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Aspects of the application of decision and information support tools in an integrated water resources management practice

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Abstract: The paper presents some problems with the use of modelling, decision, and information support tools (MDISTs), for the implementation of integrated approaches to water resources management. The problems arise because in many cases current monitoring practices do not provide sufficient amount of reliable data for model calibration and verification. The paper emphasises the need for a system analysis approach at all levels of magnitude in a water system - considering all elements, subsystems and their interactions – and the integration of the MDISTs with the corresponding monitoring practices, regulatory instruments and management activities in a closed-loop cycle. Finally, we discuss how MDISTs could be used in the particular case of developing countries.

Keywords: water systems; monitoring; regulation;

1. INTRODUCTION

The integrated approach to water resources management (WRM) practices has been accepted as a leading concept in the field. This approach requires a catchment orientated analysis and the consideration of factors and interactions in the following directions: 1) All natural aspects of the system: surface and ground water, the physical behavior of water, environmental water requirements, impacts and interactions with other environmental media, such as soil and air; 2) Simultaneous consideration of both quantitative and qualitative aspects of water resources; 3) All sectors of the national economy that depend on water, with corresponding engineering structures; 4) The relevant national and local objectives and constraints: legal, institutional, financial, and environmental; 5) The institutional hierarchy and arrangements at international, national, provincial, and local levels, and their corresponding interactions; 6) The spatial variation: upstream and downstream interaction, basin-wide analysis, inter-basin transfer.

It is clear that the implementation of an integrated water resources management (IWRM) practice is a multi-objective task that requires the consideration of numerous factors, and conditions, expertise from different fields of specialization, as well as a large amount of information that needs to be collected, organized, analysed and presented in clear and understandable form. This task cannot be achieved in a sustainable and objective way without the use of MDISTs. The aim of this paper is to emphasize the need for practical application of MDISTs and to discuss specific shortcoming (gaps) in the process.

2. THE SYSTEM APPROACH TO IWRM

The system analysis approach requires the development of the system architecture which identifies the major elements, subsystems and their interrelationship. Often, the formulation of the system is highly subjective, and according to Lendaris [1986], "the system is in the eye of the beholder". Still, the formulation of the conceptual framework can be defined in terms of individual tasks or problems. From the perspectives of IWRM, the basic system under consideration is the catchment basin of given water body [WFD, 2007], including all physical elements: natural water bodies, and man-made structures that influence the water resources status. This paper concentrates on the physical aspects of the catchment elements, as a basis for the system framework formulation, but also emphasizes interconnections among system elements and some "soft" issues, such as institutional and legal arrangements, public involvement and socio-economic development.

An example of a system framework at basin level is presented in Figure 1. The elements of the system include surface and ground water natural resources, as well as, man-made water subsystems that use and influence natural water bodies. A sustainable approach to IWRM requires assessment and simultaneous consideration of both quantitative and qualitative parameters which characterize the current status, trends and variations due to human interaction with enough accuracy. The major quantitative parameters under control are flow rates, rainfall volumes or intensities, water volumes per given period of time and surface/ground water levels. The major water quality parameters under control - such as BOD/COD, solids, specific ions, nutrients, toxic substances, microbiological characteristics - indicate the environmental health of the system. Qualitative assessments of the system behaviour are often estimated based on pollution transport principles and are represented as pollution loads (the product of flow rates and pollutant constituents' concentrations). Mass-balance principles are applied to assess the status of the system and alterations due to human interference.

Under an IWRM approach, all factors shown in Figure 1 should be considered during the decision-making process. Each one of the natural water bodies (rivers, lakes/dams, and ground water aquifers) are usually analysed and modelled at basin or inter-basin levels. One of the most widely applied tools for such analysis is BASINS, developed by USEPA, which provides a framework for integrated basin analysis, based on national water quality, soil and climate data, GIS and different environmental modelling and assessment tools.

