INTERACTIVE SPATIAL DECISION SUPPORT FOR WATER MANAGEMENT AND PLANNING PURPOSES

R. Laudien[a], S. Brocks[a], A. Christmann[a], A. Krüger[b]

[a]Dr. Rainer Laudien (rlaudien@uni-koeln.de)
[a]Sebastian Brocks (sebastian.brocks@uni-koeln.de)
[a]Alexander Christmann (christmann@www-dev.de)
Dept. of Geography (GIS & RS)
Albertus-Magnus-Platz
University of Cologne
50923 Cologne
++49 221 470-7428 Fax: -1638

[b]Dr. Andreas Krüger (akrueger@meteo.uni-koeln.de)
Institute of Geophysics and Meteorology
Kerpener Str. 13
University of Cologne
50937 Cologne
++49 221 4703686 Fax: -5161

Abstract
Due to the immense amount of data, models and expert knowledge, decisions in the field of management and planning are no longer easy to make. As modern computers are able to process comprehensive data, innovative decision support functionalities and processors can be used to maintain such complex decisions.

As soon as spatial data is included in the decision making process, GIS tools shall be integrated into the related procedure. To provide stakeholders standalone, user and question specific spatial decision support tools, the ESRI developer library ArcGIS Engine can be used to fulfil these requirements. The tools can be combined within a comprehensive software program, which is defined as a Spatial Decision Support System (SDSS). Based on the current state of science and technology, computer based SDSSs can be used for modern management and planning purposes. To fulfill the requirements of being advanced comprehensive systems, such modern SDSSs provide access to individual data and computer models. They combine tools and analysis functions of Geographical Information Systems (GIS), Decision Support Systems (DSS), Remote Sensing (RS), and numerical, expert or statistical models. In addition to that, such complex systems include expert knowledge and enable the user to interact with the SDSSs during run-time. By programming individual SDSSs the usage of an object oriented programming language, i.e. Java in combination with ArcGIS Engine is useful to guarantee SDSSs which are accessible from different platforms.

This paper describes a methodological approach how a SDSS can be designed and developed by using ArcGIS Engine and Java and how it could be provided as a standalone software tool for water management and planning purposes.

Keywords: Spatial Decision Support, software engineering, coupling of models, Java, ArcGIS Engine, water circle

1. BACKGROUND

Nowadays, spatial data, mathematical models and expert knowledge are more and more incorporated in the decision making process. A modern Spatial Decision Support System (SDSS) combines such data and knowledge within a process-based tool which is developed question-specific according to a given logical decision tree (Turban et al. 2005). Detailed information about the requests, knowledge and personal needs of the potential users are essential during the development of such a computer based system. Therefore, the programming of an innovative SDSS needs to depend on the GIS-, RS-, and model-knowledge of the decision maker (Laudien and Bareth 2007).

This study presents the development and implementation of a modern SDSS for water management and planning purposes. The programming of this modular designed system is based on Java to guarantee a platform independent software tool. By using of the specific Java based library ArcGIS Engine, the developed system meets the requirements of being comprehensive GI-, RS- and model based SDSSs.

The SDSS-design and -programming approach described in this paper was being developed for the interdisciplinary research project IMPETUS (*An integrated approach to the efficient management of scarce water resources in West Africa*). Within IMPETUS several SDSSs were developed focusing on different specific questions with regard to the water circle. The programmed systems were implemented in a Java/XML based framework (Enders *et al.* 2007). Further information concerning IMPETUS is given by Speth *et al.* (2005).

2. SPATIAL DECISION SUPPORT SYSTEMS

Before focusing on the definition of Spatial Decision Support Systems (SDSSs), it is necessary to point out the term Decision Support System (DSS). The relevant scientific literature does not show a consistent definition of a non-spatial DSS (Leung 1997, Malczewski 1999, Singh 2004, Sprague 1980, Sprague *et al.* 1982, Turban *et al.* 2005, Wright 1993). However, according to El-Najdawi *et al.* (1993), a DSS can be considered as a computer based system, which allows the user to solve semi-structural processes by using comprehensive datasets and analytical models. This definition points out that the applied methods of a DSS are not trivial at all. In contrast, a complex DSS is an interdisciplinary solution using comprehensive datasets, models, etc. Hence, the overall DSS approach consists in (i) making numerous different methods and analysis available (Sprague *et al.* 1982), and in (ii) providing data visualization, interpretation and evaluation (El-Najdawi *et al.* 1993).

