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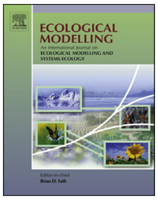

Operationalizing environmental indicators for real time multi-purpose decision making and action support

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

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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; Minacapili 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,

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* 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).

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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.

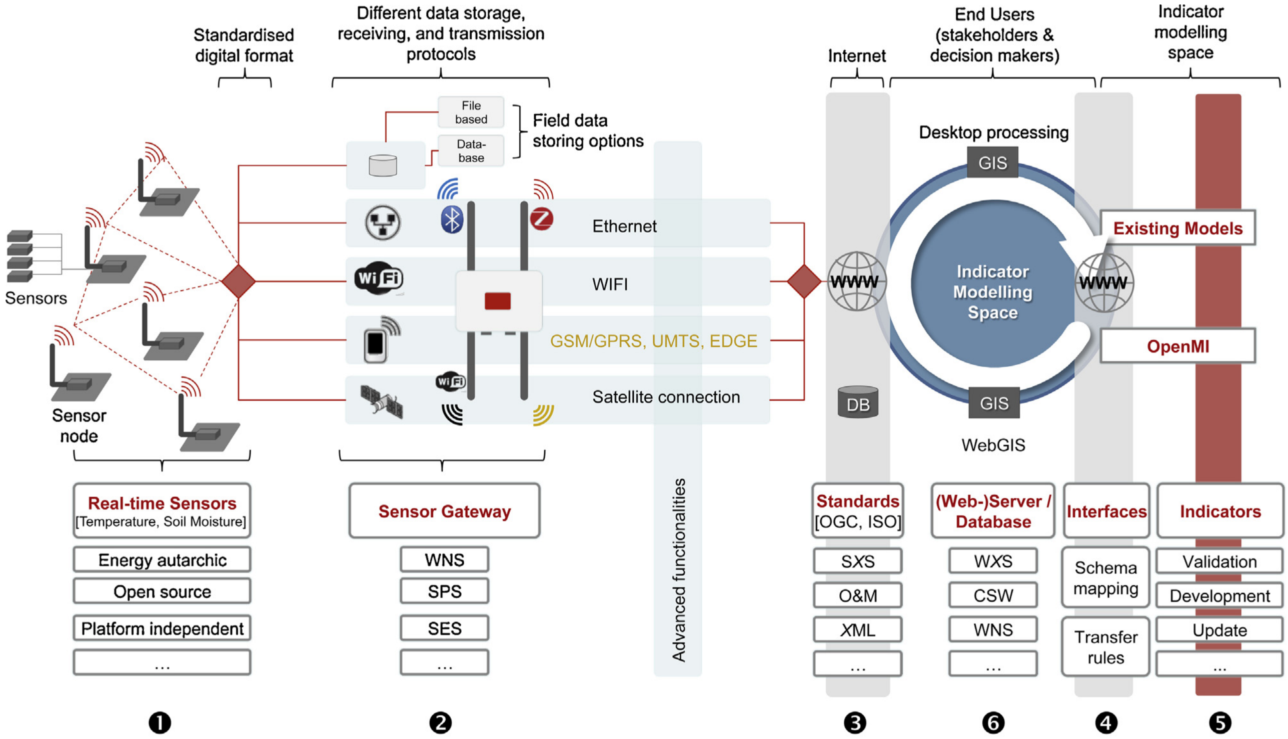
2. The real time indicator framework

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



WXS: Web Map Service, Web Feature Service, Web Coverage Service, Web Processing Service, etc.
XML: SensorML, WaterML, GroundwaterML, etc.
SXS: Sensor Observation Service, Sensor Planning Service, Sensor Event Service, Sensor Alert Service, etc.
DB: database
GIS: Geographical Information System

Fig. 1. From in situ measurements to advance near real-time decision making.