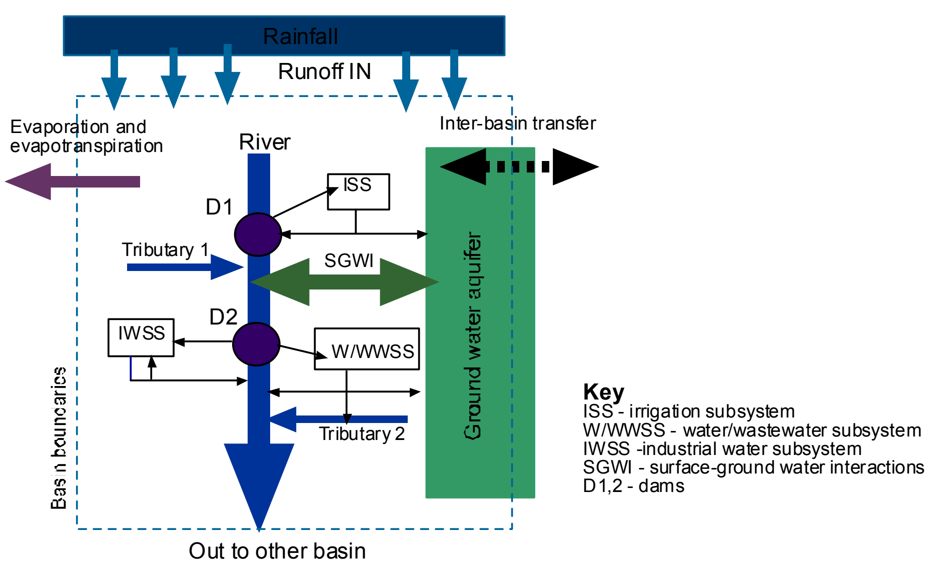

Figure 1 Conceptual framework at basin level

It incorporates the QUAL 2, the HSPS and alternatively the SWAT models. QUAL 2 simulates contaminants transport and transformations in rivers and streams, while the HSPS and SWAT models simulate and allow the evaluation of the impact of different management scenarios on the basin hydrology, water quantity and quality status (point and diffuse pollution), including surface water, sediment transport, ground water and their interactions. HSPF is a lumped parameter model (FORTRAN), while SWAT is based on a command language and includes the subdivision of the basin on hundreds to thousands sub-basins, thus allowing great spatial detail. Comparison of the performance of both models applied to a rural area with intensive agricultural activities [Saleh and Du, 2004], and to a predominantly forest area with urban development [Im et.al, 2003], shows that HSPF requires a bulk amount of data and a more complex calibration process. Regarding their predictive accuracy, both models show more or less similar characteristics, except that HSPF gives better prediction of the variation of daily flows and sediments, while SWAT estimates more accurately nutrient loadings, except for phosphorous.

The implementation of the IWRM approach in the European Union (EU), under the Water Framework Directive [WFD, 2000], also promotes the need for a systematic analysis. It sets a staged approach to an IWRM implementation, with a goal to achieve a good status of the EU's water resources by the year 2015. The DHI group offers an integrated tool to support this goal by a set of software products such as MIKE BASIN (water allocation), MIKE 11 (rivers and streams), MIKE SHE (surface/ground water interactions) and MIKE LOAD (a pollution load estimator). In addition, it provides software to incorporate the analysis of engineering subsystems in urban and rural areas.

The engineering subsystems are entities on their own, involving complex configuration and processes involved. Therefore, a different level of analysis (in terms of spatial magnitude) is necessary in order to the define inputs and outputs affecting the basin system. Figure 2 shows an example of a water engineering subsystem related to the use of water in population centres with a combined sewerage. It comprises of elements and third level subsystems, such as water/wastewater treatment plants and distribution or wastewater/storm water collection networks. Under a separate wastewater system, storm water conveyance and flood prevention structures would be represented as an independent subsystem. It should be noted, that the subsystem in Figure 2 reflects centralized solutions of both water and wastewater conveyance and treatment. Decentralized solutions regarding water supply or wastewater structures would lead to a different system framework and to different levels of magnitude of space – suburb, neighbourhood, individual building.

One important aspect during the engineering subsystems' analysis is the consideration of existing and planned land use patterns in the catchment and the specific urban development plans. The link between land use planning and water resources management is often overlooked. New development projects, especially in urban areas, relay on classic supply-orientated water management solutions. They do not explore and apply thorough analysis and innovative concepts that consider improved water demand and storm water management practices, and reduction of pollution loads to the environment.

