

Modeling and Decision Analysis with Multiple Objectives of Water Quality Management Problems*

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1. Introduction

The Decision Making in the field of water resources management represents a task of high importance and responsibility due to the following reasons:

1. The indispensable participation of a number of state and municipal institutions is required in this process. In Bulgaria, for example, these are the departments of the Ministry of Regional Development and Public Works (MRDPW), the Ministry of Environment and Water (MEW), the district and municipal administrations. The participation of private organizations as construction companies, investors, consulting organizations, etc., is also possible.

2. The decisions are made and are intended to be in force within a relatively long period – 20, 30 and more years. This means that once they have been approved and implemented, to change them or make corrections in them would be neither easy and cheap or rapidly accomplished in time.

3. The areas, “affected” by these solutions, as a rule are large geographic regions, economic districts, human resources. Indirect influence is also exerted on the business-economic relations of the whole state.

4. The realization of any of these decisions requires significant investments, the greater part of them being in principle state resources.

For this reason the adequate decision making in the management and use of water resources is an extremely delicate and responsible task [1]. This trend will be enhanced further on in future due to the crucial importance of water resources for society.

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2. DSS conception and organization of models

Decision Support Systems (DSS) are modern instrument in aid of making comprehensive decisions. The DSS will have to refer to a database, with Geographic Information System (GIS) and related applications playing a prominent role. The GIS is supposed to play a vital role at the initial stage of spatial decision-making. Spatial visualization enables an easy overview for users, and a pre-defined data bank sub-system simplifies the work with the DSS. One such DSS is TRANSCAT DSS (TDSS) [2] used here as a prototype. It is designed to support decision making in TRANSboundary CATchments for integrated water resources management. TRANSCAT is composed of three essential kinds of elements (Fig. 1):

- the decision analytic applications, including MULINO DSS (mDSS), Mediator, ProDec, BarTend (Bargain) and ArgWar, most of them associated with strategic type of decisions (policies, large projects, etc.), but also with the design of decision procedures (ProDec),
- the core system cTD, being the main data provision, processing and interfacing tool, orientated mainly at operational functions, and
- the models, and the related applications, serving to represent individual components of the natural, technical and socio-economic object system (e.g., the HEC-HMS surface flow model, the ModFlow underground flow model, etc.).

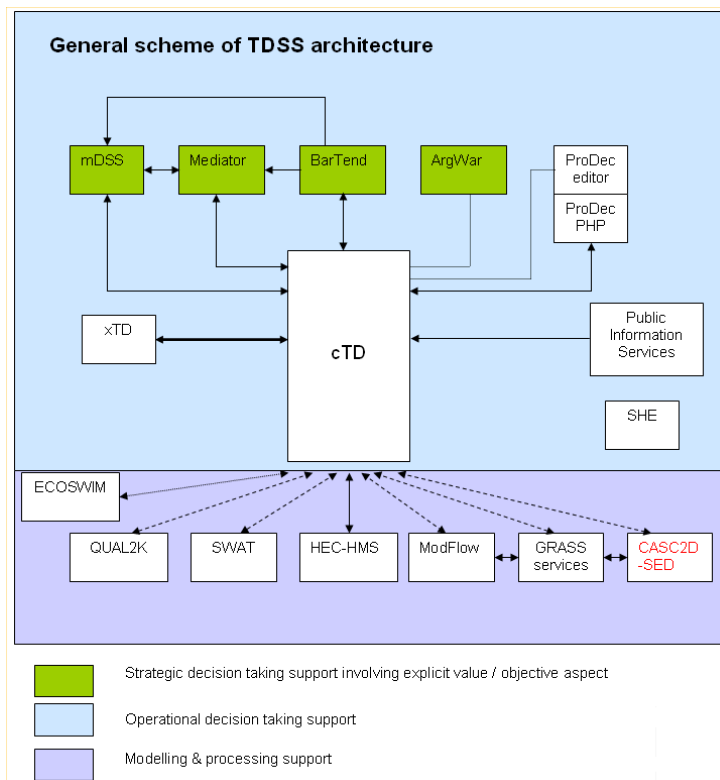


Fig. 1. Principle elements of TRANSCAT DSS

The TRANSCAT DSS is not an integrated system in the sense of “stiff” connections between the system elements. All of its elements can be used as self-standing entities. The connections are actually established according to needs, though the (interfacing) facilities for them are made available.