Consortium (OGC) compliant Sensor Web Enablement Botts et al. (2008) show how to distribute interoperable, platform-independent environmental information in a uniform way. The setup might collect data centrally from many sensor nodes or it is a node and gateway at the same time. Possible individual sensor network setups are (already) outlined in Morreale et al. (2011), Kawai et al. (2009) and Kafetzoglou and Papavassiliou (2011). We consider the following points as most important for transferability and reusability of Wireless Sensor Networks (WSN) developments:

- implementation of high quality but low cost and low energy consuming sensors capturing environmental information at a higher density in space with the same investment budget,
- ensuring platform independency (e.g. MacOS, Linux, Windows) and open source developments on server and client side for transferable and multi-purpose uses,
- enabling energy autarchic systems for a place independent positioning of sensors without the need of a power grid connection, and
- applying internationally recognised data transmission standards (e.g. ZigBEE, WiFi, Bluetooth, GSM/UMTS/EDGE/HSDPA/HSUPA/LTE, satellite connection) to ensure global near real time access of datasets.

2.2. Sensor gateway

2.2.1. Central functionalities

The central element of the locally installed Wireless Sensor Network is the gateway located in the field to collect the sensor information from the sensor nodes. Ensuring platform independency, this gateway can be a MacOS, Linux or Windows system designed to store raw incoming environmental information like a data logger. Raw datasets are either stored file based or in a database (e.g. MySQL or PostgreSQL) and then distributed to the internet via OGC compliant Sensor Observation Service (see Section 2.3) using the wireless transmission standards as described in Fig. 1.

2.2.2. Advanced functionalities

2.2.2.1. Data transformation and quality control. The central gateway converts raw data from voltage or resistance into proper measurements such as wind direction (instead of a resistance value) or wind speed (instead of a number of rotations in time) (Jardak et al., 2010; Han et al., 2010; Zhang et al., 2010; Terzis et al., 2010). Domain specific modelling procedures from climatology or hydrology check data validity. These procedures are placed in between the database and the submission to the Sensor Observation Service (SOS, OGC, 2012a) to provide reliable, understandable and publicly accessible information. Thus, the sensor gateway is closely connected to the indicator modelling environment described in stage 5.

2.2.2.2. Measurement logic. Usually the measurement interval is unique and dependent on the application context or the data provider's preferences. However, in a multi-purpose context the status of the measuring interval might need to change to higher or lower frequencies. Under 'normal conditions' the sensors might perform measurements in a 15 min interval. This interval might not be considered sufficient for 'unexpected conditions' such as extreme precipitation events where for instance discharge measurement information should be delivered in a 5 min interval. Thus, sensor configuration needs to be adjustable on-demand. Rule sets define changes between the sleep and awake cycle of sensor nodes and thus the time interval for measurements. The rule sets are based on anthropogenic triggers or direct measurements from one or more sensors. The Sensor Planning Service (SPS, OGC, 2011c) and Sensor Event Service (SES, OGC, 2011b) provide updates of the measurement frequency in times where the sensor is awake. The specific environmental conditions observed define the intervals.

2.2.2.3. *Alert logic.*

At the same time as sensors change their configuration, they can trigger notifications via SMS, email or mobile app alert. These messages might contain single environmental conditions or reports derived from environmental indicator models. Thus, alert messages are defined based on indicators but might have different meanings to different stakeholders. Therefore, alert messages based on indicators need to be 'translated' into understandable user defined messages (see Section 2.6.1).

2.3. *Standards*

While the previously described stages are usually based on individual setups (data transmission routines, database structures, etc.), the standard compliant distribution and access to data is a central component to ensure interoperability and the interplay and union of different distributed time series datasets and indicator models. In our framework in Fig. 1 the gateway delivers the measurements via a SOS compliant connector library to the Sensor Observation Service.

Field measurements are streamed via SOS in the data formats Observations and Measurements (O&M, OGC, 2011a) and Water Markup Language (WaterML2.0, OGC, 2012b) from distributed sources into modelling and simulation applications mentioned in stage five. These indicator models are implemented as Web Processing Services (WPS, OGC, 2007b) and provide indicator results, which are linked with advanced decision support as outlined in stage six. Environmental modelling routines for policy support are already available for instance in Lux and Matthews (2007), Letcher and Giupponi (2005), and Cuddy and Gandolfi (2004).

To ensure the capability to rapidly discover available resources central knowledge portals interconnected via Catalogue Service Web (CSW, OGC, 2007a) interface, an implementation as described by Klug and Kmoch (2014a,b) is helpful.

