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What kind of water models are needed for the implementation of the European Water Framework Directive? Examples from France

JEAN-GABRIEL WASSON, *Cemagref, UR Biologie des Ecosystèmes Aquatiques, 3 bis Quai Chauveau, CP 220, 69336 Lyon cedex 09, France.*
Corresponding Author. Tel: (+33) (0) 4 72 20 87 99; Fax: (+33) (0) 4 78 47 78; E-mail: jean-gabriel.wasson@cemagref.fr

MARIE-HÉLÈNE TUSSEAU-VUILLEMIN, VAZKEN ANDRÉASSIAN and CHARLES PERRIN, *Cemagref, UR Qualité et Fonctionnement Hydrologique des Systèmes Aquatiques, Parc de Tourvoie, BP 44, 92163 Antony, France*

JEAN-BAPTISTE FAURE, *Cemagref, UR Hydrologie Hydraulique, 3 bis Quai Chauveau, CP 220, 69336 Lyon cedex 09, France*

OLIVIER BARRETEAU, *Cemagref, UR Irrigation, Domaine de Lavalette – 361 rue J.-F. Breton, BP 5095, 34033 Montpellier cedex 1, France*

MATHIEU BOUSQUET and BERNARD CHASTAN, *Cemagref, Direction Générale, Parc de Tourvoie, BP 44, 92163 Antony, France*

ABSTRACT
The European Water Framework directive (WFD) promotes an integrated management approach, defines the river basin as the relevant management unit, and sets the objective of good ecological status for all waters in Europe before 2015. Based on research activities underway in France, this paper presents five examples of issues related to water modelling for the implementation of the WFD. The new concept of "good ecological status" calls for a necessary shift from a classical biogeochemical modelling to an ecological modelling, and for new kind of models which can describe the biological response of aquatic ecosystems to physical disturbance. The integrated management approach demands new kind of models, based on a more global approach, adapted to the scale of work and management to be done; this is illustrated with the rainfall-runoff models. In the field of hydraulics, the complexity is addressed through the creation of models, consisting of several modules, which are optimised as a function of the application desired. Finally, the need of tools in the process of allocating water resources among several actors in a river basin, as foreseen in the WFD, may be addressed by the use of multi-agent systems. All these examples show clearly that the hydrosystem complexity, the study of which requiring the use of physical, ecological, social and economic sciences, cannot be solved easily with a unique type of water modelling. Research is still needed to address this complexity, but also to provide in the same time tools and results for water managers.

Keywords: Water framework directive; models; biogeochemical; ecological status; aquatic habitat; hydro-ecoregion; hydrology; hydraulics; multi-agent system; integrated management.

1 Introduction

Policy on water at European level started in the 1970s with the adoption of the first directives, focusing mainly on water quality objectives. A good example is the drinking water directive of 1980 which set binding targets for drinking water quality. There was a second wave of European directives in the early 1990s, with several directives based on the emission limit value approach. Several major directives were adopted at that time, including those on urban waste water treatment and on nitrates. However, at the end of the century, European regulations were relatively fragmented and did not provide a clear vision of European water policy. The Water Framework Directive (WFD) was prepared in this context, with the aim of ensuring the overall consistency of European water policy on the basis of a common objective of "good status".

Entried into force in December 2000, the WFD sets out the following key points:

– The WFD concerns all the waters in Europe and aims at preventing further deterioration, at protecting and enhancing the status of aquatic ecosystems.
– There is a general objective to attain "good status" for all waters by 2015. This implies characterising the chemical and ecological status of all waters, the development of measures (including legislation based on a combined approach of emission limit values and quality standards) and management plans to attain this good status.

This concept of "good ecological status" raises questions. Several water quality models in France have been essentially based on physico-chemical parameters. Section 2 presents the state of

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the art related to biogeochemical modelling and the necessary shift towards another, more integrated, kind of modelling.

The biological reference conditions of different water types are primordial for the implementation of the WFD. Section 3 stresses the need for water models describing the links between physical structures and biological communities.

Modelling has long been used in the fields of hydrology and hydraulics. Increasingly complex models have been developed, coupling underground, surface and atmospheric phases of the water cycle. The ideal of the general model, in parallel with increasing computer calculation and processing capacities, continues to push forward research into a forever more complete and faithful representation of phenomena. However, the difficulties of implementing, handling and interpreting such tools constitute mounting obstacles to their rapid use in an operational context, and for applications intended to satisfy the needs of managers. Thus there is a return to more synthetic models that require fewer local data and which are oriented toward a more overall vision of the river basin, which is the correct scale for the integrated management approach promulgated by the WFD. This issue is illustrated in Section 4 on the basis of hydrological rainfall-runoff models.

