Screening of strategies for water quality planning

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Abstract

A new approach to screening of environmental strategies is described, and its application to water quality planning in large river basins is considered. The approach is based on a joint application of MIKE 11, which is a well-known system for modeling rivers and channels, and of a new graphic tool that supports a search for efficient strategies and is called Feasible Goals Method / Interactive Decision Maps (FGM/IDM). The hydrodynamic and advection-dispersion models of MIKE 11 are applied as data preparation tools for the FGM/IDM technique. The FGM/IDM technique helps to select a few efficient strategies for water quality planning. After that one can use Mike 11 once again for simulation of selected strategies. Thus, the FGM/IDM technique is an additional system component that broadens the scope of decision support services provided by water quality simulation systems like MIKE 11.

The DSS based on combination of MIKE 11 and FGM/IDM technique was developed on the request of Russian Federal Ministry of Natural Resources in the framework of the federal programme “Revival of the Volga River”. Further development is related to a distributed DSS that would provide ordinary people directly influenced by the water quality planning with Internet access to the FGM/IDM-based screening tool.

Keywords: decision screening, DSS, Feasible Goals Method, Interactive Decision Maps, MIKE 11, water quality planning

Introduction

Problems of water pollution abatement in Russia's rivers are of vital importance. Because of a difficult economic situation and the lack of funds, there is a high need for efficient application of environmental investments. In order to get a moderate investment it is often necessary to persuade federal and regional authorities, owners and management of enterprises, banks and other institutions, that the investment will result in a substantial improvement of environmental situation. Therefore different interests and concerns must be taken into account. It means that the traditional search for water quality planning strategies based on a single-criterion optimization is not adequate to the task. Therefore, a new approach was developed. The new approach is based on the fact that any decision making process consists of two main stages (see Figure 1). The first stage is a selection of a small number of decision alternatives from the whole variety of possible alternatives for further exploration (early screening of decision alternatives). The second stage consists in the final choice among selected alternatives on the basis of their detailed exploration and informal discussions.

Modern information technologies that combine simulation with multimedia, virtual reality, and geographic information systems (GISs), provide water managers with new exciting opportunities for rapid graphic assessment of one or few water management strategies. That is exactly what one needs while going through the second stage of decision making process. In contrast, these technologies do not support decision screening. Therefore, new computer-based tools are needed that can support the screening stage. Such a tool is described in the paper.

The tool is based on a graphic technique of Feasible Goals Method / Interactive Decision Maps (FGM/IDM). The technique can be used for display of outcomes of an infinite variety of possible decision alternatives and can help to select a small number of strategies (see Lotov, Bushenkov, Kamenev, Chernykh, 1997; Lotov, Bushenkov, Kamenev, 1999). During 90s, the FGM/IDM-based methodology for environmental strategies screening was developed (Lotov, 1994, 1998) and applied for screening of water quality improvement strategies (Lotov, Bushenkov and Chernykh, 1997; Lotov, Bourmistrova and Bushenkov, 1999). Now it is applied in a new DSS developed on the request of the Russian Federal Ministry for Natural Resources in the framework of the Federal programme "Revival of the Volga River".

The FGM/IDM technique takes into account multiple decision screening criteria. It means that it can be classified as multiple criteria decision support (aid) technique. Examples of application of multiple criteria methods for decision screening in water management are given in (Cohon, 1978; Loucks, Stedinger, Haith, 1981; Moiseev, 1982; Louie, Yeh, Hsu, 1984). The main difference of the FGM/IDM technique is related to its graphic interactive form that includes such features of modern information technologies as animation. Thus, it seems that the FGM/IDM technique is in line with these technologies, and therefore it can be accessed by ordinary people.

The concept of application of the FGM/IDM technique for environmental decision screening was introduced in (Lotov, 1984, 1988). In accordance to it, the FGM/IDM technique is applied to simplified integrated models of environmental systems. In this paper a surface water quality problem in a river basin is considered, and an integrated model of pollution emission, wastewater discharge treatment and pollution transport in a river flow is used. It is constructed by integrating simplified models of pollution emission, treatment and transport. The simplified models of pollution emission and treatment are based on expert knowledge and technological data. The simplified model of pollution transport is constructed using the results of simulation experiments with MIKE 11. An influence matrix, which gives a simplified description of pollution transport along the river, results from the parameterization of models, which are the parts of MIKE 11.

Once influence matrices for several pollutants have been constructed, they can be combined with an expert model of pollution emission and a technological model of wastewater treatment. The integrated model obtained in this way is studied with the help of the FGM/IDM technique. It provides fast interactive graphic display of decision information in a form of decision maps, which are collections of efficiency frontiers of several pollution and cost criteria. This information allows the user to identify a preferable feasible goal on a decision map with a simple click of computer mouse. After that an investment strategy resulting in the identified goal is computed automatically and displayed in a GIS. Later on it may be checked and refined in simulation with MIKE 11. An investment strategy obtained this way provides a starting point for discussions and negotiations on development of a detailed project of water quality improvement in the river. The DSS that incorporates the above decision screening technology can be used on pre-negotiation stage for preparation of negotiator's position for negotiations among officials of the federal ministry, regional authorities and other institutions involved in investment formation and allocation.