The work with TDSS is based on multi layer client-server architecture [2, 3]. In such case the thin client is represented by web mapping application with appropriate information, querying, analytical and modelling functions. On the server side, the system utilizes the WWW server, database system, map server and an application server. The last one provides a connection to hydrological/hydraulic/hydrogeological modelling systems, based mainly on existing software solutions. The model must be prepared and calibrated in environment of some modelling framework before loading it into the system.

3. Multiple Criteria Decision Analysis

MULINO software [4] is an operational support system for the management of complex multi-sectoral problems of water resources and water quality at the catchments and river basin scale. It integrates the conceptual framework, hydrological model, multi-criteria evaluation and sensitivity analysis. MULINO realizes the scheme for decision analysis adapted by European Environmental Agency (EEA) [5]. It is based on the so called DPSIR conceptual framework (Driving forces, Pressures, State, Impact and Response). The use of MULINO has been conceived as a part of a larger process of involvement of the different stakeholders that were requested in collecting data, declaring their preferences for the alternative options, giving suggestions for decision criteria and their ranking, explaining the role, responsibilities and relationships between different stakeholders (group decision making). In this approach the Multiple Criteria Decision Analysis (MCDA) [6, 7] is used as a powerful tool for solving problems where decision maker has to choose the “best” solution among a finite set of possible alternatives (discrete policy options) according to several objectives.

An example of such applications is water quality management [8]. To start with we have to formulate a number of criteria or objective functions and to formulate a set of alternatives (actions for achieving the objectives).

Remember that in MCDA approach the objectives are considered as a whole. In this case the optimal solutions do not exist as in the single criteria case. Instead Pareto optimal solutions are defined [7, 9, 10]. Also the human factor as experts and decision makers (DM’s) plays an important role in solving MCDA problems. The DM sets his preferences and/or evaluates the computed solutions to achieve the best compromise solution.

Let us denote the objectives as f_i , $i = 1, \dots, k$, and the alternatives with a_j , $j = 1, \dots, n$, and the value of alternative a_j according to the objective f_i as v_{ij} . Then the formulation of MCDA problem becomes in matrix form (e.g. rows as objectives and columns as alternatives) to choose an alternative according to some rule (method) [7, 9, 10, 11] that satisfies all objectives as much as possible.

The following scheme could be used for water quality management problems [6]:

Step 1. Defining of a set of objectives for water quality.

Step 2. Defining of a set of possible actions (alternatives, solutions) for solving the problem – for example construction of treatment stations and/or reservoirs.

Step 3. Filling the cells of decision matrix.

Step 4. Choose the best alternative by using appropriate method for Multiple Criteria Decision Analysis.

Step 5. The selected alternative could be investigated further by using sensitivity analysis.

Step 6. If the chosen alternative is not satisfying due to some possibly unknown reasons then the model could be changed – the set of objectives and/or the set of alternatives. Also Group Decision Making can be applied.

Steps 1 and 2 can be performed in reverse order or simultaneously. Steps 3, 4, 5, 6 are usually performed with the help of DSS and by participation of Decision Maker(s) (DM). In our case we use the Mulino DSS software [4, 12, 13].

Among others this is one of the tasks that TRANSCAT DSS can perform [2].

4. Formulation of a model

We shall demonstrate the application of TDSS module MULINO that is designed for multiple criteria decision analysis in water quality management. Let us consider a region (watershed) with 5 principal towns T_i , $i= 0, \dots, 5$, along a main river. Further, let us assume that 3 water monitoring stations S_i , $i= 1, 2, 3$, are available in the region.

4.1. Input data

The following water-quality parameters representative of a river basin were used: water temperature, pH, dissolved oxygen, nitric dioxide (NO_2), biological oxygen demand (BOD_5), electric conductivity, permanganate oxidizability, chloride, sulphide, ammonium nitrogen, nitrite nitrogen, nitrate nitrogen, phosphates, calcium, magnesium and water hardness. All data needed for calculations are taken from the recent Bulgarian river engineering practice. The data of these parameters are related to the three water monitoring stations.

