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Modeling freshwater uses in coastal areas – the case of Pertuis Charentais (France)

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Abstract: The SPICOSA European Project aims at implementing a system approach framework as a tool bridging ecosystem management, definition of policy options and system dynamics. An ExtendSim numerical modeling platform is being developed to share and integrate economic, ecological and governance modules, and to assess coastal systems functioning and changes. The implementation of a hydrological model is presented as an example of generic module. It is tested and applied on the Charente catchment study site in France where the freshwater share is the core issue of coastal zone management strategy in relation to several ecological services – e.g. supply of drinkable water, support of aquatic biodiversity, carrying capacity of coastal areas for shellfish farming, water demand for agriculture. The definition of hydrological units was based on sub-basins features, management rules and agriculture demand for freshwater. A typology of agricultural activities was built to define relevant spatial units based on the type of physical environment, technical parameters, types of crops and uptake of water. Irrigation rules and decision rules regarding Crisis Minimum Flow and Target Minimum Flow are included in the model. The model will be used to simulate freshwater shortage using climatology observed during the past 20 years and scenarios of agriculture changes. Several indicators have been constructed to assess the vulnerability of the catchment area and the coastal zones to freshwater shortage

Keywords: hydrology, coastal zone management, system approach, ExtendSim

1. INTRODUCTION

In many aspects, sustainable development requires the integration of information on economic, environmental and social factors (Kelly, 1998). The structure of the information is therefore a key issue and several authors have emphasized the need for a system approach to select and combine the appropriate information to be used in the decision making process. Kelly (1998) identifies four main reasons to use System Approach: i) understanding the system dynamics due to the interactions between several components, ii) identification of knowledge gaps regarding some relationships, iii) learning about the system which results in changes of system perception by the decision makers, iv) support of an interdisciplinary approach by using a common language. In the frame of such as system approach, pioneer works on system dynamics start with Forrester (1971), Meadows et al. (2004) and were followed by many applied examples addressing sustainable issues (see

Kelly, 1998) and considering the dynamics of systems derived from interactions and feedback loops.
On this basis, the SPICOSA project has been funded by the European Commission in 2007 with the aim of improving the sustainability of coastal systems by developing and combining System Approach for integrated assessment and deliberative tools to support decision-making. The implementation of system approach follows four logical steps. First, System Design step identifies the structure, function, and dynamics that should be studied to address a policy issue. Second, System Formulation step aims at represent the functioning of the system in both quantitative and qualitative terms by describing all the processes and interactions in the environmental and socio-economic spheres. Third, System Appraisal step assembles the components of the system and evaluates each functional parts. Fourth, System Output step involves the organization of the information for policy deliberations, scientific publication, and for dissemination the non-science end-user community. This procedure has been applied to 18 study sites to demonstrate how science and policy can be integrated (www.spicosa.eu).
One of the study sites is the Pertuis Charentais (France) where the policy issue is related to the quantitative management of the freshwater in the Charente river basin. This basin is characterized by low freshwater flows in summer and some needs related to human activities may not be satisfied – e.g. availability of drinking water for households and tourists, good ecological status of the coastal ecosystems (rivers, salt-marshes, nurseries, coastal water productivity) which support several services and environmental amenities. In addition, two private industries of the primary sector depend on Charente river flow: agriculture uptakes water for irrigation during summer for crop cultivation (mainly irrigated maize) and shellfish farming needs freshwater for spat production and river nutrients for oyster growth. This policy issue has been addressed by the regional plan for water management, which includes a "Water shortage Management Plan" (WMP). The implementation of SPICOSA methods is conducted jointly with a public agency (Territorial Public Agency for the Management of the Charente River) in charge of the implementation of the WMP (http://www.fleuve-charente.net/) in order to address the users conflicts generated by the freshwater scarcity in relation with ecosystem services provided by freshwater and knowing that the occurrence of conflicts will change due to long term trends (climate, agriculture activity, demographic changes). We developed a numerical model to compare different management options, under several assumptions regarding the forcings of the system and the behaviours of users. This paper focuses on the modelling of three components of the system which are tightly connected: hydrology of the Charente river, irrigation for the main agriculture crop, coastal zone primary productivity. It describes their implementation in the modelling tool used within SPICOSA project and shows some preliminary simulation results.