In parallel, the complexity of general models makes them difficult to use, even for the specialist. This leads to the need for new methods for designing, together with more rational and economic handling of such tools. Thus the concept of a computer toolbox has emerged in which the assembly and co-operation of different modules will be organised and optimised as a function of the applications desired. This problem of integrating methods and tools, which is also a means of progressing towards integrated management, is dealt with in Section 5, in the area of hydraulic modelling.

Lastly, the WFD underlines the fact that, to achieve the objectives of "good ecological status", all member states should adopt a river basin approach to water management. River basin management plans will be established and updated every six years. In France, water management has already been carried out at river basin level since the 1964 Water act. The 1992 Water act calls for the preparation of SAGE (Schéma d'Aménagement et de Gestion des Eaux – water management plans) for each river basin. As all the major stakeholders should be involved in the preparation of these plans, which aim, *inter alia*, at allocating water resources between sectors and actors, potential conflicts are numerous. There is a need for negotiation tools. An example of water resources management modelling using a multi-agent system approach is provided in Section 6.

2 A new definition of water quality

The WFD is likely to bring about different modelling needs: modelling will certainly be needed to improve the description and qualification of river basins (Article 5), due to the usual lack of consistent data-sets. Secondly, modelling will be extremely useful to predict and appreciate the impact of any further discharge or change in land-use. This information is required in the management plan associated with each river basin (Article 13). Thirdly, a modelling tool will also prove useful for designing an adequate sampling strategy on river basin scale, as required by Article 11.

Present French legislation (derived from the EU 1991 Water directive) relies on "water quality" objectives that sections of river are expected to meet. Current models are therefore "water quality" oriented and simulate relevant physico-chemical parameters: pH, temperature, suspended matter, oxidizable and/or biodegradable matter, dissolved oxygen, nutrients, phytoplankton, etc. Moreover, they are usually restricted to a relatively short river section.

However, there is no further reference to "water quality" in the last version of the WFD. The new environmental objectives of the directive are described clearly in Article 4 and refer to the water bodies "ecological status" and "chemical status", which require appreciation by referring to a reference ideal situation. The relevant parameters are listed in Annex V and do not only include the former "water quality" parameters, but also much more integrated bioindicators, such as the quality and the biodiversity of various biota (phytoplankton, macrophytes, fish, invertebrates) with reference to ecological status. Classical models are usually incapable of describing an entire river basin with such parameters. Therefore, "water quality" modelling faces the challenge of progressing to "ecological and chemical status" modelling and to higher spatial scales.

2.1 State of the art of French water quality modelling

We put here a special emphasis on the experience of the "PIREN Seine" river basin research programme (website: http://www.ccr.jussieu.fr/umr-sisyphe/PIREN-Seine/). "Water quality" or "biogeochemical" models are usually divided into two categories: the so-called "black-box models", and the deterministic models. The first group includes models that are based on extensive data-sets and as few parameters as possible. The aim of these models is to reproduce the observations, usually the concentration of dissolved oxygen, chlorophyll, or Biochemical Oxygen Demand (BOD), as a function of external factors (e.g. temperature, nutrient concentration), but regardless of the meaning of the parameters involved. One of the earliest of these models was described by Streeter and Phelps [37] and describes the decrease of BOD through time by using simple first-order kinetics. This equation has been widely used, especially in the framework of the QUAL2 model, distributed free by US Environmental Protection Agency. Black-box models are easy to use and powerful, provided that a lot of data are available. However, they are of no use for predicting situations that are out of the scope of the data from which they have been derived.

Conversely, deterministic models are devoted to the mechanistic study of the processes and theoretically able to predict the evolution of the system out of its present state. Those models include a great number of state variables and parameters that render them quite complex. However, as both parameters and state variable have a biological, physical or chemical meaning, they are theoretically measurable and thus the uncertainty is reduced.

The biogeochemical models of the Seine river, developed in the framework of the multidisciplinary research programme

PIREN-Seine, provide a meaningful example of deterministic models. In-depth knowledge of the biogeochemical cycles of carbon, nitrogen, phosphorus, silica and oxygen has been gathered in a fairly complex conceptual description of the flows of these elements between the different state variables (the RIVE conceptual model). More than fifteen state variables (dissolved inorganic and organic nutrient concentrations, phytoplanktonic biomasses, heterotrophic, autotrophic bacteria biomass, etc.) and several dozen parameters are necessary to describe the kinetics of chemical, microbial and planktonic processes, finally leading to the observable state variables in the river [33]. However, this biogeochemical model must be coupled to dynamic ones in order to be used for the purposes of water management. RIVE has been coupled to a 1-D hydraulic model describing the flow of the river along the last 700 km of its course to the Channel. The resulting PROSE model [12] is able to predict the variations of all the state variables, according to time and space, provided that the initial and boundary conditions are specified. This powerful model should be considered as a research tool, allowing in-depth analysis of the biogeochemistry of the river and allowing the quantification of non-measurable flows (e.g. the quantity of nitrates that yearly escapes from the river through denitrification). Moreover, the model has been intensively used by the SIAAP (Syndicat Interdépartemental pour l'Assainissement de l'Agglomération Parisienne – Paris Water Board) for its current management of water quality in Paris and its suburbs. It also proved to be an essential tool during the design of the Paris regional master plan for sewerage until 2015. The model simulations helped it to decide when and where to install oxygen diffusers in the river to prevent anoxia. Recently, the coupled model was implemented at the reach scale of a small river (5th Strahler order). A benthic compartment was added in order to assess its relative contribution to the biogeochemical fluxes in such kind of shallow streams [17].

