MODELING OF HYDROLOGICAL AND ENVIRONMENTAL PROCESSES THROUGH OPENMI AND WEB SERVICES

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Abstract

Integrated collaborative modeling has been proven lately to be the most accurate computer methodology that allows modelers to scrutinize the environmental processes using a holistic approach. Due to the dynamic and interdependent nature, such processes involve the interlinking of hydrological, meteorological, environmental, ecosystems and socio-economical characteristics. In this paper we deal with the development and the integration of a collaborative system of models devoted to the water quantity and quality monitoring, and also to the management of water resources in a watershed. The system is also tailored by a socio-economical study that highlights the impact of the aforementioned management to the local community of the region under study. Models that integrate the collaborative system need to be coupled so that to run simultaneously under the spatial and temporal synchronization condition. To achieve such a simultaneous synchronization, the Open Modeling Interface, (OpenMI) is invoked. The system has been applied and tested to the Lake Karla watershed in Thessaly region, Greece. However due to the loose integration methodology used for its development and to its open ended property, the system can be easily parametrized to offer such an analysis on other similar case studies. An extension to the OpenMI standard provides the remote simultaneous run of models using web services and allowing the development of a cloud repository of models for future use.

Keywords: Water resources management, web, services, coupling, OpenMI

Introduction

Research dealing with the simulation and the monitoring of complex interdependent environmental processes is mostly inspired by a cascading methodology that simulates each phenomenon in sequential fashion aggregating the individual outcomes into a collection of general results. This research methodology attempts to produce integrated and collaborative environmental software frameworks that 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) adaptable functionality of the decision process and (c) reuse of the framework for various case studies and scenarios. On the opposite site lately, there is a considerable amount of research that prioritizes the holistic thinking and assessment of water management problems. According to this approach, the interest in the development of an integrated modeling framework shifts towards the knowledge unification of different heterogeneous domains into a coherent and user friendly representation (Kragt et al., 2011; Otto-Banaszak et al., 2011). Advocates of this methodology argue in terms of creating a standardization procedure of model interlinking and coupling for integrated modeling. Two major methodologies are proposed: (a) the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) Hydrologic Information System (HIS) (Maidment, 2008; Tarboton et al., 2009) and (b) the Open Modeling Interface (OpenMI) (OpenMI, 2015). Both attempt to facilitate model coupling. OpenMI additionally provides a reference Software Development Kit (SDK) for a standard implementation. Because the two systems were developed by independent groups, there is no formal mechanism for using both the HIS and the OpenMI collectively. However, the systems share important similarities that make interoperability possible (Castronova et al., 2013).

This study attempts to interlink the criteria set by (Laniak et al., 2013) with the coupling functionalities promoted by the holistic approach and thus, provides a new roadmap in water resource integrated modeling. More specifically, we propose a set of milestones that need to be achieved in order to capture all the idiosyncrasies of the hydrological phenomena under study, the optimization of the conceptual models that simulate these phenomena and the interlinking of the models in a holistic simulation paradigm (Kokkinos et al, 2014):

- Documentation of the best practices and development guidelines for the system conceptualization, quantitative modeling methodology, and synthesis of the modeling results.

- Development of rigorous methods for data exchange among components of collaborative systems that resolve dimensional conflicts (e.g. space and time aggregations, socio-economics, chemicals etc.).
- Development of standardization process in metadata annotations and description semantics.
- Development of a conceptual framework dedicated for comprehensive analysis in integrated modeling systems and,
- Provision of spatial and temporal synchronization of the participating models in an open-ended architecture that allows the inclusion of further models and the generalization of the analysis independently of the case study.

In this work, a collaborative environmental modeling prototype is presented which is based on the loose integration paradigm. According to this technique, several participating models can individually or simultaneously simulate the surface and groundwater hydrology processes in a watershed as well as the lake water balance and the development of cyanobacteria in it. Simulation time steps of running the aforementioned models may vary and the produced time series may result in values of various units. However, when models need to collaborate with unidirectional or bidirectional linking and time series interchanging is necessary, we involve the OpenMI technology that has the ability to invoke the simultaneous runs of the models taking care of their spatial and temporal differences. This feature provides a flexible operational environment both for the stakeholders and the researchers. Additional features include a visualization component of the time series produced, an integrated database repository of all input and output data and the ability to append this database in adding new model data using a converter to modify these data based on the "*any model to OpenMI*" functionality. For models that carry code of proprietary nature that does not allow the implementation of OpenMI-wrappers to apply the coupling process, a semi-automatic methodology is used which is based on the background data interchanging directly from the stored input and output files of the models.