2. MODEL STRUCTURE

2.1 Modelling tool

The need of a common language for describing and modelling systems has been outlined by several authors. Costanza and Ruth (1998) mention the STELLA software as a tool capable to involve a group of relative modelling novices with the help of facilitators. ExtendSim (www.ExtendSim.com) belongs to this family of modelling software such as Vensim (http://www.vensim.com/), Stella (http://www.iseesystems.com/), PowerSim (http://www.powersim.com/), Simile (www.simulistics.com) which have a graphical user interface facilitating the construction of a model, the setup of simulations, the visualisation of the model outputs and the communication with non modelers (Odum and Odum, 2000; Ruth and Hannon, 1997). Compared to other softwares, ExtendSim has some appealing capabilities which make it a good candidate to simulate complex systems and which are extensively used in our modelling approach: i) ExtendSim handles databases which can be either built by importing external databases (Excel, Access) or generated with ExtendSim own tools. Databases are used to exchange data with other applications, store model results, exchange data between the model components; ii) the architecture of the model components (called blocks) is built by using extensive libraries of predefined objects which are assembled and connected graphically to one another in order to simulate discrete time or continuous time processes. For more complex modules, ExtendSim allows to develop customized blocks with its own powerful programming language very close to the classical C language and augmented with a lot of specialised functions – e.g. access to local database functions; iii) libraries of blocks are commonly used to share blocks with other modelers. Each block has its own user interface and contains the description of its functionalities. Libraries can be distributed and used for other purposes (a good example in Ecology is given by Odum and Peterson, 1996); iv) to help simplify and clarify models, ExtendSim makes possible to create hierarchical blocks that group several blocks together into one block while still allowing the user to drill down into the lower levels to access the individual blocks.

2.2 General model structure

The general architecture of the Pertuis Charentais system is displayed in Figure 1. The Hydrology box represents one Natural Component (NC) which interacts directly or indirectly with other NC (Coastal Productivity), Economic Components (EC - e.g. uses of freshwater, namely Agriculture/Irrigation, Biodiversity, Aquaculture) and Social Components (SC, e.g. Regulation). Arrows show the flow of information between these modules. Since the main issue is related to freshwater uses and production, much effort has been spent on the development and test of the Hydrology module.

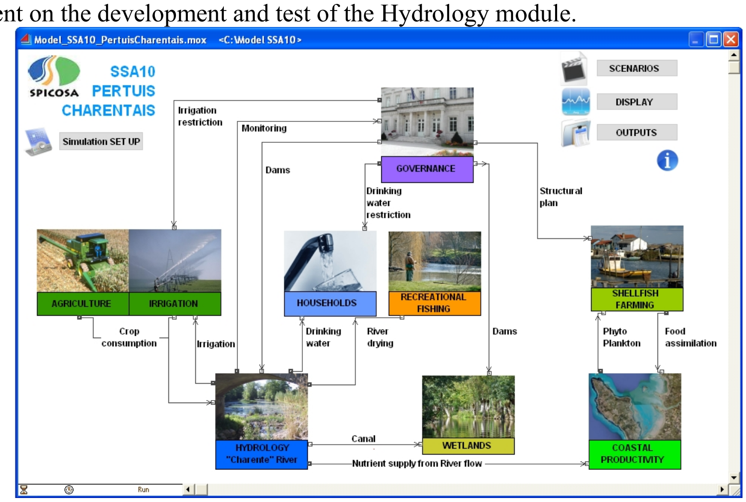

Figure 1. The simulation platform: user interface.

