Ecological Modelling 295 (2015) 66–74

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Operationalizing environmental indicators for real time multi-purpose decision making and action support

Hermann Klug[a,*], Alexander Kmoch[b]

[a] Paris-Lodron University of Salzburg (PLUS), Interfaculty Department of Geoinformatics—Z_GIS, Schillerstr. 30, Building 15, 3rd Floor, 5020 Salzburg, Austria
[b] AUT University, Geoinformatics Research Centre (GRC), School of Computer and Mathematical Sciences, Auckland University of Technology, AUT Tower, Level 6 (Wakefield St Entrance), 2-14 Wakefield St, Auckland 1010, New Zealand

ARTICLE INFO

Article history:
Received 8 January 2014
Received in revised form 26 March 2014
Accepted 7 April 2014
Available online 20 May 2014

Keywords:
WebGIS
Sensors
SDI
Early warning system
Water resources management
OGC

ABSTRACT

Within the last decades tremendous progress has been made in analysing, characterising and understanding the processes, functions, and structures of the environment. Numerous indicators have been proposed and operationalised using computing techniques. However, many of the approaches are based on specific case study areas and the transfer of approaches is hampered due to incompatible data formats, data availability limitations, and/or unavailable modelling routines. Information on modelling routines, existing result datasets, and updates of previously derived analyses are missing. Considering the recent technological and methodological developments, environmental modelling providing indicators for decision support is likely to change in the next decade. This research provides a heuristic conceptual basis for driving the next generation of real-time multi-purpose data assembling, evaluating, modelling, and visualisation towards the operationalisation of decisions. Turning field observations into useful (near) real-time decision support information is demonstrated based on a hydrological example of future Integrated Water Resources Management. This paper describes new ways of near real-time indicator processing using Wireless Sensor Networks and standardised web services. Publicly available and standardised environmental information as Open Geospatial Consortium compliant Sensor Observation Services with its data formats Observations & Measurements and Water Markup Language 2.0 automatically feed into Web Processing Services for timely information delivery, discovery and access of the spatially explicit environmental conditions as pull and push based web services accompanied with notification for immediate actions in crisis times.

1. Introduction

The environment is multi-dimensional, multi-functional, inherently complex, of transdisciplinary nature and highly dynamic (Grabaum and Meyer, 1998; Tress et al., 2003; de Groot, 2006). The interwoven nature of real-world problems challenges for higher-order transdisciplinary systems thinking. Holistic-integrated approaches are needed to apply state-of-the-art knowledge to explain, explore, and predict landscape phenomena to ensure proper mitigation strategies. Most importantly, location-based environmental information is required in near real time in crisis situations to ensure timely adaptation. Example stressors are climatological extreme events or overexploitation of water resources. To analyse and describe conditions such as extreme precipitation and overuse of groundwater resources e.g. for irrigation purposes, many ecological modelling routines resulting in indicator proposals have been developed. Among the modelling routines are many hydrological modelling examples specifically dedicated for irrigation needs (Blaney and Criddle, 1950; Minacapilli et al., 2008; Wriedt et al., 2009; Dechmi et al., 2012), ecological minimum flow in rivers (Thomas et al., 2011; Gao et al., 2010), or flooding (e.g. Ahmad and Simonovic, 2006). With the introduction of the European Water framework Directive (Directive, 2000/60/EC) researchers increasingly consider the analysis of these single components in an integrated way. Thus, integrated environmental modelling became a vision and roadmap for the future (Laniak et al., 2013; Granell et al., 2013).

Both modelling and monitoring efforts are considered as the key for sustainable environmental planning (Jorgensen et al., 2007) resulting in environmental decision support systems rapidly progressing since the beginning of this century (Matthies et al., 2007). Interdisciplinary and multi-purpose integrated models are becoming more important but also more complex (Voinov and Cerco,

* Corresponding author. Tel.: +43 662 8044 7561; fax: +43 662 8044 7560.
E-mail addresses: hermann.klug@sbg.ac.at, office@hermannklug.com (H. Klug), alexander.kmoch@aut.ac.nz (A. Kmoch).

http://dx.doi.org/10.1016/j.ecolmodel.2014.04.009
0304-3800/

2010; Pahl-Wostl, 2007). Multi-purpose examples are "Coupling a hydrological water quality model and an economic optimisation model to set up a cost-effective emission reduction countermeasure scenario for nitrogen" (Cools et al., 2011) or "An integrated approach to linking economic valuation and catchment modelling" (Kragt et al., 2011). However, both examples did not consider real time measurements for modelling despite the fact that Hart and Martinez (2006) already insinuate the importance of real-time environmental information from sensor networks for better process-understanding and informed decision making.