In this paper we develop an integrated monitoring and simulation software framework (monitoring and modeling system) to assess the hydrological, environmental, ecological and socio-economic dynamics in lakes basins or wetlands and to manage their water resources. This framework consists of a series of interconnected (or coupled) models and even though it has been developed as a general tool for any basin, in this paper we show its implementation for the recently restored Lake Karla in Thessaly, Greece. We aim in the creation of a decision support system able to help towards more efficient use of water resources and thus protect the environment. Furthermore, the creation of such research and experimentation tool (test bed) can be a quick and easy tool for hydrologists, environmentalists and other scientists for taking measurements concerning specific characteristics of wetlands. The following sections of this paper, illustrate the details of this logical software architecture. We first present the case study of the monitored watershed and justify the characteristics of our approach. We then provide a schematic and verbal illustration of the logical modeling architecture and the overall simulation framework implemented. Following is the presentation of the participated models. At the end of the paper we discuss the specifics of the model coupling using the OpenMI standard. We also show the development of a web application to link models based on this standard. This allows modelers to remotely use models of other modelers and couple them through this user friendly environment. All these functionalities mentioned above make this operational environment integrated and productive in assessing water resources in a watershed.

The Lake Karla, Thessaly, Greece case study

Thessaly is a region in central Greece which faces the most prominent example of today's water resources over-exploitation problem due to the fact that the area is intensely cultivated. The available surface water resources of the region, correspondent to the Pinios River, are not sufficient to meet the needs of the extensive agriculture of water demanding crops (cotton, maize, etc.). This situation has led to a remarkable increase in water demand, which is usually fulfilled by the over-exploitation of groundwater providing an irrational pattern of groundwater that result in a gradual deterioration of the already disturbed water balance and the acceleration of water resources degradation.

Apart from the problems that the overall region has, the watershed of Lake Karla faced various human interventions over the years. Up until the 1960's the lake area fluctuated from 40 to 180 km^2 due to the very gentle land slope and the inflow-outflow balance thus; a large part of the surrounding farmland was often inundated facing soil salinity problems. Karla was converted to agricultural land in order to protect Thessaly from flooding, to extend the farming area to the poor farmers and to minimize the malaria problem, but the results of that conversion were much more complex. Some of those results were: change of the area microclimate, reduction of the aquifer water level, introduction of sea water in the aquifer, lack of drinking and irrigation water, common flooding of the farmed areas, pollution of the adjacent gulf, loss of an important habitat for endangered European birds, as well as overall reduction in the number of farmers in the area (Gerakis and Koutrakis, 1996). In many cases, official authorities' interventions that converted wetlands into agricultural land caused an unexpected effect: the people that were supposed to benefit from this conversion - the farmers - were the first ones that eventually suffered the negative consequences of it. Figure 1 depicts the broader area of Thessaly and the boarders of the watershed under study.

