ENVIRONMENTAL SYSTEMS

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Contents

Summary

> *"Erkenne, was die Welt im Innersten zusammenhält. Wie alles sich zum Ganzen webt, eins in dem anderen wirkt und lebt."* (*Faust*, Goethe)

To enable the use of data sets for management and protected classical and non-classical methods of data filtering and aggregation, modeling and decision making, as well as monitoring are required. This asks for environmental agencies and related companies to collect large, raw data sets. But there is the bottleneck of evaluating the data and applying them for environmental management and protection. Therefore, statistical methods of data handling have been developed. More and more challenging tasks of environmental management and protection have forced the conceptualization and development of models of environmental objects based on systems engineering approaches with the natural and social sciences background. Advanced information technologies like simulation, networking and monitoring help to understand the behavior of complex environmental systems and their parts and to forecast the influence of human activities on the environment. Analyzing the human environment has been a fundamental problem. The task and fascination of forecast (to know something before) and not understanding (to explore something after) is caused by basic contradictions. On the one hand, man is part of the whole of nature. Necessity and change, as well as order and chaos determine his destiny. On the other hand, man is an active part of nature and driven by the will to investigate nature with objectives of using nature. Science in its long history has contemplated in turn these aspects. But now, with the idea of life support and sustainable development, it is time to realize both aspects as a whole.

1. Introduction: Systems Approach to Environmental Objects

First we should reflect on the new understanding of the role of determinism and probability, the whole and its parts and order and chaos in (environmental) sciences and in modeling.

The stochastic nature of the microcosmos is well-known (since L. Boltzmann). A further and relatively new finding is the fact that the macrocosmos also outside the molecular level is not only determined by the concept of determinism. The American meteorologist E.N. Lorenz gave an example besides M. Born, W. Heisenberg, P.D. Thompson and A.M. Obudow before.

Atmospheric and fluid fluxes or population dynamics all show chaotic behavior. In opposition to stochastic behavior they display deterministic behavior.

Second the great progress in the development of information technology and the social need to apply these techniques must be mentioned.

Environmental management and protection have become a general task on all levels of society. This fact results from global industrialization. After the end of the cold war the military budgets were cut. The military was eliminated by environmental research. Advanced environmental technologies, especially information technologies were developed. Sensor technologies have to be mentioned. Computer technology has made great progress. The price/performance ratio of processors, prices of disk spaces and main memories are decreasing rapidly.

Sensor networks have been installed to monitor the quality of water, air and the ground in most countries. Satellites are increasingly used to capture environmental data. This environmental information technology enables the claimed large and complex data sets to be administered as global systems.

1.1. Environmental System Conception

The conception of systems is very general. In system science it is used to analyze complexity, to bring a greater amount of transparency into the interaction of parts. It maps the flow of information or energy or material etc. through the complex system. It is based on the decomposition of the complex system into subsystems. The chosen subsystems should be simple to handle. Mostly, they are object-orientated. The topology of the real object determines the structure of the mapped system. Systems are characterized by inputs and outputs. They can be controlled via the inputs and observed via the outputs.

The difficulty of analyzing and especially forecasting the environment consists in the fact that man as an actor is himself part of the complex environmental system/complex ecosystem – the biosphere (Figure 1).

