Best modeling practices in the application of the Directive 2000/60 in Greece

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Abstract: - The main characteristics of the modeling procedure, especially these related to the application of the Water Framework Directive, are presented. These are (a) the building of models with sufficient degree of integration and (b) the requirement of calibration and verification of models with "high quality" field data. The relationship between modeling and monitoring is emphasized with the presentation of the optimization of the design of monitoring networks. The main "elements" of the water bodies are presented, focusing on the morphological and hydrodynamic "elements". Methods are described for the calculation of these "elements". A methodology is presented for the investigation of water management scenarios with mathematical models. Various applications of this methodology in Greece are discussed. These include: calculation of the values and the reference conditions for various water quality "elements", methods for facing an incident of accidental pollution in trans-boundary rivers or reservoirs used for water supply and controlling pollution in ground-waters.

Key-Words: - Mathematical Models, Integrated Models, Water Framework Directive, Surface Water, Ground water

1 Introduction

The purpose of the Water Framework Directive (WFD) 2000/60/EC [1] is to establish a framework for the protection of surface and ground waters. Mathematical models can be applied in various water management issues, related directly or indirectly with the implementation of the WFD in Greece. These issues range from simple water quality problems, such as the modeling of the fate of pollutants (due to point and/or non-point pollution sources) in a one-dimensional river, to complicated problems, such as the management of water (both quantity and quality) of a multiple-purpose reservoir (heavily modified or artificial water body) in which the complicated hydrodynamic and physical-biochemical processes in the various layers of the reservoir are taken into account.

According to a strategic EU document [2], research and technological development play an important role in the implementation of the WFD. In key activity 2 of this document on "the development of guidance on technical issues", references to models are specifically made in the following areas of application:

1. Analysis of pressures and impacts (Project 2.1).
2. Designation of heavily modified bodies of water (Project 2.2).
3. Classification of inland surface water status and identification of reference conditions (Project 2.3).
4. Monitoring (Project 2.7).
5. Assessment and classification of ground water (Project 2.8).

Modeling is a multifaceted tool by which better understanding of the physical, chemical and biological conditions in surface and ground waters is achieved. A mathematical model can be considered as a "simplified version of the real" and is composed by a set of equations, which are usually solved numerically.

The scope of this work is to present the main characteristics and general types of the mathematical models that are related to the implementation of WFD, focusing on the expected applications of these models in Greece.

2 Mathematical models

2.1 Classification of water bodies according to the WFD

According to Annex V of the WFD water bodies have to be classified, based on their "ecological status" (a general definition is provided in WFD), in 5 "classes of ecological quality" (high, good, moderate, poor and bad). The characteristics, which are used for the assessment of the "ecological status" of water bodies, are called "elements". Separate lists of "elements" are provided for each surface water category (rivers, lakes, transitional waters and coastal waters) and for groundwater. The "elements" for surface water bodies are divided into 3 groups: (a) hydro-morphological (HYD-ELs), (b) physico-chemical (PCH-ELs) and (c) biological (BIO-ELs) "elements". HYD-ELs refer to the hydrological regime (e.g. some HYD-ELs for lakes are quantity and dynamics of water flow, residence time, connection to ground water bodies) and the morphological conditions (e.g. lake depth variation, structure and substrate of the lake bed, structure of the lake shore). PCH-ELs include general physical and chemical characteristics, such as temperature, pH, salinity, DO, nutrients, as well as specific pollutants (non-priority and priority pollutants, specified in Annex X of the WFD). BIO-ELs include various biota, such as phytoplankton, macrophytes, benthic invertebrates and fishes. Most of these BIO-ELs have already been used by various member states, before the entry of the WFD, but not in accordance with the WFD [3].

The classification of a surface water body can be performed by the assessment (estimation or calculation) of the deviation of the "real" values of its "elements" from their "ideal" values in undisturbed or "reference conditions". Such a procedure requires (a) the identification of the "elements", which will be used in the assessment and their relevant significance, (b) the definition of the "reference conditions" to define the "ideal" values and (c) the performance of measurements to obtain the "real" values with monitoring programmes.