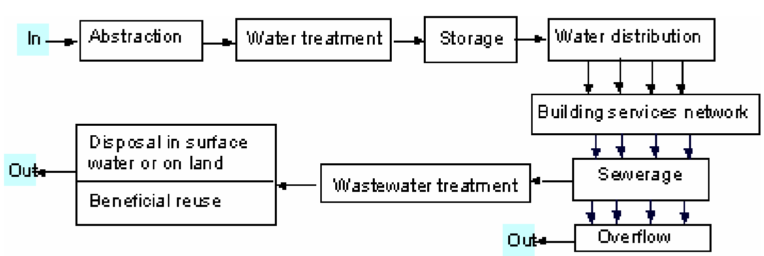

Figure 2 Conceptual framework at population centre level

The implementation of demand orientated approaches, decentralized wastewater systems, rainwater harvesting, and water reuse alternatives could reduce significantly future water demand estimates, and would lead to more sustainable water use scenarios, but only if anticipated during the planning stage of urban development plans and after thorough evaluation of all technical, economic and social factors [Hranova, 2006a]. In this respect, Hurley et. al., [2007] describe an urban development projects' assessment tool (Flexiframe), which integrates information across disciplines, stakeholder groups and professions, and also considers economic, environmental, social and technical criteria. Another example of the application of integrated approaches to urban planning and urban water systems management is the development of sustainability assessment methods and tools [Carden et.al., 2007]. Spears [2006] underlines some drawbacks in the policy formulation and the decision-making process regarding a sustainable urban water development, and points out that the application of new information technology tools could speed up the process and lead to a "leap frog" change towards sustainable solutions.

In general, the systems analysis approach to IWRM requires the definition of all systems elements and sub-systems at different levels: starting from the smallest systems in terms of spatial magnitude and following up the different levels up to basin level of major rivers (continental scale). Such an analysis is often narrowed or not implemented, because in many cases local and national administrative boundaries do not coincide with river basin boundaries, and also, in many cases of major rivers, the basin spatial magnitude involves a number of countries. Lack of coordination and optimal use of available information is aggravated by the fact that systems at the basin level are managed by national authorities, while engineering subsystems are managed by local authorities, and the corresponding information is collected, used and controlled by different institutions. In addition, water resources managers are usually focusing only on quantitative aspects only and their major concern is to provide the estimated demand for water. On the other hand, qualitative aspects are the domain of environmentalists and their major objective is to protect the status of the water resources. Both aspects, if not integrated under the system approach, often lead to conflicting management decisions. The implementation of the system approach avoids this by allowing for an integrated analysis of all aspects of the system at its different levels, and contributes considerably to the formulation of sound and sustainable objectives of water resources management programs.

3. INFORMATION NEEDS AND MONITORING PRACTICES

Water management institutions at different levels perform regular monitoring programs regarding quantitative and qualitative parameters in order to assess the status of water resources and the impacts of man-made engineering structures. The data collected is the basis for calibration and validation of any modelling or decision-support tool, and in addition, serves as a benchmark or as an environmental indicator. Therefore, the successful application of such tools depends heavily on the amount and reliability of such data.

3.1 Gaps in the monitoring practices

The structure of any monitoring program depends on the formulated objectives, but the major characteristics are: monitoring network (sampling locations), types of monitored parameters (with specified testing methods and accuracy levels), and frequency of measurements. Under an integrated and systematic approach to WRM, monitoring programs should supply reliable, relevant and accurate information to support the system analysis process and the application of MDISTs. In practice, several problems related to monitoring can be mentioned.

Monitoring networks should be designed to provide information regarding both quantitative and qualitative parameters, at specific points of interest, as inlets and outlets to systems and subsystems, as well as, data about background (natural) pollution. Unfortunately, existing monitoring networks often do not conform to these requirements and it would be advisable to reassess the existing networks and to modify them in order to fit the system analysis process.