2.4. *Data interfaces and transfer rules*

Real time datasets from stage 1 connect to models deriving indicators in stage 5. However, as described in Klug and Bretz (2012) and Klug and Kmoch (2014a,b) many datasets exist in different formats and national standards. For application-neutral encoding of geoscience thematic content GeoSciML (Sen and Duffy, 2005), GroundwaterML and WaterML as standard based data formats are now developed under the governance of the OGC and allow exchange of digital, interoperable geospatial information between data providers, users and models. Thus, these GML (Geographic Markup Language) application schemes enable technically and semantically harmonised data transfer via comparable content and format.

2.5. *Indicator development*

Already pre-processed and standardised datasets are fed into the indicator modelling environment. Indicator modelling routines expressed as analytical algorithms to data can range from simple algorithms (e.g. selection of min, max, or median value) to complex algorithms reading contemporaneous sets of information coming from different distributed data sources but the same format. Advanced data fusion algorithms lead to back-, now- and forecasting results presenting the previous or present state of the environment or the course of its development as spatially explicit results (Havlik et al., 2011).

To ensure a broad use and understanding of modelling results, scientists but also stakeholders and decision makers need to get insight into the appropriateness of modelling routines. Nativi et al. (2013) proposed the provision of models in a service oriented approach to increase model access and sharing possibility while Castronova et al. (2013b) proposed an integrated modelling within a hydrologic information system using an Open Modelling Interface (OpenMI) based approach (The Open Association Technical Committee, 2010a,b; Castronova et al., 2013a; Knapen et al., 2013). OpenMI defines how independently developed computer models of environmental processes can exchange data at run time. This facilitates the integrated modelling of interacting processes to understand Earth system processes to be translated into proper decision support messages. Similar to the Object Modelling System (OMS3, David et al., 2013) as a modelling framework for component-based model and simulation development on multiple platforms, OpenMI can be used as a model integration platform across disciplines (Knapen et al., 2013). Special interest groups such as the Community Surface Dynamics Modelling System (CSDMS) provide models of the earth surface processes and disseminate these as integrated software modules to be used on dynamics modelling systems (Overeem et al., 2013). Similar is the Earth System Modelling Framework (ESMF, http://www.earthsystemmodeling.org/index.shtml) for building and coupling weather, climate, and related models.

Real time model runs enable the immediate validation of environmental conditions against defined (inter-)national indicator standards/thresholds (e.g. water quantity). Comparisons to previous measurements and thus trends can be communicated in real time. However, since models are a simple representation of the complex environment and datasets bear some vagueness as well, we regard uncertainty modelling and a provision of uncertainty measures incorporated in the indicator modelling stage. UncertWeb can be considered as the basis for this challenge (Bastin et al., 2013).

2.6. *Information distribution*

Turning data into useful information is the key for better informed decision making. Information needs to be delivered in different formats dependent on the level of knowledge and the responsible stake. Thus, the information distribution varies according to end user demands and categories. Primary datasets (e.g. raw data or pre-processed quality controlled data from stage 2) or secondary datasets (e.g. resulting from the environmental indicator modelling in stage 5) are available in tabular form, in figures, or as maps. These tables, figures or graphs might not be appropriate since interpretation of results and respective action items are missing. Important is the provisioning of solutions tailored to end user demands.

2.6.1. *Conditioned information delivery*

The information conditioning refers to the reduction of complex, multidimensional and highly dynamic environmental information to responsible persons (e.g. blue light organisations) but also to the public. We consider the conditioned information delivery as a structured synthesis of given conditions and as a learning process by which the importance of single information pieces become dependent on the users interacting with the system. As specified by Klug and Kmoch (2014a,b) "the provision of 'conditioned information' is the separation of the crucial from the tangential; thus 'essentialising' those items which are most important for the users". This information reduction is especially important in crisis times where time resources are needed for action rather than interpretation of complex results. Thus decision makers require concise information on a timely basis to base their decisions on the latest state of the environment. To underpin stakeholders' decisions, information about the accuracy/uncertainty and the context dependent interpretation is required as described in stage 5.