Let us assume certain worsening of some parameters as BOD_5 and N-NO_2 in the specified sections of the river. Usually the presumptive pollution sources are [1, 8]:

1. Household wastewater from the settlements in the catchment area.
2. Industrial wastewater for example from wood industry; it cannot be predicted exactly which branch of industry will be developed in future.
3. Wastewater from mining activities.
4. Agriculture – we assume that due to the restricted areas there are no possibilities for significant development of agriculture.

5. Tourism – for example the region offers good conditions for the development of tourism.

To have a good water quality in a river relevant Waste Water Treatment Plant (WWTP) for purifying wastewater flows is usually constructed. Let us assume that there is a WWTP in the first town T_0 . However if certain steps are not made in ecological respect, then serious aggravation of some of the water quality parameters may be expected in the region in the future. For this reason the water quality problem in the river basin is very important and relevant decision should be done.

4.2. Alternatives and objectives

In practice the treatment of domestic and industrial waste water is based on construction of Waste Water Treatment Plants (WWTPs) and/or river dams for biological purification of the water. Also wetlands are used for treatment of waste water. However a relevant territory of wetlands downstream of the settlement is needed. Construction of a WWTP is a less expensive and faster alternative than a dam. But the dam serves also as a reliable water source, as a protection against flooding, and it can be used for electricity production. Therefore in our study we combine WWTPs and dams of different volumes as practical approach to the problem for sustainable and long-term improvement of water quality and safe water use in the region. Thus the following alternatives are formed:

1. The construction of four WWTPs for the main settlements along the river course – the towns T_1 , T_2 , T_3 , and T_4 is proposed. This means altogether five WWTPs.

2. The construction of four WWTPs as in the first alternative is proposed, in combination with a mini-dam (volume of 2-4 million cubic meters) for improving the river water quality in the region of T_4 .

3. The construction of three WWTPs for the main settlements along the river course – the towns T_1 , T_2 , T_3 , and of a medium-sized dam at a tributary of the main river with envisaged volume of 20-25 million cubic meters.

4. The construction of two WWTPs for the towns of T_2 , and T_3 is proposed, and of a medium-sized dam (20-25 million cubic meters) at a tributary of the main river.

5. For comparison it is included as a fifth alternative the option of not undertaking anything, i.e. the present situation with only one WWTP in the town T_0 .

The following assumptions are made:

(i) With respect to the water-quality measuring point: We suppose that the point of measurement will be after all treatment plants and one is close to the end of the region. In this way the problem with ensuring the necessary quality of the water flowing downstream the region will be solved. At the same time it will be achieved good water quality in the possibly longest section of the water course in the region. In our case we work with one main control point at the end of the region, and set the task of achieving parameters for *II category pure water and III category satisfactory pure water* according Bulgarian water quality legislation (see [1]).

(ii) With respect to the waste water treatment plants (WWTPs): We suppose that their capacity is sufficient to meet the requirements for reaching the above formulated water quality parameters within a time horizon including for example tens of years in future, corresponding to the WWTP operational lifetime. It is expected that the growth of population, development of tourism, industry and agriculture, should be taken under consideration. This applies also to the characteristics of dams. It is also supposed that an appropriate hydropower plant for electricity production will be constructed downstream the medium size dam.

We have selected the following decision criteria, which could be classified in two groups: economic and ecological criteria.

Economic criteria

- 1 – costs of the project (alternative) realization (BGL)
- 2 – time of the project realization (years)
- 3 – period of operation of the realized project (years)
- 4 – operation costs of the given project (BGL)

Ecological criteria

- 5 – level of ammonium nitrogen (mg/l)
- 6 – level of nitrate nitrogen (mg/l)
- 7 – level of nitrite nitrogen (mg/l)
- 8 – level of phosphates (mg/l)
- 9 – biochemical oxygen demand – BOD₅ (mg/l)
- 10 – level of dissolved oxygen (%)
- 11 – level of permanganate oxidizability (mg/l)

The following considerations were taken into account when selecting the above criteria. The mentioned economic criteria provide sufficiently full description of the “cost” of each alternative. The ecological criteria include the most important (but not all) parameters for the water category determination. We have included the parameters, for which observations have been made.

