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AN INTEGRATED FRAMEWORK FOR SOLVING WASTEWATER PROBLEMS AT THE REGIONAL LEVEL

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ABSTRACT
The implementation of the Water Framework Directive (WFD) asks for the commitment of all European member states. There are many different issues to be considered simultaneously and appropriate methodologies and tools are needed to overcome the complexity of this mission. This article presents an integrated framework for solving wastewater problems, at a regional level, aiming at achieving the WFD goals. This is a challenging task from all viewpoints: environmental, economic, social, and technical. The various levels of intervention deemed necessary for this purpose are described and the need for appropriate methodological tools is analyzed.
Keywords: decision models, wastewater systems, Water Framework Directive.

1 INTRODUCTION

In the European Union, the great concern about water is expressed through the Water Framework Directive (WFD). The integrated water resources management (IWRM) approach to water problems is adopted and a "good" status must be achieved by all water bodies by 2015. The necessary decisions are constrained by this operational issue, and so the approaches used in the past have to be revised and new methodological tools should be developed for the implementation of the WFD.

In spite of the progress made in recent years, many improvements still have to be accomplished for the achievement of WFD goals for wastewater systems. In fact, wastewater generated in 183 of the 556 European Union cities with populations over 150,000 is discharged into rivers and other water bodies either completely untreated or insufficiently treated [1].

Fresh water is a strategic resource, but human activity in river basins has had a great impact on water status, changing the physical, chemical, and biological conditions of many rivers, and considerably interfering with the ecological state of riverine communities. Point sources of municipal and industrial pollution and non-point sources arising from various activities like agriculture are among the most critical threats to such systems. So, it is of major importance to guide the development of sanitation schemes in order to be in harmony with the WFD. These problems should be tackled in a regional context to take advantage of economies of scale and higher environmental efficiency. The scale of investment usually involved in establishing wastewater systems at the regional level and the different issues to be considered within the scope of a holistic intervention give rise to a set of complex decisions that have to be implemented.

Decision models, as pointed out by the guidance document for a Common Implementation Strategy for the Water Framework Directive [2], can be very helpful for decision makers in the context of IWRM. Decision models can simultaneously consider the different facets (economic, social, technical, environmental, legal) characterizing such problems, thereby leading to more sustainable decisions. Their use involves a structured approach to finding the best solutions that are appropriate for solving problems of sizing and siting the different components of a wastewater system. These components include the sewer network that will take the wastewater from the different sources (villages, small, towns, and cities) to be treated in the other component of the system, namely the wastewater treatment plants. Such a system is established on the basis of the decisions that have to be taken in relation to

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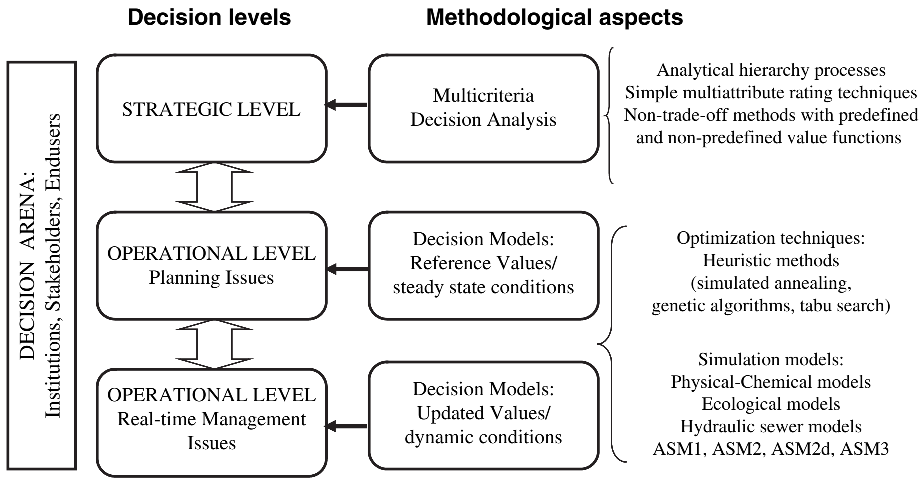

Figure 1: Integrated framework.

diverse levels of intervention. An integrated framework that considers three levels of intervention is proposed for the integrated solution of wastewater system problems at the regional level (Fig. 1).

The various models for defining the decisions at different levels, to be developed in this framework, are:

- Models to help the decision-making procedure relating to regional wastewater systems at a strategic level, considering the different actors that should cooperate to identify and define the major action criteria.
- Planning models for regional wastewater problems at an operational level aiming at the operationalization of the WFD, thus explicitly taking into account the impact of effluents in terms of "good chemical and ecological status".
- Management models for the real-time operation level of wastewater systems, taking into account the quality dynamics of receiving waters.

2 DECISION LEVELS

2.1 Strategic level

The decisions to be defined at a strategic level should take into account the different actors who may be involved in wastewater problem resolution at the regional level (private and institutional stakeholders, and interest groups).