From the societal point of view, more important is the opportunity to developed a distributed version of the DSS that could support screening of possible strategies via Internet. The importance of computer network tools, which help people influenced by the environmental decisions to access and evaluate them, was stressed, for example, in (Yan et al., 1999). Since it is fairly simple to master the graphic FGM/IDM technique, ordinary computer-literate people may use the DSS to exercise their "right to know" the unbiased information on all possible strategies, i.e. information that usually is screened by experts and other mediators. Moreover, the Web-based version of the DSS can support their independent search for preferred strategies. In turn, this can help them to understand decision making problems faced by stackholders and to be actively involved into public discussions.

Section 2 of the paper discusses the concept of an integrated model and describes application of MIKE 11 for constructing simplified pollution transport models, which are parts of the integrated model. Section 3 introduces the FGM/IDM technique and describes its applications for decision screening. In Section 4, the DSS is outlined and an example of decision screening in framework of it is provided. The same section also describes the features of an evolutionary process of the DSS application, when different DSS tools are used for decision screening in an arbitrary succession. In Conclusions, Web application of the DSS is considered.

Copies of color display of the DSS are given in black and white in the journal. Color pictures can be found in its Web version. The first variant of the paper was published at the DHI Software Conference (Lotov, Bourmistrova, Bushenkov, R.Efremov, et al., 1999).

Integrated models and their construction

Water quality management problems often have a very large (or infinite) number of alternative decisions. Nevertheless, most of computer-based DSSs provide an analysis of only few decision alternatives. An attempt to support decision screening by using single criterion optimization failed since this technique was not able to incorporate decision makers intuition and diverse interests. So, decision makers have to select several alternatives by themselves without any computer support guided by their experience and feelings only. Often, experts are asked to select a small number of alternatives for further exploration. Expert involvement saves time for decision makers, but it introduces additional complications related to the fact that the alternatives developed by experts usually reflect their experience, perceptions, and goals, which may differ from those of decision makers. Such approach is likely to result in a deadlock during the final stage since decision makers often are forced to choose among strategies that do not reflect their opinions or interests. Therefore there is a need for computer-based techniques that would involve decision makers into the process of decision screening.

It seems that the idea to use simplified models on the screening stage was introduced in water quality management by (R.Dorfman, 1965). Indeed one can not usually explore the whole lot of possible decision strategies on the basis of detailed sophisticated models. Decision screening in environmental water management requires integration of knowledge from a number of disciplines that provide information about different subsystems such as wastewater discharge, wastewater treatment, pollutants transport, the effect of pollutants on ecological systems, as well as economic impacts, environmental measures, and so forth. For this reason, simplified models are to be used in an integrated mathematical model applied for screening procedures. In the case, an original mathematical description of a subsystem does exist, a simplified model can be deducted from that description. In this case, a simplified model may have the form of an influence matrix. In an opposite case, expert judgments and empirical data may be used to help develop a simplified model.

Constructing of an influence matrix

The universal way to build a simplified model is to establish an approximation (or parameterization) for input-output dependencies in a system. The influence matrix is a linear description of the relations among inputs and outputs. Let us consider possible ways for constructing the influence matrix.

We start with a linear original model. Consider, for example, a stationary linear model of partial derivatives that describes regional transport of a single pollutant from several pollution sources along a river. Assume that the pollution discharge per unit time is constant and that the linear model can be used to evaluate the pollutant concentration at any point in the region. If formulated correctly, the problem of determining the concentration of the single pollutant can be solved.

If pollutant discharge data are not known in advance, the point source method can be used; source functions describing the concentrations that result from individual sources with the unit rate of discharge may be constructed. Since the pollutant transport model is linear, the concentration resulting from a single source can be calculated as the product of the source function value (the influence coefficient) on real discharge. Due to the same linearity of the pollutant transport model, one has to sum up concentrations resulting from different sources. In other words, pollutant concentration at any point (for example, at a monitoring station) is a linear function of pollution discharges. It may be computed as the scalar product of the influence coefficient vector and the discharge vector. Given a finite number of points (monitoring stations) where the pollutant concentrations are of interest, one has to consider a matrix, which rows are provided by influence coefficient vectors. This is the so called influence matrix. Concentration values can be calculated by multiplying the influence matrix by the discharge vector.

In the linear case, influence matrices can be constructed precisely by using the values of the source functions. In the non-linear case, an influence matrix approximates the discharge-concentration dependencies. How influence matrices can be constructed depends upon a particular scientific field. The universal approach is based on the application of regression analysis of data on input-output dependencies, obtained by simulation of non-linear models. Along with the approximation of input-output dependencies, simulation provides their applicability ranges.

If there is no adequate mathematical model for a subsystem, an influence matrix can be constructed through regression analysis of experimental or historical data. Sometimes, experts can provide both an influence matrix and its applicability range. On the other hand, expert or empirical information can be arranged in different forms that will be exemplified later.

A combination of influence matrices and other simplified descriptions, balance equations, and restrictions imposed on variables contributes to an integrated model that describes an environmental system. Simplified integrated models are typically less precise than original models but that fact is not of great importance as integrated models are used on the first stage of the decision process for screening of decision strategies.

Now let us describe how coefficients of an influence matrix that describes the transport of an pollutant along a river were developed. In contrast to the previous DSS for surface water quality planning based on the same approach (Lotov, Bushenkov, Chernykh, 1997), the coefficients of the influence matrix were developed in the new DSS through simulation of an pollutant transport model, which is a part of MIKE 11.

