COLLABORATIVE ENVIRONMENTAL MODELING: A ROADMAP FOR INTEGRATED WATER RESOURCES MANAGEMENT

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ABSTRACT

Collaborative modeling (CM) is motivated by modern environmental problems, complex policies, and solution decisions. CM is empowered by environmental science along with modern computer technology that allows modelers to scrutinize the environmental processes using a holistic approach. Such modeling systems are characterized by a dynamic and interdependent nature and involve social, economic, and environmental contemplations. In this paper, a collaborative system has been developed which evaluates the hydrological, environmental ecosystem and socio-economic dynamics in lakes and wetland watersheds. The developed system consists of the following models for: surface hydrology, groundwater hydrology, lake/reservoir water balance and operation, environmental ecosystem and a socio-economic interactions. These models have been developed to be spatially and temporally synchronized and they are coupled using the OpenMI standard to produce simultaneous simulations. A model calibration service has also been incorporated in the modelling system. Output visualization is presented in elegant and useful tabulated and graphical formats. The system has been applied to the Lake Karla watershed, located in Thessaly region, Greece. However, it is general enough that can be easily applied to other similar case studies. The design of the modelling framework follows the loose integration paradigm allowing the inclusion of other similar, yet heterogeneous models, with seamless modifications. We finally include a version of a web service tool for the intercommunication between the surface hydrology and the lake water balance model via the internet. This modeling and model coupling methodology sets the foundation of an online repository of models which may run and interchange online time series data.

Keywords: collaborative modeling, surface and groundwater hydrology, ecosystem, web services, OpenMI.

1. Introduction

A great amount of research has been recently published and dealt with the simulation and the monitoring of complex interdependent environmental processes. The study presented in this paper is inspired from the need for solving real problems that involve human intervention into environmental processes and relate human activities with these processes. In such cases, stakeholders (mostly competent authorities) necessitate the construction of complex collaborative software for the simulation of such environments.

The most popular approach of addressing such problems is to involve specific models to simulate all sub-processes in a cascaded or sequential fashion and aggregate the individual outcomes into a collection of general results. In most cases, the selection of participating models is crucial. All prior attempts to produce integrated or collaborative environmental software frameworks tend to focus in three distinct aspects as to how they see the use and the functionality of these frameworks (Laniak *et al*., 2013): (a) stakeholder involvement, (b) adaptability functionality of the decision process and (c) reuse of the framework for various case studies and scenarios. Additionally, a great amount of research has been focused towards the holistic thinking and assessment of water management problems. According to this idea, the application of an integrated modeling framework must unify the knowledge of different and sometimes heterogeneous domains into a coherent and user friendly representation (Kragt *et al*., 2011; Otto-Banaszak *et al*., 2011).

A set of steps should be followed according to this methodology: a) document best practices and develop guidelines for the system conceptualization, quantitative modeling methodology, and synthesis of the modeling results, b) develop methods for data exchange among components of collaborative systems that resolve dimensional conflicts (e.g. space and time aggregations, socio-economics, chemicals etc.), c) develop standard metadata for describing semantics and d) develop a conceptual framework of comprehensive analysis for integrated modeling systems. Such collaborative systems must be capable of providing spatial and temporal synchronization of the participating models in an open-ended architecture for the inclusion of newer models.

In this work, a collaborative environmental modeling prototype is presented which is based on the loose integration paradigm. In the next sections of the paper, the logical architecture of this system, its components and the model coupling and linking using the OpenMI-standard (OpenMI, 2007) or a semi-automatic approach are presented. The modeling system has been applied for the water resources management of the Lake Karla watershed in Thessaly region, Greece.

2. Collaborative prototype milestones and logical architecture of the system

A collaborative environmental modeling prototype is presented. Five major steps for its development have been followed: (a) problem statement, (b) system conceptualization, (c) model coupling and linking, (d) case study and its management and (e) model development and model repository as is shown in Figure 1.