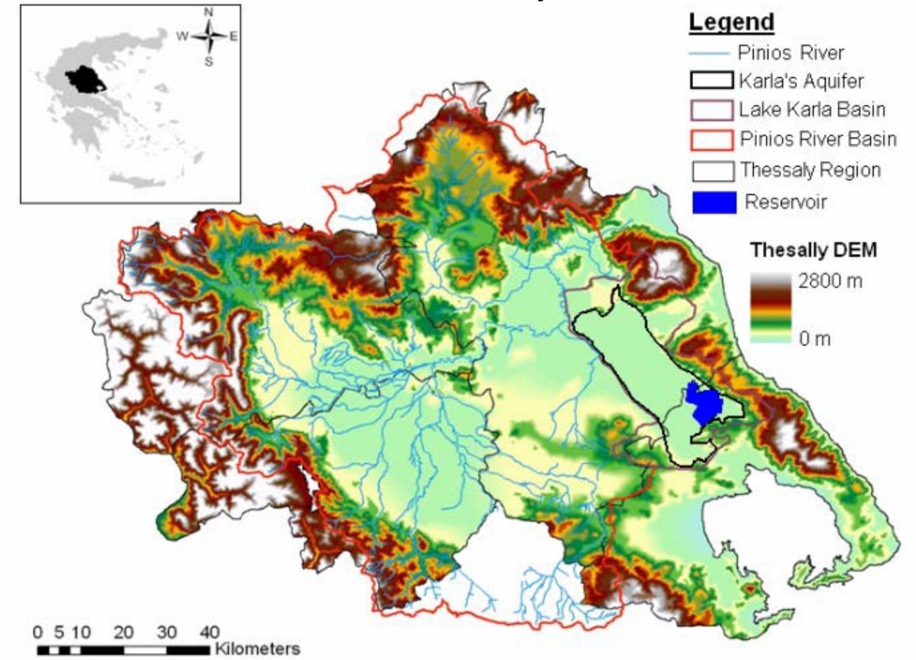

Fig.1 The field of study of the Lake Karla Basin in relevant scale to the Thessaly region.

The government decided to restore the lake with the construction of a reservoir, which started to operate in December of 2010. A historical overview of the environmental policies that lead to the drainage of the lake is presented in (Laspidou and Gialis, 2014). For the above reasons, the competent authorities continuously promote the development of an integrated monitoring system that evaluates the surface and groundwater water resources, observes the nutrient flows' dynamics in the reservoir, analyzes the important natural ecosystem under restoration behaviour and tries to draw conclusions on the socio-economics' impacts of the above to the local community.

Logical Architecture of the Modelling Integrated Framework

The proposed system consists of a collection of numerical and conceptual hydrological and environmental models for the simulation of surface and groundwater hydrology, lake balance, ecosystem and socio-economic conditions affecting the dynamics of the physical processes.

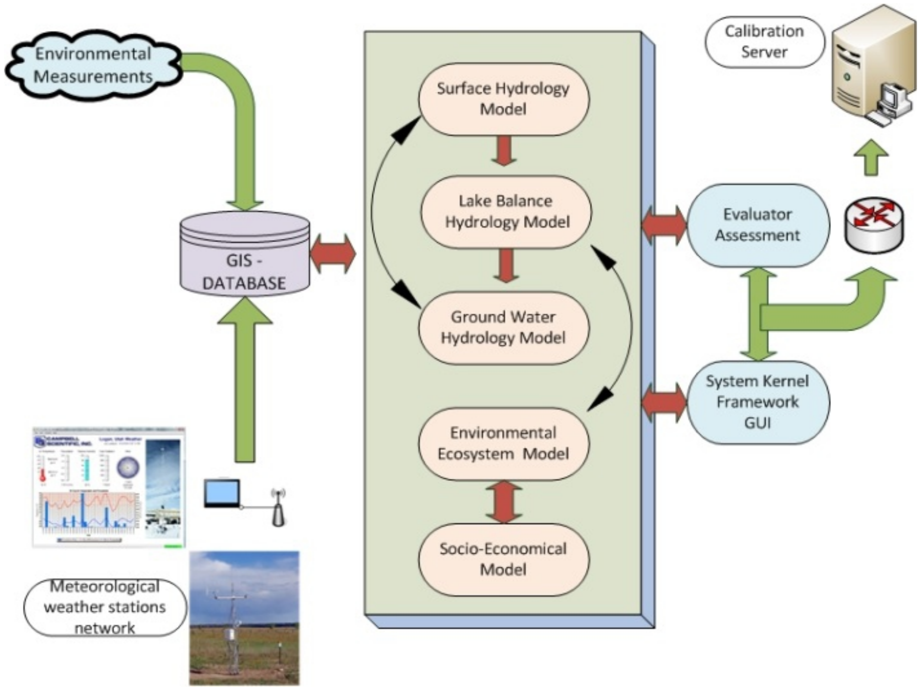

Fig. 2 The architecture of the collaborative modelling framework.

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-economic model. Data are aggregated from various sources into a GIS-database that captures both the spatial and temporal characteristics of the model input variables. Observations of meteorological data coming from meteorological stations set in the area as well as satellite remote sensing data are put into the database. Environmental data are gathered on a monthly basis to determine the occurrence and production of Microcystis Aeruginosa cyanobacteria development in a reconstructed lake environment. A full-scale monitoring study of Microcystis Aeruginosa and relevant environmental, hydro-meteorological factors and water quality parameters are also conducted in the restored lake Karla. Nutrient fluxes from and into lake sediment are measured, assessing the role of lake sediment as source or sink of nutrients. All these time series data are included in the database and are updated on an appropriate time step basis.