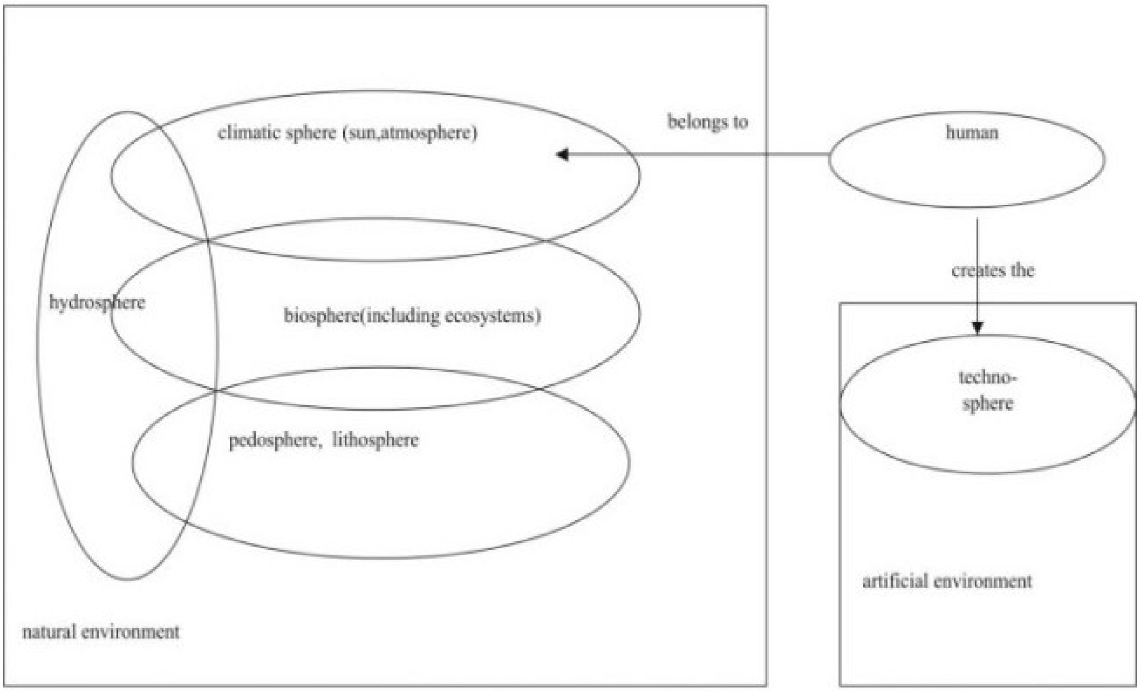

Figure 1. Human environment

The concept of systems builds a bridge between the world of real objects and mathematics. Typical terms of systems methodology are linear and nonlinear systems, continuous and discrete systems, lumped parameter and distributed parameters, automata, events, hierarchical systems etc. Terms of modeling are systems identification, and parameter estimation, input and output analysis, sensitivity analysis, uncertainty, fuzzy sets, control, decision making, etc.

Systems analysis requires to design a conceptual model consisting of submodels. The conceptual model is a plan for mathematical modeling. Mathematical modeling is based on measurement before or during the control process. Modeling is not a purpose for itself. Its focus is to solve problems and according to the problems, selected models are developed. Some models are developed only for one problem. Generally, the systems approach provides models for control, decision and planning processes.

Vice versa one physical object would be modeled by different descriptions. So the term environmental system is more or less a synonym for models describing a set of models. Naturally, the selection/choice of a model starts with the topology of the environmental object and generally with the analysis of the planning/decision/control problem.

1.2. Complexity of Environmental Systems

The complexity of environmental systems is known to all who need to make decisions in the management of plants, in environmental politics or in the study of global change, etc. (Figure 2). The complexity is inherent in the nonlinearity of mathematical models, the dynamic and stochastic nature of natural resource problems, the multipurpose, multiobjective attributes of decision problems. The complexity is also caused by the natural coupling and interaction of parts of the biosphere. The complexity depends also on problems of measuring, transmitting, processing and analyzing data and the decision-making process under environmental, technical, institutional, economic and political aspects.

