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ILMS – a Software Platform for Integrated Environmental Management

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Abstract: Integrated environmental system assessment and planning requires the application of different methods and software tools in a systematic and consistent workflow, often involving spatial data management, remote sensing and environmental modelling. Moreover, flexible and powerful interfaces are needed to allow for a seamless integration of these tools while avoiding file format and other transfer conflicts. This paper presents the Integrated Land Management System (ILMS) – a modular software platform that is addressing the demands of users involved in land and water resources management. By joining state-of-the-art methods and interfaces mainly based on open-source software modules it covers different aspects of environmental system analysis and management in a step by step, flexible, and user-friendly workflow.

Keywords: integrated land and water resources management; data management; environmental modelling; remote sensing; GIS

1 INTRODUCTION

The pressures on environmental resources are increasing worldwide due to population growth, land-use conflicts, socio-economic development and the consequences of climate change. Adaptable tools and methods are needed to elaborate information, develop understanding and create strategies for their sustainable use and management. These tools should assist scientists, natural resource managers and decision makers who are not GIS or modelling experts by providing them with

1. information about relevant drivers, attributes and factors from primary data,
2. methods for user friendly access and integrated analyses of such data, e.g. environmental information systems and remote sensing techniques, and
3. environmental simulation models for estimating a system's current state and for the prediction of its future development to test and identify suitable management strategies.

For an integrated assessment of complex environmental systems and the identification of suitable strategies to solve their related problems as proposed e.g. by the DPSIR model (EEA 1999), a seamless integration of environmental information systems, remote sensing techniques, simulation models and related data analysis methods is desirable. In order to address this demand, the *Integrated Land Management System* (ILMS) has been developed at the University of Jena to provide an integrated, modular software platform that uses well-tested, state-of-the-art methods and interfaces (Kralisch et al., 2011).

The next sections introduce the overall ILMS architecture and its single modules. Following, example applications of ILMS components are presented in section 4.

2 ILMS MODULES

The ILMS development was guided by the overall objective to design and implement a modular software platform that supports the integrated and sustainable management of land and water resources on spatial scales ranging from upper local- to upper meso-scale. The following major tasks were identified to be addressed by ILMS: (i) the collection and management of environmental data, (ii) the processing of remotely sensed spatial data via object-oriented classification methods for the generation of up-to-date land-cover/land-use (lulc) information, (iii) the qualitative and quantitative evaluation of the current situation of the landscape and its dominant processes by using mathematic simulation models, and, based on this analysis, (iv) the prognostic modelling of management scenarios in order to provide decision support for sustainable landscape management. Accordingly, the overall ILMS design shows a modular structure with four main modules:

1. a central database for saving and processing environmental data (*ILMSinfo*),
2. a linked information system as main platform for geodata management and processing (*ILMSinfo*, *ILMSgis*),
3. an image analysis and classification software to provide current, extensive and thematically valuable geo-information from remote sensing data (*ILMSimage*), and
4. a platform for generating problem-oriented environmental simulation models and exploring their results (*ILMSmodel*, *ILMSexplore*).

The following sections will introduce *ILMSinfo*, *ILMSimage*, *ILMSgis* and *ILMSmodel* in more detail.

2.1 *ILMSinfo*

The *ILMSinfo* module is based on the *River Basin Information System* (RBIS) (Zander et al., 2011). RBIS is a modular-structured, web-based information system for the management, analysis, visualization and presentation of environment related information. The common layout of RBIS follows a 3-tier architecture. On the server side, the system is implemented using a standard Linux web stack with Apache web server, PHP programming language and PostgreSQL¹/PostGIS² database management system. As a client, any current web browser can be used. RBIS is built in a modular way to enable a flexible adaptation to actual requirements. User interfaces to view, search, edit and interlink datasets are automatically generated by RBIS based on a description layer which uses XML documents to map the database schema to user defined views (Kralisch et al., 2009). Due to this generic approach new data types can be added easily to RBIS.