The system is equipped with a model calibration server, where the user may calibrate the surface hydrology and the lake water balance models using a variety of input data lengths. The primary calibration and optimization method used is the Generalized non-linear Reduced Gradient (GRG2), however, the system provides the appropriate hooks for inclusion of additional techniques. The framework kernel allows the user through an intuitive Graphic User Interface (GUI) to run individual models of the system or couple models into a simultaneous simulation. The coupling of models is designed according to the set of input and output exchange items needed by the models from other models to run. Models are coupled in a unidirectional manner for our case study due to specific hydrological processes monitored. However, bidirectional coupling can be included in a seamless way using the OpenMI Application Program Interface (API). The implementation of the coupling wrappers is accomplished using the OpenMI-SDK in Visual Studio C# programming language.

Description of participating models

Surface Hydrology

For monitoring the surface hydrology of the region, a monthly conceptual water balance model, called UTHBAL was developed and validated by (Loukas et al., 2003; Loukas et al., 2007). The model has been developed in lumped, semi-distributed and fully distributed spatial aggregations. The model uses as inputs the time series of precipitation, temperature and potential evapotranspiration and allocates the watershed runoff into three components, namely, the surface, the medium and the base flow runoff using a soil moisture mechanism. The actual evapotranspiration, the surface runoff, the soil moisture, the snowpack water equivalent and the groundwater recharge are the outputs with the last being the linking data to the groundwater model.

Lake-Reservoir Water Balance

The reservoir model is called UTHRL given in (Loukas et al., 2007). It's a conceptual model using the following equation to describe the operation of the reservoir in a monthly time step:

$$V(j) = V(j-1) + Q(j) - E(j) - A(j) - Y(j)\,. \qquad (1)$$

where $V(j)$ and $V(j-1)$ correspond to the stored water volumes in the reservoir on the months j and $j-1$ respectively, $Q(j)$ is the inflow to the reservoir on the month j, $E(j)$ is the net water loss from the reservoir for the month j, $A(j)$ is the real withdrawal for the month j, and $Y(j)$ is the real overflow during that month. The reservoir storage and overflow are calculated using (1). The monthly net water loses of the reservoir are estimated from the equation:

$$E(j) = E_0(j) - P_0(j) + L(j) + Q(j)\,. \qquad (2)$$

where, $E(j)$ are the net water loses of month j, $E_o(j)$ is the evaporation from the reservoir water surface of month j, $P_o(j)$ is the direct precipitation on the reservoir during month j, $L(j)$ are the estimated deep percolation loses to groundwater and $Q(j)$ is the natural surface runoff that would have been generated from the area of the reservoir if the reservoir does not exist. The above quantities are expressed to volume units (hm^3). The water level and the surface area are estimated using the reservoir storage-water level and surface area-water level curves. Using these curves, an expression is developed relating the reservoir water surface area, *F*, to reservoir storage, *V*:

$$F = a + bV^c \quad (3)$$

where, *a, b, c* are estimated coefficients through curve fitting.

Groundwater Hydrology

The Groundwater MODFLOW System (GMS) modeling software is a commercial product of MODFLOW model 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.

Environmental Ecosystem Model

The PCLake model calculates the water quality parameters chlorophyll a, transparency, phytoplankton types and the density of submerged macrophytes. It also calculates the distribution and fluxes of the nutrients N and P. Inputs to the model are: Lake hydrology, nutrient loading, dimensions (mean depth and size) and sediment characteristics. An extensive description of the model may be found in (Janse, 1996). The model describes a completely mixed water body and comprises both the water column and the upper sediment layer (Figure 3). In this figure, doubled blocks denote compartments modelled in both dry weight and nutrient units. Three functional groups of phytoplankton are distinguished: cyanobacteria, diatoms and other small edible algae. Arrows with solid lines denote mass fluxes (e.g. food relations), arrows with dotted lines denote ‘empirical’ relations (minus sign denotes negative influence, otherwise positive influence).