As soon as spatial data is embedded in a DSS, GIS functionalities get an important role. These functions support the user making spatially diverse decisions. In this context, the term Spatial DSS was established in the mid 1980s/1990s (Armstrong *et al.* 1986, Armstrong *et al.* 1990, Densham 1991, Goodchild *et al.* 1993, Wilson 1994, Crossland *et al.* 1995). Mennecke (1997) sees a SDSS as an easy-to-use subset of a GIS, which incorporates facilities for manipulating and analysing spatial data. In addition to that, Malczewski (2006) addresses that a SDSS also includes functionalities of multicriteria decision analysis. Furthermore, SDSSs provide the opportunity of integrating, visualizing and evaluating various analytical models, and therefore can be used to develop management strategies (Muller 1993, Keenan 1996, Leung 1997, Malczewski 1999, Manoli *et al.* 2001, Yeh 1999). The structure of such systems is introduced considering latest technology developments and can be considered as the geo-data infrastructure for decision support related to specific spatial based questions and problems (Bareth 2009).

The SDSSs are connected to extensive geo-databases which include (i) all data for the system modelling, (ii) the models itself in a Modelbase Management System (MBMS), (iii) the interfaces between data, models and user knowledge, as well as (iv) the functions for data generation and data mining (Goodchild 1993, Wright 1993, Leung 1997). Additionally, metadata is included in the systems considering international standards like ISO and OpenGIS (Bernhardsen 2002, Guptill 1999).

In general, modern SDSSs combine functionalities and modules of GIS, DSS, RS, models and expert knowledge (Laudien *et al.* 2007, Rizzoli *et al*. 1997) and therefore definite options for management and spatial planning actions (Turban *et al.* 2005). This also corresponds with the tasks of Resource Management Information Systems (McCloy 2006), as well as with the systems using multicriteria decision analysis (e.g. Carver 1991, Eastman 1999, Laaribi *et al.* 1996, Malczewski 1999, or Thill 1999). SDSSs allow the integration of numerical, statistical or knowledge based expert-models and meet the requirements of being all-inclusive decision support tools (Keenan 1998, Laudien *et al*. 2006 & 2007). Consequently, such a system contains data and analysis functions of the above-mentioned modules.

3. DEVELOPMENT, ENVIRONMENT AND DATA STORAGE

The object oriented programming language Java was used to develop the SDSSs. By using Java based coding the source code is translated into byte code and then executed in a special environment, the so-called Java Runtime Environment (JRE). The major part of the JRE is the Java Virtual Machine (Java-VM), which interprets and executes the byte code. By the existence of a Java-VM, the major advantage of programming with Java consists in the fact that all developments run on different computers and different operating systems. Therefore, software, which is developed with Java, is nearly platform independent (Herter *et al.* 2006).

To fulfill the given requests of guaranteeing GIS- and RS-functionalities within the SDSS, the ESRI® developer library ArcGIS Engine was used to complete the Java source code. With ArcGIS Engine the software developer gets the opportunity to implement spatial analysis functions. The full version of ArcGIS Engine which is accessible by C++, VB.NET, C#, or Java comes with several different extensions which can be integrated based on the user needs. In detail these are: *Spatial extension*, *3D extension*, *Geodatabase Update extension*, *Network extension*, *Data Interoperability*, *Schematics Maplex* and *Tracking*.

To execute the SDSS, the JRE and the ArcGIS Engine Runtime Environment need to be installed on the computer. The SDSSs are developed by using the programming environment Eclipse SDK, which contains the Eclipse platform (Eclipse 3.2), tools for Java programming and the environment to develop Eclipse plug-ins. In addition to that, Subclipse is used to backup the source code. Subclipse is an Eclipse plug-in that gives the opportunity to connect to a Subversion Repository (SVN). Subversion is a source code repository, which allows several software developers to work on the same project independently without causing backup or versioning errors.

Besides the established Java beans, specific GIS- and RS-components were used for the programming. Latter are implemented in ArcGIS Engine and can be integrated in the source code easily. Furthermore, coding of additional Java libraries completed the developed SDSS.

The (geo-) data (e. g. raster, vector, and alphanumerical data) of the SDSS were stored in ArcGIS file-based geo-databases. These file-based geo-databases are platform-independent and compressible when used in a read-only context, e. g. when deploying an SDSS to the user who does not write any data to the geo-database. Furthermore, they show a much higher performance when large amounts of data are involved, and these databases are almost not inherent in size limit (the limit is that of the file-system itself). These geo-databases interact directly with the operating system's file-system. This results in the absent size limit.

