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An extensible, generic environmental process modelling framework with an example for a watershed of a shallow lake

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ABSTRACT

We present a modelling framework for the generation of environmental process models. The framework builds on the Direct Computer Mapping method with an editable, process network based expert module and interpreter. The expert interface supports mapping of objects from the GIS layers onto the prototyped state, transition and connection elements of the case specific generic process model. The developed general purpose interpreter generates the standardized declarative facts and clauses, describing the actual model with the locally executable program prototypes. This input is executed by the general kernel. The model interpreter generates also the case specific templates for the (optionally web based) user interface, while map-server utilizes the GIS shape files of expert model. The implementation supports the extension of the model with new components in space and time. The framework is illustrated by an example for the watershed of Lake Balaton.

Software availability

Implemented demonstration of the framework is available at:: http://aic.ke.hu:8081/balaton
Year first available:: 2015
Hardware and software required:: PC (1 GHz CPU, 1 GB RAM, screen resolution of at least 1366 × 768) with internet access; modern web browser (preferably Mozilla Firefox, Google Chrome or Safari).
Applied components of the framework:: GIS (QGIS) for the edition of layers about geographical objects, yEd Graph editor for the graph manipulation and GraphML editing, general kernel of the simulator (written in GNU-Prolog), web interface (Wt with MapServer), database for meteorological, hydrological data, as well as for intitial and saved simulation states with results (PostgreSQL).
Cost:: Demonstration and test use is freely available upon registration.
Contacts:: Model and test examples: varga.monika@ke.hu
Web interface:: balogh.sandor@ke.hu

1. Introduction

Deep analysis and understanding of complex environmental processes and of their interactions in sensitive geographical (e.g. watershed) areas are in the forefront of research topics many years ago. Integrated research, spanning over different disciplines, as well as new methodologies and solutions are still required (Kragt et al., 2013). As it is addressed in a position paper of the field experts, holistic overview of complex interactions is claimed for effective environmental policy and decision making (Kelly et al., 2013).

Dynamic computational models intend to cover both natural and human-built processes, while the complex investigations have to take into consideration the anthropogenic effects. This complexity and the highly multidisciplinary characteristics of problems require the involvement of integrated computer modelling frameworks for the analysis, design and operation of sustainable environmental management. The application of an appropriately identified and validated model, besides its prediction ability, can enhance the understanding of the hidden cause-and-effect relations (Knapen et al., 2013) and it can provide a sound basis for the communication between the experts of different disciplines. Because of the strong need, arisen from both researchers and decision makers, the availability of such modelling systems has been increasing in the past decades.

In spite of the rapid methodological developments, there are

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some obvious gaps in this field. Most typical problem is the flexible coupling of multi-scale hydrological process modules with human made process systems for the complex investigation and assessment of natural and human effects on the environment at watershed scale. Second challenge is linking of the combined natural/artificial process systems with the human evaluations for socio-economic problem solving.

In a well-applicable and reliable environmental modelling system the following components are to be integrated:

1.) As the basic interfacing element in environmental modelling frameworks, GIS serves the visual input/output interface for the determination of the investigated spatial reality, providing a tool for the "handling of geographic information in a digital form" (Goodchild, 2009). In most cases, the overview and description of the spatial information starts from the map and GIS can be considered as a pre-processing tool that helps the preparation and visualization of environmental structures and data (Gimblett, 2001; Triana and Labadie, 2007; Guan et al., 2011; Gebbert and Pebesma, 2014). Current developments have been made to transfer these GIS based solutions to the web (Delipetrev et al., 2014).
2.) Hydrological model describes the vertical system of hydrological cycle related sub-processes for the investigated area, involving meteorological, physical and biological processes (e.g. precipitation, evaporation, transpiration, runoff, infiltration, percolation etc.). Hydrological modelling needs also the basic geographical properties (e.g. DEM, land type, soil type, etc.), relations and empirical observations, determining the related processes.
3.) On the basis of the hydrological model, next level is the description of the horizontal sub-processes that can cover the functionally different water sections and land use from agriculture and natural protection to urban/industrial processes. Several works focus on the effects of land use changes (Choi and Deal, 2008; Verburg et al., 2008; Luo et al., 2010; Haiming et al., 2010; Wijesekara et al., 2012).
4.) Identification and validation of the simulation model requires long term and accurate data series about meteorology, hydrography, topography, soil characteristics, land coverage, etc. Considerable efforts were made to collect and to publish various sets of these data. In USA, the Consortium of Universities for Advancement of Hydrologic Science established the Water Data Centre that provides data services to the hydrological science community. Geographic extent covers mainly the areas of USA. As another initiative, a comprehensive set of knowledge on earth surface dynamics and hydrological models, tools and data are available in the community of earth scientists and programmers (Overeem et al., 2013). Despite these efforts, in the model implementation and/or development for a newly investigated area, it is still a critical step to put together all the necessary data (Fenicia et al., 2011).
5.) The most important task of environmental models is to assist both field experts and governmental/NGO decision makers in studying the effects of climate change, land use and other factors, as well as to assess e.g. the water quality in this context. Accordingly, socio-economic evaluation and decision support methods can be built in the identified and validated environmental models. Connecting natural science models with socio-economic aspects is an old issue (Voinov et al., 1999), but it is still in the focus of current research topics (Bryan, 2013; Hewitt et al., 2014).