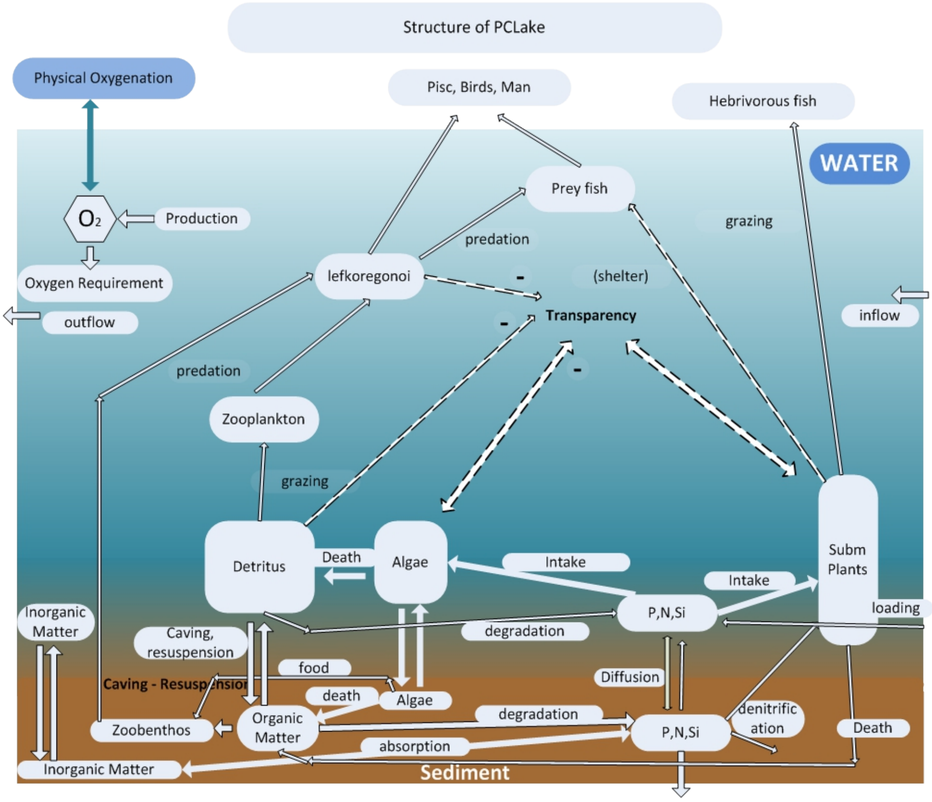

Fig. 3 The structure of the PCLake model. Courtesy of (Janse, 1997).

Socio-economics

The socio-economic model analyzes the relationships between the physical/natural system conditions, the human interventions to water environment and the relevant socio-economic procedures. More specifically the study tries to identify the impacts of the lake restoration to the social lives of the residents in the nearby regions of the lake. Factors that are important are the water irrigation costs and the environmental side effects caused by the lake restoration.

Model Coupling

Model coupling is achieved by migrating the computational engines of the models to the OpenMI-standard. This migration essentially enables the spatial and temporal synchronization of the participating models prior to their simultaneous run. In the possible scenario that the models cannot be migrated to the OpenMI standard due to the proprietary nature of their code then, a semi-automatic coupling methodology is implemented that reads and writes data directly to the relevant input and output files of the models. More specifically, all transformations of data are stored into xml-type files that provide the properties as to the model type, the time step of the simulation, the geometry (cell-id, cell size), the entity and the value calculated. UTHBAL participates in two coupling processes. In the first, the basin surface runoff from UTHBAL is passed to UTHRL that balances the inflows and outflows of the reservoir in order to calculate the spillway overflow and the reservoir water storage. In the second, UTHBAL passes the calculated groundwater recharge to MODFLOW but with a semi-automatic way.

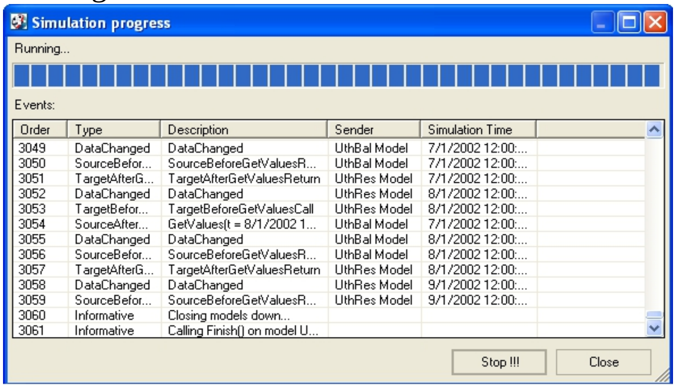

Fig. 4 Linking of UTHBAL and UTHRL models to run simultaneously.