4. THE SDSS ILUPO

4.1. Methodological Approach

The SDSS ILUPO (Impetus - Land Use Change and Precipitation for the Ouémé area) answers questions on the possible developments of evaporation and precipitation for the Ouémé catchment (Central Benin, Africa) until the middle of the 21st century. As the knowledge of these climatological parameters is of high value for the water cycle of West Africa, this system was chosen as an example to present how such a SDSS could help to support water management and managing purposes.

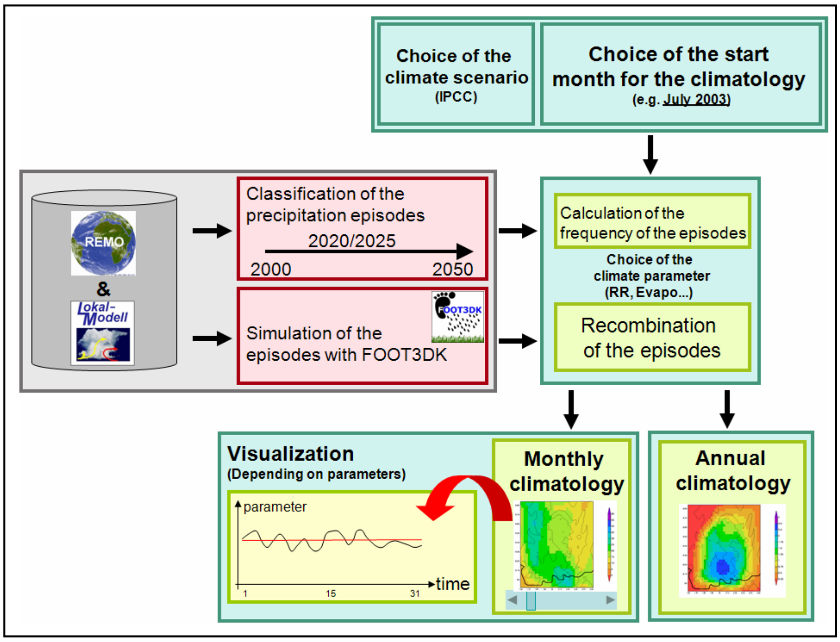

Figure 1. Structure of the Spatial Decision Support System ILUPO.

The SDSS ILUPO (a flowchart is presented in Fig. 1) is constructed by means of (i) a classification which is gathered from a cluster analysis, and (ii) from simulations conducted with the mesoscale model FOOT3DK (**F**low **O**ver

Orographically structured **T**errain **3D K**ölner Version). The latter model is forced by the Lokal-Modell LM (cf. Doms and Schättler 1999).

Firstly, for the accomplishment of the cluster analysis the relevant temperature parameters maximum temperature, minimum temperature, mean temperature, difference of maximum and minimum temperature, and the maximum potential sunshine duration are selected for a representative grid point of a REMO model run (cf. Paeth *et al*. 2009). To generate predictions for a future scenario the REMO model was driven by the ECHAM4 model according to the IPCC A1B and B1 – three simulations for each - forcing scenario for the years 2001 to 2050. Note, for the later aspired assignment the time series of the year 2025 of the FOOT3DK simulations are included in the data set. For the application of the cluster analysis the upper introduced parameters are standardized by their root mean square deviation. This is often called z-transformation. After that a principal component analysis is conducted. In a final step, the clusters are generated with a non-hierarchical k-means algorithm (cf. Hartigan and Wong 1979 or Steinhauser and Langer 1977). For this purpose the so-called Mahalanobis distance is utilized (for more details confer to Duran and Odell 1974). In this case the number of resulting clusters is not prescribed. Thus, the relevant result of the cluster analysis is a time series with a certain cluster number per day for the years 2000 to 2025.

Secondly, the model FOOT3DK is applied to provide episode simulations of relevant precipitation events of the rainy season of the year 2025. The model is a non-hydrostatic mesoscale model, which has been used for several settings in many different areas of the globe (cf. Pinto *et al.* 2010). The model is based on the primitive equations and was particularly designed for the needs of the IMPETUS project in the West African environment (cf. Krüger *et al.* 2010). Hence, the model output of several typical rainfall episodes during the rainy season 2025 serves as a data-base for the creation of time series on a regular grid, which are implemented in the SDSS ILUPO.

The final recombination of the future daily rainfall is constructed on bases of the cluster analysis and the simulated episodes for the year 2025. For each day of the REMO simulations according to the IPCC scenario for one cluster number an associate rainfall episode is identified randomly. This is done for each day of the time series. The final product is a grid based time series of all provided parameters of the model FOOT3DK. In this case precipitation and evaporation are the parameters of importance.