Application of MIKE 11 for constructing the influence matrix

The DSS was calibrated for the Oka river, which is one of the largest tributaries of the Volga river. The Oka river is about 1,500 kilometer long, it also has multiple tributaries. The flow in the river is changing from 10 cubic meter per second during the dry summer period in the upper Oka river up to 1000 cubic meter per second in the lower Oka river. Geometric characteristics, roughness and other parameters of the river-bed vary substantially along the river. In Figure 2, the map of the Oka river basin is provided.

Frontiers of seven regions located at the main flow of the river are depicted along with frontiers of several other regions. The river-bed was split into fourteen segments that approximately describe membership of riverbanks to the regions. Monitoring stations were located at the downstream ends of the segments. The location of monitoring stations is provided in Figure 2, too.

Constructing of influence matrices was started with calibration of the hydrodynamic submodel of MIKE 11 (HD MIKE 11) to the stationary flow of the Oka river during the summer period with a minimal flow. There were 23 main tributaries considered in the model along with 33 conditional inflows that describe inflow from the neighboring land to the river. The water inflows were supposed to be given. The influence of the Volga river on the flow in the lower part of the Oka river was taken into consideration. It turned out that the roughness coefficients used in the model are sufficient to determine the flow during the summer low-flow period. The hydrodynamic model of the Oka river was applied for the calibration of the advection-dispersion model of MIKE 11 (AD MIKE 11) that was used for description of pollution transport in the river.

Multiple sources of pollution do exist along the river-bed. They include natural sources, industrial wastewater discharge sources, municipal point and non-point wastewater discharge sources, agricultural non-point sources, large animal breeding enterprises, etc. In accordance to the information we managed to collect, six pollutants were considered in the model, namely concentrations of suspension, phosphates, nitrates, oil products, and ferrous combinations as well as biological oxygen demand. Both discharges and concentrations of pollutants were used to calibrate AD MIKE 11 for the summer low-flow period. Data on wastewater discharge from large cities and banks of the river were collected partially from state statistical institutions and partially they were obtained as a result of expert evaluation. Known pollutant concentrations in large tributaries were averaged on the basis of data for several years. The rest of discharge was spread among small rivers proportionally to their flow. In the process of calibration of the model, the decay constants of the advection-dispersion model were adjusted. Sometimes it was needed to correct data on wastewater discharge, the contribution of the expert, Dr. A.Maksimov from the research institute Vodgeo was inestimable in this field. Figure 3 displays the black and white copy of MIKE 11 display that informs about concentration of nitrates in the river computed by AD MIKE 11. Though data are artificial, they are plausible, dark shading is used at the points where the concentration is greater than the maximal admissible level.

The model AD MIKE 11 has an extremely important property: for a given water flow, a pollutant concentration at a monitoring stations depends on the capacity of the pollutant sources in a linear way. One can prove this feature of the model theoretically, on the basis of its equations, or experimentally, using simulation. This feature was used for precise constructing of influence matrices for pollutants under consideration in the following way.

In a particular river segment, three types of pollution can be considered: pollution from the sources located on the right and the left banks and pollution that the flow brings from the river segment located up to the segment under consideration. According to it, the simulation experiment for a particular segment consists of four runs. In all runs the pollutant flow was computed at the monitoring station located at the downstream end of the segment. In the first run, the pollutant flow at the upstream end of the segment (i.e. at the downstream end of the upper segment) was set equal to the current value and the discharges from both banks of the river segment were set to be equal to the background emission. In the second and the third runs the background flow was set to be the pollutant flow at the upstream end. The discharge from the left-bank (or right-bank) region was set to be equal to the current emission, while the background value was set equal to discharge from the region located at the opposite bank. In the fourth run the capacities of all sources of pollution were set equal to the current level. Since the pollution concentrations for the background discharge were given, the results of the three first runs were sufficient to estimate the coefficients of the linear model of the pollution in the segment. To be precise, the pollutant flow was the sum of the flow from the upper segment and of the discharges from the banks multiplied by the related coefficients. The fourth run was used only to check the results. Though usually the additional pollutant flow computed in the fourth run was the same as the sum of the additional pollutant flows calculated in the previous runs, sometimes mistakes in data were found. By this the linearity of the influence of the pollution sources was proven experimentally. It had persuaded those people who did not trust the theoretical results received by the analysis of the equations of the model.

Coefficients of the linear models for all segments provide sufficient information for computing the influence matrix the particular pollutant for the whole river. Due to this, it was possible to compute the concentrations of a pollutant at the monitoring stations by simple multiplying the related influence matrix by the discharge vector. The influence matrices approximately describe the pollutant transport. They relate the decrement of the wastewater discharge to the decrement of concentrations of the pollutants at monitoring stations in the integrated model.

Description of the integrated water quality model

The integrated model used in the DSS consists of three sub-models (see Figure 4):

- a wastewater discharge sub-model that describes the current discharge attributed to a particular region, a river segment, an industry or different services; structure of the wastewater discharge is provided, too;

- a wastewater treatment sub-model that relates the decrement of wastewater discharge to the cost of constructing and performance of wastewater treatment installation;
- a pollution transport sub-model that allows compute the concentration of pollutants in monitoring points for discharge given in all sources.

Unfortunately, available data on wastewater discharge happened to be very rough. The wastewater discharge was attributed only to particular regions, but not to industries. So, in contrast to the previous DSS for water quality planning based on the IDM/FGM technique (Lotov, Bushenkov, Chernykh, 1997), we had to restrict ourselves to a regional pollution model, though we keep on hoping to receive related industrial data sooner or later. It is clear that the influence matrices constructed in the framework of the development of the current DSS can be easily combined with a multi-industrial multi-services pollution discharge model.