Variables are passed from one block to the other by using the database capabilities, thus keeping a history of all relevant variables. Each module has its corresponding database that also records all model parameters. A specific effort was made in the development of graphical tools in order to visualize relevant indicators of the model and in a user friendly organization of the different blocks and modules. Scenarios, display and outputs blocks have been set to regroup all the model control panels.

2.3 Hydrological model

The watershed area of Charente river is around 10 549 km². Agriculture activity covers about 60% of this area and about 11% of the cultivated area is irrigated. The annual water supply to human activities is 4 millions m^3, with 34% dedicated to drinking water and 57% to irrigation which are therefore the two main human activities of concern in the freshwater issue selected for this study site. Water supply is related to the hydrology of Charente river which depends on daily rainfall, soil characteristics and evapotranspiration (function of temperature and demand by plants, forests and agriculture). The hydrological model therefore simulates daily changes of river flow at the scale of the whole catchment area.

The watershed was discretized in a dozen of hydrological sub-basins which offered several advantages: i) it accounted for some specificity and spatial differences between soil features (e.g. karstic vs non karstic areas); ii) it was consistent with the spatial scale of the governance and water regulations (no shown here); iii) the mathematical equations were easily translated into ExtendSim software; iv) the model was already implemented in EXCEL®, calibrated, operational and used by managers to make decisions on restrictions of water supply to agriculture during drought events.
This model was initially developed by Eaucea, a private company which agreed on translating the equations and test datasets into ExtendSim. The Hydrology box was then built as a hierarchical block in ExtendSim to allow for more flexibility. Opening this block yields the structure shown in Figure 2 and composed of sub-basin models represented by a new series of blocks. Connectors were defined in each block to pass the value of the river flow calculated for each sub-basin to downstream blocks.

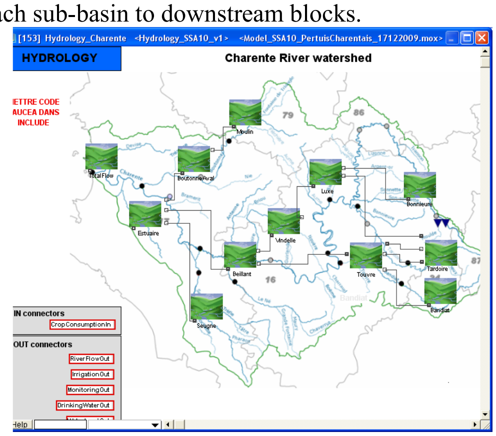

Figure 2. Design of the global watershed model. The model is based on a subdivision of the Charente watershed into sub-basins (referred to watersheds in the model terminology).

Following the ExtendSim procedure to pass the information between blocks, connecting lines were drawn between the connectors defined in each block. The name of each block is based on the location of its most downstream point. In our model terminology, this block is referred to as a watershed block. The watershed block is composed of three components to facilitate the model implementation. Thanks to ExtendSim programming facilities, data management and mathematical equations were coded in custom blocks which are generic blocks contained in the Hydrology library. The mathematical equations describe the dynamics of water levels in a series of reservoirs, the levels of which depend on rainfall, soil properties and evapotranspiration and which communicate with one another (Figure 3). Hydrological processes are therefore used to compute the river flow and the water available for crops and natural plants. Each reservoir is associated to one state variable and the time step used to simulated water levels in each reservoir is equal to one day.