The transformation of raw data through modelling to environmental indicators need to follow a further refinement through interpretation of findings and expressing those interpretations in an end user understandable way. End users for certain environmental conditions have different acting roles and thus information needs to be tailored accordingly. Thus, user centred information distribution to different user groups e.g. stakeholders, actors, public people is the key for immediate and proper action to prevent hazardous events such as heavy rainfall events causing floods or overconsumption of groundwater leading to decreasing groundwater tables (see Section 3).

2.6.2. Pull based information retrieval

Pull based information retrieval requires users actively taking action to receive information from a web service. They either take accessible datasets to their desktop environment or access information directly from the web services.

Advanced users directly feed real time data into their desktop modelling routines (without copying the datasets) and derive end user demanded results. These time series datasets usually are available in an XML based machine readable format and/or data file download.

In a second possibility users actively consume ready to use information via web services as

- observations in tabular (e.g. CSV) or diagram format,
- point datasets with observations on a map,
- mono-thematic conventional spatially distributed modelling result from WPS routines (e.g. spatially explicit temperature distribution) where time sliders might provide the opportunity to discover spatial-temporal changes in a WXS (Web Map Service, Web Feature Service, Web Coverage Service, etc.),
- multi-thematic integrated modelling results retrieved from e.g. indicator modelling approaches provided as conditioned information.

2.6.3. Push based information retrieval

We consider a push based information distribution supportive for pro-active planning and early decision making. Participants register at a service and receive status information as short message (SMS), email or mobile app notification on the environmental conditions. Messages are triggered via a Web Notification Service (WNS), Sensor Planning Service (SPS), and Sensor Event Service (SES). Messages are customised to end user needs and report for instance single measurement values or a defined status message based on developed rule sets. The status message can be accompanied with action tasks related to the specific circumstance the message was triggered by (see Section 3).

3. An early warning system as an application example

IWRM should be addressed by a comprehensive Early Warning System (EWS). The EWS should be developed as a multi-purpose instrument observing, monitoring, analysing and informing about the present state of the environment. A hydrological EWS should be based on real time hydro-pedo-meteorological observations at field stations. Knowledge and experiences from these observations can be used to set-up combined natural scientific and anthropogenic models to characterise the present situation and likely future scenarios. Historical datasets help understanding the past and recent variability and trends in water resources conditions. This ensures strategic political and integrated water resource management decision support for the prevention and anticipation of water related stress situation on a general level. The EWS as a decision support system (DSS) analyses water stress and helps drafting decisions for potential crisis situations. These decisions might answer questions like "When we are likely affected by an extreme precipitation event?" On a short term basis the EWS should be able to take action for a crisis situation already in place or expected soon. Short term water stress situations have different meanings. In expected heavy rainfall events information need to be available up to 72 h in advance the event is expected to happen. Forecasts need to be revised on a 12- (better 6-) hourly bases. Forecasting for instance water scarcity can be based on a longer time period of about a week to a month dependent on the focal region.

3.1. Now- and forecasting

For the now-casting in situ measurements provide the present state of the environment from the sensors as described in stage 1 (e.g. soil moisture level, discharge conditions). At the same time, models such as (WRF-ARW Model, http://wrf.rometex.org/) use real time in situ measurements to forecast meteorological parameters such as precipitation up to 48 h in advance on an hourly base. Result datasets are provided as GeoTiff raster files and can be made accessible via standardised interfaces such as Web Coverage Services.

Integrating both standardised input datasets into a web based OpenMI compliant hydrological modelling system would enable a spatially explicit forecast of runoff conditions and flooding probability in 48 h ahead. However, this flooding probability is based on numerous parameters which are not easily to be discovered by end users. Thus tailored rule sets on information delivery need to be established.

3.2. Rule sets in the framework of multi-purpose decision making

As outlined in Potschin et al. (2010) setting up of technical infrastructures supporting environmental planning is not enough. Priority weighting, setting of preferences and stating decisions in water crisis situations is indispensable. Rule sets as mentioned in stage 2 are data processing algorithms representing latest scientific knowledge and automated reasoning on past, present and forecasted datasets.

The sensor logic can be multi-purpose, e.g. delivering information at low groundwater levels indicating an ecological minimum flow in near rivers or at high water level indicating flooding. Low soil moisture levels might turn on an irrigation system or triggers a flood warning message at full saturation level. Combined with rain forecast models resulting from stage 5 the forecasted amount of rain and the present in situ condition provide an indication on the alert level and the respective adaptation information.