The RIVE biogeochemical model has also been coupled to an hydrological model of the whole river basin. This hydrological model (HYDROSTRAHLER) uses an idealised morphological description of the watershed, based on the Strahler's concept of stream order. The resulting coupled model (SENEQUE) is able to compute, every ten days, the mean concentration of every state variable defined in RIVE, for each stream order. This model is less precise but much easier to handle than PROSE. It is an interesting management tool at river basin scale and has already been used to analyse the seasonal succession of phytoplanktonic species in the Seine river [18]. The RIVE biogeochemical model has also been coupled to a 3D hydrodynamic model to describe the geochemical flows in the Mediterranean coastal zone [38]. In the specific case of the Gulf of Lions, the relative contribution of terrestrial (via the Rhône river) and oceanic inputs of nitrates to coastal primary productivity has been established. The role of sediment-water exchanges in these flows has been highlighted, and a new version of the 3D water column model coupled with a dynamic early diagenesis model has been formulated in the frame of the METRO-Med project (website: http://erato.fl.ariadne-t.gr/metromed).

The International Water Association task group on river water quality modelling recently proposed another modelling tool [34], based on the same processes and compatible with the older Activated Sludge Models [21] that simulate the quality of urban discharge. Those deterministic models are among the most detailed developed in Europe for describing biogeochemical cycles in rivers. They partly address the concept of "ecological status", in that they explicitly include at least two phytoplanktonic species and the related processes of photosynthesis and grazing by zooplankton.

2.2 Narrowing the gap between biogeochemistry and "ecological status"? Two hints for future research

The WFD is really challenging in that it forces scientists to consider simultaneously different aspects of the same river: biogeochemistry, ecology and eco-toxicology. On the one hand, models are now able to simulate the transport, dispersion and, to a certain extent, the evolution of some chemicals, together with a number of biogeochemical parameters related to the chemical status of the river. On the other hand, toxicity dose-effect models of increasing complexity have been derived from laboratory experiments and can predict how many individuals of a given species would die under given exposure conditions (c.f. the lethality of combined oxygen depletion and ammonium exposure [28]).

However, those two kinds of models are not yet able to communicate and produce a description of the ecological status of a river. At least two links are still missing (Figure 1).

Firstly, there is clear evidence that the toxicity of many pollutants is modified by different biogeochemical factors, including pH, the presence of organic matter of different origins, the presence of suspended matter, etc. Therefore, the real impact of these pollutants on the biota is likely to be completely different from that which would be predicted with the simple dose-effect model. There is a real need for knowledge on the processes governing its bioavailability. This includes not only process studies in laboratories, but also the use of new monitoring technologies in-the-field, like the recently proposed diffusion gradient in thin film and semi permeable membrane device. If simple relationships between the environmental parameters and the bioavailable fraction of a pollutant could be established (see a first try with polycyclic aromatic hydrocarbons [20]), it would be easy to include them in a deterministic biogeochemical model.

Secondly, the output of a dose-effect model does not permit describing the ecological status of a complex biota. There is a need for integrated models that propagate the information obtained on individuals to the level of a whole population, and what is more, from populations to ecosystems. Those questions are currently addressed in the framework of national research programmes underway at *Cemagref*.

3 Hydro-ecological modelling of river habitats

Concerning river habitats, the first key point of the WFD is the definition of biological reference conditions for each river type.