The various arms should cooperate in identifying and defining the major possibilities of action criteria for the intervention that is to take place. First, the decision-making context must be understood and established. This means defining the actual decision-makers, everyone with a stake in the outcome and the agreement in the decision procedure to attain the objectives of the intervention. In almost all decision-making procedures relating to environmental systems, there are several goals to be considered at the strategic level. The management of environmental and natural resources systems is intrinsically a multiobjective task, where environmental quality is pitted against economic considerations. Intervention in environmental systems usually demands huge investments of time and money and very complex analysis. The world is, in fact, multifaceted and the decisions will have to satisfy several, potentially conflicting, interests.

The resolution of regional wastewater problems almost always exposes conflicts between upstream and downstream interests. Where to locate wastewater treatment plants, which zones to traverse with the sewer system, what treatments to use, what environmental standards are to be achieved by receiving water bodies – all these questions will be in the decision arena. The relative importance of the objectives represented by a set of preferences has to be established, and therefore a set of decision criteria (including technical criteria, and economic, environmental, and social principles of sustainability) has to be defined to facilitate debate.

The problem described could be tackled using cost-benefit analysis, by considering only a single objective after converting all the objectives into the same currency. These cost-benefit functions can be used for the maximization of net benefits.

But there are a large number of objectives involved in the resolution of environmental systems management that cannot be easily translated into common units (e.g. human health and life, environmental impacts, convenience, and aesthetic quality). Even if they can be converted in some cases, it is still necessary to make judgments to perform the conversion, which implies agreement between the parties. A strictly economic interpretation of benefits does not capture aspects like loss of quality of life.

The decision-makers have to find ways of weighting non-economic dimensions of value against economic benefits. Decision-makers have to clearly understand and evaluate all the alternatives, recognizing the trade-offs among objectives. An analysis tailored to cope with ambiguous and uncertain situations is needed.

2.2 Operational level/planning issues

Once decisions are taken at the strategic level, the operational decisions have to be made. This can, in fact, be a feedback process. Operational decisions should take into account the information provided in the previous level. A planning decision model should be used to determine the sites for treatment plants (using the possible areas defined previously), their characteristics (using environmental constraints defined previously and the environmental requirements of the WFD), the design of sewer networks connecting communities to treatment plants (using the possible areas and the groups of communities defined previously), so that the discounted total cost of the entire system is minimized and environmental requirements are fulfilled.

The configuration of a general decision model (including an objective function Z subjected to a set of constraints $g(x)$, with x as the decision variables) is shown in Fig. 2. It is of crucial importance that the formulation of the planning model includes:

- Constraints to achieve the good chemical status and the good ecological status of receptor water bodies;
- Measures of robustness to find decisions that will permit the good performance of the wastewater system, even under adverse conditions;
- Environmental costs and resource costs as proposed in the WFD (besides the installation, operation, and maintenance costs).

These are fundamental aspects for the implementation of the WFD, bearing in mind the combined approach. The costs of implementing a given alternative should be dealt with by more detailed planning models built for operational purposes. The incorporation of chemical and ecological models will influence the location and size of treatment plants and the type of treatment each provides.

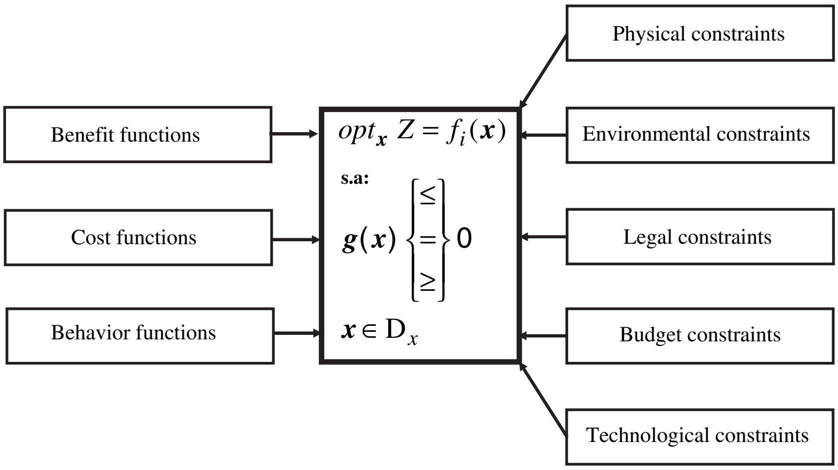

Figure 2: General decision model.

The sensitivity of the solutions to the different demands of water quality parameters is evident [3, 4]. Systems with a larger number of plants obviously have a more uniform distribution of pollution load, and thus better water quality. However, as decisions are to be made that take into account both environmental requirements and economic aspects, scale economies must be analyzed too. Therefore, the decisions regarding the site and sizing of these components should be made with a view to minimizing costs and fulfilling environmental requirements.

2.3 Operational level/real-time management issues

Decisions for real-time management have to be dealt with here. The wastewater planning models mentioned previously define the location and size of treatment plants, and the type of treatment each provides. These decisions will be based on the inclusion of a water quality model in the planning model.