Example 1. Flooding

Heavy rainfall events detected at the rain gauges trigger higher frequency measurements of other devices in the catchment. This should ensure a better understanding of spatial–temporal interdependencies of water flow processes. Thus, in case a (to be locally defined) amount of rain passes the rain gauge, discharge, water table, and soil moisture measurement intervals are updated to a higher frequency. The frequency is reduced back to 'normal conditions' after a (locally to be defined) time after the latest recognised rainfall event. The same is true for the snow melting period where the (locally to be defined) changes in snow water equivalent measurements trigger the before mentioned devices.

Example 2. Water scarcity

Low groundwater levels often correlate to increased groundwater exploitation due to irrigation purposes in water scarce times causing reduced discharge rate affecting the ecologically required minimum flow in rivers. Thus, (locally to be defined) groundwater levels trigger the discharge measurement frequency and the water abstraction rates.

SOS available groundwater levels are correlated with rain forecast and municipal and agricultural water abstraction/allocation schemes to reduce over-consumption and environmental impact. Again early notifications of states and trends with simple green, yellow, red warning indication of expected criticality is ensured with respective explanation of further decision acts for different stakeholders. Couplings with utilities/local water supplier ITC systems for integrated management would help to balance the water demands from different parties including the environment.

3.3. Information distribution

Based on an evaluation of impacts and relevancies the adaptation strategies with defined countermeasures should take local action which requires a proper understanding of the hydro-meteorological conditions and the affected people and environment. The EWS should enable knowledge-based decision making by combining (real time) data and models.

An early warning system for us directly relates to the push-based information distribution. As discussed, tailored information is considered the key for proper decisions for people with different responsibilities. To demonstrate the multi-purpose decision making framework and the tailored information distribution to different actors we provide simple examples from IWRM in Table 1.

The design of the monitoring programme and the frequency of collecting data are implicitly grounded in the demand for multi-purpose decision making. The decision support is either based on the measurements or the modelling results while the action items relate to the interpretation of results. For instance, driving forces of environmental conditions (soil water content in volume percent, expected rainfall in millimetres) are formulated as pressure or problem statement (a fully water saturated soil and forecasted heavy rainfall might lead to flooding). The state describes the present conditions which in case of the expected rainfall event might change to critical levels. The related impact corresponds to the alert level, which is dependent on the specific present and/or forecasted environmental condition. Impacts based on the conditions are outlined and concerns expressed (certain infrastructure might be at risk and cellars likely at risk being flooded). Based on present knowledge and the conditions of the environment decision opportunities detailed responses are provided as pro-active statements (e.g. start filling sand bags and place them to certain places to prevent cellars being flooded).

4. Discussion

The constitutive objective of this research was to capture the basic characteristics from in situ measurements, standard compliant real-time transmission of environmental measures, integration of measures to standardised modelling frameworks and provision of sound indicators for advanced decision making and calls for (adaptation) actions. The proposed framework places stakeholders and decision makers in the situation to access the real-time state of the environment but also condensed conditioned information. This enables the users to estimate the landscape capability, resilience and loading capacity with respect to water resources examples. This is consequently to ensure the proper functioning of natural processes and human security and avoid irreversible damages to the environmental integrity.

From the methodological point of view, a unique analysis and decision planning support framework has been investigated. It incorporates the design of near real time observations and modelling routines considering spatially explicit indicator models with reference to natural processes, functions, structure, and change while offering tailor made decision support to respective stakeholders. Different information sources are synthesised in one framework. It enables stakeholders to predict ecological consequences from near real time point observations and spatially explicit modelling results in a multi-purpose planning environment. Being based on automated procedures, the concept serves as a transparent basis on decisions taken. It provides criteria for continuous control of environmental resources through a near real time monitoring process. Monitoring and high frequency information supply about the environment challenges scientific knowledge through their constant flux. Our own understanding about environmental processes continually evolves with new observations and requires reviewing the rule sets triggering other sensors or alert messages. Despite many procedures could be automated already, the automated incorporation of updated knowledge gained from the analysis of in situ measurements as a self-learning system mechanism is a future challenge.