One of the RBIS core modules provides functionality for the management of metadata (RBISmeta) according to the ISO 19115 Standard for Geodata. Along with RBISmeta the system offers the following core modules:

1. RBIS_{ts} for the management, analysis, statistical processing, gap filling and visualization of measured and simulated time series data,
2. RBIS_{map} for the management and visualization of geo-data based on vector or raster data,
3. RBIS_{doc} for storing documents (e.g. project related PDF documents) or to associate documents to other dataset in RBIS (e.g. images associated to a measurement station), and
4. RBIS_{sim} to store information related to environmental model applications (e.g. parameter sets, input data), modelling scenarios and indicator calculation.

In addition to these core modules various optional extensions are available, e.g. the RBIS_{soil} module for the storage of soil profile and horizon data with a special focus on hydrologically important parameters.

¹ <http://www.postgresql.org>

² <http://www.postgis.org>

In order to exchange time series data with other software applications, RBIS offers interfaces for direct, i.e. proprietary data access and provides a Sensor Observation Service (SOS) to access time series data encoded in the WaterML2.0 format. Geodata management and visualization with RBISmap is supported by the Mapserver³ and OpenLayers⁴ software packages which are used to visualize geodata in web-based user interfaces. Using Mapserver, RBISmap offers standardized geodata interfaces (WFS, WMS) for external applications. Linking its geospatial data management, analysis and visualization features with other RBIS modules results in powerful functions for map-based search and selection of information about measuring stations, time series, observation points or hydrological catchments.

2.2 *ILMSimage*

For spatial modelling up to date lulc information is indispensable. Therefore, an image information extraction component had to be implemented into ILMS. *ILMSimage* has been designed to also allow users who are not remote sensing experts to extract information from remotely sensed data according to the requirements of their individual tasks. *ILMSimage* is a software system for object-based analysis of digital imagery and allows the extraction of spatial thematic information from digital image data as it is required as input dataset for the simulation of hydrological systems (Matejka et al., 2008; Reinhold and Selsam, 2009). Based on a modular implementation as a QGIS⁵ plugin, *ILMSimage* offers functions for image segmentation, feature retrieval and classification in a user-friendly, step by step workflow (Figure 1).

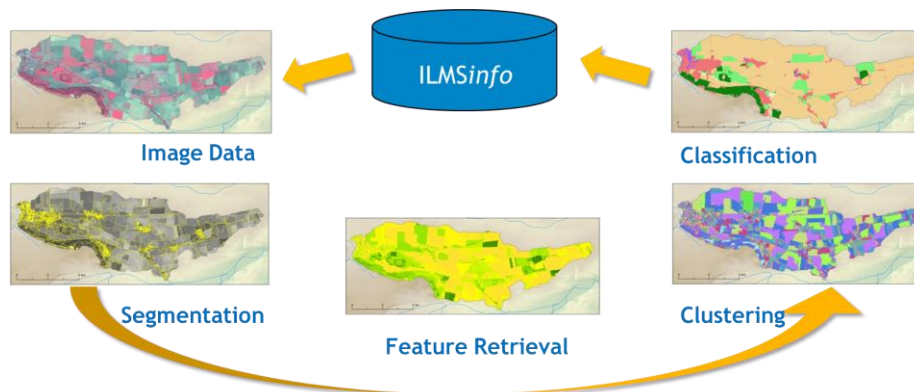


Figure 1. *ILMSimage* data processing workflow

During image segmentation, statistically homogeneous regions (cells) are delineated which are the basis for the following object-based analysis. The algorithm allows to control size and distribution of the cells by just a small number of parameters, allowing to adjust the cell size to the size of the expected land-cover elements. The feature retrieval step serves the calculation of integrated attributes for each cell based on its original image data (i.e. pixel values), its geometry (i.e. form and size), statistical and textural attributes calculated within the cells and optional additional data layers. All following classification steps are based on these calculated cell attributes. The final classification is subdivided into two steps. The first step combines cells with broadly similar image features by means of an unsupervised classification approach (clustering). The second step uses reference areas and supervised classification including spatial combinations of the previously generated clusters to produce the final object-based classification result. The *ILMSimage* input and result data can be stored in *ILMSinfo* via appropriate data I/O interfaces, thus ensuring a seamless exchange of information with other *ILMS* modules.