In the WFD, the emphasis is given on the BIO-ELs; the HYD-ELs and the PCH-ELs just support the BIO-ELs. This view was verified by the results of the European project REFCOND [4], which was focused on the BIO-ELs and more specifically on the estimation of a series of parameters, called "metrics" that are indicative of the condition of the BIO-ELs. Metrics should be selected, so as to respond in a predictable manner to anthropogenic pressures. For example, for the BIO-EL "fish" such metrics may be species sensitive to the PCH-ELs "Dissolved Oxygen (DO)" due to organic pollution or species sensitive to the HYD-ELs "quantity" and "flow rate". Over 100 fish metrics are used on a European level, most of which have only regional application depending on ecosystem composition and local pressures [3]. Thus, to assess the ecological status of a water body, it is important (a) to identify the local pressures and (b) the sensitivity of the biological "elements" to these pressures. For example, as shown in Fig.1, benthic invertebrates are good indicators of organic pollution, while fish are sensitive to flow variation due to abstractions and phytoplankton to eutrophication.

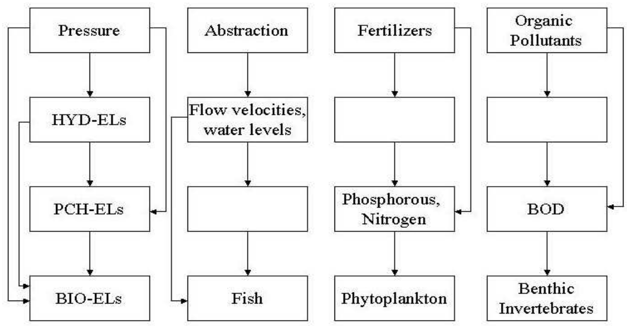

Fig.1: Relationship between pressures and "elements".

According to the WFD, ground water bodies are classified according to their quantitative (ground water level) and chemical (conductivity, concentration of pollutants) status. Although the WFD adopts specific criteria for the classification of the status of surface water bodies, detailed provisions related to ground water are not made. Article 17 of the WFD, however, requires that the European Parliament shall at a future date and on the basis of a proposal from the Commission adopt specific measures to prevent and control ground water pollution by defining common criteria on good chemical status and on quality trends. The Groundwater Directive 2006/118 (GWD) [5] meets that requirement.

2.2 Models, main types and variables

The main types of mathematical models, which are directly related to the WFD are: Hydrological or water balance (WAB) models, hydrodynamic (HYD) or flow field models, water quality (WAQ) models and ecological (ECO) models [6]. These models calculate the main (1) hydrological, (2) hydraulic and (3) water quality characteristics of a water body. These characteristics include most of the "elements" described in Annex V of the WFD.

2.3 WAB models

WAB models calculate the various components of the hydrological cycle and the relevant hydrological characteristics of water bodies by applying water mass balances.

For surface waters these characteristics include the following HYD-ELs: (a) hydrological regime, (b) lake depth and its variation, (c) connection to ground water bodies, (d) river continuity and (e) quantity of water flow. This element is the flow rate, Q, for rivers and transitional waters and the volume of water for lakes and enclosed coastal areas. The flow rate is a very important element, because it links directly "water quantity" with "water quality" via the equation "mass load of pollutant = concentration X flow rate". Usually, minimum values for Q are set as reference values for water quality purposes, e.g. not to exceed permissible pollutant concentration values. Moreover, maximum values can be set for flood protection or bed erosion purposes.

For ground water such HYD-ELs are not defined. WAB models provide information for some of the components of the hydrological cycle related to groundwater, such us: (a) the quantity of water in an aquifer, usually calculated over a specific time period, (b) ground water inflow and outflow through the aquifer boundaries into neighboring aquifers, (c) seepage from/into effluent streams and lakes and (d) natural replenishment (infiltration due to precipitation) and evapotranspiration.

2.4 HYD models

HYD models are used to calculate the main characteristics of flow of surface and ground water bodies by applying the equations of continuity and momentum [e.g. 7]. These characteristics include the following HYD-ELs: (a) dynamics of water flow (temporal and spatial variations of depth and average velocity, local velocities, mixing regime etc.), (b) residence time, (c) tidal regime, (d) wave exposure, (e) freshwater flow and (f) ground water level regime (the main parameter for the classification of the quantitative status of ground water bodies).

2.5 WAQ models

WAQ models calculate the concentration fields of water quality variables by applying the equations of mass conservation. The water quality variables include the following PCH-ELs of the WFD: (a) thermal conditions, (b) oxygenation conditions, (c) salinity, (d) nutrient conditions, (e) concentration of various pollutants, (f) phytoplankton and zooplankton concentration and (g) conductivity and concentration of pollutants for groundwater.