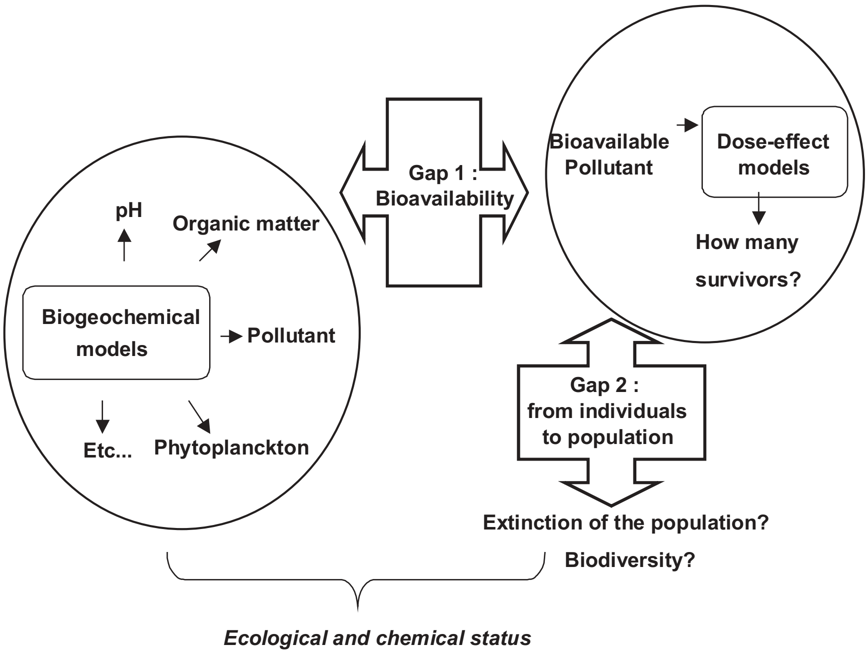

Figure 1 Gaps in the current knowledge between biogeochemistry and ecological status.

The typology is defined either on the basis of a fixed range of altitudes, geology and drainage area (Annex II, System A) within a very broad "ecoregional" framework (Annex XI), or on a more flexible combination of the same factors (altitude, geology, size) and other physical and chemical characteristics (Annex II, System B); but both systems have a geographical basis. This natural typology must be completed by identifying anthropogenic disturbance sources, such as point and non-point pollution, hydrological and morphological alterations, and global land use, to evaluate the probability of ecosystem alteration.

The second key point is the evaluation of the "ecological status" by comparing the actual status of river ecosystems to the characteristic "Reference Conditions" (RC) for each river type (Annex V). The parameters to be used for this evaluation refer to biological, physical and chemical features, but clearly point out the biological community as the final "referee" in terms of defining the high, good and fair conditions, since the modification of abiotic parameters is evaluated on the basis of the biotic structure they can support.

These two premises constitute the correct way of evaluating hydrosystem status over a broad range of geographical conditions, and for this reason we consider the WFD is taking the right direction. This type of approach was developed by *Cemagref* on the scale of a large hydrographic basin, (the Loire basin, 117 000 km^2), demonstrating the feasibility of a reference typology based upon the delimitation of hydro-ecoregions and simple physical features.

The problem is now to develop methods for application at national or even at European scale. For this purpose, modelling would be very useful to (1) define reference conditions at a broad spatial scale, and (2) link biological modifications (especially in fish populations) to physical disturbances. We shall give some examples of the research currently developed in two directions:

– Statistical Regional Reference Models for physical and biological parameters;
– Functional Response Models linking physical factors to physical and biological responses.

3.1 *Regional reference models*

The problem is to define the physical and biological characteristics of undisturbed rivers within a simple geographical framework at national level. An exhaustive evaluation of reference sites would be extremely time consuming, and the major problem deals with the natural geographical variability of hydrosystems, i.e. what is the proper reference condition for a given disturbed site?

The WFD requires at least type specific reference conditions, on the basis of the typological system chosen; RC must be based as far as possible upon data from a reference sites network, and modelling can be used for spatial extrapolation in the RC definition process. But nevertheless, reference models needs reference data. A choice is open between two approaches: regionalisation (like System A) or global modelling (like System B). The latter has the advantage of allowing a more precise description of the longitudinal variation of physical parameters and associated biota within a hydrographic network. However, such models (such as RIVPACS initially developed in the UK) are not easy to construct in more heterogeneous countries and, as seen with certain experiences in France, their predictive capacity would be poor when transported from one ecoregion to another. On the other hand, the regional framework proposed in System A is probably too broad to define the natural characteristics of hydrosystems with sufficient accuracy. But a regional approach has many advantages:

– The ecoregional framework of Annex XI, which is rather of a biogeographical nature, must be detailed with geology and altitude, parameters that can be easily regionalised.

By including other climatic and geomorphologic features, we can define more accurate "hydro-ecoregions", as tested in the Loire river basin and in the bolivian Andes. The working hypothesis, based on ecosystems hierarchical control theories, and already validated on various physical and biological parameters, is that hydrosystems will present a limited variation range in each region as well as a typical longitudinal pattern [39,40]. Hydro-ecoregions have been defined in France and are now in use, coupled with Strahler's order, as a basis for the river typology [41,42]; (website: http://www.lyon.cemagref.fr/bea/lhq/regionalisation.html).
– Working in relatively homogeneous regions will stabilise many fundamental "input parameters" in modelling processes: geology (and thus sediment input rates), precipitation regimes (and thus hydrological variation), hydro-chemistry (controlling biological productivity), etc. Thus, in each region, a limited set of parameters, mainly related to longitudinal variation (slope, drainage area) might be powerful control variables, leading to robust statistical models.