³ <http://mapserver.org>

⁴ <http://openlayers.org>

⁵ <http://www.qgis.org>

2.3 ILMSgis

Distributed environmental modelling relies on a spatial decomposition of the region of interest, usually into raster cells or polygons. Due to its superior ratio of spatial information content and number of elements, the Response Units (RU) approach, i.e. the delineation of spatial input data as polygons, is used in most of the ILMS simulation models. Representing areas with homogeneous process characteristics by spatially explicit modelling entities, the RU approach can be used to create efficient and knowledge based spatial decompositions for different types of models, e.g. into Hydrological Response Units (HRU) for hydrological models (Flügel, 1995) or into Erosion Response Units (ERU) for erosion models (Flügel and Märker, 2002).

Based on a client-server architecture, the *ILMSgis* module (Schwartz et al., 2012) has been developed to support this process of RU delineation and other geospatial analysis tasks in the context of ILMS (Figure 2). Within this architecture, the popular open-source geographic information system QGIS acts as a client, providing great mapping and data visualization capabilities. The functionality for geospatial processing is placed on the server side, offered by GRASS GIS⁶ and additional libraries. The communication within this setup is realized using a Web Processing Service (WPS)⁷, i.e. a standardized interface for the description and execution of remote processes. The PyWPS⁸ implementation is used here, offering native GRASS support and powerful Python scripting capabilities that can be used to implement more complex geospatial processing tasks.



Figure 2. *ILMSgis* client-server architecture

The HRU delineation is assisted by a special QGIS plugin that guides the user step-by-step through the process. In each step, it offers graphical user interfaces to request required input data and processing parameters and finally generates the necessary WPS requests to access the geospatial functions on the WPS server. After the termination of a WPS request the resulting XML response document either contains literal outputs or an URL linking to more complex results (e.g. GeoTiff images). For an easy and flexible exchange of geodata files between client and server the WebDAV protocol is used, e.g. for delivering the final HRU shapefile. Figure 3 shows the single processing steps of the HRU delineation workflow offered by *ILMSgis*.

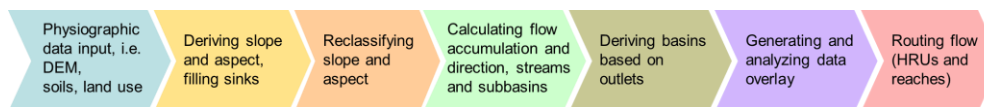


Figure 3. HRU delineation workflow of *ILMSgis*

The use of a standardized interface for invoking geospatial processing on servers introduces a high degree of flexibility regarding the client component development. Submitting a process may be performed from traditional Desktop GIS application as well as from recent web mapping platforms fully language independent, which is why the plugin above is currently restructured for a dynamic internet mapping client using OpenLayers. In doing so, the development process may benefit from the modular workflow design and new tasks or extensions can be easily integrated into the existing HRU delineation concept.

⁶ <http://grass.osgeo.org>

⁷ <http://www.opengeospatial.org/standards/wps>

⁸ <http://pywps.wald.intevation.org>

2.5 *ILMSmodel*

The *ILMSmodel* module for environmental process modelling is based on the *Jena Adaptable Modelling System (JAMS)* implemented in JAVA (Kralisch and Fischer, 2012). Originally developed with a focus on hydrological processes it has become a framework for environmental modelling in general. Its purpose is not the coupling of existing environmental models, but the creation of problem-tailored models from well-defined, scientifically sound process simulation components. Here, a component is a JAVA class that implements some defined software interfaces that are used to link it to other components in a standardized fashion. As an example, such a component could simulate interception, potential evapotranspiration or soil temperature with conceptual or physically based algorithms. Depending on the model's purpose and available input data, users can choose from the available process implementations that best matches their demands. With regard to the spatio-temporal domain, JAMS aims on simulating environmental processes at discrete points in time and/or space, often referred to as timed event systems.