Some examples of WAQ models for rivers are the EPA-QUAL2E [8], which is the most widely used WAQ model (or more accurately computer code) for the simulation of 15 variables, the UK SIMCAT [9], which is a hybrid Monte-Carlo deterministic WAQ model and QUASAR [10]. The majority of the existing WAQ models for lakes deal with the status of eutrophication and the DO depletion [11,12].

2.6 ECO models

ECO models describe the interactions between the characteristics of the ecosystem of a water body. These characteristics are groups of organisms, mainly natural units of living and non-living components that interact to form a system in which an interchange of materials and energy takes place. ECO models can be used to calculate some of the BIO-ELs of the WFD like (a) phytoplankton, (b) macrophytes, (c) benthic invertebrates and (d) fishes. ECO models can be deterministic or empirical-statistical [12].

Deterministic ECO models are similar to the WAQ models and they are often characterized as WAQ models. ECO models, like the WAQ models, use equations of mass conservation to describe interactions between the living and non-living organisms of the ecosystem and between the organisms of the ecosystem and the environment. All deterministic ECO models involve simplifications, since it is not feasible to include every organism individually or even every species. The majority of the ECO models aggregate biological components into functional groups with the same behavior. For example, all types of phytoplankton can be considered as one functional group or variable (with units of concentration, e.g. chlorophyll a), which participates in various processes, such as production, consumption and decomposition. Such ECO models are also "population based" or "functional group" or "food chain models". Deterministic ECO models can be "structured", when considering cohorts of specific species [13] or "individual based", when tracking individual (usually single) species through time and considering their interactions with the environment [14].

A typical deterministic ECO model [15] includes a series of variables, which can be divided into 3 major groups: phytoplankton-zooplankton food chain (algae, herbivorous zooplankton and carnivorous zooplankton), non-living organic carbon (particulate and dissolved) and nutrients (ammonium nitrogen, nitrate nitrogen and soluble reactive phosphorus). Chemicals and food chain interactions are modeled. Chemicals interact with organisms in two primary forms: first the organisms can directly take up dissolved toxicants from the water and second the organism can consume contaminated food. The model simulates the movement of chemicals through the various trophic levels. Lakeweb [16] is a comprehensive ECO model, which accounts for phytoplankton, bacterioplankton, two types of fish (prey and predatory), as well as zoobenthos, macrophytes and benthic algae. Another example is a 3-D ECO model [17], which calculates macrophytes and their interactions with water quality characteristics, such as DO, organic nitrogen, ammonia, nitrate, BOD, phytoplankton and the sediment layer in shallow lakes.

Statistical ECO models are regression equations, which describe the relationships between (a) hydro-morphological, chemical or physicochemical characteristics and (b) biological characteristics of a water body. RIVPACS [18] is a typical statistical ECO model, which involves statistical relationships between the fauna and the environmental characteristics of a large set of high quality water bodies (reference sites). RIVPACS can be used to predict the macro-invertebrate fauna to be expected at any water body in the absence of pollution or other environmental stress and thus to define proper reference conditions. The main disadvantages of such models are (a) they are not easy to construct in more heterogeneous countries and (b) their predictive capacity would be poor when transported from one region to another.

2.7 Relationship between models and WFD “elements”

Fig. 2 depicts that the inputs and outputs of the WAB, HYD, WAQ and ECO models (shown with solid lines) for a given surface water body are linked. Usually, HYD models use the output of WAB models as input to calculate the dynamics of water flow, and WAQ and ECO models use the output of HYD models as input to determine the water quality and ecological status. There are also interactions of these models with their corresponding ground water models (not shown in Fig. 2).

Fig. 2 shows that these models can be used to calculate directly or indirectly the majority (if not all) of the HYD-ELs and the PCH-ELs, but only a few BIO-ELs. Direct calculation (shown with dashed lines) of a WFD element can be performed, when the element coincides with a variable of the model; and thus the element is part of the model output. Some examples are (a) the hydrological regime, the lake depth and its variation, the flow rate (i.e. quantity of water flow), the connection to ground water bodies and the river continuity, which are calculated by a WAB model, (b) the dynamics of water flow, which is calculated by a HYD model and (c) concentrations of DO, salinity, nutrients, phytoplankton, zooplankton and various pollutants, which are calculated by a WAQ model.

Indirect calculation of a WFD element can be performed, when the element is linked with a variable of the model via equations (empirical or theoretical) or other relationships (shown with dashed lines and a square in Fig. 2). Some examples are the level of water surface and the residence time in lakes, which are calculated using the output of a WAB model.