Thus, we recommend an approach by "Regional Reference models", (i.e. a combination of regionalisation and modelling) on the basis of previous regionalisation derived from the "hydro-ecoregion" method. Examples of parameters that could be statistically modelled on a regional basis are:

– *Ecohydrological variability*: current theories predict strong influence of the discharge variation regime on aquatic communities. Integrative parameters of this variability present a fairly good regional pattern, in relation to precipitation regimes and geology. The actual influence of ecohydrological variability upon aquatic community structures remains to be evaluated [2].
– *Morphological patterns*: in riffle-pool sequences, the percentage of rapid units is expected to vary with stream slope. However, this relationship differs strongly between hydro-ecoregions, and regional models are much more robust in predicting the occurrence of morphological structures controlling aquatic habitat [10].
– *Aquatic communities*: the longitudinal evolution of fish communities, in relation to stream order (Strahler), has a strong regional pattern. Simple models predicting the composition of fish communities on the basis of hydro-ecoregion and stream order could be tested. In small streams (order 2–3), invertebrate communities also have regional characteristics and reference models are under development [41].

3.2 Functional response models

The aim of these models is to explain either the response of morphological variables to hydrological control factors or the dynamic response of biological communities (especially fishes) to morphological characteristics and discharge regime. The latter, based on the comprehension of physical biological interactions, are valuable tools for analysing the effect of regional and temporal variability and the impact of anthropogenic physical modifications. Both physical and biological models could be useful to define reference conditions more accurately and evaluate the role played by physical disturbances on the current ecological state of the rivers. This opens the possibility of formulating the most effective restoration policy for a given system. Models under development concern:

– *Morphogenetic discharge*: in natural alluvial rivers, morphodynamic equilibrium leads to correspondence between river geometry and hydro-sedimentological regimes; consequently, the bankfull discharge (Qb) corresponds to the dominant discharge (Qd), i.e. the most effective morphogenetic discharge. However, the frequency of Qb depends on the natural characteristics of the basin and might present a regional pattern. Anthropogenic disturbances of watershed, discharge, and river morphology modify the ratio Qb/Qd which could be used as a morphological disturbance index [22,36].
– *Dynamic habitat limitations*: instream flow models (such as the microhabitat method, EVHA) are used at site scale to evaluate habitat suitability for different development stages of various fish species as a function of discharge. 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 [9,36]. This approach highlights the effect of duration and timing of limiting habitat episodes upon the fish development stages. It allows better understanding of the impacts of repetitive hydrological modifications and opens the way to defining ecologically sound regulated discharge regimes.
– *Statistical habitat models*: a new generation of instream flow models, coupling statistical hydraulic models and multispecific fish habitat preference models, permits evaluating the influence of hydraulic conditions alone on fish communities. In these models, the fish community structure can be related, at the reach scale, to integrative hydraulic variables, such as the Froude number at low flow. Hydraulic conditions depend primarily on reach morphology and respond to discharge variation according to this morphology [23–26]; (website: http://www.lyon.cemagref.fr/bea/lhq/logiciel.html).

Such models could be extremely useful for implementing the Framework Directive in two ways: to obtain more robust Regional Reference models in medium sized rivers; and to analyze the impacts of river geometry modifications and the possible effects of long term change of base flow discharge.

4 What do managers expect from hydrological models?

4.1 How to progress towards the integrated river basin management?

Integrated river basin management is an important objective for water resources managers. The models developed by the scientific community during recent years represent obvious advances in our knowledge of how catchments and aquatic environments behave. However, scientists have been developing models that focus on certain aspects of the catchment, each attempting to improve his knowledge of a well-defined topic. We now have considerable expertise in a number of disciplines, without however being able to explain all the interactions that occur between each one. To move forward and provide tools corresponding to the orientation of the Water Framework Directive, we now need to define a framework of interaction and cooperation between these disciplines. This is an ongoing research within the framework of the EU funded concerted action HarmoniCA (website: http://biomath.rug.ac.be/ harmonic/).

In the following paragraphs, we first review the lessons of *the utopia of the omniscient model* that lasted until the end of the eighties. We then give our opinion about what it is possible to carry out today, with several examples taken from quantitative hydrology issues.

4.2 The utopia of the omniscient model

The development of computing power from the sixties onwards led to belief in the hydrological community in the mirage of the omniscient model which, thanks to the three horsemen of the apocalypse (differential equations, calculation power and remote sensing), should have led to the construction of a model capable of calculating water and material flows at each point of a river basin. This model, regulated solely by physical equations, would have been interfaced immediately with all sorts of ecological models.

It seems that this approach failed [6] due to two reasons:

- Difficulties of a conceptual nature related either to grid discretisation, or to the physical laws used (e.g. Darcy's law was developed for homogenous and isotropic environments and its extension to a kilometric grid is far from obvious);
- Technical difficulties: a great many data, especially those concerning subsoil, are inaccessible. Generally, acquisition of all data is economically incompatible with an operational context. This means that certain parameters require calibration, quickly making the associated numerical problems (parameter sensitivity) insolvable.