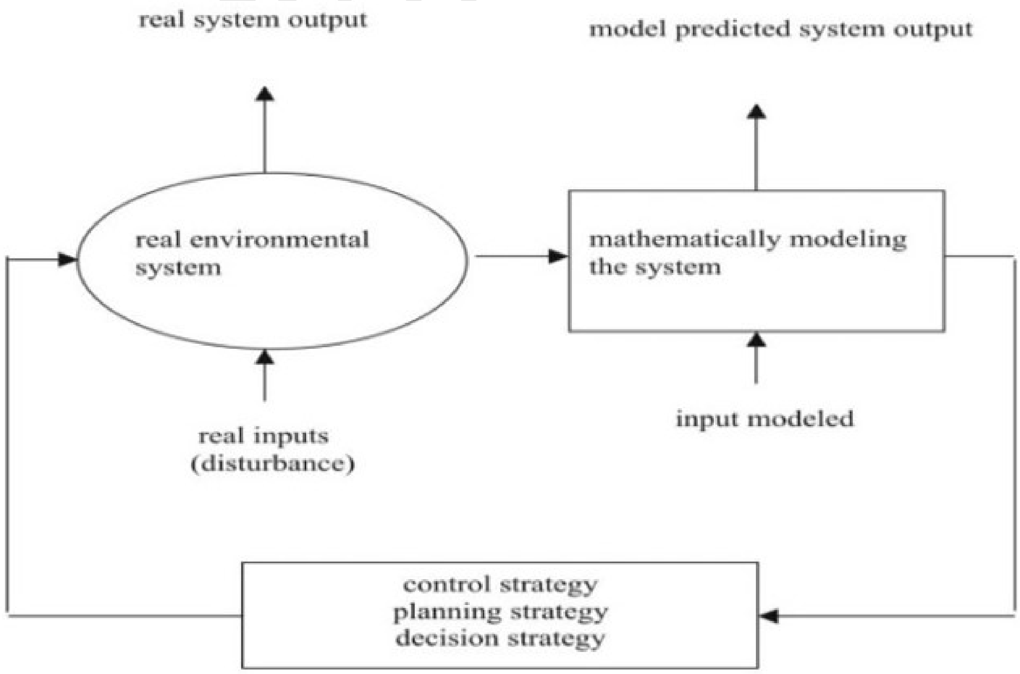

Figure 2. Modeling and decision making

Systems methodology provides theoretical and computational tools for modeling, analyzing, understanding and controlling, optimizing or planning complex, environmental systems.

The systems approach brings transparency into the interactions of the system's parts. Simulation tools support numerical insights into the system behavior. The idea of sustainable development is the overall goal in treating the biosphere and its parts, which takes into consideration their high complexity.

1.3. Systems Analysis

Systems analysis consists of various steps. Basically, these are described in the following outline:

1. Analyzing the decision problem (goals, decision or control variables).
2. Formulating a model which is adequate in quality and accuracy for the complex problem (structure, parameter, interconnections).
3. Testing the model (usually by computer simulation) (validity, sensitivity).
4. Solving the decision problems by scenario analysis, optimization (control, decision strategies, planning)

Computer simulation and optimization tools provide essential aids as regards most of the steps.

Typical examples of environmental problems should explain the use of the systems approach in different model areas (regional, global). Environmental systems are very often used in economical and social context.

Global natural resource management problems, for example, are only to be considered together with population growth and world economy. It is similar for other problems. That means that ecological systems should be compatible with other necessary systems.

Hierarchical systems methodology was developed with systems theory and basic knowledge of cybernetics (information, control and loop function, signal processing) and related engineering applications. Systems engineering provides a tool box with approved methods in engineering sciences.

On the level of systems or "symbolic systems" mainly control, decision and planning problems will be analyzed. Modeling on the systems level is based on the input-output analyzes and needs mathematics, natural life and economic sciences as a background. System identification and parameter estimation are the main steps of modeling.

Example: water quality. As an example of the systems approach a control problem of water resources is considered (Figure 3):

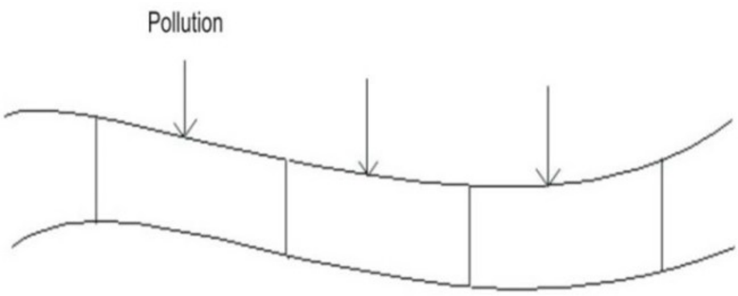

Figure 3. The water quality of a river

- What variable should be measured and controlled?
- How to control and by which variables?

According to the wastewater inflow the river is decomposed into subsystems (Figure 4).