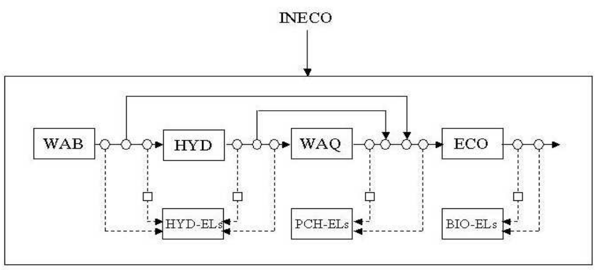

Fig.2: Relationship between models and WFD “elements”.

2.8 Boundary conditions and inputs

The initial characterization of a water body includes the identification of its location and boundaries (see Annex II of the WFD). These boundaries can be physical, such as the bed of the river or the water surface of a lake, or fictitious, such as the boundary between a river and a transitional water body, between a coastal region and the open sea (open sea boundary) etc.

The formulation of a model requires the exact definition of (a) the geometry of the water body and (b) the interactions with the surrounding processes occurring in its boundaries (boundary conditions). These data include the following:

1. Environmental data. This information is used in all models. For example, meteorological characteristics are used to calculate rainfall and evaporation (for a WAB model), velocity and direction of the wind to determine the direction of dominant currents (for a HYD model in a coastal region), water temperature variations to

determine rates of processes for water quality variables (for a WAQ model) etc.

2. Characteristics of the solid boundaries, which include the morphological characteristics of the bed and the sides of water body. These characteristics include some of the "elements" of Annex V. The most important of these "elements" are: (a) quantity, structure and substrate of the bed, (b) structure of the riparian zone (for rivers), (c) structure of the lakeshore (for lakes) and (d) structure of the intertidal zone (for transitional and coastal waters).

For ground water models, there is a high degree of uncertainty in the identification of the water body. Quite often, the geophysical and hydro-geological characteristics of an aquifer, the boundaries and the interaction with neighboring bodies of surface and ground waters are not known in detail and/or present a high degree of uncertainty [19]. Generally, in ground water models the following types of boundary conditions may be encountered: prescribed potential, prescribed flux (inflows and outflows, impervious boundaries), semi pervious boundaries, unsteady phreatic surface with accretion and seepage face [20].

2.9 Model calibration and verification

Models should be calibrated and verified, prior to their application. Model calibration and verification (or validation) is performed with experimental or field data of high quality.

The models contain various coefficients to describe the effects of e.g. surface runoff (i.e. soil properties) for WAB models, bed characteristics (i.e. roughness coefficient) for HYD models for surface waters, transport and storage of water and pollutants (i.e. permeability of the porous medium, the aquifer transmissivity, the porous medium dispersivity) for HYD and WAQ models for groundwater, etc. These coefficients are determined in the process of calibration by comparing model predictions with field data. Calibration is performed by trial and error calculations (using various combinations of values for the coefficients) or directly using optimization techniques (i.e. inverse models).

Model verification (or validation) is related to the adequacy of the model. Model calculations (using the values of coefficients determined in the calibration) are compared with a new, independent series of field data. If the comparison is satisfactory, then the model can be considered as adequate.

Calibration and verification of ground water models is very complicated, because of the high degree of uncertainty of the various coefficients and parameters involved. When the consequences of a wrong prediction are expected to be severe, a "post audit step" is introduced, in which model predictions are compared with a new series of field data, usually derived with new hydrological and hydraulic conditions [19].

In the cases, where a satisfactory amount of field data is not available, an arbitrary calibration can be performed and the model is applied after performing a sensitivity analysis. These cases should be avoided.

2.10 Field data – Modeling and monitoring

High quality field measurements are necessary for the calibration and verification of models. For WAB models, field measurements for flow rate and volume are used for rivers and lakes, respectively. For HYD models flow velocity measurements and FTC data can be used. For ground water HYD models, piezometric heights or levels of the water table are used. WAQ models may be calibrated and verified using field measurements for the concentration of the water quality parameters [21].

The success of the application of a mathematical model depends on the availability of high quality field data. Field data are collected in the procedures of monitoring programs, either surveillance or operational (see Article 5 and Annex II of the WFD). These data can be used for the calibration and verification of mathematical models. Therefore, it is essential to correlate the processes of monitoring and modeling with a continuous feedback between modeling and field data information. This feedback permits the optimization of monitoring networks (see 3.3).