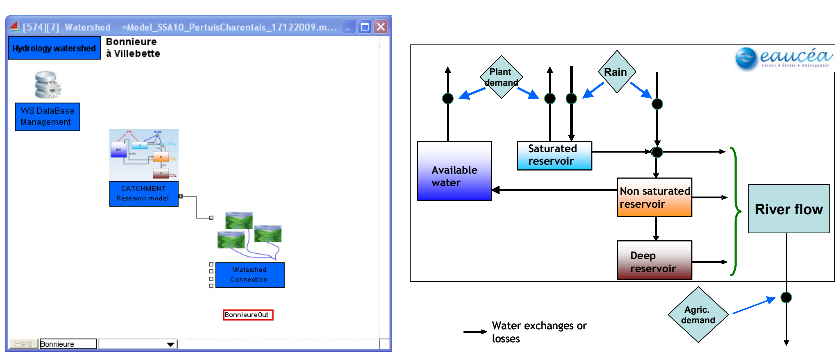

Figure 3. Conceptual scheme of the reservoir-based hydrological model (right) and implementation into ExtendSim.

For each watershed one Database has been created with the same name as the watershed hierarchical block. It contains several distinct tables for parameters, forcing time series, observed river flow time series, and state variables (see Figure 4). Such databases give much flexibility to the model, help in organizing the enormous quantitative information and facilitate the exchange of data between all the model components.

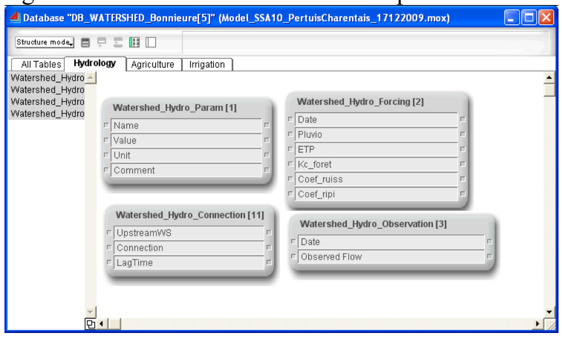

Figure 4. Examples of tables defined in the Database corresponding to one watershed and containing parameters, forcing variables, observed river flows, etc.

2.4 Irrigation module

The agriculture-irrigation module is closely linked to the Hydrology module. Since the hydrological model is based upon an existing hydrological model which has already been calibrated, it was chosen to preserve the structure of this model and to use the same set of sub-basins. The Agriculture module calculates, in a spatialised way -for each sub-basin- the values of the areas of irrigated and non irrigated crops, depending on the chosen scenario. It defines all the values of technical parameters needed for the calculation of the water demand by crops, which is done in the irrigation module. An output of this module is an indicator of an economic impact depending on the variations in irrigation water supply and the chosen scenario.

A typology has been built to define relevant spatial units and to describe the Charente watershed and agricultural activities in a simple way. With 40% of the usable farm area covered by cereals, the Charente basin is part of the second French pole of cereal production. Maize is the main irrigated crop and represents almost 80 % of irrigated area. Furthermore, 60% of the maize area is irrigated. For crops, it is important to evaluate maximum water loss under certain climatic conditions and under unlimited water availability at the root system level, i.e. the "maximum evapotranspiration" (ETM). The value of the "potential evapotranspiration" (PET) is taken from institutional data. The irrigation module allows to compute the daily volume needed for the irrigation of the irrigated crop area on the sub-basin. This volume is then subtracted from the river flow calculated in the Hydrology module. There is also a link with the Governance module: the thresholds defined by the local policy constraints have to be compared to the values of the estimated flow in the river. The comparison between the volume needed by the crops for irrigation and the available volume (either due to policy constraints or to climatic conditions) is used for the calculation of a stress indicator and losses in crop production (not detailed here).

The current version of the sub-basin irrigation block follows the same rule as the watershed hydrology sub-block and combines a custom block containing the equations and a database keeping track of the outputs (daily water demand for irrigation) and parameters. It is a simplified version of the Irrigation module based on a single culture and water uptake directly from the river.