Figure 4 depicts the process of the UTHBAL and UTHRL coupling in a simultaneous simulation using OpenMI. As shown, the user can easily inspect the passed values and the time horizon of the simulation. On the other side, MODFLOW uses the water inflow, the evaporation and the withdrawal quantities 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. Finally, the aquifer volumetric budget is passed to the PCLake environmental software since the calculation of phytoplankton, macrophytes, sediments (suspended, active and deep), bottom detritus, phosphorus in the sediments and phosphorus in the water column are depended on the water volumetric budget of the aquifer.

Furthermore, we added the involvement of Web Services as a concept for integrating scientific models in this collaborative environment. However, this methodology is successful for environmental model coupling if and only, all participating models are modularized into self-containing geo-processing units (Granell et al., 2010). On the other hand, using such a web application, we can make operations available to end-users who do not have the expertise required to solve an indispensable step in a compound modeling process (Pebesma et al., 2011). However, the gain in flexibility when linking models will be directly proportional to the availability of the services provided. If the service components are basic, generic and self-explanatory they are more likely to meet the end-users' requirements.

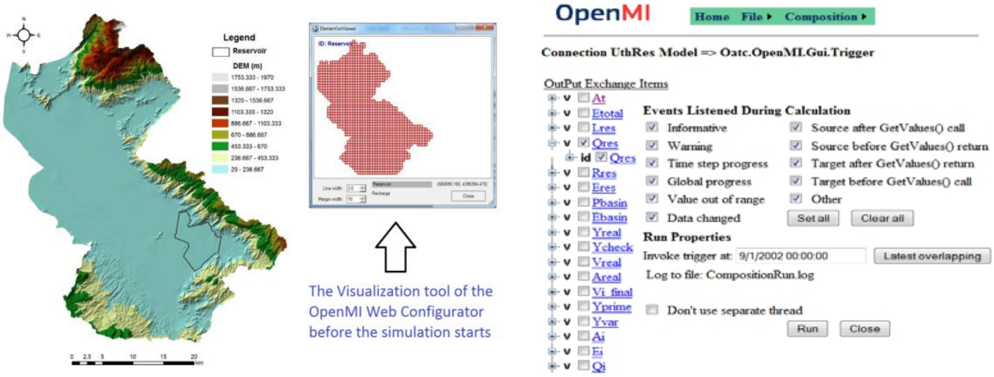

Fig. 5 Left) Digital Elevation Model of Lake Karla watershed in the location of the reservoir and visual representation of the model grid cells in the Web Configurator. Right) Variability of input/output exchange items in the linked simulation and monitoring of process interrupts

The web application is based on the composition class which implements all the web methods relating to the coupling composition consisting namely of: adding models, initiating triggers, setting up connections, indicating input and output exchanged items and monitoring output properties. The web application works with the session oriented methodology to assist the user authentication and the security of data. Every user starts his own session in order to deposit a model and its input data so that, there is no sharing among other users. A session variable is used to store the serialized composition class every time when an update or an interrupt occurs. Through the OpenMI web configurator, shown in Figure 5 (left), modelers can upload models which carry their model descriptions (GeoLocation, involved variables, node specification, model revision, time series etc.). Information is passed into the web service using the Simple Object Access Protocol (SOAP), specification for exchanging structured information in the implementation of Web Services. The calling of the trigger to start the simultaneous simulation in the OpenMI web configurator preserves the specifications of the WSDL language generated by the service which basically is an XML-based language that is used for describe the functionality offered by the service.

Conclusion and Future Challenges

We have implemented a collaborative environmental modeling and water resources prototype under which, several water resources models can be plugged, interlinked and exchange data during concurrent simulation. For models that due to their proprietary software functionalities cannot be coupled, we provide a semi-automatic methodology by integrating an additional database in parallel to the GIS that stores all the necessary data format conversions, supports strong data assimilation in the visualization component and converts the stored measurements in XML format. The system uses the standard of OpenMI for data interchange when spatial and temporal synchronization of the models is achieved. We added an extension to OpenMI through which, users can migrate models, couple models and run simultaneous simulations of them as web services. Via a web configurator, this coupling allows users of the system to remotely run the coupling module, and therefore initiating a cloud repository where modellers can deposit models and data to be simulated. The synergy and interoperability between models under the same framework is therefore a more complete solution to the challenge of integrated environmental modeling. The approach we use with the inclusion of an online and remote model coupling gives the modeller community a useful tool to run hydrological simulations using a variety of models and to provide ground for comparative analysis. We therefore believe that, decision support systems that use this type of model interoperability are able to help towards more efficient use of water resources and thus protect the environment.