2.11 Integrated models

The models used for the implementation of the WFD should ideally have the highest possible degree of integration to comply with the integrated river basin approach. Therefore, in the building of the mathematical models linkages should be ensured between:

1. WAB, HYD and WAQ models.
2. Surface and ground water models.
3. Inland, transitional and coastal water models (according to the principles of Integrated Coastal Zone Management).
4. Impacts from agricultural, industrial etc. activities.

The importance of the integration can be illustrated with the following example. It is required to define critical (minimum) value for the flow rate (Q_{min}) in the stretches of a river, based on ecological criteria, e.g. not to exceed a critical loss (for example 5%) of the protected species of the vegetation and fauna (e.g. sensitive habitats) in the area of the river. The following procedure is applied:

1. A WAB model is applied to determine the possible scenarios of flow-rates in the river and in groundwater. Then, values of flow rates are assigned in every section of the river taking into account the relevant local pressures, mainly water abstractions.
2. A HYD model for river flow is used to determine water levels in the stretches of the river for all the scenarios of flow rates.
3. A HYD model for ground water flow is used to determine the ground water hydraulics, i.e. mainly levels of water table in the area of study.
4. Information (mainly from field surveys) is collected on the characteristics of soil, vegetation and fauna and is combined with the information of step 3 to determine the humidity of the soil.
5. A WAQ model is used to determine the populations of the protected species of the vegetation and fauna (e.g. sensitive habitats) and the associated losses compared to the reference populations, using the values of the humidity of the soil determined in step 4.
6. These values are compared to the critical value of the losses of the sensitive habitats (5%). If these values are acceptable, i.e. are lower than 5%, then the flow rates in the stretches of the river are also acceptable and above minimum values.

By repeating the model calculations for various scenarios of flow rates, it is possible to set minimum values for flow rates in all the stretches of the river. These values should always be maintained by regulating the relevant pressures (e.g. abstractions).

In the above-mentioned example the integration of the models involved can be performed with the simultaneous solution of the equations of the models. Alternatively, and more easily, the integration can be performed by the linking of the models involved with appropriate (a) common boundary conditions and (b) inputs-outputs. The second method, which is simpler, can be easily applied (a) in the linking between the HYD models for surface and ground-water and (b) in the linking of WAB, HYD and WAQ, using the output of WAB as input to the HYD and the output oh HYD as input to the WAQ.

The linking between WAB and HYD models and between HYD and WAQ models for a certain water body (see Fig. 2) is a routine task. However, this is not the case with the linking between HYD and ECO models and between WAQ and ECO models (see Fig. 2). Despite the fact that both hydro-morphological and physico-chemical characteristics affect the ecological characteristics, deterministic INtegrated ECO (INECO) models have not been yet developed.

However, such a coupling is recognized and various attempts have been made to develop simple "empirical" INECO models, following the general ideas of the statistical ECO models. These initial INECO models, which can be considered as "precursors" of the deterministic INECO models, include the so-called "habitat – hydraulic" models. The first INECO models deal with the dynamic response of BIO-ELs (biological characteristics, especially fishes) to HYD-ELs (morphological characteristics and discharge regime). Examples of such models are the one-dimensional codes EVHA, PHABSIM HABITAT [22,23], which are used at site scale to evaluate habitat suitability for different development stages of various fish species, as a function of stream flow rate. Two-dimensional habitat-hydraulic models [24,25] can provide more complete representation of suitable habitats in channels of complex cross-section structure [26]. By coupling these models with hydrological data, habitat suitability chronicles can be derived for a given site and compared to the current fish population structure. This approach allows better understanding of the impacts of repetitive hydrological modifications and opens the way to introduce INECO models. A new generation of INECO models couples statistical HYD models with multi-specific fish habitat preference models [27]. Such INECO models permit the evaluation of the influence of modifications of the hydraulic conditions (e.g. via modifications of the reach morphology), which are represented by gross hydraulic variables, such as the Froude number at low flow, on the structure of fish communities.

Integration of the hydrodynamic and water quality characteristics between surface and ground water bodies that may interact in a river basin is also a relatively new approach. Usually surface and ground water are considered two unique and individual entities. A separated modeling approach can be acceptable, when the permeability of the aquifer layers surrounding the surface water body is relatively low and there is no interconnection between surface water and groundwater. The WFD recognizes that when surface and ground water are hydraulically interconnected, interaction between the two flow components can play an important role for both water supply and quality and it is desirable to develop tools to describe the interactions between the two.

