Modelling Environmental Information Processes:
A Meta-model Approach for Water Management

Albrecht Gnauck
Brandenburg University of Technology at Cottbus, Dept. of Ecosystems and Environmental Informatics
Konrad-Wachsmann-Allee 1, D - 03046 Cottbus
umweltinformatik@tu-cottbus.de

Abstract

The management of natural resources and political and socio-economic subsystems requires complex simulation models supporting decision making procedures. Such models cover not only natural processes on different time horizons and spatial scales but also societal, industrial and agricultural developments as well as sociological constraints. Different structural dynamic models had to be combined to support multi-objective environmental decision problems. Because of the great variety and complexity of natural and anthropogenic processes considered for water management such an approach does not cover all the dynamic process extensions. For this reason, and to make different subsystems comparable, meta-models have to be developed. The questions that must be answered for water management options are how much water is available, for what purposes it will be used, who are the actors and stakeholders, and what kind of consequences follow from distinguished management options for the public, agriculture and industry, and what kind of environmental (or ecological) responses result from anthropogenic activities. In the paper, a meta-model approach will be propagated as a tool for a holistic management of environmental processes. Especially, the use of ecosystem services will be described and discussed as a base for environmental decision making.

1. Introduction

Mathematical models of environmental processes and complex systems are well known as substitutes for real world objects. They will be widely used for environmental management and decision making. For this reason, the model behaviour has to be comparable to the real object. Mathematical models can also be considered as synthesizing tools for theoretical knowledge on an environmental system and the respective actual process results which are represented by monitored data. Relations between the major state variables of a given model (e.g. for a freshwater ecosystem) will usually not be in full congruence with the relations between state variables in a real ecosystem (Stráškraba and Gnauck 1985, Patten and Jørgensen 1995). Reality will thus be distorted (error of relations). Therefore, a real world object – model comparison can be made for error assessment which is continued until the model is in sufficient agreement with the real system. Such a model testing leads to an improvement of the mathematical model or to an accumulation of wider knowledge on the real system and can be repeated several times. Sustainable informational processes on the environmental are only given by long-term spatio-temporal monitoring programs. Together with the concept of ecosystem services environmental information based on meta-models has become a well accepted procedure in environmental research, management and policy making (De Groot et al. 2010 a, b).

The management of freshwater ecosystems requires simulation models for different time horizons and spatial scales which allow a process oriented control of water resources. An interdisciplinary sustainability management program integrates complex ecological, engineering and socio-economic aspects (Müller and
Leupelt 1998). The control options are related to special goals of water resources management (Wierzbicki et al. 2000). The use of simulation models for water resources management is not new (Biswas 1981). They can be considered as integrators of theoretical knowledge and practical experiences about specific freshwater systems with actual information gained by natural processes and man-induced activities. They are also applied to natural processes to produce new systems knowledge (Jørgensen 1994).

2. Meta-modelling procedure

The management of water resources systems depend on different types of subsystems as physical, chemical, biological, economic, or social subsystems. To unify these different aspects, to compare the subsystems and their resulting functionalities on the same level meta-models are necessary (Pillmann 2010). The term “meta-model” is applied to characterise an abstraction of models that is used to gain insights in the general structures describing the essential components or relationships representing an environmental problem area. With a meta-model a twofold effect is achieved: it can help to identify gaps in information about particular environmental or sustainability problem descriptions, and it helps in accessing information from a holistic point of view on problems and their operational solutions.