The situation was the same while constructing the model of wastewater discharge treatment. The model was based on the concept of wastewater purification technologies. That concept provides an opportunity to include hundreds of possible technologies into consideration. Nevertheless, we had to restrict ourselves to a small database of the discharge treatment technologies that was developed by Dr. A.Gotovtsev from the Institute for Water Problems of Russian Academy of Sciences using data given in (Henze and Oedegaard, 1995).

The technologies from the database were combined in discharge treatment installations in the model. Thus, a decision variable of the model described an investment into a particular discharge treatment technology in a particular region. Since the river was split into segments according to the borders of the main-flow regions, only one or two regions were attributed to each river segment. For this reason, it was possible to use influence matrices to compute the resulting concentration of pollutants at monitoring stations for a given strategy, i.e. for given values of decision variables. The total and regional costs can be computed, too.

Since we do not expect the user to set the decision variables in advance, the FGM/IDM technique is used that supports a search for preferable strategies by screening the variety of feasible strategies. Application of it starts with the specification of criteria of decision screening. To satisfy different decision makers with different interests, a large list of performance indicators is provided. The user can specify screening criteria directly in indicator list that includes two kinds of indicators:

- environmental indicators – regional or maximal concentration of pollutants in a region or in the river (in relative units, while the value of an indicator equals to one if the pollution level precisely satisfies the medical requirements),
- economic indicators – investment in particular regions as well as the total cost of an investment project.

The user can choose two to seven performance indicators from the list to be the screening criteria. Moreover, restrictions on the values of other indicators may be imposed. The FGM/IDM technique supports screening by the exploration of non-dominated (efficient) frontiers among investment and pollution criteria, and the identification of a feasible goal. Let us consider the FGM/IDM technique more carefully. It was described earlier in a lot of papers and books, say (Lotov, 1984, 1989, 1998; Lotov, Bushenkov, Kamenev, Chernykh, 1997; Lotov, Bushenkov, Chernov, 1997). Next section offers an informal introduction to the technique on the basis of an example.

The FGM/IDM technique

Efficiency frontiers

Here we consider application of the FGM/IDM technique in the case of two criteria. Let us suppose that two criteria were specified by the user: total cost of the project (in billions of US$, denotes as F) and maximal concentration of oil products in the river (in relative units, denoted by Z5). After that computer processes the model and displays feasible values of the criteria (black and white copy of the display is provided in Figure 5). The values for pollutant concentration are given along the vertical axis, and values of cost are given along the horizontal axis. Feasible combinations of the values of the two criteria are displayed by the colored area (dark area in Figure). Combinations of criterion values outside the colored area are not feasible. The feasible value of cost (F) changes from zero to $2,876 million. The feasible value of pollutant concentration (Z5) changes from 0.83 to 3.4. Since a decrement of both criteria is of interest, the frontier of the colored area in Figure 5 (so called efficiency frontier) is explored by the user. The minimal (zero) cost is related to the maximal pollutant concentration, i.e. Z5=3.4. Vice versa, the minimal pollutant concentration Z5=0.83 is related to the maximal cost F=$2.876 billion. The efficiency frontier connects these two extremes. It shows how much one has to pay for an additional decrease in pollution, i.e. it displays the so called criterion (efficient) tradeoffs between the criteria values.

One can see that the cost of $190 million is sufficient for a substantial decrement of pollutant concentration that falls till the value of 1.78. The point of the efficiency frontier that corresponds to these criterion values is marked by cross. Its precise coordinates are given in the box in the upper left corner of display. So, about one half of the possible pollution decrement is provided by only 7% of the maximal investment! Further investment, however, is not so efficient: the slope of the frontier changes drastically in the vicinity of the cross. One can easily estimate that the pollutant concentration about Z5=0.85 can be achieved for not less than $2.2 billion, and the rest of investment (about $700 million!) is practically inefficient.

As it was said above, the knowledge obtained from Figure 5 includes information about feasible criterion values as well as information on how much one has to pay for an additional improvement of an environmental criterion. The last type of the information is extremely important to decision makers and other people interested in the problem. It may be the decisive knowledge in the decision process. It is worth mentioning that the notion of criterion tradeoff we use differs from the notion of value tradeoff used by (Keeney and Raiffa, 1976); the latter implies subjective compensation of losses in one criterion by gains in the other. It is important that the users obtain the knowledge in a clear graphic form.

It is necessary to stress that the information on the criterion tradeoff, in contrast to the value tradeoff, is objective, i.e. it does not depend on the preferences of the user. To express his/her subjective preferences, the user has to identify a preferable point on the efficiency frontier. Say, in Figure 5 the point identified by cross may happen to be most preferable among points of the efficiency frontier. In this case it is identified by the user by a click of computer mouse. This point is actually a goal, but, in contrast standard goal methods (Ignizio, 1976), now the goal is feasible! This means that there exists an investment strategy that results in the identified goal, i.e. in the chosen values of total cost and pollution. That is why the method we suggest and describe is termed the Feasible Goals Method (FGM).

The idea to display efficiency frontiers in the case of two criteria was proposed by (S.Gass and T.Saaty, 1955) and transformed into an important direction of multiple criteria decision making (so called non-dominated set generation methods) by (J.Cohon, 1978). The FGM/IDM technique develops the idea of Gass, Saaty and Cohon for the case of multiple criteria (three, four, five, six, and may be more). When the number of criteria is greater than two, the Interactive Decision Maps (IDM) technique is used to display criterion tradeoffs.