MULINO DSS realizes the scheme for decision analysis based on the DPSIR conceptual framework. According to this approach the factors of main importance are divided into three groups: (1) Driving forces and (2) the resulting environmental Pressures on (3) the State of the Environment, and all are measurable. Then the set of criteria is formed as a subset from the set of D-, P- and S-factors. For this purpose the so-called DPS-chains are constructed in a definite manner. The respective Driving forces, Pressures and States are taken from preliminarily developed to this end catalogues [12]. The user can also develop additionally such catalogues, and at the later stages this set can be changed according to DM’s wishes.

It is important to point out that one DPS chain may contain only one or two (and not three) elements. The indicators that will be used as criteria in our model are selected from the list of already created DPS chains. It is not obligatory for all indicators to be criteria. An example of DPS chain is: urban-population → urban-net-emission-of-BOD₅ → BOD₅-level-in-river.

4.3. Filling the cells of the analysis matrix (AM) and transforming to the evaluation matrix (EM)

Following the scheme from the beginning we enter values in the cells of AM (analysis/decision matrix) as follows:

For the economic criteria (2 – time of project realization and 3 – period of operation of the realized project) we have expert data on our disposal in real units (years), which we write there. However we have no concrete data for the next two criteria (1 – costs of the project (alternative) realization (BGL) and 4 – operation costs of the given project (BGL)). This may happen and direct comparison of the alternatives with each other is envisaged in MULINO DSS – [12]. For this purpose a 9-degree scale is applied. A similar scale was used for the first time by Saaty in the method of Analytic Hierarchy Process [14]:

- 1 – the alternatives are equal with respect to the corresponding criterion
 - 3 (1/3) – the alternative is moderately (better/worse) than the other alternative
 - 5 (1/5) – the alternative is strongly (better/worse) than the other alternative
 - 7 (1/7) – the alternative is very strongly (better/worse) than the other alternative
 - 9 (1/9) – the alternative is extremely (better/worse) than the other alternative
- The levels 2 (1/2), 4 (1/4), 6 (1/6) and 8 (1/8) are intermediate ones.

We set thresholds for the ecological criteria No 5-11 that would be met by the alternatives (projects). These are the conditions for water quality of the second (II) and third (III) category. They are proposed by experts in the field from Bulgarian Academy of Sciences [1].

In this way we have already filled in all the cells of our AM matrix (Fig. 2).

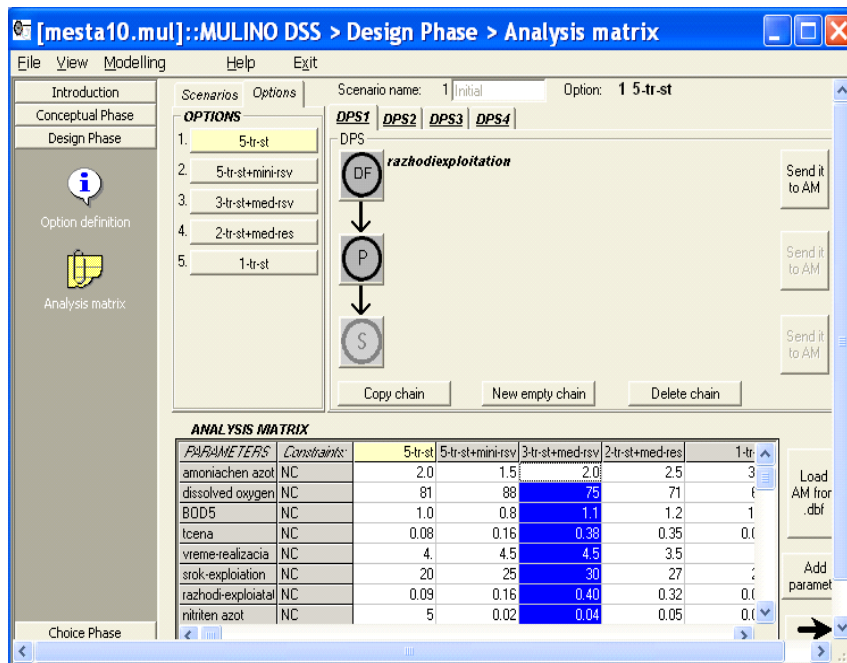


Fig. 2. AM matrix

After the completing the AM matrix, it is transformed into normalized evaluation matrix (EM) by performing “Value Function transformation”. Three types are provided – cost, benefit and user defined transformations [12]. In our case we use cost and benefit types of transformations.