2.5 Costal Productivity model

The Coastal Productivity component is designed to link the freshwater inputs from the Hydrology block and the Shellfish farming block. It aims at simulating primary productivity of Marennes-Oléron bay, which depends on nutrient fluxes from the watershed, ambient water temperature and light, and amount of cultivated oysters. The Coastal Productivity component is built as a hierarchical block which contains a few modules belonging to the same Coastal Productivity library (Figure 5). The main module is a generic custom block where the mathematical equations are written using the MODL programming language. As for all the other components, databases were designed to store parameter values, forcing variables and model outputs and are part of the model implementation in ExtendSim. The Coastal Productivity block also accesses the Hydrology database where it can retrieve the value of riverflow needed to compute nutrient inputs into the bay. In the same way, the block provides the phytoplankton concentration to the Shellfish Farm component through the History table used to save model outputs.

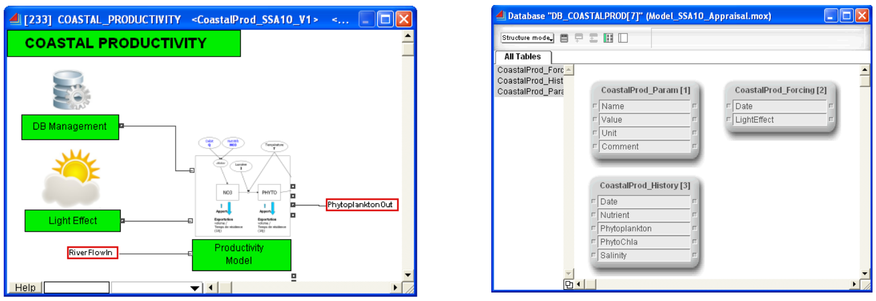

Figure 5. Conceptual diagram of the Coastal Productivity block (left) and database structure (right)

3. MODEL TESTS

Since the model is based upon an existing model which has already been calibrated, we checked that both models are producing the same results. This work is under progress, and we only show the output of one watershed, compared to the simulation produced by CycleauPE. Some slight differences between the two simulations were found, they are mainly due to differences between initial conditions and differences between the sequence of equations in EXCEL and ExtenSim, but they do not affect the overall good agreement between the 2 models (Figure 6).

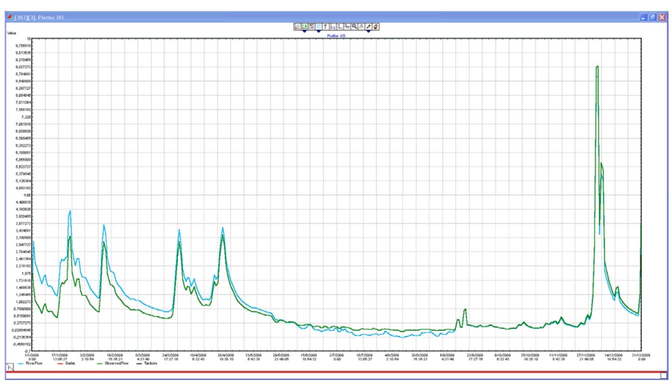

Figure 6. Example of the riverflow of watershed simulated during one year (blue) and comparison with the CycleauPE simulation (green).

Regarding the coastal zone, a huge amount of environmental data have been collected since 1977. Monthly values of the main environmental descriptors from 1977 until 2003 clearly show a strong seasonal pattern and, to test and calibrate the primary production model, we averaged annual variations and built an annual cycle for Salinity, Phytoplankton, Temperature, Nutrients. We also considered an average annual riverflow derived from available database, in order to test the model with real values of river inputs. The test simulation shows a good agreement for salinity and nutrient concentration (Figure 7), though the phytoplankton seems to be underestimated.