The problem statement step exists in the prototype to help developers to distinguish the role of competent authorities and other stakeholders in water resource management, to identify and assess the existing regulations protecting water resources and to provide recommendations relatively to effective ways of managing water resources in the study area. The thorough investigation on the system conceptualization is the main factor that assists the model development. The process of conceptualization is the investigation of the case study i.e. the field area on which all models will be applied along with the effective analysis of simulation results. On the other hand, the development of models frequently involves both commercial and custom made formulations. Linking or coupling of models is necessary in most cases when there is a need for mutual interchanging of data. This process however becomes difficult especially when the participating models have proprietary restrictions of the source code. The most popular interlinking standard is OpenMI which can be configured to exchange data during computation (at run-time) and allows models to run simultaneously and share information at each time-step making therefore model integration feasible at the operational level.

The proposed prototype supports a model repository where developers can extent the system with new models or alternatively other commercial models can also participate. This is usually custom made and it is implemented as a framework or a wrapper that triggers simulations, manages data and handles the model interlinking (Kokkinos *et al*., 2014).

In this paper, an integrated modeling system is developed for the evaluation of hydrological, environmental ecosystem and socioeconomic dynamics in lake or wetland watersheds. The proposed system consists of individual models for the simulation of surface and groundwater hydrology, ecosystem and socio-economic factors affecting the dynamics of the physical processes. The participating models are: (a) a surface hydrology model, (b) a lake/reservoir water balance and operation model, (c) a groundwater hydrology model, (d) an environmental ecosystem model and (e) a socio-economical model. Models are coupled to share common data or to interchange data. The model coupling is depicted in the architectural framework of Figure 2. This framework consists of a database containing all the input time series data, the simulation results and the GIS thematic maps for the depiction of the spatial distribution of the results. The system is also equipped with an optimization server for the model calibration. The participating models are presented in the following section of the paper. The spatiotemporal synchronization of the models, needed for their interlinking and coupling, is also presented.

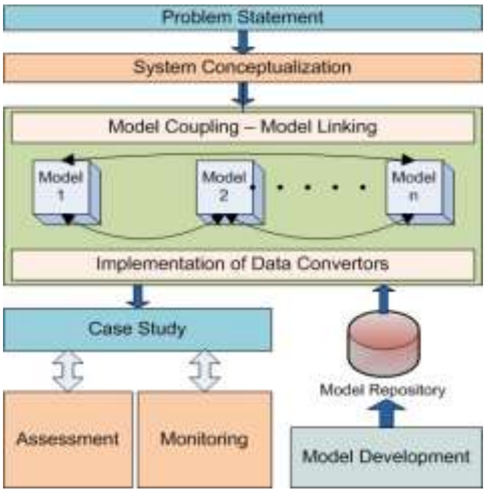

Figure 1: Implementation mile-stones for a collaborative environ-mental modeling system.

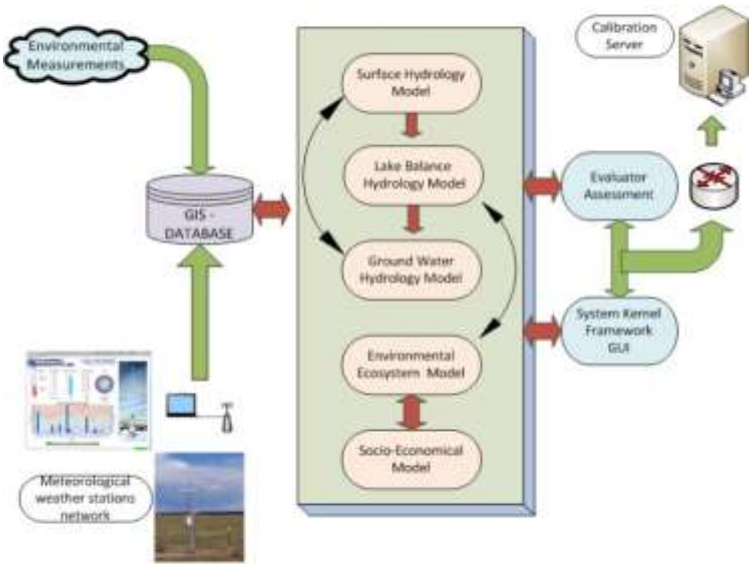

Figure 2: The architecture of the collaborative environmental framework.