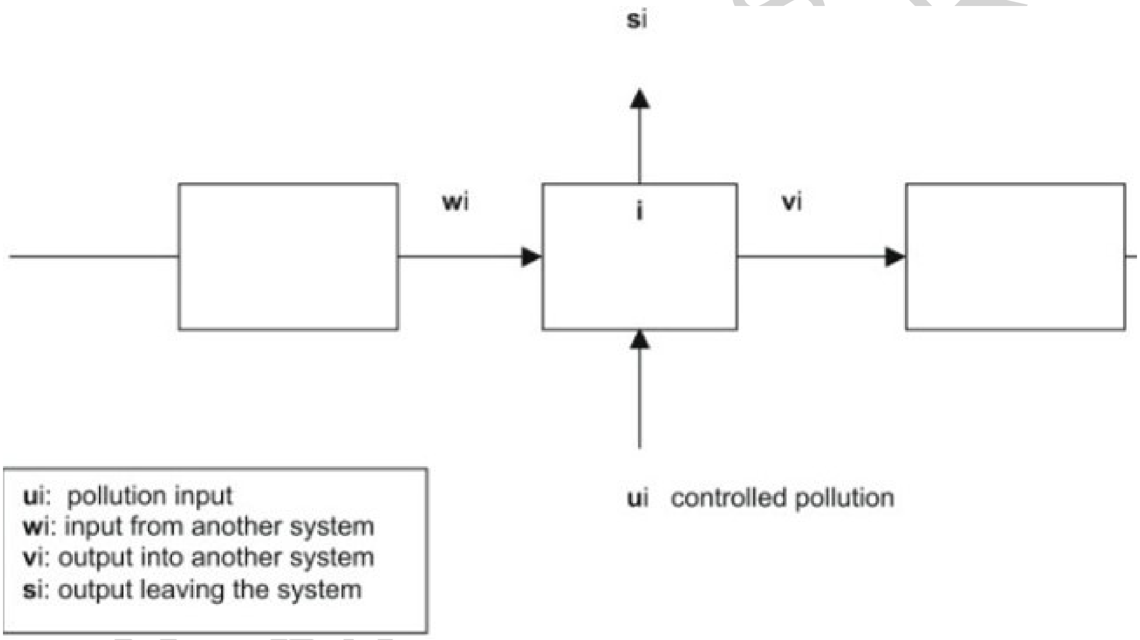

Figure 4. Systems approach description

The pollution is directly discharged into the river or over a wastewater plant. The control problem for water quality consists in the fulfillment of certain conditions (biological oxygen demand, dissolved oxygen) and optimization of the overall costs, including the costs for the wastewater treatment. This is a distributed parameter system based on a *partial differential equation*. The control problem would be considered a multicriteria optimization problem and solved by hierarchical optimization.

2. Measurements: Data Capture, Validation, Interpretation

Environmental object classification leads to the taxonomy distinguishing between atmosphere (all objects above the surface of the Earth), hydrosphere (water-related objects), lithosphere (relating to soil and rocks), biosphere (all living matters) and technosphere (human-made objects), cf. Figure 5.

Figure 5 shows a comprehensive classification for databases. Because the environment is a complex object some parts could be allocated to different classes. Analyzing environmental objects and problems is an interdisciplinary task. An important question is how to assign data to classes of a given taxonomy.

As an example think of satellite observation and land use classification. How to allocate pixels to land use classes?