For accessing external data during modelling, JAMS offers unified functions via a common software interface that allows abstracting from the actual data storage device and data format. Using this approach, JAMS can access SOS servers that offer WaterML2.0 encoded time series data as done by the *ILMSinfo* SOS implementation (see page 3).

For model parameter calibration, *ILMSmodel* includes a software assistant (OPTAS) that provides support in the task of calibration setup and application in a step-wise fashion (Fischer et al., 2009). OPTAS offers a variety of single- and multiple-objective calibration methods (e.g. Latin Hyper Cube Random Sampler, Shuffled Complex Evolution or NSGA-II) and a range of different objective functions. Other functions offer support for the analysis of sensitivities and uncertainties associated to model parameters. For this purpose, the Monte-Carlo-Toolbox (MCAT) developed by Wagener and Kollat (2007) was integrated in JAMS. The uncertainty analysis is based on the *Generalized Likelihood Uncertainty Estimation (GLUE) Framework* (Beven and Freer, 2001).

Based on the JAMS framework, various models have been developed and successfully applied, focusing mainly on the simulation of the hydrological and nutrient cycles. Implemented simulation components cover hydrological processes (e.g. evapotranspiration, infiltration, soil water balance, snow processes), the nutrient cycle (e.g. the biomass production, LAI, nitrification, denitrification, volatilization, plant uptake), landuse management (e.g. tillage, fertilization, harvest), soil erosion and phosphorus transport. The hydrological model J2000 (Krause 2002) is the most frequently used JAMS model. It simulates the water balance of hydrological catchments based on their spatial decomposition into HRUs for daily and sub-daily time steps. J2000 has been successfully applied in a large number of catchment studies covering the lower to upper meso-scale. J2000g is a simplified version of J2000 and can be used on larger scales, e.g. for the state of Thuringia in Germany (Krause and Hanisch, 2009) or for the catchment of lake Nam Co on the Tibetan Plateau (Krause et al., 2010). The J2000-S model (Fink et al., 2007) extends J2000 by components for the simulation of the nutrient cycle based on the SWAT model (Arnold and Fohrer, 2005). Combining the fully distributed modelling of the hydrological process dynamics from J2000 with the well-tested representation of the nutrient cycle from SWAT, J2000-S has proved its suitability in different meso-scale catchment studies in Germany and Tasmania (Bende-Michl et al., 2007).

3 *ILMS SOFTWARE PACKAGE*

To offer easy access to *ILMS*, a graphical interface was designed to launch its different modules. All server-based modules (*ILMSinfo* and parts of *ILMSGis*) have been packaged as a virtual appliance, i.e. a pre-configured runtime environment that comes with its own operating system and use-oriented application stack. For *ILMS*, VirtualBox⁹ is used as virtualization platform, minimizing

⁹ <http://www.virtualbox.org>

installation/configuration costs and guaranteeing rapid deployment (Schwartz et al., 2012). ILMS has been developed in close cooperation with companies operating in the areas of environmental management and planning, remote sensing and software development for geo-information management. Due to the fact that parts of *ILMSimage* are protected by intellectual property rights, ILMS comes in two flavours: (i) a free version (ILMS light) without *ILMSimage* and (ii) a non-free version with full functionality. ILMS light can be downloaded from <http://ilms.uni-jena.de/ilms/files>.