Testing methods and level of accuracy of measured parameters should be uniform throughout the system analysis process, in terms of space and time, so that it allows for comparison and estimation over the whole system. However, it is common for different laboratories to apply different testing procedures for the same parameter, even in the same population centre, thus leading to ambiguity of the data obtained. Standardization of the testing procedures throughout the system and the creation of common databases for system analysis would contribute considerably towards reducing the errors and uncertainties related to MDISTs applications and, in addition, would contribute to the optimal use of data obtained by different institutions. Also, it would eliminate ambiguity due to the differing magnitude levels of accuracy and ranges of measurements regarding monitored parameters. This applies specifically for water quality parameters: suspended solids, nutrients and BOD/COD are measured in mg/l; toxic metals are measured in μg/l, while some emerging constituents such as pharmaceuticals or endocrine disruptors are measured in nanograms/l. For example, a MDIST tool that supports the water quality management practice of Lake Biva [Ichiki et.al., 2005] provides information regarding the spatial variation of internal and external COD concentrations, with values varying between 0.13 and 4.4 mg/l; however, the American Standards [Standard methods, 1992], recommend a testing procedure with an acceptable level of accuracy between 5 and 50mg/l, and more accurate testing methods for concentrations above 50 mg/l. This shows that the use of such a data set to validate the MDIST would be unreliable and, as an alternative, the TOC (Total Organic Carbon) or other parameter could be used to investigate the organic matter variation in the lake, which is much more sensitive regarding low concentrations, with corresponding change in the monitoring practice.

The frequency of sampling incorporated in the monitoring program is another important point to be considered during the development, validation and application of MDISTs. In principal, the frequency of sampling should reflect with enough accuracy the status of the water body during the period when sampling is not done. For example, if measurements are taken once per month (monthly frequency), it should be anticipated that during this period the actual value of the measured parameter will not change significantly. Unfortunately, in surface water, both quantitative and qualitative parameters vary more often, especially during rainfall events. Increasing the sample frequency will make the monitoring program more expensive but the information provided will be more accurate. Ideally, automated monitoring stations would be the best alternative. However, they are more expensive and also, a number of important parameters can not be measured automatically. Therefore, the choice of monitoring frequency is a trade-off between the level of reliability of the data obtained and the cost of the information obtained.

3.2 Field data and model uncertainty

Model uncertainties are related to: input data and data used for calibration/validation, structure of the model, transformation functions and numerical operations. This section discusses uncertainties related to the use of data. In general, MDISTs are universal tools, based on scientifically proven assumptions, methods and computational techniques. However, their application in specific conditions requires locally obtained data that reflects with enough accuracy the operations and processes involved. Therefore, a reliable adaptation of given MDIST to the specific site conditions in the area would require a thorough validation process, based on locally obtained data from well established monitoring programs. If such data is missing, a data base from other locality with similar conditions might help, but such an approach should be used with caution. Thus, the adequacy of the available local data will determine at large extent the viability of the application of a MDIST.

Hydrological models estimate runoff, based on hydrological and climatic data and land use patterns, and logically, consider uncertain events (rainfall) as a random variable. However, MDISTs applied in water quality often don't consider the randomness in water quality data (as a consequence of rainfall), but work with fixed values, usually averaged annual parameters [Hranova, 2006b]. This approach might be acceptable for ground water quality modelling, where, due to the slow pollution transport process, pollutant concentrations do not show high variability. In contrast, surface water, storm water discharges and some point source discharges show much higher variability, and this needs to be considered during the monitoring process and during the models' development and application. Bertrand-Krajewski [2007] reports the result of an analysis of the influence of monitoring frequencies of a given data set on the calibration and verification of a simple model for evaluation of TSS Event Mean Concentrations (EMCs). It was observed that a significant difference in the frequency of measurements does not influence significantly the results of the calibration procedure. However, a significant impact was observed regarding the model verification procedures, such that the model outputs vary significantly, based on increased frequency, and furthermore, it indicates to a possible change in the model structure, which could not be observed, based on a data set with a smaller number of measurements.