The integration of the models is directly related to the scale of application, which influences the selection of the models. The models that are used at a river basin scale are expected to be different from the models that are used at a local scale. Moreover, the great variation in the size of river basins within and between the EC countries means that models suitable for one location are not automatically applicable elsewhere. In any case, the application of the models at different scales should ensure that information derived at the river basin scale is transferred to a local scale and vise-versa, via ‘top–down’ and ‘bottom–up’ approaches.

3 Application of mathematical models in Greece

In Greece, there are 21 lakes (2 trans-boundary), 35 significant rivers (5 trans-boundary), 14 reservoirs, 300 biotopes, 11 wetlands (protected by the Ramsar Convention) and 33 river deltas. The total length of the seashore is about 15000 km, 1000 km of which is sandy beach.

3000 islands with important and sensitive ecosystems are spread in the Aegean, the Ionian and the Cretan seas, 227 of which are inhabited and only 78 have more than 100 inhabitants. In the majority of the islands, there is a lack of water and ground water is usually the most important water resource. Seawater intrusion in ground water aquifers constitutes a severe problem for the islands and coastal aquifers.

The Greek ecosystems, which consist of lakes, rivers, transitional waters including wetlands and coastal areas, require the use of integrated models. The modeling procedures, which can be applied, are similar to the procedure described in 2.11. Some examples of applications are the following:

1. Determination of type areas and reference conditions.
2. Development and application of early warning models.
3. Optimization of monitoring networks.

In these applications, GIS are expected to play an important role [28].

3.1 Determination of type areas and reference conditions

The integrated models that will be used to determine type areas and reference conditions in the Greek ecosystems, can also be used to identify:

- the degree of deviation from reference conditions and
- the likely response of Greek coastal ecosystems to reduced anthropogenic pollution, such as nutrient loadings, pollution and mechanical impact.

Using the results of the models, simple empirical models can be developed, which can describe the relationship between:

- the pressures (e.g. anthropogenic),
- the key factors triggering ecosystem alteration and their relative importance,
- key indicators and
- reference conditions in the Greek ecosystems.

Furthermore, recommendations can be made for the optimization of monitoring networks of Greek coastal ecosystems (see 3.3), based on the derived typology, reference conditions and key indicators.

3.2 Application of early warning models

The development and application of “early warning” or “alarm” models are expected to be used in Greece and especially in (a) trans-boundary rivers and lakes and (b) artificial or heavily modified water bodies, such as reservoirs and artificial lakes, mainly used for water supply purposes.

“Alarm” models determine the fate (i.e. convection, mixing-dispersion and physical, chemical and biological processes) of a pollutant in the water body and consequently in the water supply network, which has been discharged accidentally into a trans-boundary river or reservoir.

The application of “alarm models” permits (a) the identification of the accident (location and time of occurrence) and (b) the immediate facing of the problem with control measures.

3.3 Optimization of the design of monitoring networks

Monitoring networks should be designed so as to provide a coherent and comprehensive overview of ecological and chemical status within each river basin. Ideally, a monitoring network should cover all the significant parts of a water body. This would have required an enormous amount of information, monitoring stations and cost. Integrated models can be used to calculate the main hydro-morphological and water quality elements at a large number of positions using information (i.e. monitored data) from a limited number of measuring stations.

This procedure, which permits the optimization of the design of monitoring networks with the use of mathematical models, is illustrated in Fig.3.

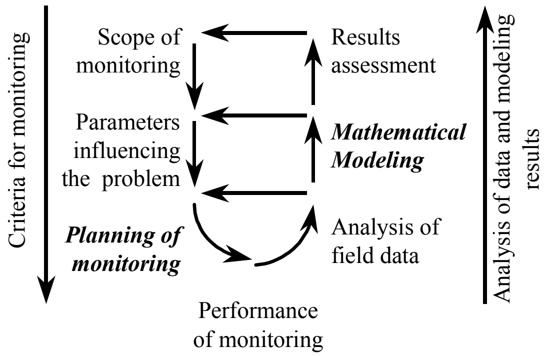

Fig.3: Optimization of a monitoring network.