5. Solving of the problem

This is the stage where the DM solves the problem by MCDA method. Three well known methods in MCSDA’ literature are provided in MULINO DSS – SWA (Simple Additive Weighting method), OWA (Order Weighted Averaging method) and TOPSIS (Technique for Order Preferences by Similarity to Ideal Solution).

Assume the DM sets equal order weights for each objective (i.e. equal preferences to objectives). Then the solution by OWA method (Fig. 3) is the alternative No 2.

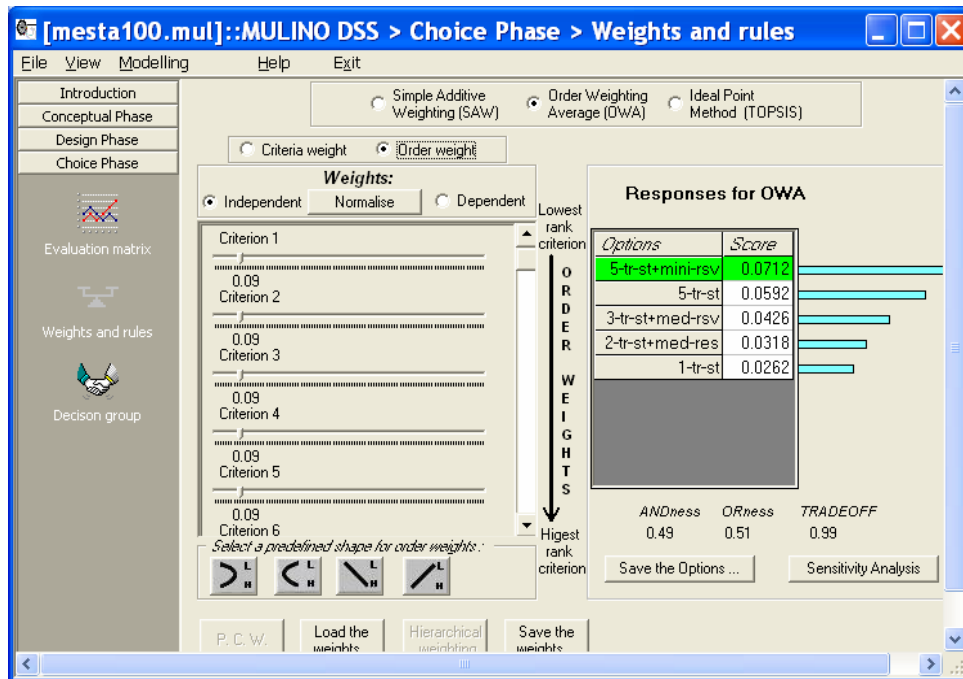


Fig. 3. Solution by OWA method

The selected alternative for sustainable and long-term improvement of water quality in the region offers construction of 5 WWTPs plus mini-dam. Intuitively, it seems to be one of the promising alternatives with the third alternative also. This is due to the fact that we pursue the goal to have a good water quality along as long as possible section of the river and moderate investment costs. Indeed, the method produces this alternative. The same solution is received also if we use TOPSIS method.

But when solving the problem with more detailed data and when the DM gives different weights to different objectives the result can be very different. For example, the objective “price-of-the-project” (limited investment costs) and/or “time-for-exploitation” (maximize) could have significant influence to the final solution. The solution in the first case is the alternative No1 (one WWTP per town).

Therefore it is recommended the problem to be solved several times at different stages of design and by different DMs.

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Моделирование и многокритериальное принятие решения для проблем управления качеством воды

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(Резюме)

Принятия решений при управлении качеством воды базируется на мнении разных управленческих и заинтересованных институтов и специалистов. Здесь демонстрируется один прототип системы поддержки принятия решений, которая интегрирует три современные многокритериальные методы. На основе одиннадцати экономических и экологических критериев наглядно демонстрируется выбор решений на улучшение качества воды из пяти возможных альтернатив.