4.3 Model interfacing as an alternative solution

Faced with the impossibility of applying these physically-based models, it is possible to imagine working on more empirical interfacing of the models specific to each discipline. The Table 1 presents some benefits of this approach.

The need to redefine the limits of the modelled compartments implies that their aggregation will require a large-scale project, demanding co-ordination and negotiation between the different disciplines involved. At present, it is possible, however, to develop less cumbersome approaches. In the following section, we illustrate the possibility to implement rainfall-runoff models, which match the users' objectives. We shall also approach the possibility of using assimilation techniques, which can in certain cases and under certain conditions, create links between models and permit progress towards the integrated systems sought by water resources managers.

4.4 Example of rainfall-runoff modelling

The WFD considers rational quantitative management as contributing to the sustainable use of water resources. To this end, it is crucial to implement simulation models. Up to now, rainfall-runoff modellers have chosen different approaches, with various levels of complexity being used to describe the catchment.

The great complexity of physical models does not guarantee more reliable coupling with models stemming from other disciplines, due to uncertainty on their parameters (related to the numeric problems of calibration). Furthermore, they do not permit significant gains in performances (in terms of flow simulation quality) and they remain difficult to implement operationally. In contrast, lumped rainfall-runoff modelling approaches, which do not attempt to reproduce all the hydrological processes involved, seem us preferable. They are easy-to-use, require few data (typically rainfall, streamflow and evapotranspiration records) and are based on a global analysis of the catchment hydrological behaviour – the reference element for integrated management.

Taking this line of research, *Cemagref* has developed over the last fifteen years a family of rainfall-runoff models (Génie Rural models or GR). Their main characteristic is the extremely parsimonious number of parameters to be determined [11]. These models have been extensively tested through comparative studies on a very large sample of catchments with varied hydrological conditions [31]. The simplicity of the GR models, combined with a structure developed without preconceived ideas, allows to reach performances as good as those of more complex models, and with better robustness and reliability. For the model, these qualities are essential from the operational standpoint since, for the user, they guarantee greater credibility for all the applications derived from the model. The latter therefore becomes a reliable tool, permitting managers to answer questions and take decisions. Although the use of such models remains marginal, their usefulness can be illustrated by three examples:

- Reservoir management: here, it is important to anticipate the future behaviour of the catchment, depending of its moisture state. A model allows simulation of a large number of possible scenarios to aid decision-making in a multi-objective context.

Table 1 Benefits and drawbacks of model interfacing.

Advantages	Disadvantages
• Preserves the skills and know-how gathered in each sector: assertions and premises are based on validated models.	• Interfacing is not always possible (problem of dependency on modelled variables)
• Helps acceptance of the chain of tools by developers and users.	• Need to redefine the modelled compartments.

- Detection of human impacts: this type of detection, which requires separating human impacts from those due to the natural climatic variability, requires a model that uses climate forcing variables as input data. A rainfall-runoff model allows the posterior detection of anthropogenic effects, but is yet unable to forecast them reliably [1,27].
- Flow forecasting: in this domain, the rainfall-runoff model is essential to obtain a sufficient lead time in forecasting. A novel technique for implementing the model has been proposed [43]. It also allows the assimilation of other input data in the model, and can therefore be a means for interfacing models that simulate independently variables that interact in the natural environment.

4.5 Perspectives

By emphasising catchment-scale integrated resources management, the WFD leads us to take into greater account the needs of model users, thereby raising questions that cover several disciplines simultaneously. In spite of the complexity of the natural systems he has to deal with, the manager must have access to reliable tools on which he can keep a critical judgement, since our models are still far from perfect and may not always be well-adapted. Furthermore, to support the decisions he has to make, the manager requires diagnostic tools he can use without outside help and at a reasonable cost.

Given these expectations, we feel that the most pragmatic and promising direction consists in seeking links between the models of the different disciplines involved (as opposed to those who defend a fully integrated interdisciplinary model). This approach would require more thorough comparative evaluation of the models used in each discipline, better validation of the applications proposed to engineers, and a reflection on the coupling methodologies able to make the know-how of different disciplines interact.

5 Collaboration or coupling of models: a common platform for different applications

The WFD emphasises sustainable and integrated water management, thus expressing the need to take into account every dimension whether economic or ecological. Although it expresses a widely recognised need, the methodological tools enabling comprehension of the increasing complexity of the problem do not yet exist. Nevertheless, the aim of current research to take into account this complexity results in increasing requirements for computer tools, that integrate or allow the interaction of software tools and models of different origins, and with different purposes. Finally, these complex tools are difficult to assemble, maintain and keep open ended. This is the problem facing *Cemagref* in the case of its free surface hydraulic software.