3.4 Controlling ground water pollution

The WFD sets out general provisions for the protection and conservation of groundwater. As provided for in Article 17 of that Directive, measures to prevent and control ground water pollution should be adopted, including criteria for assessing good ground water chemical status and criteria for the identification of significant and sustained upward trends and for the definition of starting points for trend reversals. The GWD establishes such measures, in particular:

1. Criteria for the assessment of good ground water chemical status, such as ground water quality standards (Annex I of the GWD) and threshold values that have to be established by the Member States for the pollutants, groups of pollutants and indicators of pollution (Part B of Annex II of the GWD).
2. Criteria for the identification and reversal of significant and sustained upward trends and for the definition of starting points for trend reversals. The term "Significant and sustained upward trend" means any statistically and environmentally significant increase of concentration of a pollutant, group of pollutants, or indicator of pollution in ground water for which trend reversal is identified as being necessary in accordance with Article 5 of the GWD.

Mathematical Models may be very useful for the purposes of investigating whether the conditions for good ground water chemical status are met, may be used to estimate concentrations and support, where necessary, appropriate aggregations of monitoring results.

4 Conclusions

The scope of the present paper is the investigation of the best modeling practices that have to be adopted for the implementation of the WFD in Greece. These include: (a) the development and use of models with sufficient degree of integration and (b) the calibration and verification of the models with filed data.

Mathematical models can calculate the main hydrological, hydraulic and water quality characteristics of a water body, which include most of the "elements" described in Annex V of the WFD and can be used for various purposes such as (a) the analysis of pressures and impacts, (b) the classification of surface and ground water status, (c) the identification of reference conditions and (d) the design and optimization of monitoring networks.

The term "integration" covers the various types of surface and ground water bodies (rivers, lakes, transitional, coastal and ground waters), but also the quantitative, water quality and ecological characteristics of these water bodies. The integration of WAB, HYD, WAQ and ECO models is expected to result in the formulation of INECO models, which will be able to be used for the needs of the WFD, such as the determination of the ecological status of surface waters. The linking between HYD and ECO models and between WAQ and ECO models is not an easy task and thus deterministic INECO models have not yet been developed. Integration of the hydrodynamic and water quality characteristics between surface and ground water bodies that may interact in a river basin is still a subject under research and only a few integrated surface water-ground water models have been developed.

Models should be calibrated and verified prior to their application. A large amount of high quality field data is necessary for the calibration and verification of the models. For the case of ground water models the calibration and verification is very complicated because of the high degree of uncertainty of the various parameters involved. Field data are collected from monitoring networks. Therefore it is essential to correlate the processes of monitoring and modeling with a continuous feedback. After calibration, integrated models can be used to calculate the main HYD-ELs and PCH-ELs at a large number of positions of a water body using monitored data from a limited number of characteristic measuring stations, optimizing thus the design and operation of monitoring networks.

The Greek ecosystems, which consist of lakes, rivers, transitional waters including wetlands and coastal areas, require the use of integrated models. The modeling procedures, which can be applied, include: (a) determination of type areas and reference conditions, (b) development and application of early warning models and (c) optimization of monitoring networks.

References:

[1] EC, Water Framework Directive 2000/60/EC, *Official Journal of the European Communities,* 2000.

[2] EU, Elements of Good Practice in Integrated River Basin Management-A Practical Resource for implementing the EU Water Framework Directive, 2001a.

[3] A. Economou and N. Skoulikidis, Reference conditions, ecological quality and classification of the ecological status on inland waters in accordance with the WFD 2000/60, *in Water Framework Directive, Harmonization with Greek reality,* 2001.

[4] R. Owen, Definition and establishment of reference conditions, *Background Document, REFCOND project,* 2002.

[5] E C, Groundwater Directive 2006/118/EC, *Official Journal of the European Communities,* 2006.

[6] A. I. Stamou, A. Nanou-Giannarou and G.C. Christodoulou, The implementation of Directive 2000/60 in Greece-Use of Mathematical Models, *Proceedings of the 5th International Conference on Water Management in the era of transition,* Athens Greece, 2002, pp. 556-565.

[7] A. I. Stamou, G.C. Christodoulou, L.A. Bensanson and I.E. Lazaridis, A Comparison of Models for Coastal Circulation, *Water Science and Technology,* Vol.32, No.7, 1995, pp. 55-70.

[8] L. C. Brown and T.O. Barnwell, The enhanced stream water quality models QUAL2E and QUALE-UNCAS: Documentation and User's manual, *U.S.E.P.A. Report 600/3-87/007,* 2002.

[9] B.A. Cox, A review of currently available instream water-quality models and their applicability for simulating dissolved oxygen in lowland rivers, *The Science of the Total Environment,* Vol. 314/316, 2003, pp. 335-377.