Most ILMS components are fully based on open source software (i.e. *ILMSinfo*, *ILMSgis* and *ILMSmodel*) and were implemented in a modular fashion using standardized software and interfaces whenever possible. This strategy guarantees a high flexibility to future extensions of the system and ensures that new developers can get involved easily. As an example, the *ILMSgis* module (cf. section 2.3) utilizes the WPS⁷ interface for communication between its geospatial processing component (GRASS-GIS) and its user interface (QGIS). Due to the standardization of this approach, alternative WPS clients like e.g. the web-based OpenLayers⁴ library can easily be combined with *ILMSgis*.

In order to provide ILMS users with detailed information and tutorials about the different modules, a Wiki¹⁰ has been created and is continuously updated. In addition, all ILMS modules provide some online help.

4 ILMS APPLICATION

ILMS and its components have been intensively tested and applied in environmental research and consultancy projects in Germany, India and Nepal¹¹, Vietnam¹², southern Africa¹³, and Brazil¹⁴.

Example results of an *ILMSmodel* application using the J2000-S nutrient model are shown in Figure 4. Carried out for the Ministry of the Environment of the state of Thuringia in Germany, the aim of this application was to estimate the efficiency of nitrogen reducing measures in a catchment in central Germany (860 km²) which is intensively used for agriculture (Bäse et al., 2007). The maps show the overall nitrogen inputs (left) and simulated outputs (right) for the baseline scenario.

In another application, *ILMSimage* was used to derive the sealing index for the whole state of Thuringia (16,000km²) from Landsat satellite data in 2010 in order to compare the results with the situation 10 years ago. Taking advantage of the image segmentation and object classification functionalities of *ILMSimage*, the sealing index and the development of sealing in Thuringia could be related to socio-economic changes (TLUG 2012). Figure 5 shows the detailed results for the city of Jena and generalized results for all communities in Thuringia.

A last example of an ILMS application is the ongoing implementation of the *Okavango Basin Information System* (OBIS)¹⁵. In the scope of the international research project *The Future Okavango* (TFO), *ILMSinfo* is used as software platform to create an integrated, web-based information management system that aims to provide environmental baseline data and research results for the Okavango River region and that will ultimately serve as a basis for an integrated, trans-boundary river basin management.

Using *ILMSinfo* as a centralized data storage platform, all ILMS modules are enabled to retrieve their needed input data directly from *ILMSinfo* which serves also as a repository for generated output data and their related meta-information. Output data of *ILMSimage* can be, for example, a land use map which is input for the delineation of spatial modelling entities with *ILMSgis*. Derived modelling entities and gap filled time series data in turn are used as input for environmental simulation models in *ILMSmodel*. The results of a simulation model, e.g. time series data or geodata, can be directly uploaded to *ILMSinfo* for dissemination or later use.

¹⁰ <http://ilms.uni-jena.de/ilmswiki>

¹¹ <http://www.geoinf.uni-jena.de/udl>

¹² <http://www.lucci-vietnam.info>

¹³ <http://www.future-okavango.org>

¹⁴ <http://dinario.fh-koeln.de>

¹⁵ <http://leutra.geogr.uni-jena.de/obis>

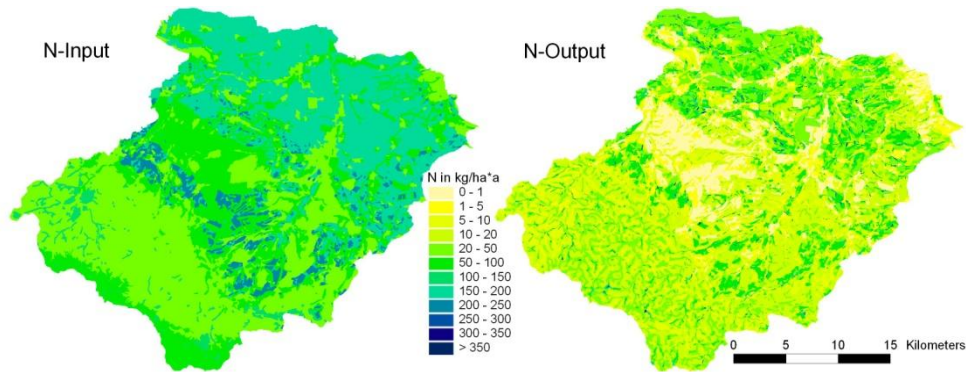


Figure 4. Distributed nitrogen input and output via different runoff components in the Gera catchment, Germany (860 km²) (Bäse et al., 2007)

