, however, require more detailed monitoring data than was available in this case.

References

(1) H.Klapper , Control of Eutrophication in Inland Waters, Ellis Horwood, London, GB, (1991)
(2) US Clean Lakes Program, A Review of the first decade, EPA 440/5-85-033, Environmental Protection Agency, USA, (1985)
(3) F. Stolberg. P. Peura, and P. Sevola, Decentralized Wastewater Treatment Strategy for Eutrophied Water Body - Catchment interaction , Productivity & Quality Management Frontiers, MCB Univ. Press, Vaasa, Finland, (1999)