3. Participating models in the collaborative framework

The surface hydrology model is a monthly conceptual water balance model, called UTHBAL which was developed and validated by (Loukas *et al*., 2003; Loukas *et al*., 2007). The model has been developed in three spatial aggregations; lumped, semi-distributed and fully distributed. It uses three inputs: precipitation, temperature and potential evapotranspiration. UTHBAL uses a soil moisture mechanism to allocate the watershed runoff into three components, namely the surface runoff, the medium runoff and the base-flow runoff. Its output is the actual evapotranspiration, the surface runoff, the actual soil moisture and the groundwater recharge, with the last being the linking data to the groundwater model.

The UTHRL model (Loukas *et al*., 2007) has been used for the simulation of lake/reservoir water balance and operation. This is a monthly conceptual model in which the stored water for each month is calculated as the sum of the stored water in the previous month and the inflows after the subtraction of the net losses, the real withdrawal and the real overflows. The net loses are the sum of the net losses of the previous month, the estimated deep percolation loses to groundwater and the natural surface runoff after the subtraction of the direct precipitation on the reservoir during that month.

The GMS modeling software, which is a commercial product of MODFLOW model has been used for the simulation of groundwater. MODFLOW is considered a worldwide standard model for groundwater simulation. MODFLOW is a modular finite-difference flow model that solves the groundwater flow partial differential equations using the values of hydraulic conductivity along all the coordinate axes, the potentiometric head, the specific storage of the porous material, the time and the volumetric flux per unit volume representing sources and/or sinks of water, where negative values are extractions and positive values are injections.

The PCLake model is an environmental/ecosystem model which is used in the modeling system. The model calculates the water quality parameters chlorophyll, transparency, phytoplankton types and the density of submerged macrophytes and the ecological state of a lake. Additional calculations include the distribution and fluxes of the nutrients N and P. Inputs to the model are: the Lake Hydrology, nutrient loading, dimensions (mean depth and size) and the sediment characteristics. An extensive description of the model may be found in the paper of Janse and Aldenberg (1996).

The socio-economic model used analyzes the relationships between the physical/natural system conditions, the human interventions to water environment and the relevant socio-economic procedures.

4. Case study: the lake Karla watershed

The collaborative system of the aforementioned models was applied in the watershed of Lake Karla, Thessaly, Greece. A variety of simulations were performed under several operational scenarios to subsequently adopt appropriate management strategies in order to avoid adverse environmental effects and reconcile conflicts between modelers, users and stakeholders. Assessments were performed for historical and future climate conditions. Interlinking and coupling of models was applied in several cases: UTHBAL participated in passing the basin surface runoff to the Lake Balance model and to pass the calculated groundwater recharge to the groundwater model, (MODFLOW). MODFLOW used the inflows evaporation and the withdrawals from UTHRL along with the calculated groundwater recharge from UTHBAL to create maps of the hydraulic heads and to calculate the volumetric budget of the aquifer. In turn, the aquifer measures were passed to the PCLake since they were used as input to the calculation of phytoplankton, macrophytes, sediments (suspended, active and deep), bottom detritus, phosphorus in the sediments and phosphorus in the water column.

5. Conclusions

A collaborative environmental prototype has been developed in which, several models can be plugged in and coupled for concurrent simulation. Based on this prototype, a logical architecture framework is provided, which can be used for the evaluation of water resources of a watershed. The system is an open-ended framework with the ability to include other models in the future. Models are integrated into the framework by a standardized wrapping process that uses the OpenMI-standard. Other proprietary software is linked in a semi-automatic way. The system supports strong data assimilation and it can be self-calibrated.

The correctness of the produced simulation results was verified by comparison to the corresponding observed values when the modeling prototype was applied in the Lake Karla watershed. This prototype has been designed as open-ended having the capability of incorporating other models and providing an integrated modeling tool for water resources management.

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