Wireless sensor networks are available since decades and have been regularly reviewed and continuously improved (Akyildiz et al., 2002; Baronti et al., 2007; Yick et al., 2008; Schimak et al., 2010). However, all before mentioned approaches did not thoroughly consider the standardised data distribution. Usländer et al. (2010) and Díaz et al. (2013) provide insight in designing environmental software applications based upon an open sensor service architecture, however, they did not discuss the coupling to real-time modelling and pull and push based conditioned information delivery. Moreover, without proper measures for validation, model (auto-)calibration is hardly achieved (Raj Shrestha and Rode, 2008; Green and van Griensven, 2008). Streamlining inputs and outputs of data from and to models and the implications of complexity and uncertainty for integrated modelling and impact assessments are a big scientific and technical challenge and need to be considered as equally important as uncertainty propagation (Beven, 2000; Refsgaard et al., 2007; Krysanova et al., 2007). Thus, with increasing complexity the uncertainty of model results increases and there is a strong need for emulation techniques for the reduction and sensitivity analysis of complex environmental models (Ratto et al., 2012; Makler-Pick et al., 2011; Andrews et al., 2011; Crout et al., 2009; Ziehn and Tomlin, 2009; Reusser and Zehe, 2011; Guse et al., 2014).

As discussed by (Klug and Kmoch, 2014a,b), the challenge is that many of the modelling approaches need a thorough data basis as a foundation but spatial data for integrated environmental modelling is scattered and difficult to obtain, publicly unavailable and data access is hampered. In consequence a lot of time resources and costs need to be invested for state of the art data acquisition. Subsequently, updates of previous indicator modelling results are almost unavailable on a real-time basis since real-time data are rarely accessible. Spatially continuous modelling exercises across administrative and/or state boundaries are impossible yet since interoperable – technically and semantically harmonised and standardised – datasets and modelling interfaces are not exhaustedly available (Horsburgh et al., 2014). Furthermore, software routines for environmental modelling often are neither publicly accessible nor do they support standardised data interfaces for their integration. Thus, repeatability and transferability of approaches are hampered. Modelling tools and software often are not well described to properly exploit the full modelling power. Automated interchanges of model results are presently almost unavailable (Granell et al., 2013). As a consequence of lacking near real time data access in a proper ready to use interoperable format, events such as flooding from heavy rainfall are rather post-processed than forecasted. This lacks proper preparation on extreme events causing for instance people, infrastructure and the environment at risk in flooding times. Thus, the main future challenge is to complete and automate the workflow from initial data capturing to the real-time provision of conditioned information delivery to end users for prepared decision making.

With this manuscript we provide a science base structure to organise and technically implement transdisciplinary multi-purpose knowledge and indicator approaches for near real time decision making with a call for pro-active local action to prevent stress to human and the environment in six main stages. This places decision makers and stakeholders in the situation to estimate the landscape capability, resilience, vulnerability and loading capacity of the environmental balance to avoid irretrievable damages to humans and the environment.

We increase understanding of the possibilities for a web based data and information sharing framework of near real time environmental status delivery with access to environmental models utilising common data interfaces to provide indicators for advanced decision support. The reflection of the comprehensive framework setup for near real-time indicator updates is exemplified on a hydrological example. We consider flood conditions and human interventions effecting changes of groundwater tables. We discourse the future research direction of real-time decision making that helps addressing "what if" questions to adapt against certain environmental or more specifically climate change impacts. We provide a scientific framework to organise and technically implement transdisciplinary multi-purpose knowledge and indicator approaches for near real time decision making with a call for action to prevent stress to humans and the environment.

We hypothesise that with publicly available near real time environmental measurements accessible in standardised data formats we are able to drive modelling routines on request and provide messages on present and future environmental conditions to those who need them. With present available methodologies, technologies, and internationally accepted standards we are able to provide real-time information on the state of the environment indicators from distributed data sources to allow concrete mitigation action for conflicts of interests coming into force at local level.

2. The real time indicator framework

Comprehensive and integrated spatial planning presupposes a high degree of on-site knowledge (Klug, 2012). Considering specific conditions, vulnerabilities, risks and interdependencies, real-time multi-purpose conditioned information delivery is a great mental and conceptual challenge across applications, scientific disciplines, technology, and communities where many parameters need to be connected in a proper way. Thus, comprehensive and integrated environmental planning presupposes a high degree of technical and interdisciplinary knowledge and experiences. (Electro-) technical and engineering skills are required to setup the wireless sensor network infrastructure while Geographic Information Science (GIScience) is providing insight to the spatial relationships and the Spatial Data Infrastructure. The hydrology domain provides the methodological frameworks on Integrated Water Resources Management (IWRM). The modelling is strongly coupled to GIScience but also includes disciplines such as soil sciences and climatology when considering the entire water cycle. Once water consumption is considered, social and economic domains come into play as well.

Fig. 1 shows the theoretical background of our proposed complete and automated concept from initial data capturing to the real-time provision of conditioned information delivery to end users for prepared decision making. The following subchapters describe our concept regardless of context or scientific domain but explain it on hydrological examples we are working on.

2.1. Near real time measurements

Monitoring is a continuous observation of an environmental parameter at a certain place over a certain time period contributing to a better understanding of environmental processes and functions (Hart and Martinez, 2006). This monitoring can be done with in situ sensors (ground sensor devices) or ex situ sensors (e.g. satellites). With the focus on in situ sensors Bröring et al. (2011) demonstrated that "integrating diverse sensors into observation systems is not straightforward". However, with the Open Geospatial