For proper decision making the validity for the masses of data need to be guaranteed; especially if the dataset should be directly used in forecasting models before and during crisis times. Existing meteorological and hydrological mathematical and/or statistical methods implemented as Web Processing Services help automating data validation to certain extend. However, manual data quality validation is needed for sustained quality controlled dataset but not for real-time applications.

Data validity and thus uncertainty quantification is a scientifically challenging part; especially when not only observing single point measurements but spatially explicit modelling results. The higher the complexity of a model is, the lower is the prediction power that can be expected. The complexity of the model(s) used for spatial interpolation generally reflects the end user needs and is limited by the considered spatial–temporal scale (resolution and extend) and the cloud computing power. Also the data transfer from the data repositories to the modelling routine might be limited when considering big data analysis. However, data integration into models should be straightforward if the data interfaces on data provider and modelling side are standardised.

Since the proposed concept enables human or sensor based changes of the measurement frequency of single sensors there might be a discontinuity in the data records causing impacts on data handling and evaluation. This is true if the overall sensing concept is designed arbitrarily. The measuring concept need to follow a rule based structure ensuring all required sensors measure at the same time to ensure a cross-comparison of environmental values. The frequency of these joint measurements depend on (i) the spatial–temporal scale of the analyses performed in the landscape and (ii) the reaction and/or processing time of the sensor itself.

From a transdisciplinary multi-purpose decision making perspective, modelling with stakeholders (Voinov and Bousquet, 2010) – as done for the exercise leading to Table 1 – increases acceptance and impacts of scientific efforts. Scenario analysis is possible in real-time using a usual web browser. In the future this would increase the value of for instance landscape development after the Leitbild approach as described in Klug (2012). Changes in spatial processes, functions and structures can be visualised tailor made to the stakeholder needs with latest cartographic and technological standards. Benefits will arise from free and open source software and open standard developments. This organised transdisciplinary working environment according to scientific procedures (Scholten

Table 1
Examples of multi-purpose decision making with different actors.

Actor	Driving force	Pressure	State	Impact	Response
Municipality mayor	Forecasted heavy rainfall event in *x* hours	Flooding probability	Alert level red	People, cattle and/or infrastructure at risk	Inform head of fire brigade to take action
Head of fire brigade	Soils fully water saturated	No water infiltration possible	Alert level orange	Likely effect of flooding in case of rainfall	Observe rainfall probability
Head of fire brigade	High soil water saturation level and forecasted heavy rainfall event in *x* hours	Reduced water infiltration capacity. Retention basin spill over. Rivers bank full	Alert level red	People, cattle and/or infrastructure at risk	Inform firemen on flooding probability. Coordinate action for filling and placement of sand bags
Head of fire brigade	High soil water saturation level and heavy rainfall	Surface runoff. Increasing water level	Alert level red	People, cattle and/or infrastructure at risk	Observer online discharge and water level measures. Run flood forecast model
Farmers	Soils fully water saturated	No field work possible	Alert level red	Soil surface sealing due to heavy machinery possible	Wait with field work until soil water saturation is reduced
Farmers	Soils at field capacity (issued after a released warning message)	Field work possible and best plant available water conditions	Alert level green	No impacts foreseen	Continue with field work of necessary
Farmers	Very low soil moisture level	Plant available water is reduced	Alert level red	Reduction or loss of grassland yield with consequences on fodder quality for cattle. Fire danger	If possible, turn on the irrigation system
Water authority	Critical discharge measurements	Flooding of settlements	Alert level red	Damage to people, animals and infrastructure	Steer the through flow of weirs
Water supply company	Low groundwater table level	Water scarcity	Alert level red	Drying out of groundwater well	Reduce groundwater abstraction rate
Public	High soil water saturation level and forecasted heavy rainfall event in *x* hours	Flooding of houses	Alert level red	You and your property might be at risk from floods	Protect yourself and your property against flooding. Close cellar windows. Call the fire brigade if they do not show up
Public	Very low soil moisture and groundwater table level	Water scarcity	Alert level red	Limited availability of water	Please reduce your water consumption. Do not wash cars or watering the garden. Keep your hygiene showers short