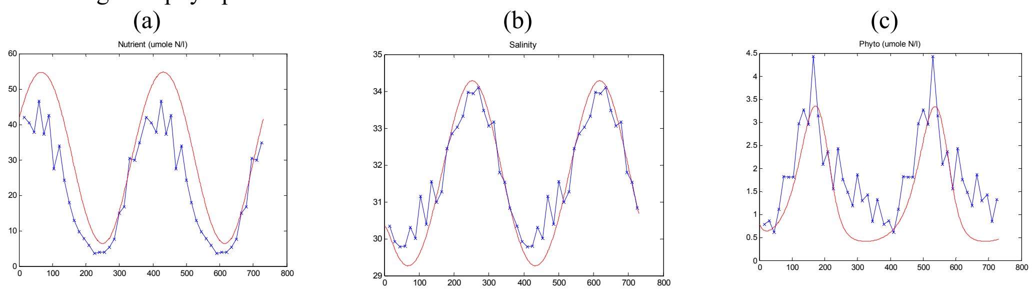

Figure 7. Comparison between observations and simulations a) Nutrients, b) Salinity, c) Phytoplankton.

4. DISCUSSION

Our modelling group involved hydrological modelers, specialists of system approach and decision-makers in charge of advising local authorities with respect to irrigation for agriculture and water level in the watershed reservoirs. We debated in details the modelling strategy, e.g. the spatial scale and resolution of the watershed model. Alternative strategies have already been described or compared in other works (Voinov et al., 1999; Mathevet, 2005; Reynaud et al., 2008) and, technically, it is possible to interface ExtendSim with other softwares. For instance, some SPICOSA partners have considered the coupling between ExtendSim with PCRASTER (http://www.pcraster.nl/), a free community based software simulating spatially distributed systems. In our case, the subdivision in several catchment areas was preferred to a more detailed spatial discretization for several practical reasons, the most important being that this level of aggregation was consistent with the decision making scale. The model will therefore include a governance module which incorporates the rules regarding the access rights to water and their restriction during summer crisis. Such rules are based on freshwater availability and water demands. They are described in technical documents which will be translated into ExtendSim through decision rules which will act as feedback mechanisms on the irrigation component.

Communication with stakeholders and decision makers is essential in the System Approach framework. Heemskerk et al. (2003) shows how this way of thinking resulted in a common and transparent representation of systems during a multidisciplinary workshop where groups of participants analysed and represented different systems with a common set of symbols. Costanza and Ruth (1998) also emphasize the importance of supplementing mental models with dynamic models of systems which are too complex to be shared by different stakeholders and used to build a consensus upon a policy issue. A step further, Voinov and Gaddis (2008) describe in details the lessons learned from a participatory approach of watershed modelling and, among these, emphasize the role of stakeholders at all levels of the modelling process. In our case, stakeholders and decision makers have been involved from the very beginning of the project to identify policy issues, discuss and bring information on the appropriate temporal and spatial scales and boundaries of environmental, social and economic processes. Working groups have been held on the hydrology/agriculture components with several objectives : define appropriate spatial scales, construct system representations (mental models), identify policy options, provide input data (parameters, forcing functions, validation datasets), select scenarios of change. It is a continuous process, along the line defined by Voinov and Gaddis (2008) since the lifespan of the model is not limited to the project duration and expectations by decision makers and stakeholders will increase with the demonstration of model functionalities. As part of the system approach framework, other meetings with stakeholders were also dedicated to the definition of scenarios. The future of the system was divided into three domains: trends (climate, demography), management options and changes in uses and practices. Stakeholders have been asked to vote on combinations of assumptions and to select and refine the main indicators. In addition, scenarios of agricultural activities have also been assessed through specific surveys among local authorities and professionals (experts, advisers, farmers) about the evolution of agriculture during the next ten years: evolution of the irrigated crop area, substitution of irrigated crops by other irrigated systems or other farming systems, implementation of specific policies, increase in the number of reservoirs or dams.

The amount of water in the watershed reservoirs and the river is used to build indicators of water shortage which show the locations and periods of time where and when regulation of water supply must be activated (this is the role of the Governance component, not shown here, Figure 1). It is clear that the availability of freshwater depend on several factors: climate (rainfall, evapotranspiration), agriculture activity (amount of irrigated crop), requirements of nutrients for shellfish farming. Simulations of scenarios will therefore allow to assess how such changes will increase or decrease the risk of conflicts between users.

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