Interactive decision maps

Let us introduce the IDM technique for the case of three criteria. We add a third criterion into account. Let the third criterion be the maximal value of nitrates concentration for the whole river (denoted as Z4). Now the efficiency frontier among the criteria F and Z5 depends on the value of the third criterion Z4. Exploration of the influence of the third criterion can be based on animation of the efficiency frontier. Since it is impossible to demonstrate the animation in a journal, we can advise to read the Web version of the paper or download the demo software from our Web page (http://www.ccas.ru/mmes/mmeda/soft). Here we are able to display the snap-shots of animation imposed one over another (Figure 6). Th figure is relatively simple and informative since the efficiency frontiers do not intersect, they only can touch one another sometimes.

Once again, the values for Z5 are represented along the vertical axis, and values for F are given along the horizontal axis. The value of Z4 is given in this picture by shadings, which are colored in computer display. The relation between the value of Z4 and the shading intensity (color in computer display) is provided in the palette located under the picture. The range of Z4 was selected between 2.6 and 1.2. One can see that the efficiency frontiers do not coincide, i.e. money should be invested for the decrement of the value of Z4. The quantity of the additional nitrates-oriented investment can be measured by the distance between efficiency frontiers, i.e. by the width of the strips. One can see that the additional cost for the decrement of Z4 is maximal for the maximal value of Z5, but if the value of Z5 is becoming smaller, the frontiers are getting closer, i.e. the additional cost related to the decrement of Z4 is getting smaller. For small values of Z5, the efficiency frontiers start to coincide informing by this that the additional cost of the decrement of Z4 for these values of Z5 tends to zero.

Let us consider a fixed value of Z5, say, Z5 is about 1.7. One can see that the additional cost related to the decrement of Z4 is relatively small if Z4 goes down from 2.6 to 2.2. Further decrement of Z4, however, requires a larger cost. More than $200 million are needed to decrease the value of Z4 from 2.2 to 2.0. This information is given in a clear graphic way, which is especially effective in color. Pictures of this kind are called decision maps. Thus a decision map plots a collection of efficiency frontiers between two criteria related to a collection of restrictions imposed on the value of the third criterion. By this, a decision map provides a rough guide on the criterion tradeoffs among three criteria.

To be precise, the FGM/IDM technique uses modified decision maps. In the standard decision map technique (Haimes et al., 1990), several two-criterion cross-sections of the multiple-criterion non-dominated frontier of the feasible set in criterion space (FSCS) are depicted. Though the modified decision maps is similar to the standard decision maps, the technique of modified decision maps has several advantages. The most important one is the way the decision maps are computed.

To discuss this topic, we introduce the method mathematically. Let the variety of feasible decisions $X \subset W$ be given, where W is a decision space (finite-dimensional linear space R^n, for example). Let the a decision x be related to criterion vector y, which is the element of linear finite-dimensional space R^m, by a given mapping $f: W \to R^m$. Then, the FSCS is defined as the variety of attainable criterion vectors

$$Y = \{y \in R^m: y = f(x), x \in X\}.$$

Since in our case the user is interested in minimizing the criterion values, a criterion point y' dominates (is better than) a criterion point y, if and only if $y' \leq y$ and $y' \neq y$. Then, the non-dominated (efficient, Pareto-optimal) frontier of the FSCS denoted as *P(Y)* is defined as a variety of non-dominated points $y \in Y$, i.e.

$$P(Y) = \{y \in Y : \{y' \in Y : y' \leq y, y' \neq y\} = \varnothing\}$$

The Edgeworth-Pareto Hull (EPH) of the FSCS is defined as $Y^* = Y + R^m_+$, where R^m_+ is the non-negative cone of R^m. It is important that the non-dominated frontiers of the FSCS and of its EPH coincide, but the dominated frontiers disappear in the EPH. The EPH for two criteria is actually depicted in Figure 5 by the shaded area. The algorithms that are used to approximate the EPH are described in short in (Lotov, 1996; Lotov, Bourmistrova, Bushenkov, 1999). Detailed mathematical description of the technique is given in (Lotov, Bushenkov, Kamenev, 1999).

Modified decision maps used in the framework of the IDM technique are computed as collections of two-criterion cross-sections (slices) of the EPH, which has been approximated before the exploration of the decision maps is started. Due to this, modified decision maps can be depicted on-line. That is why the technique is called Interactive Decision Maps. Animation of the decision maps is possible due to the same feature of the approach. Later on our references to decision maps will imply the modified version without any additional indication.

Decision maps have several common features in common with topographical maps. Since the efficiency frontiers of decision maps do not intersect (although they may coincide), they resemble the height contours of a topographical map. Value of the third criterion in a decision map is similar to height in a topographical map. Common knowledge of topographical maps will help in the analysis of decision maps. It is easy to view the variety of feasible combinations of the first and second criteria in relation to the value of the third one ("places higher than ..."). It is also easy to understand which values of the third criterion are feasible for a given combination of the first and second criteria ("height of this point is between ..."). The proximity of efficiency frontiers in the vicinity of a point indicates a steep slope, as in a topographical map: a slight shift in the efficiency frontier must be caused by a substantial change in the value of the third criterion.