et al., 2007; Castelletti and Soncini-Sessa, 2006) creates trust in the decision support system and stakeholders are expected to take stewardship of developments they are able to use in their day to day work. While the labour force on the development of the system might be high, the maintenance of the system is expected to be moderate compared to the gain of frequently captured measurements of the system. While the scientific labour force for setting up the proposed concept and fine tuning data validity (dependent on the landscape analysis topic) is high, the applicability in our experience is not limited to available manpower. However, a permanent human control of model output in real-time is impossible but also not necessary. If sensor values remain critical after the rule-based filtering, the responsible person can be informed on potential data inconsistencies via the notification service. The provision of conditioned information is semi-automated and is based on rules to reduce respective work load. The rules as shown in Table 1 are very simple and in our case neglect possible conflicts between stakeholders. However, these transdisciplinary conflicts need to be addressed with all involved parties during the course of rule set definition and need to be reflected in the messages to be sent out.

5. Conclusion

This paper capitalises already existing knowledge and synthesises it into a new stage of higher-order systems integration providing new context and situation specific information. Bringing primary and secondary derived data and models together into one single decision support framework and advancing it by the delivery of end user tailored push messages is a major future challenge for a transdisciplinary science still in its infancy.

Wireless Sensor Networks for monitoring water flows and water abstractions ensure the timely provision of spatially explicit information to reduce delay times in data provision for a real-time decision making. Spatially enabled databases and consequent standard compliant data services serve as connecting elements in a greater distributed Spatial Data Infrastructure bundled in a one-stop-shop central portal to obtain datasets from distributed sources.

6. Outlook

Interactive natural resources modelling will enhance the understanding of the dynamics under various conditions as well as the impact of single modifications of the system conditions (Boschetti et al., 2010). Understanding the single relationships of nature through a quantification of the environmental benefits or impacts of practices can be facilitated (White et al., 2010). Integration of further economic software modules might also support transparent decision making on countermeasures or compensation payments where appropriate (Marinoni et al., 2009; Ulbrich et al., 2008). The modularity of the approach (i) enables a reduction or extension of the complexity, (ii) facilitates an exchange of single components according to the case study/thematic best fit, and (iii) enables the transferability of approaches to different areas. Comparability and transparency of results are considered as highly important as explained in Potschin and Klug (2010).

From the technological viewpoint, the progressive character of this approach provides transparent and pursuable tools to monitor, analyse, and inform stakeholders about environmental conditions and changes. Whereas earlier indicator approaches were impacted by inconsistent data formats and model access, future exercises will increasingly benefit from distributed geodatabases with common open data formats, interfaces and models providing access towards multi-functional approaches. These capabilities correspond with the increasing complexity of environments but its employment leads to a promising integrated, transdisciplinary and multi-purpose decision making approach. The latter is expected to reduce costs while using free and open source tools, open standards and interfaces, publicly and free of charge datasets and due to its pro-active and timely decision making ensuring the avoidance of damage costs. Also the onerous, expensive, time consuming, and often bewildering development and adaptation of models for the resource managers could be avoided (Caminiti, 2004). Standard compliant interfaces for data distribution and model integration reduce the burdens of data pre-processing or model adaptation. However, we see that for instance the INSPIRE process towards harmonised and seamlessly available geodata across Europe has not finished yet and full comprehensive modelling across boarders still need some time to come. Nevertheless, the potential of using standardised spatial data infrastructure and the visualisation of spatial information are already available. Especially web-based mapping products bear the powerful potential to visualise complex interdisciplinary situations quite simple and is supporting decision making at local and regional level. Online based continuously updated web services help monitoring the environmental conditions on a frequent basis (Chapman, 2012) and according to the European Environmental Information Directive (European Commission, 2003/4/EC) the public is kept informed. Science should provide access to the modelling resources and make them available as open source. Models should comply with international standards to ensure interoperability, comparability, transferability and integration in holistic coupled approaches. Science should contribute to the open data initiative to ensure integration in data hungry models. Data, tools and models should be made available online but still remain at the location where they are maintained. Once approved, certified data, tools and methods should be registered at one to be defined place to ensure people finding the resources demanded.

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