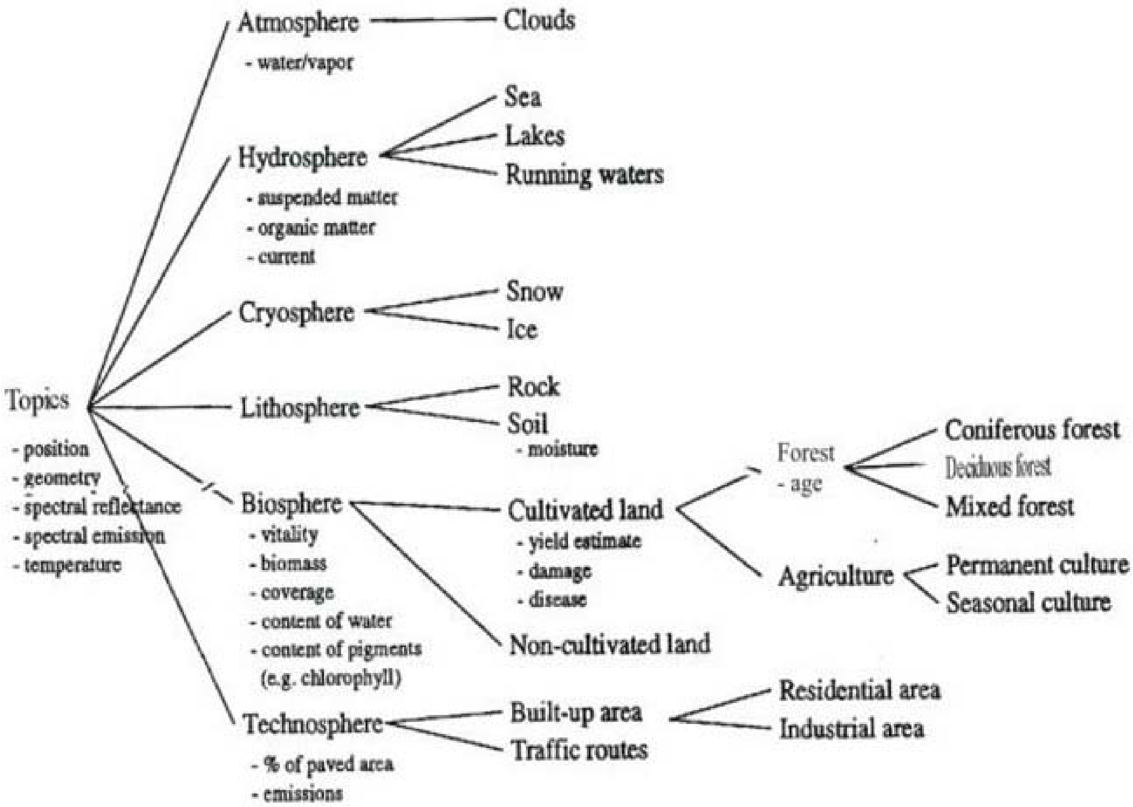

Figure 5. Taxonomy of environmental objects

A basic method to solve this problem is called maximum likelihood. For this method, one needs to know a finite number of classes for the allocation of new observations. The probability distribution for each class describes the probability that the observation belongs to the respective class. Mostly, the probability distribution is unknown. Practically, very often a normal distribution is used. Suitable data sets (trainings sets) are used to identify the parameters of probability distribution.

Environmental system models based on measurements need aggregation, validation and interpretation of the initial collection of environmental data. The measurement is associated according to the applied methods and techniques with uncertainties. Therefore, validation procedures are developed and applied (like temporal v., geographic v., space-time v., interparameter v., see Günther). Measurements in most cases are validated in the context of interpretation. Also, knowledge-based systems (expert systems) play a role for initial evaluation of environmental raw data.

For data processing, statistical classification, data management and artificial intelligence provide standard methods. Within the process of data processing, especially in the case of data fusion (by combining), methods of uncertainty management are applied.

When circumstances of measurements are known like weather, date, time of day, etc., methods based on Bayesian probability theory are used. The Bayesian model requires events which are independent of each other. This is mostly unrealistic.

Therefore, recently developed methods like fuzzy sets have to be applied. Neural nets are used to handle uncertainty.

Such validated data are the basis for information systems and monitoring of the state of environment. Furthermore, they are needed for modeling (systems identification and parameter estimation). After systems analysis the conceptual model (model design) requires input and output data of the systems or subsystems. The theory determines which and how much data are needed ("It is the theory which decides what can be observed", A. Einstein). Physics, chemistry, biology, ecology, especially engineering sciences, etc., provide measurement equipment and techniques. In general, measurement and validation are the bottleneck and a great challenge for the further development and realization of the environment.

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Biographical Sketch

Prof. Dr. Achim Sydow, mathematician; author of 4 monographs on modeling and simulation and more than 100 publications. *Last Ten Years' Activities:* National Research Center for Information Technology, Berlin; Founding director of the Research direction (department) for Systems Analysis at GMD.FIRST; Lectures at the Berlin Technical University (TU); V. Pres. of the International Association for Mathematics and Computers in Simulation (IMACS) and the International Environmental Modeling and Software Society (IEMSS); Member of the German Association of the Advancement of IIASA, Laxenburg, Austria (since 1993); Member of the Council of the Herman Helmholtz society; Chairman Genl. Chairman of the 15th IMACS World Conference, Berlin on *Scientific Computation, Modelling and Applied Mathematics;* Chairman of the Environmental Modeling Working Group of the European Consortium for Informatics and Mathematics (ERCIM); Chairman of the (SCS)-Conferences of the Society for Computer Simulation International on Environmental Modeling and Simulation (San Diego, San Francisco, Phoenix) and two IMACS Symposia on Systems Analysis and Simulation, Berlin; Guest Professor at the following universities: Hagen/Germany, Innsbruck/Austria, Las Palmas/Spain, Lyngby/Denmark, Linz/Austria; editor-in-chief of the journal Systems-Analysis-Modelling-Simulation

(SAMS) and editor of the Numerical Insights series (published by Gordon $ Breach). Various research projects (natl., European) in the field of environmental modeling and simulation.