[10] P.G. Whitehead, R.J. Williams and D.R. Lewis, Quality simulation along river systems (Quasar): model theory and development, *The Science of the Total Environment,* Vol. 194/195, 1997, pp. 129-136.

[11] K. Chatzimbiros, D. Koutsogiannis, A. Katsiri, A.I. Stamou, A. Andreadakis, P. Sargentis, C. Christofides, A. Efstratiades and A. Valassopoulos, Management of water quality of the Plastiras Reservoir, *Proceedings of the 4th International Conference on Reservoir Limnology and Water Quality,* Chech Republic, 2002, pp. 164-167.

[12] S.C. Chapra and R.P. Canale, Long-term phenomenological model of phosphorous and oxygen in stratified lakes, *Water research,* Vol. 25, No. 6, 1991, pp. 707-715.

[13] A.D., Bryant, M.R. Health, W.S.G. Cummey, D.J. Beare and W. Robertson, The seasonal dynamics of *Calanus Finmarchicus:* development of a three-dimensional structured population model and application to the Northern Sea, *Journal of Sea Research***,** Vol. 38, pp. 361-379, 1997.

[14] W.F. Wolff, An individual oriented model of a wading bird nesting colony, *Ecological Modelling* **,** Vol. 72, ,1994, pp.75-114.

[15] S.C. Chapra, Surface Water-Quality Modelling, *McGraw-Hill Eds*, 1997.

[16] L. Hakanson, and V.V. Boulion, Modelling production and biomasses of herbivorous and predatory zooplankton in lakes, *Ecological Modelling*, Vol. 161, 2003, pp. 1-33.

[17] A.B. Muhammetoglou, and S. Soyupak, A three-dimensional water quality-macrophytes interaction model for shallow lakes, *Ecological Modelling***,** Vol. 133, 2000, pp. 161-180.

[18] R.T. Clarke, J.F. Wright, and M.T. Furse, RIVPACS models for predicting the expexted macroinvertebrate fauna and assessing the ecological quality of rivers, *Ecological Modelling*, Vol. 160, 2003, pp. 219-233.

[19] K. Nanou-Giannarou, Mathematical Modeling of Groundwater Aquifers: Possibility of Applying ASTM Standards in Greece, *4th Panhellenic Congress of the Hellenic Committee for the management of water resources*, Volos, Greece, 1999.

[20] K. Nanou-Giannarou and R. Helmig, Simulation of 3-D Groundwater Flow with Free Surface, *Wissentschaftlicher Bericht 4*, Technische Universitaet Carolo Wilhelmina zu Braunschweig, Institut fuer Computer Anwendungen im Bauingenieurwesen, 1998.

[21] A. I. Stamou, M. Mimikou, I. Nalbandis and P. Papanikolaou, Surface and Groundwater Monitoring and Instrumentation in Greece,

Euraqua 2nd Technical Review Meeting, Paris, 1996, pp. 103-110.

[22] US Department of the Interior, US Geological Survey, “PHABSIM for Windows, User’s Manual”, *Open File Report 01-340*, 2001.

[23] D.A. Scruton, J. Heggenes, S. Valentin, A. Harby and T.H. Bakken, Field sampling design and spatial scale in habitat – hydraulic modelling: comparison of three models, *Fisheries Management and Ecology*, Vol. 5, 1998, pp. 225-240.

[24] Bockelmann, B.N., Fenrich, E. and Falconer, R.A., "Development of an Eco-hydrological Model for Stream and River Restoration", Proceedings of the "Environmental Flows for River Systems/Fourth International Ecohydraulics Symposium", Cape Town, South Africa, March 2002.

[25] B.N. Bockelmann, B. Lin, and R.A. Falconer, Ecohydraulics Field and Modelling Study for River Restoration, *Proceedings of XXX IAHR Congress*, Thessaloniki, Greece, August 2003.

[26] D.A. Ervine and MacLeod, Modelling a river with distant flood banks, *Proceedings of the Institution of Civil Engineers*, UK, Vol. 136, 1999, pp. 21-31.

[27] N. Lamouroux, J.M. Olivier, H. Persat, M. Pouilly, Y. Souchon and B. Statzner, Predicting community characteristics from habitat conditions: fluvial fish and hydraulics, *Freshwater Biology*, Vol. 42, 1999, pp.275-299.

[28] Fedra, K., “GIS and Environmental Modeling”, in: M.F. Goodchild, B.O. Parks and L.T. Steyaert [eds.] *Environmental Modeling with GIS,* 1994, pp. 15-19.