For this reason, all environmental data have to be integrated into an indicator system following the DPSIR concept of environmental research. For such a human-environmental system drivers and responses form constraining elements, which are focussed on the state and impact components of the DPSIR framework. To be aware of the incoming and outgoing relations, basic information is needed about pressures on the natural environment by human activities as well as the conditions of human welfare. Within this context, ecosystem services form basic prerequisites of human well-being. They can be understood as human impact indicators. Human activities lead to some pressure to natural resources where the responses of the real system are detected by informational processes. The states can be characterized by the structural items of ecosystems in relation with their functional features. These variables correspond to the biocoenotic structure and processes and functional components of ecosystem services. State variables have to be linked with environmental impact parameters, represented by the provision of ecosystem services, distinguishing provisioning, regulating, habitat and cultural services. For quantification these services have to be investigated and described on a qualitative level, indicated on a quantitative level and calculated in monetary dimensions. A change of the ecosystem services provision will have consequences for human well being and lead to changes of the socio-economic impact components of the DPSIR scheme. If these changes are assessed by society due to a change of benefits and values, a feedback will occur to change the motivations of the drivers and provide a respective response. Pillmann (2010) found out that the following components are of particular relevance for ICT:

1. Analysis of knowledge and monitoring of the natural environment.
2. Arrangement of information in ICT.
4. Design of influences on socio-political processes.
5. Changes of human activities caused by environmental responses.

3. Water resources management

Simulation models of water quantity and water quality are regarded as strategic tools in the fields of hydrology, aquatic ecology and water resources management. The management of natural water resources involves not only technical issues and features but also administrative actions, institutional procedures as well as many social actors. Water is needed for a variety of different direct and indirect water uses as industrial and agricultural production and forestry, for manufacturing processes, hydroelectric power gen-
eration, navigation, drinking and hygienic purposes, recreation, enhancement of fish and wildlife, but also for waste assimilation (fig. 1), see also EEA (2009). The main objective of the efficient, innovative and sustainable water resources management is to satisfy all water demands under consideration of given possibilities and restrictions of water supply.

Figure 1: Water resources management and water uses

For a good water resources management practice water quantity and water quality have to be considered simultaneously as an integrated framework (Biswas, 1981). To balance water demands and water supply procedures water quantity and water quality aspects have to be taken into consideration where the sustainable protection of the environment is an overall goal. For any water development project the fundamental questions to be answered are: Which water quantity is available and for what purpose will it be used.

In today’s water resources management economic instruments and social processes play key roles. To realise water resources management options, social, economic and institutional and/or administrative issues have to be considered besides natural scientific and engineering components. Depending from the developments of computer technology, important scientific and engineering developments in water resources management were the applications of system dynamics and information technology. Other engineering branches associated with information technology are developments of sensor technologies, of new monitoring strategies, of data warehouses techniques as well as innovative modelling and simulation procedures.

4. Integrated information space on water resources management

To cover all these different aspects the use of modern information technologies is necessary to build up an integrated information space. The central role of ICT within a DPSIR framework for data analysing, information, decision support and reporting environmental issues are shown in figure 2. The drivers are given by natural and artificial (man-made) processes and actions which influence respectively pressure the water bodies and their environments. Changes of water ecosystem states will be obtained by direct observations and/or information on metadata. In the case that no or insufficient data are available new observations or a space-time dependent monitoring of water system states is necessary. Then, the information base will be stored in a data warehouse which forms a fundament of a water information system (WISE) (Bil-
The WISE describes the impacts and all information available on water systems. From data analysis and modelling procedures decision making processes will be derived. The challenge of such a system is to get new knowledge on water resources management actions and related natural and socio-economic processes. Methods and standards to gather, to process and to report water quantity and water quality data are derived by Timmermann and Langaas (2004). Thus, frameworks for water resources management have to cover some distinguished thematic levels and the ICT level (Usländer, 2005). On the thematic level the DPSIR framework for reporting on environmental issues (EEA, 1999) presents the interlinks between social, economic and environmental systems in terms of driving forces of environmental changes, pressures on the environment, states of the environment, impacts on citizens, economy, and ecosystems, and responses of the society.