For the data-base of the SDSS ILUPO we use the time series of the clusters as well as the output fields of precipitation and evaporation of FOOT3DK. Both information sources enable the recombination of either yearly or monthly climate fields for the years 2001 to 2050, which gives an input for climate impact studies.

The methodological approach required that the user of the interactive SDSS ILUPO should have the opportunity to choose between the following options (cf. Fig.1 green boxes):

- It should be possible to decide between the IPCC-scenarios (SRES) A1B and B1,
- and the accumulation for one month or one year.
- Additionally the user should be able to select the starting point (Fig. 1 upper right green box) of the simulation.
- Finally, there should be an option to decide between the two climatological parameters precipitation and evaporation.

The result should be presented as a table or chart. In case the monthly accumulation is chosen it should also be possible to display a time series of the chosen parameter for each mesh of the regarded domain in a multi-temporal Graphical User Interface.

4.2 Software-technical realisation

By accessing the system within the IMPETUS Client (cf. Enders *et al.* 2007), and based on the selected language (English, German or French), in a first step the *startscreen* of ILUPO provides information about the content of the system. By clicking on the *Go* button, the ArcGIS file based geo-database is being accessed and the ArcGIS Engine license is being checked out. After this automatic step, ILUPO supplies an interactive Graphical User Interface (GUI), where the user gets the opportunity to select a specific climate scenario (IPCC A1B or B1), the number of simulation (Ensemble 1 to 3) as well as the choice of the time period (annual or monthly values), starting date of the simulation, and climate parameter (Fig. 2 left screenshot). By clicking the *Go* button, the chosen time period is calculated within ILUPO by an internal realization. As mentioned above, the recombination is based on the results of a cluster analysis - a mathematical binning method. Within this method, 24-hour episodes for the years from 2001 to 2050 are statistically meaningful grouped by means of daily REMO parameters. As depicted above these groups also contain the FOOT3DK episode simulations, which will later serve as the group (or cluster) representatives. Each group contains several representative episode simulations. Hence, each day of the scenario time series from January 2001 to December 2050 is associated with a certain group (cluster). One of the representatives of this cluster is picked by chance and the rainfall or evaporation of this episode is assigned to the time series.

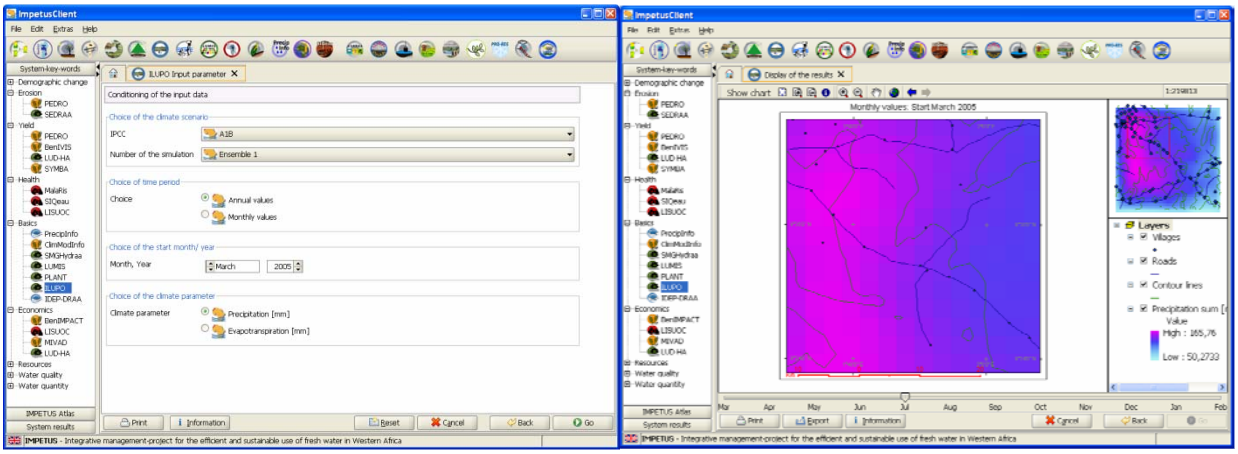

Figure 2. Sceenshots of ILUPO (left: Parmeterpanel, right: ArcGISMultiMonthPanel showing monthly precipitation sums as an example).

To prepare the data for visualization, two matrix processors were developed by using Java. Their main purpose is to read sequences of research data into multitemporal raster layers. The one processor, called *GetCodesIntervalProcessor*, extracts a sequence of epoch encoded episodes describing the temporal connection of data into several separate epoch encoded episode sequences. For each month a separate sequence is generated. In addition to that, one sequence encompassing the whole provided data set is also generated. Those sequences are then processed by the other processor, called *GetEpisodeMatrixProcessor*, which translates those sequences into several raster datasets, one for each time step in the corresponding time interval. During this step, statistical analysis of the provided data is performed by calculating sums and averages for each raster cell in the generated datasets.