Early developments, started in 1970–80's, focused on site-specific, isolated models (Duckstein et al., 1982; Alley and Emery, 1986) that are not easily modifiable and flexible enough to extend them for the investigation of processes in another spatial or temporal scale (Zagona et al., 2001). An overview about complex environmental modelling methods, involving hydrological modules, was provided by Melli and Zannetti (1992) from this period. Another comprehensive overview summarizes the attempts to connect geographic information systems with agent-based modelling methodologies to simulate ecological and even social processes, dynamically (Gimblett, 2001).

Amongst problem oriented approaches, we have to mention the various land use change models. Several overviews (e.g. US EPA, 2000; Agarwal et al., 2002) and research articles (e.g. Verburg et al., 2002; Luijten, 2003; Fuglsang et al., 2013; Verstegen et al., 2014) dealt with this topic. A frequently and still used, freely available tool is CLUE, which is a spatially explicit and dynamic land use and land cover change model (Verburg and Overmars, 2009).

Having recognized the need for multidisciplinary and multi-scale problem solving, the case-specific models were followed and replaced by generally applicable modelling frameworks. An early, detailed review of the various frameworks is given by Borah and Bera (2003), mainly from mathematical point of views. The developed general frameworks, such as ANSWERS-2000 (Bouraoui and Dillaha, 2000), MIKE SHE (Butts and Graham, 2008), Soil & Water Assessment Tool (Neitsch et al., 2011), GISHydro (2013) or Watershed Analysis Risk Management Framework (WARMF, 2013) have the ability for the combined consideration of various hydrological processes, built in each other in watershed scale.

Most of these frameworks were applied for the investigation of different watershed scale processes, however SWAT (SWAT, 2009; Bosch et al., 2011; Baker and Miller, 2013; Bhuvaneswari et al., 2013) seems to be the best known and most widely used tool.

As another counterpoint to the former, isolated, task-specific applications in water resource management, in a recent work Welsh and colleagues emphasize the need for integration of the individual model components, and accordingly they introduce the Source Integrated Modelling System (Welsh et al., 2013) to manage the complexity.

Implementation and combination of System Dynamics (SD) is a frequently used method in environmental modelling. SD method was originally created in the last century by Forrester (1961, 1969, and 1971) to understand the behaviour of complex systems. In the past decade, many SD based applications were developed and combined with GIS tools for hydrological and environmental modelling. For example, most commonly used SD implementations are Stella (Voinov et al., 1999; Meals et al., 2008a; Meals et al., 2008b; Randhir and Hawes, 2009; Rivers et al., 2011, 2013; Öztürk et al., 2013) and Vensim DSS (Yeh et al., 2006; Khan et al., 2009; Luo et al., 2010; Guan et al., 2011; Ma et al., 2012a; Zhan et al., 2012; Ma et al, 2013; Vidal-Legaz et al., 2013).

Another significant initiative is the Open Modelling Interface (OpenMI), developed by the OpenMI Association and implemented within the Water Framework Directive (Moore and Tindall, 2005; Knapen et al., 2013). This standard makes possible the data exchange between the different models in runtime, on a time-step basis. The OpenMI standard has been applied in several recent works (Fotopoulos et al., 2010; Castronova et al., 2013; Castronova and Goodall, 2013; Shrestha et al., 2013).

Object Modelling System (OMS, 2014) is another modelling framework for building agro-environmental models, developed by Agricultural Research Service of USDA. Within this framework the field experts are able to create components for the model development; next they can parameterize and modify, as well as re-use the model according to the requirements (David et al., 2013).

Combination of GIS tools with various statistical modelling