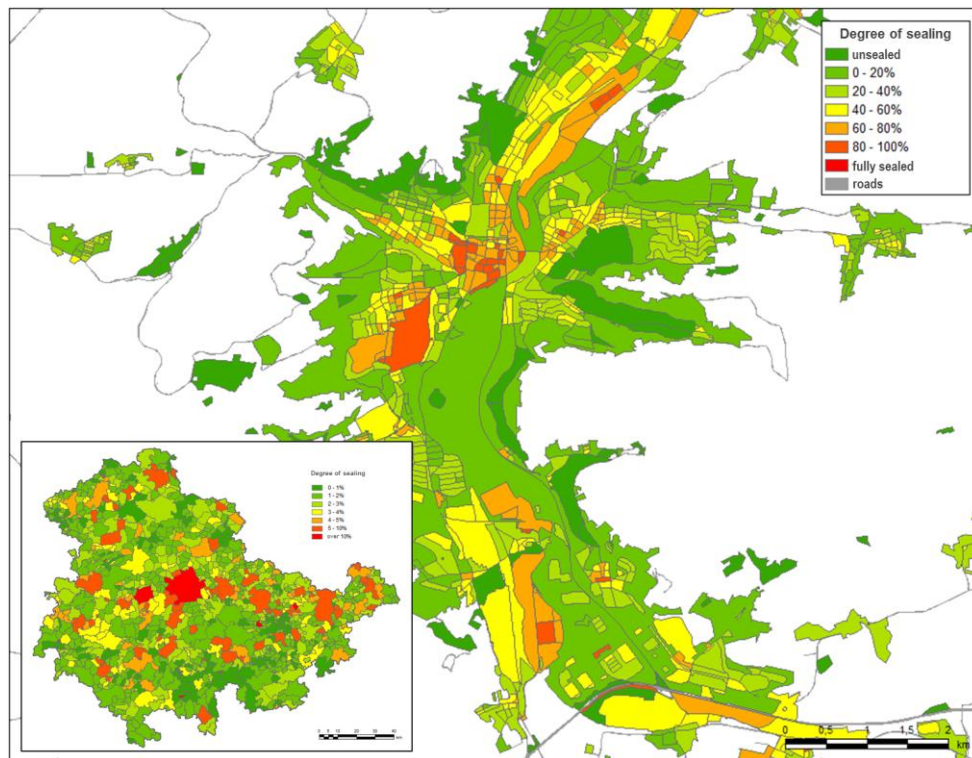


Figure 5. Mean sealing in the city of Jena (large map) and communities in Thuringia (small map) in 2010, calculated from Landsat satellite data.

5 SUMMARY & OUTLOOK

After motivating the development of a modular software platform for integrated land and water resources management, the Integrated Land Manage System (ILMS) and its different modules for environmental data management, classification of satellite imagery, delineation of spatial modelling entities and environmental modelling have been introduced. The use of existing standards like ISO 19115, SOS, WaterML2.0 and WPS ensures a future-proof and seamless exchange of information between all ILMS modules. Moreover, the utilization of open source software and interfaces offers a flexible and easily extensible system architecture. Applications in a number of research projects in different parts of the world have shown that ILMS is capable to deal with a variety of different tasks covering environmental information management, remote sensing and integrated land and water resources management. Ongoing work on ILMS is focusing on providing additional documentation and training tutorials and on the implementation of a fully web-based user interface for all modules of the system, hence lowering the barrier to entry for new users and reducing the effort for software maintenance.

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