Different tools are available, based on the same equation systems and with similar data formats [14,19,30]. On the other hand, each tool has a preferred area of utilisation for which it is has been adjusted. This adjustment is achieved by the dispersion of a common core of programs and format specification in many variants and idioms, making it difficult to maintain and develop software. Obviously, if we want to reduce this dispersion of effort by avoiding repetitive tasks, this common core must be defined explicitly as part of a sub-project. On the other hand, for reasons of technical efficiency regarding study costs, users need tools that automate all the procedures that can be. This brings to mind in particular the management of data and results which can accumulate into considerable amounts when taking into account several scenarios. Another possible area of automation is coupling hydrological tools to the free surface hydraulic solvers that they provide with boundary conditions, which is still done manually. However all this software has an implicit shared conceptual basis, regardless of its form, whether St Venant equation solvers or simple script in a spreadsheet. This shared basis concerns geographical models of an area under study, an elevation model, basic hydraulic concepts and the modelling of singularities.

The method chosen is to make this common conceptual basis explicit, in order to build a toolbox that organises the elementary components necessary in the development process of the different software products needed in studies requiring precise data on free surface flows in natural environments [13,30]. By using this toolbox, the developer can derive certain applications known as “business applications” dedicated to specific uses. The components available in the toolbox can be used after adjustments that are minor from the programming point of view, but essential from that of the end user. Such adjustments may concern the specific language used or the inhibition of useless functions. The components available in the tool box may be those that manage basic entities such as cross sections, nodes, branches, hydrographs, etc., or user interface components, such as graphic editors for geometric data, dialog boxes for hydraulic structure edition, and graphic viewers.

Thus the developer can adjust the operation of his application to the specific language used in the field of the job to which it is dedicated. For example, he can use the same components for an application dedicated to the assessment of the gain given by a river correction for flood control and another application dedicated to the design of an irrigation canal. In both cases the majority of the necessary concepts and techniques (hydraulic network and geometry description, cross structure, roughness/land use and boundary conditions modelling, numerical simulations) are essentially identical apart from certain aspects of language and the scheduling of the key steps of the study. These differences, typical of the job to be carried out, and some non-shared techniques, as in our example of overflow modelling for floods and automated irrigation, are specific points of its application that the developer can focus on, contenting himself with reusing existing and validated components.

The project of developing this tool box, subject to a quality plan, is based on the use of modern software engineering techniques, i.e. object oriented modelling in the framework of a CASE tool that permits program generation, using standardised UML (Unified Modelling Language) and Java^{TM} languages. This way one can preserve program flexibility, maintainability and portability without having to invest much money in proprietary graphic libraries. Our software tool box is still in its early stages; though we intend to enrich it with modules dedicated to:

- boundary conditions computation: rainfall-runoff models, monofrequential synthetic hydrography, tidal computation, etc.;
- pollutant dispersion modelling;
- scenario management, especially hydrological and land use scenarios and also cross section management, construction and river correction;
- implementing assistants for various kinds of standard studies, such as assessment studies and the solution to difficulties encountered during overflow modelling using 1D tools and during model calibration processes.

In addition to a general tool for free surface hydraulics, the business applications under consideration concern certain tools dedicated to the design and management of irrigation canals, implementation of the "floodability" method (developed by *Cemagref*), aquatic habitat modelling, assessment studies or, on a more formal level, flood risk prevention schemes.

6 Renewable resources management modelling

There has been steady growth in recent years of the use of Multi-Agent System (MAS) simulations in the areas of renewable resources management [7], environment management and regional development [16]. Interest in this kind of tool has already been expressed for research purposes. It is moreover very promising as a negotiation support tool, as it enables building a collective representation of the system at stake among the different actors involved, and the exploration of scenarios. These scenarios may deal with collective rules for resource sharing, credit access, initial social networks, etc. However, these models are currently questioned relatively to their validation as well as to the explanation of their contents to the actors. The actors may see the MAS as a kind of black box; however it is essential that they understand it so they can discuss the representation of their behaviour rules and they must also be confident in it as a negotiation support tool.

Following former works dealing with the use of Role Playing Games (RPG) for irrigation system management training, on the one hand [8], and for land planning in the other [32], the joint use of MAS and RPG seems to be interesting due to their potential for synergy [3]. Experimental economics has already used games in order to test economics theories, for issues of common property resources [29]. These works have also increased our interest in games as a complementary exploratory tool.

Here, RPG is considered as a tool for explaining a MAS focused on resource management. This explanation is meant to open the black box of the model, making it transparent to experts on the resource system (actors, researchers and administrations). Thus, they will be able to participate in validating the model. Explanation will also allow its use as a discussion medium for building a collective representation of the system between all the actors [5]. The RPG is actually a sort of human version of the MAS. The players are the agents, and the roles are the rules of the model. Both tools are intended to represent the rules in use, collective as well as individual, and to simulate scenarios composed of the sets of rules to be tested.