For planning purposes, steady-state conditions are usually assumed when solving the differential equations governing the physical, chemical, and biological processes involved. But, in fact, when it comes to the operation of the treatment plant, the quality dynamics of the received waters is an important factor for consideration. Weather conditions influence the flow in water bodies, so the dilution process can vary over time. It is possible that treatment plants cannot be operated as initially expected because of the maximum allowable concentration. In addition to this, the amount of waste generated can also vary during the year. Seasonal, monthly, or daily variations in the amount of waste produced, as well as the variation in the quantity and the quality of water body flows, may lead to an upstream to downstream redistribution of the wastewater to be treated in each treatment plant in order to meet water body quality standards. It is therefore important to have a model to handle the integrated operation of the multiple wastewater treatment plants.

The data needed to run an operational model that will adjust the amount of waste to be treated and the degree of treatment to be provided in each treatment plant to real-world conditions is supposed to be centralized in a data acquisition system. This system will receive information from a monitoring system providing quality parameters at treated wastewater rejection points, and the amount of waste to be treated.

Real-time management (operation) models will permit decisions to be made on the degree of treatment to be applied and the schedule of discharges to be implemented in each treatment plant, given the quality dynamics of the receiving bodies.

3 METHODOLOGICAL ASPECTS

3.1 Optimization techniques

At the strategic level, the capabilities of different multicriteria decision analysis (MCDA) approaches have to be evaluated in the context of environmental decision-making processes. Analytical hierarchy processes, simple multiattribute rating techniques [5], non-trade-off methods with predefined (PROMETHEE [6]) and non-predefined (ELECTRE III [7]) value functions have to be analyzed to assess the relative sustainability of the different alternatives that are to be built.

At the operational level, the problems involved in regional wastewater systems can only be dealt with properly if the corresponding optimization models include non-linear cost functions for the installation, operation, and maintenance of sewer networks, treatment plants, and pump stations; describe the non-linear hydraulic behavior of sewer networks; allow for yes or no decisions on the location of treatment plants and pump stations; consider the diameters commercially available for sewers, etc. This means that the models used must be mixed-integer and non-linear (MINL).

This type of model can only be solved to (guaranteed) exact optimality under assumptions that regional wastewater system problems typically do not satisfy. The alternative is to resort to heuristic methods. Until the 1980s, the heuristic methods available frequently led to local optimum solutions that were far removed from global optimum solutions because of the gradient-based search strategy that was employed. New kinds of heuristic methods were devised in the 1980s. Modern heuristics, which are often inspired by natural processes, use search strategies that often allow local optimum solutions to be avoided, and so they quickly became very popular among scientists and engineers.

Different modern heuristics approaches (e.g. simulated annealing [8], genetic algorithms [9], tabu search [10]) have to be evaluated to determine the best option for solving the problems described.

3.2 Development of physical–chemical and ecological simulation models

According to the WFD, all member states shall achieve good surface water status by 2015, which means that the ecological and chemical status of all bodies of surface water must be classified as “good” by then.

In this context, it is important to analyze the problem of effluent discharge into surface water bodies at a regional level, so as to evaluate the global effect of multipoint pollution sources on the receiving water bodies.

The advection–diffusion equation can be used for physical–chemical evaluation. The incorporation of water quality models into decision models through advection–diffusion equations can be a very complex task. There are differential equations to be solved for which analytical solutions are not known, and numerical models have to be resorted to. Given that real-world problems are usually on a large scale, the problem of how to handle them when they have to be incorporated in optimization models remains an important research topic. Solving numerical models using space and time discretized equations is extremely time-consuming, and this aspect strongly conditions the performance of the models, particularly for real-time management. At this point, it is necessary to stress that, besides the water quality simulation model of receiving water bodies, the integrated decisional model for real-time operation has to include a hydraulic simulator of the sewer system and a mechanistic model to simulate the wastewater treatment performance (based on models such as ASM1, ASM2, ASM2d, ASM3). A more appropriate simulation model for water quality evaluation should thus be built based on an artificial neural network approach or cellular automata techniques.

Another important issue concerns establishing relationships between the physical–chemical status induced by wastewater discharges and the resulting ecological status of the surface waters.

Due to the relative complexity of the relationships, for the regional planning of wastewater systems the ecological status could be assessed using a simplified approach based on the analysis of aquatic invertebrates, which are very useful indicators in biological monitoring. Therefore, it is important to identify families of aquatic invertebrates that might be used as biological indicators for different surface water types. The behavior of these species should be tested against the physical–chemical factors and/or pollutants that have higher impacts. Then specific relationships between the level of pollutants and/or key environmental parameters (e.g. dissolved oxygen, pH) and the presence/abundance of the selected aquatic invertebrates can be established and translated by mathematical expressions. These ecological models are crucial to the evaluation of the different planning alternatives. They will allow the determination of the consequences of the location and sizing of the wastewater treatment plants for the ecological parameters of the receiving water bodies.

4 CONCLUSIONS

An integrated framework for the implementation of the WFD objectives in the context of wastewater systems at the regional level is presented. With such a framework, the decisions to be taken at the strategic and operational levels are expected to be obtained with a feedback perception. Different types of decision models appropriate for identifying the decisions intrinsic to each level of intervention are analyzed and the need for adequate simulations for the quality status of receiving water bodies' tools is pointed out.

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