We plan to further extend the system, by providing additional web services, implementing new calibration algorithms for model optimization and hopefully to finally end with an online decision support system to evaluate regional water resources.

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References:

Castronova, A. M., J. L. Goodall, and M. Ercan (2013), Integrated modeling within a Hydrologic Information System: An OpenMI based approach, Environmental Modeling & Software, doi:10.1016/j. envsoft.2012.02.011, 39, 263-273.

Gerakis P.A. and Koutrakis E.T. (eds), “Greek wetlands. Greek Center for Biotopes-Wetlands”, (EKBY), Athens (in Greek), 1996.

Janse J. H. and Aldenberg T. The eutrophication model PCLake, RIVM, Bilthoven, report no. 732404005, 1996.

Granell, C., Díaz, L., and Gould, M., (2010). “Service-oriented applications for environmental models: Reusable geospatial services”, Environmental Modeling and Software, 25(2), pp. 182-198, ISSN: 1364-8152.

Janse, J. H., "A model of nutrient dynamics in shallow lakes in relation to multiple stable states", Hydrobiologia Volume 342/343, pp. 1–8, 1997.
Kokkinos K., Samaras N., Loukas A. and Mylopoulos N., (2014). A Collaborative Approach to Enviromental Modeling. IEEE 23rd International Conference WETICE, pp. 223-228.
Kragt, M.E., Newham, L.T.H., Bennett, J., Jakeman, A.J., (2011). An integrated approach to linking economic valuation and catchment modelling. Environmental Modelling & Software 26 (1), pp. 92-102.
Laniak, G. F., G. Olchin, J. L. Goodall, A. Voinov, M. Hill, P. Glynn, G. Geller, N. Quinn, M. Blind, S. Peckham, S. Reaney, N. Gaber, R. Kennedy, and A. Hughes (2013), Integrated environmental modeling: A vision and roadmap for the future, Environmental Modelling & Software, 39, 3-23, doi:10.1016/j.envsoft.2012.09.006.
Laspidou CS, Gialis S. Lake Karla and the contradictory character of Greek Environmental Policies: A brief historical overview. Proceedings to the IWA Regional Symposium on Water, Wastewater and Environment: Traditions and Culture, 22-24 March 2014, Patras, Greece.
Loukas A., Vasiliades L., and Mpastrogiannis, N., (2003). Hydrologic simulation of surface water balance in Yermasoyia watershed, Cyprus. In Sidiropoulos E., Iacovides I., (eds) Research of water resources in Cyprus, Nicosia, Cyprus, pp. 83-114 (in Greek).
Loukas A., Mylopoulos N., and Vasiliades L., (2007). A modeling system for the evaluation of water resources management strategies in Thessaly, Greece. Water Resources Management, 21(10), pp. 1673-1702.
Maidment, D.R., 2008. Bringing water data together. Journal of Water Resources Planning and Management 134 (2), 95.
OpenMI, (2007). Open Modeling Interface. www.openmi.org, (last accessed, 05.28.2015).
Otto-Banaszak, I., Matczak, P., Wesseler, J., Wechsung, F., (2011). Different perceptions of adaptation to climate change: a mental model approach applied to the evidence from expert interviews. Regional Environmental Change 11, pp. 217-228.
Pebesma, E., Cornford, D., Dubois, G., Heuveling, G., Hristopoulos, D., Pilz, J., Stöhlkerg, U., Morinh, G. and Skøien, J., (2011). “INTAMAP: the design and implementation of an interoperable automated interpolation Web service”, Computers & Geosciences, 37(3), pp. 343-352.
Tarboton, D.G., Horsburgh, J.S., Maidment, D.R., Whiteaker, T., Zaslavsky, I., Piasecki, M., Goodall, J., Valentine, D., Whitenack, T., 2009. Development of a community hydrologic information system. In: 18th World IMACS/MODSIM Congress. Cairns, Australia, pp. 988-994.