In three-criterion problems, the IDM technique may be used to provide arbitrary arrangement of criteria in decision maps. One can squeeze the criterion ranges or change the number of tradeoff curves and zoom a map. Application of the IDM technique is much more important if there are four, five or more criteria to explore. In such case, a display of a decision map requires that values of the fourth, fifth and other criteria would be given. Those values can be changed by thumbs of scroll bars located under the picture. Moreover, decision maps can be animated in accordance to an automatic decrement of, say, fourth criterion. One can require any of the decision maps or any animation film. Moreover, matrices of the decision maps exemplified in Section 4 may be displayed, too.

Identification of a feasible goal

Once the user has got a sufficient knowledge on the criterion values and their tradeoffs, he/she can identify a preferable feasible combination of criterion values (a feasible goal). Due to the IDM technique, a preferred feasible goal can be identified on a decision map with a click of computer mouse. For example, the cross displayed in Figure 6 may be identified as a feasible goal. Note that the goal is the only information provided by the user. This feature distinguishes the IDM/FGM technique from other interactive multiple criteria techniques.

After a feasible goal is identified, the same situation is the same as in the above case of two criteria: the identified goal is feasible and, therefore, there exists a decision alternative that results in it. Due to this, the processing of preference information is extremely simple: such efficient alternative is computed. We use a stable computational procedure based on the reference point concept developed by (Wierzbicki, 1981). In the framework of the concept, an identified criterion point is regarded as a "reference" in the process of efficient alternative computing. The efficient alternative can be found by solving the following optimization problem (note that we try to minimize the values of the criteria):

$$\min_{1 \le i \le m} (y'_i - y_i) + \sum_{i=1}^{m} \varepsilon_i (y'_i - y_i) \Rightarrow \max$$

$$\text{for } y = f(x),\ x \in X,$$

where y' is the reference point, $\varepsilon_1, \dots, \varepsilon_m$ are small positive parameters. Since in our case the reference point belongs to the non-dominated frontier, the output of the computed alternative coincides with it.

In the DSS we describe a wastewater treatment strategy is displayed after about one minute after the goal has been identified. The performance indicators values related to the strategy are provided in a table (see Figure 7). The user can also study diagrams or use geographical maps to explore the strategy. These and other DSS tools supplemented to the FGM/IDM technique are considered in Section 4. Before the discussion of the whole DSS is started, we provide the scheme of how the FGM/IDM technique works in Figure 8.

Decision support system: an application example

The following subsystems were included into the DSS for screening of water quality strategies:

1. subsystem for information preparation,
2. subsystem for visualization of the current pollution in the river,
3. subsystem for decision criteria specification and for formation of restrictions imposed on the values of performance indicators,
4. subsystem for EPH approximation,
5. subsystem for interactive and animated display of decision maps and for feasible goal identification,
6. subsystem for computing of a goal-related strategy,
7. subsystem for visualization of the computed strategy in GIS.

The role of the subsystems is clear from their names. Only short comments are needed here. The input information is prepared in the first subsystem by experts. Users start their job with the second subsystem. They receive information on the current pollution in the river in the form of diagrams as well as on a GIS-generated map. The information is used in the process of formulation of a screening problem, i.e. in the process of specification of screening criteria and restrictions imposed on the values of performance indicators.

Let us consider an example of how the DSS can be applied for water quality planning. The data used in the example are fairly plausible though not real.

Example

Figure 9 contains several diagrams provided by the second subsystem. The upper (black) column diagram provides data on the flow during dry summer season at all 14 monitoring stations (cubic meters per second). Six other column diagrams display pollution at the stations in relative units discussed above. The left-hand column of diagrams contains data on (from the top) BOD, phosphorus and oil, while the right-hand column contains data on suspension, nitrates and ferrous combinations.

One can see that the most drastic pollution problems are related to the upper Oka river (monitoring stations 2 and 3). Moreover, pollution with the oil products in too high in all segments of the river. In this example, we are going to deal with the latter problem. Let us consider an example negotiations concerning investment into wastewater treatment facilities among representatives of the Moscow region (M-region) and Nizhny Novgorod region (NN-region). Those regions are economically most developed ones in the Oka river basin.

Let us suppose that the following five criteria are used in the negotiations:

- maximal concentration of oil products at the monitoring stations located in the M-region (z_r45),
- maximal concentrations of oil products at the monitoring stations located in the NN-region (z_r75),
- total cost of the project (F),
- investment in the M-region (F4), and
- investment in the NN-region (F7).

The EPH was approximated for the five criteria listed above. Let us consider several decision maps. Figure 10 displays efficiency frontier among concentrations of oil products at monitoring stations located in the M-region (horizontal axis) and in the NN-region (vertical axis). The upper scroll-bar informs that the total cost is restricted by $207 million here. Restrictions imposed on the values of F4 and F7 have no influence on the efficiency frontier.

One can see that the efficient values of oil pollution in these regions are related when the cost of the project is restricted. Pollution in the M-region can be decreased from the current pollution of 2.7 till 1.75 that is minimal for this cost. If z_r45=1.75, the pollution in the NN-region can not be lessthan 1.7. So, if $207 million are applied in the interests of the M -region, the pollution in the NN-region can drop from the current 1.8 till about 1.7, but not less. In contrast, if $207 million are applied in the interests of the NN-region, the pollution in it can be as low as 1.3. The efficiency frontier among pollution in both regions clearly shows other intermediate efficient tradeoffs for the total cost of $207 million.