5. Meta-model for water resources management

The use of mathematical models for modern water resources management has to cover all aspects announced above. The objective of such a combined water resources management model is to give a scientific and operational base for planning and management (including decision making) of a water body and its natural and anthropogenic environment by using advanced information and computer technologies. Figure 3 gives an overview on the interrelationships between natural and anthropogenic subsystems relevant for water resources management. They cover natural and anthropogenic interrelations as well as informational and socio-economic processes connected with water quantity and quality. The purpose of the model is to visualise, to describe and to explain the general interrelationships between the water system and its natural and anthropogenic as well as informational environment. The focus of the model is how to manage water systems and their natural and man-made environment by utilisation of information processes between different actors to provide management decisions (including political and socio-economic decisions) and operations.

Figure 2: ICT and the DPSIR concept
While natural processes are more or less directly coupled with the water system influencing water quantity and water quality, man induced couplings are based on water uses and recycling processes. All these different system states and processes are covered by single and combined environmental information to control water uses and developments of water systems.

Figure 3: Meta-model for Water Resources Management (from Pillmann 2010)

The numbers given in the figure are indicating system states and/or processes:

1. Water bodies (surface waters (marine and freshwater) and groundwater). Coupling of water and atmosphere by evaporation, by evapotranspiration, by heat exchange, by water circulation. The processes are mainly determined by physical reactions.

2. Water uses by public water demands and supplies (drinking water and process water), by industrial water supply, by irrigation, by take-off of cooling water, by desalinisation.

3. Water loadings by wastewater, by inorganic pollutants (easily degradable), by synthetic organic pollutants (heavily degradable), by suspended matter (biotic and abiotic matter), by bacteria and viruses (human well-being and health), by heavy metals (non-degradable), by heating.

4. Coupling atmosphere and water by natural processes (physical and chemical processes), clouding, dry and wet deposition, wind, solar radiation, climate and weather, and efficient precipitation.

5. Data capture (design of an information system) on water system related states and processes (water uses and the respective natural and anthropogenic loads) by state variables, indicators, orientors by means of monitored data, field sampling, laboratory analysis, summary data (derived by statistics), or by simulated data (obtained from water simulation models).

6. Data fusion and data storage by aggregation and storage of single information in data banks, data warehouses by the following procedures: database management, knowledge management, statistical classification, modelling and simulation tools, process control options, decision support, and water information systems.
7. Decision support systems to control anthropogenic processes, and to form a base for preparation and development of policy making processes for governmental and non-governmental organisations and institutions by information analysis, by formulation of decision rules, by metadata management.

8. Development of political and economical instruments to control complex water-society systems by legislation, environmental standards (e.g. WFD), and river basin management action plans, founding of river basin authorities. Quantifying ecosystem services and socio-economic relations the following services should be regarded: provisioning services, regulating services, habitat services, cultural services and amenity services.

9. The water-society system covers all natural and anthropogenic processes as well as changes of states of water systems due to water users and political and economic control options.

10. The system of water users is formed by industry, trade, agriculture, forestry, citizens, and the Society.

6. Conclusions

From a holistic point of view the methodology for developing meta-models for sustainable environmental management is under progress. The application of meta-models for water resources management requires not only intensive investigations of subsystems and their interrelationships as well as a study on the availability of the information pools available. Especially, the last point is important. For each subsystem a different information pool exists with special types of data often with some degree of uncertainty. The data are often captured with different time horizons and different spatial scales. This means that short-term events and long-term effects are overlaid. Therefore, to get better knowledge on the ecosystems responses long-term data series are necessary. For this reason, the data pools have to be unified including the dynamics of environmental and socio-economic processes. It can be expected that meta-model frameworks and their quality will increase in future using higher level information pools with long-term data on the environment.

Furthermore, researchers have to make sure that the results of meta-model procedures can be exploited optimally by the scientific community and the practitioners who have to manage human-environmental systems. This task should help addressing potential restrictions and resistances by management authorities and policy makers against the use of ecosystem services through adequate communication and knowledge sharing and capacity building. The analysis of the relations between ecological processes, ecosystem functions, ecosystem services and human activities will help to widen the field of applications of meta-models for understanding environmental information processes.

7. References