Only the daily sequence of the representatives according to the regarded IPCC-run and a table of the parameter of interest (rainfall or evaporation) are released within ILUPO. This result is visualised in a GUI in terms of the developed *ArcGISMultiMapPanel* (Fig. 2 right screenshot). This *ArcGISMultiMapPanel* has been especially developed for environmental and social research, which need to compare a calculated scenario at different time steps. With the help of a *PageLayoutBean*, multitemporal feature layers can be displayed, and the user can intuitively compare the different time steps. A Java slider (*JSlider*) component, located below the map, allows the user to view changes of the scenario over time. This slider has access to the multitemporal feature layers and provides the different time increments. Using a specific processor that accesses the specific time step of the layer, the *ArcGISMultiMapPanel* is being updated during run time. Based on the classification applied to the map, layers change color in response to movement of the time slider.

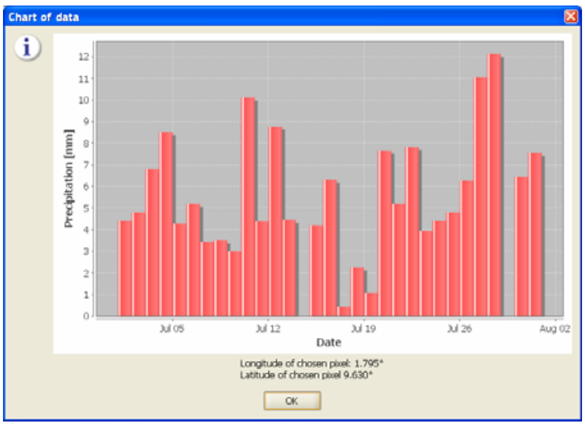

Figure 3. Screenshot of a time series (provided by clicking a pixel within the ArcGISMultiMonthPanel).

To meet the requirements of visualising time series a special functionality was developed which shows the multitemporal values of a single pixel in terms of a bar chart (Fig. 3). By activating the implemented button *Show chart* (cf. Fig. 2 right screenshot, menu bar), and by clicking on a pixel within *the ArcGISMultMonthPanel* an additional GUI shows the values in terms of precipitation or evaporation amounts resulting from certain land use and meteorological scenarios.

5. CONCLUSION

This paper shows the incorporation of individual functionalities within modern SDSSs. By the usage of ArcGIS Engine in combination with the object oriented programming language Java, SDSS developers get the opportunity to code advanced computer based Spatial Decision Support Tools, which can be designed and developed based on the users' requirements and a specific question. The presented example SDSS as well as the overall ArcGIS Engine based development for the IMPETUS SDSS Client show that ESRI's technology is feasible and very useful for modern computer based Spatial Decision Support.

The SDSS ILUPO (Impetus - Land Use Change and Precipitation for the Ouémé area) answers questions on the possible developments of evaporation and precipitation for the Ouémé catchment (Central Benin, Africa) until the middle of the 21st century. By using this interactive system the system user has the following options: It is possible to choose between the IPCC-scenarios (SRES) A1B and B1 as well as the accumulation for one month or one year. Additionally the user is able to select the starting point of the model calculation. After arranging the adjustments, the frequency of appearance of the episodes for the chosen period is calculated within ILUPO.

Consequently, the results of ILUPO serve as a source of information or can be further integrated into other simulations. By using such decision supporting tools it is possible to identify years with a potential of water shortages interactively. Thus, SDSSs like ILUPO can be used to optimize management and planning purposes.

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Dr. Rainer Laudien is Lecturer for GIS and Remote Sensing at the University of Cologne. His major field of work is software development of Spatial Decision Support Systems by using GIS, model, expert knowledge and remote-sensing data.

Sebastian Brocks was a student assistant in the BMBF Project IMPETUS Westafrika at the University of Cologne. His major interest is software development, specifically integrating ArcGIS Engine components in custom applications.

Alexander Christmann was a student assistant in the BMBF Project IMPETUS Westafrika at the University of Cologne, studying at the Faculty of Computer Science and Engineering Science of the Cologne University of Applied Sciences. His major interests are software engineering, visualization of complex systems and algorithms.

Dr. Andreas Krüger is scientific assistant at the University of Cologne. His major field of activities are atmospheric dynamics, statistical analysis, mesoscale climate modelling, and interdisciplinary exchange of knowledge..