6.1 Water management – the institutional context

National water policies and the enforcement of these policies have changed considerably. In France the 1992 French water law has placed emphasis on negotiation and participatory processes with the emergence of SDAGE (Schéma Directeur d'Aménagement et de Gestion des Eaux – water management masterplans) and SAGE (Schéma d'Aménagement et de Gestion des Eaux – water management plans) and an increasing number of "river contracts". *Waterschappen* in the Netherlands and *Confederaciones hidrograficas* in Spain are other examples of water management at a more or less local scale, independent from other local institutions. The WFD is based on these three experiments with the creation of River Basin Districts all over Europe, enabling each of them to implement a River Basin Management Plan. Moreover the new directive emphasises the necessity for good public information and participation, which are crucial in the establishment of French SAGEs and river contracts.

However, French experiments have come up against certain difficulties in enforcing these new ways of defining local rules of resource management: only a few SAGE have reached the point of enforcement. A few cases in the south of France show that the common feature of success or failure among them is the existence of a legitimate mediator to supervise the negotiation process. Very few actors are keen to take this role due to the lack of support tools, considered by potential mediators as consultancy companies [35].

6.2 Development of new tools

Cemagref, with several partners in France and other European countries, is currently working on the definition of tools which could be used by mediators in the process of water management negotiations. The method of using these tools is tackled at the same time. Therefore MAS is used to represent river basins and incorporates water dynamics and the social dynamics of their use. It also enables representing different levels of organisations and institutions. It focuses on interactions among actors of all categories. The MAS is constituted of several components, each of them representing a piece or a group of pieces of the real world: farmers, institutions, plots, breaches, crops, etc. All of these components are described with attributes and some of them, defined as "agents", may act upon others or communicate with them according to autonomous goals [15]. The behaviour of these agents is described with rules and methods.

This is therefore a fully integrated method of modelling watersheds. Integration is done through the interactions between various components of the MAS and not through the exchange of data between sub-models, as it is often the case. Such a representation of real watersheds enables the simulation of management scenarios with different sets of assumptions concerning individual as well as collective patterns of behaviour. These simulations may trigger discussions in a participatory process on the results obtained from them.

The question is then how to communicate the results of simulations in such a manner that actors are at ease with them. This is not only an issue of validation, which is part of the process, but also an issue of the tool's legitimacy. We are therefore undertaking work with role playing games in order to open the black box of the model for the actors involved. This enables them to agree or not on the model, the validation method, and to share a common representation of the system on which they depend collectively.

6.3 Several case studies

Such a tool has already been developed and partially validated for viability of irrigated systems in the Senegal River Valley. A MAS model, SHADOC, has been created as a kind of virtual irrigated system, with special attention being given to the rules in use for access to credit, water allocation and crop season assessment, as well as to the organisation and co-ordination of farmers [4]. It has already been converted into a role playing game in order to explain its content to Senegalese farmers. These game sessions have triggered considerable discussions among farmers on their co-ordination habits, since they informed them of their collective practices and their consequences, even though they were aware of these on an individual level [5].

The same kinds of tool are currently being used for small water basins in France, with two cases of SAGE and two of river contracts, where issues of water sharing during drought and water quality are at stake. One of these experiments has been conducted in the framework of a recently finished EC funded project, FIRMA (Freshwater Integrated Resource Management with Agents – EVK1-1999-70 – website: http://firma.cfpm.org), whose aim is to study the relevance of agent based models for the integrated assessment of water management rules, through the evaluation of five case studies all over Europe. These include water supply in Barcelona and Zurich, the integrated management of the Meuse river at Limburg and the Orb river in the south of France.

7 Conclusion

The different approaches described in this paper illustrate clearly the methodological difficulties and the complexity arising from various notions, such as "reference conditions", "good ecological status" and "integrated management", which are at the core of the Water Framework Directive. These notions concern several disciplines and knowledge areas, where modelling is perceived and used in very different ways, mainly because of different historical developments. Thus a large number of views coexist: some search for an increasingly detailed schematisation of the phenomena while others put forward a more global approach better adapted to the scale of the work to be done; still others tackle its complexity by assembling specialised modules and, lastly, others consider that the most efficient way is the suitable nesting of these different approaches. The arguments in favour of these different approaches are relevant and none deserves to be disqualified vis-à-vis the others. For all that, none of them is capable of fully meeting these new challenges that together can be labelled as "the study of hydrosystem complexity" which will require the development of specific thinking and methodologies, which, for the most part, belong to the future.

Moreover, integrated management can rarely be achieved by applying a group of physical laws, even when complex. The preferences, strategies and interests of the different actors are part of the problem to be solved. Modelling was originally seen as a means of furthering our knowledge, but is now also considered as a means for better preparing our actions. Thus modelling is progressively capable of providing the tools for dialog between different actors. Little by little, water modelling is entering into the still new ground of studies of the relations between the physical and natural sciences and the human and social sciences.

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