4. REGULATORY APPROACHES AND THE APPLICATION OF MDISTs

The regulatory and legislative basis (legal and administrative documents, criteria and guidelines) is a key factor in IWRM. In respect to environmental and public health protection, the philosophy or the basic approach applied to the development and implementation of regulatory documents is the "Water Quality Objective (WQO)" approach, where the main goal is to maintain the status of natural water bodies at a required and specified level. This approach allocates different permissible pollution loads from man-made subsystems (considering both point and diffuse sources) at different locations, based on the current status of the water quality and its assimilative capacity. In the USA, a more detailed version is applied – the "Waste Assimilative Capacity Concept (WACC)", which requires the estimation of two parameters: the total maximum daily load (TMDL) from man made and natural sources (including background pollution), and the loading (assimilative) capacity of the water body under consideration. The comparison of the specific values of these parameters allows the determination of an admissible load (if any) to the surface water body, and based on this estimation, management decisions and plans may be developed. It is clear that both approaches require a systematic analysis at basin level, the collection of massive data sets, and the application of reliable tools for data analysis and processing. It should be emphasised, that the determination of the assimilative capacity of surface and ground water natural bodies could not be determined without the use of models describing with enough accuracy the pollutants transport and transformation processes. The proper development and application of such tools requires reliable and adequate monitoring data to reflect the specific conditions. However, many existing regulatory documents fail to provide enough specific information and detailed requirements, linking the management objectives to a well-specified monitoring practice (including networks, parameters with standardized testing methods and corresponding frequency of measurements) and a to recommendable MDIST, thus leaving gaps in the process of application of such an integrated and systematic approach.

The above-mentioned regulatory approaches allow for the estimation of impacts as a result not only of discharges from point or diffuse sources, but also, the impacts of significant volumes of water withdrawals from natural water resources. Another important aspect in this regard is the consideration of the environment as a legitimate user of water, thus providing the basis for a sustainable use of water resources and their preservation for future generations. In this regard, Breckenridge [2007] points out that current regulatory documents are focused predominantly on management actions in order to prevent pollution, but do not give enough emphasis on activities related to water bodies' rehabilitation, and suggests institutional changes, where local authorities or agencies need to be custodians of both the man-made subsystems and the natural systems under their jurisdiction. However, this raises the need of institutional arrangements, which should be structured in such a way that their authority could reflect the system as a whole.

5. MANAGEMENT PRACTICES WITH EMPHASIS ON DEVELOPING COUNTRIES

In the light of IWRM, the planning process of any activities related to natural or man-made water structures should be based on the outputs of the system analysis. It should incorporate "hard" (engineering structures) and "soft" activities, such as institutional arrangements, economic/financial analysis and public involvement, in conjunction. During this process, the application of MDISTs cannot be over-emphasised. They should be applied at all levels of magnitude in the system. In this regard, the development and analysis of several viable scenarios for a potential solution should be made with corresponding cost estimations and the choice of optimal solution, considering multiple factors, and often, multiple objectives. Thus, the selection process would be based on measurable and concrete criteria. For this purpose, linear, non-linear and evolutionary programming and optimization techniques, as well as, MDISTs based on them, are essential. Such approach to the evaluation of different alternatives is relatively simple to apply, and should be adopted not only by managing authorities but on a broader basis, by consultants working in the field. Furthermore, requirements for the development of multiple alternatives and a scientifically based choice of optimum alternative should be included during the tendering process of large water projects.

The considerations discussed in this paper are valid for all countries; however, developing countries usually face considerable challenges during the implementation process, due to lack of economic, technical and human resources. It is a common practice that management decisions are taken based on very limited local data, thus leading to subjective estimates and costly solutions. In addition, development goals often contradict environmental considerations and an acceptable trade-off should be made. Despite of these limitations, MDISTs should be implemented in the WRM practice because of the following considerations: 1) it would be an incentive for the implementation of proper monitoring and other data collection practice; 2) it would provide reliable means for record keeping and data accumulation; 3) it would provide for a sustainable and cost effective development; 4) it would help in an optimal use of available resources, which in the vast majority of the cases are limited; 5) it would provide for shearing of knowledge and general scientific information and methodologies among developing and developed countries.

5. CONCLUSIONS

The implementation of the IWRM practice requires an extensive, costly and technically intensive background, and many countries do not have the capacity to implement it on a broad basis. However, even if it would be implemented on a limited basis, in terms of spatial application and/or specified objectives, it requires a closed-loop cycle: system analysis at all levels → objectives→ conceptualization → regulatory basis→ MDISTs → monitoring programs → MDISTs → management practice→ system analysis. Such a cycle would contribute towards avoiding gaps in the implementation, helps to reassess the strategy periodically, and thus allows for a phased approach in the implementation process and for a sustainable use of the available resources.

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