Influence of the total cost on the efficiency frontier among the regional pollution under consideration can be illustrated by an animation film (see the Web version), but here we turn right a way to Figure 11. It contains the decision map for which the value of the total cost changes from zero till $800 with the step of $200. Once again, restrictions imposed on the values of F4 and F7 have no influence on the decision map. It is clear that the form of the efficiency frontier substantially depends on the total cost. The cost of $200 solves the pollution problem to a large extent (compare pollution values related to the frontier with the right upper corner that corresponds to zero cost). Additional $200 are very efficient, too (next frontier). For example total cost of $400 can solve the problem for the NN-region if the investment is used according to its interests. At the same time, minimal pollution in the M-region is achieved while pollution in the NN-region is about 1.7. Nevertheless, representatives of the NN-region can hope to make representatives of the M-region to agree to move along the efficiency frontier from point z_r75=1.7 to the point of the kink (z_r75 about 1.1) using minimal concessions in a different field.

To understand the reason why it is so, let us have a look at Figure 12, which contains the same decision map as Figure 11, but in a different form: only efficient (weak-efficient, to be precise) frontiers of slices are displayed there. The new form of the decision map provides more detailed information on the criterion values. One can easily understand that while moving along the efficiency frontier (F=$400) from point z_r75=1.7 to the point of the kink (z_r75 about 1.1), the pollution level in the M-region increases from 1.6 to 1.8 only.

Now let us consider the influence of restrictions imposed on investment in the regions. In the Web version the decision map given in Figure 12 is animated. Here we can use matrices of decision maps to estimate influence of the regional investments. In the decision maps matrix given in Figure 13, columns are related to restrictions imposed on the values of F4 and rows are related to restrictions imposed on the values of F7. These restrictions are provided above the columns or to the right from the rows. The decision map displayed in Figure 12 is located now in the upper row of the extreme right column. It is related here to such restrictions imposed on F4 (not greater than $800) and on F7 (not greater than $200), which still do not influence the decision map. By moving to the left in the same row one obtains the snap-shots of the animation film related to the influence of the restriction imposed on the value of F4. By moving downwards in the same column one obtains the snap-shots of the animation film related to the influence of the restriction imposed on the value of F7. Note that the number of columns and rows depends only on the quality of the display and may be regulated by user.

Let us consider some features of the matrix of decision maps. For example, let us discuss the map located in the lower row of the most left column. The decision map is related to zero investment in both regions (i.e. investment will be applied elsewhere). It is interesting that pollution in the M-region can fall until 2 and pollution in the NN-region can fall until 1.5. A total cost over $400 has no sense at all! It means that further improvement of water quality needs investment in these two regions.

Other decision maps show how relaxation of the restrictions on the investment in both regions influences the decision map. One can find multiple effects of such relaxation. For example, one can explore how a particular efficiency frontier, say, the frontier related to the total cost of $200 million, depends upon those restrictions. Additional effects can be found on color display.

Other matrices of decision maps can be displayed and explored. Double click of a computer mouse on a decision map results in the selection of that decision map for a detailed exploration. Let us suppose that a decision map was selected, which is related to $100 million investment in the M-region and $20 million investment in the NN-region (Figure 14). One can see that the shading related the total cost of $800 million is absent there, i.e. such cost has no sense for the restricted values of F4 and F7. Moreover, it is clear that the total cost, which exceeds $200 million, is not too efficient here.

Let us suppose that the expert has decided to consider the range of the total cost between zero and $200 million split into 9 shadings (Figure 15). One can see how the increment of the cost influences the water quality. A feasible goal is identified in the decision map. It is related to the total cost of $150 million. The strategy that results in the identified goal, is provided in Figures 16 and 17.

Figure 16 contains the same column diagram that was provided in Figure 9. In addition to current pollution concentrations, new pollution concentrations (i.e. pollution concentrations after the project will be completed) are displayed in it in gray shading. One can see that oil products pollution is substantially less in monitoring stations located lower than the Moscow region (stations 5,6, etc.). Nevertheless, the problem of oil product pollution has not been solved finally since investment is low. It is important that the values of several other pollution indicators were improved, too.

In Figure 17, a GIS-generated map of a part of the river basin is displayed. The display contains icons that provide an opportunity to receive information about regional pollution levels, investments, pollutants discharge, etc. It is very interesting that $150 million of total cost were allocated in such a way that the investment in the M-region is $56 million and the investment in the NN-region is $16 million. The rest is allocated among other regions where small volume of investment turned to be most efficient.

Since the integrated model is used on the screening stage, the generated strategy is based on exploration of the simplified model of pollution transport. For this reason, the strategy should be studied and refined in simulation experiments with MIKE 11 that provides an opportunity to explore it, in addition to the most important low-flow season, for other seasons as well. An influence of various precipitation scenario can be explored, too.

Interactive mode of DSS application

In the above example, the simplest straightforward mode of DSS application was described. Usually experts use interactive mode of application of its tools (that is the FGM/IDM technique, maps, diagrams and tables). Several loops of strategy selection are possible.

The first loop may be related to the display of the strategy in the GIS-generated maps. The map-based display of a strategy generated by the FGM/IDM technique results in a better understanding of its features. Often it results in desire to change the specification of the screening problem. It means that the user returns to the third subsystem, specifies new decision criteria and imposes new restrictions on the values of performance indicators. Then the user has to go ahead and to follow the screening procedure until the new strategy is generated and displayed in the map.

Let us consider an example. Suppose that by exploring a strategy in the geographical map with data icons (say, given in Figure 17), the user has found that the pollution levels are too high in several important monitoring stations. Then the user may decide to restrict pollution with ideal values (so called first class water) only for those stations and to formulate a new screening problem. Exploration of new decision maps can results in a new goal and a new strategy that is displayed in the geographical map and can be used for further reformulation of the screening problem, etc.

Another loop of strategy selection may be related to the integrated model used on the screening stage. As it has been said above, the generated strategy is studied and refined in simulation experiments on the basis of MIKE 11 for all possible seasons and precipitation variants. The strategy can happen not to be appropriate. We have soon described how the user can change the formulation of the screening problem by adding new (or more severe) restrictions on pollution indicators. Another option is to improve the integrated model by combining the influence matrices for the low-flow season with influence matrices related to other seasons and (or) precipitation conditions. This is possible in principle, but has not been implemented in the described version of the DSS.

Real-life application of the DSS

The DSS described here was developed on the request of the Russian Federal Ministry for Natural Resources in the framework of the federal programme “Revival of the Volga River”. The reason for this request was a successful real-life implementation of the FGM/IDM technique in water quality planning in small rivers in 1992-1994 (Lotov, Bushenkov and Chernykh, 1997). The DSS was adapted to the information for the Oka River, and it was used by environmental engineers for strategies screening. It turned to be a convenient transparent tool for screening of water quality improvement strategies. During one of the meetings at the Russian federal ministry for Natural Resources in April 1999, the vice-minister in charge for internal water management, Mr. N.N.Mikheev stressed that the DSS must be used in all river basins in Russia.

Unfortunately, application of the DSS is restricted by the problems of information collection. Indeed, only a part of the information for the Oka River, namely the MIKE 11-based pollution transport model is reliable. The wastewater discharge pattern and the wastewater treatment technologies are only plausible. The problem of information collection is vital to application in other river basins, too. Investment into data collection activities may solve the problem.

Thought the application of the FGM/IDM technology was related here to surface water quality, it can be applied for decision support in water quality problems related to groundwater (Kamenev et al., 1986) or coastal water (Lotov, Chernykh et al., 1998).

Conclusions. Distributed DSS on Web

Now let us consider opportunities of the DSS application on Internet. It is important that the FGM/IDM technique can be easily implemented on computer networks. Indeed, approximation of the EPH, which is related to 99% of the computing efforts of the technique, is separated from the human-computer exploration of decision maps and is performed automatically. Therefore it can be accomplished on a server while exploration can be executed by means of Java applets on user’s computer. Interaction among user and server related to specification of criteria and restrictions can be based, for example, on the standard HTML.

In the case of Internet, a Web server can be started equipped with the Java-based FGM/IDM tool. Federal and regional authorities could use it for negotiation preparation. However, it is even more important that millions of ordinary Internet users will be able to apply such Web server individually to obtain information on the whole variety of possible strategies (in contrast to one or two strategies usually provided by mass media). Internet users will receive information directly from the source independently from mass media that inevitably screen and distort it. As it was said earlier, the FGM/IDM technique is simple enough to be mastered by any computer-literate person, and so multiple users will be able to screen the variety of possible strategies by themselves. To get an impression of this concept, one can try the FGM-based Internet resource developed as soon as in 1996 on the basis of the CGI-scripts technology (Lotov et al., 1996-1997). Soon, a new resource based on Java technology will be completed and located at the same Web site. Such Internet resources will help ordinary people to understand decision making problems faced by authorities and to control public decision processes actively.

Different applications of Web resources devoted to the water quality planning problem and equipped with the FGM/IDM software may be possible, too. In addition to the support of decision screening on pre-negotiation stage, a concept of Internet tools that can support negotiation process was proposed. The concept applies the idea of Principled Negotiations developed in the framework of the Negotiation Program of Harvard University (see, for example, Raiffa, 1982, as well as Fisher and Uri, 1983). One of the main ideas of Principled Negotiations is related to focusing negotiators on interests (choice criteria) rather than on particular positions such as being for or against a particular decision (United Nations, 1988). It is clear that the FGM/IDM technique is a perfect tool for providing graphic information on criterion tradeoffs, which describe interests of negotiators. Details of the concept that are beyond the scope of the paper are given in (Lotov et al., 1998).

Unfortunately, application of open networks like Internet for data management and decision making is out of the scope of the tradition in Russia now. So, to implement network negotiation between ministry and regions one has to wait until some kind of intranet will be implemented for data exchange in the framework of the Ministry of Natural Resources. Even in this case the idea to inform ordinary Internet users about the whole variety of possible strategies of water quality improvement and to support their independent search will remain still a dream. One has to wait until the people somewhere on the Earth would be ready for such projects.

Dedication

This paper is dedicated to the memory of Dr. Oleg L. Chernykh, a brilliant researcher who passed away in December 1996. Words can not express our sorrow and deep appreciation of Oleg's contribution to the techniques used in this paper.

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Acronyms and abbreviations

Feasible Goals Method / Interactive Decision Maps (FGM/IDM)
Decision support system (DSS)
Geographic information system (GIS)
Interactive Decision Maps (IDM)
Feasible set in criterion space (FSCS)
Edgeworth-Pareto Hull (EPH)
Nizhny Novgorod region (NN-region)
Moscow region (M-region)

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