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# Trends in Environmental Information Processing

F.J. Radermacher[a], W.-F. Riekert[a], B. Page[b], and L.M. Hilty[b]

[a] Forschungsinstitut für anwendungsorientierte Wissensverarbeitung (FAW) an der Universität Ulm, Postfach 2060, 89010 Ulm, Germany; E-Mail: {radermac | riekert}@faw.uni-ulm.de

[b] Universität Hamburg, Vogt-Kölln-Str. 30, 22527 Hamburg, Germany;
E-Mail: {page | hilty}@informatik.uni-hamburg.de

**Abstract**

In recent years, systems for processing environmental information have been evolving from research and development systems to practical applications. Today, many of these systems already support environmental activities at the industrial, governmental, and worldwide levels. A broad range of applications in environmental protection is covered by these systems, including monitoring and control, conventional information management, computation and analysis, as well as planning and decision support. A new discipline, known as *Environmental Informatics*, is emerging which combines research fields such as data base systems, geographic information systems, modeling and simulation, computer graphics, user interfaces, neural networks, knowledge processing, and systems integration.

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## 1. INTRODUCTION

The environment is one of the topics which are of crucial importance for the transition of industrial civilizations into the next century. To date, individual standards of living have been growing rapidly in the developed countries of the world while global population growth is exploding. Both trends are adding to ever increasing global consumption. We are now becoming aware of the limits of our natural resources, while producing global effects with our daily activities, thus leading to a situation which can hardly be controlled, and which may eventually lead to global instabilities.

It is not surprising that the discussions about measures for preserving the environment often lack the necessary information. On the one hand, we suffer from the huge amount of available data – people sometimes speak of data graveyards – on the other hand, the really relevant data may still be missing, either because they are not contained in the available data or because the researchers are not able to extract them.

Therefore, the design of information processing systems for the appropriate utilization of environmental data is a big challenge for computer scientists and other interested parties. The existing solutions often suffer from a narrowed, unidisciplinary view of the problem scope. These solutions fail if additional requirements are introduced, such as interoperability with other environmental information systems and adaptability to future system environments or application scenarios. Another requirement, which has not yet been adequately covered, concerns the transformation of results into reports or other public communication formats which necessitates a strong integration with the domain of multimedia and desktop publishing. Moreover, a major obstacle on the way towards generalizable solutions is the nature of the environmental data which are sometimes very large, very complex, and which require non-standard data structures and processing methods in most cases. Finally, an even bigger problem may be the fact that many politicians, and also scientists, in this field do not yet fully understand the central importance of the proper incorporation of computer science know-how into this framework.

For coping with all of these requirements and problems, a new discipline, known as *Environmental Informatics*, is emerging. In the following section, application domains and essential scientific aspects of this discipline are presented in more detail.

## 2. THE GLOBAL DIMENSION

Global development and the environmental situation are becoming more and more critical and dangerous. Driving factors are the uncontrolled growth of the world population combined with the increase in consumption described above. Both trends (more people, more consumption) have been viewed throughout history as unanimously positive. However, this view is now changing. With more than half of the people living on Earth today below the age of reproduction, a time bomb is developing which will be difficult to manage. Even worse, the level of consumption in the developed world is viewed as a target by billions of people around the globe, influenced by modern worldwide communication, while, at the same time, we are already witnessing scarcity of water resources, extension of desert areas, loss of tropical rain forests, and, particularly, the accelerated growth of megacities with many negative effects on hundreds of thousands, if not millions, of people.

It is quite clear that all these trends can only be broken with very decisive programs, limiting further population increase, or, preferably, reducing the world population over the coming generations.

To achieve this, however, will mean radical changes in our general attitude. The political and the ethical leaders of the world do not yet seem to be willing or able to fully address these problems. However, the past several years have brought many changes in this direction. Particularly, the Rio Summit has finally led to the acceptance of a point of view that is best characterized by the term "sustainable development". Here, sustainable development means a way of living and a form of using resources that does not discriminate against future generations.

Sustainable development is an important concept. However, it is difficult to operationalize and to make concrete. We will probably be confronted with quite sophisticated counter-arguments, and it might happen – as it has so often before – that uncoordinated development will actually lead to a state of affairs that is acceptable to no one. It is not at all clear what can be done to help to fight such a negative development. Certainly, information will be a very critical resource in changing attitudes and making decisive political actions possible. Among the many information sources to be considered, remote sensing and the coupling of data streams from all over the world, a policy of sharing information, the formation of networks and broad-based discussions will probably be the best that can be achieved and arranged in this framework (GÜNT94). Certainly, the most advanced computer science techniques must be employed here, from networks to information processing, image analysis, federated database computing, artificial intelligence, and neural networks, among other topics. Environmental informatics is contributing here to a matter of utmost importance. More on this topic is presented in the following sections.

## 3. SUPPORTING THE PUBLIC SECTOR

In recent years, environmental protection as an objective of public activities has reached quite a high standard in Europe, particularly in Germany. Communal tasks, for example, include land use planning, approving compliance with environmental standards, management of hazardous waste, and water and energy management for public facilities. Several states and regions of the European Union have already installed effective environmental information systems and powerful sensor networks. There is a broad laboratory infrastructure both in the public sector and in industry.

Official systems such as the Environmental Information System Baden-Württemberg (MAYE93) support environmental tasks at various levels: Decision Support Systems are provided for the high-level environmental management, reporting and planning systems are available for middle management, while basic components support the acquisition and management of specific environmental data at the operational level. In addition, interdisciplinary information systems are being used in public environmental management; these systems are not restricted to environmental tasks such as the topographic or cadastral information systems of the surveying offices.

## 4. INDUSTRIAL APPLICATIONS

The need for environmental management systems in industrial production is a recent challenge to information technology. An environmental management system is the overall framework for the actions that an enterprise takes to manage its effects on the environment (FAW94). European regulations such as the “Eco-Management and Audit Scheme” (COMM93) are intended to standardize this framework. Information systems designed to support such actions or the overall framework are called *industrial environmental information systems* or *environmental management information systems* (LITT93).

In so far as such systems are used for production planning tasks, they may be designed in accordance with conventional production planning and control systems and incorporated into a CIM- or CIP-architecture (HAAS91). Their task is to continuously document the environmental load caused by the production process (emission monitoring) and to optimize the material and energy flow through the production system.

Other approaches emerge from the field of *ecobalances*. This term refers to studies or methods that are used to investigate and evaluate the total mass and energy throughput of a given system. In most cases, the system under investigation is a product life cycle. Such an investigation is then called *life cycle analysis* or *life cycle assessment* (LCA). The goal is to assess the environmental impacts of a product “from cradle to grave”, i.e., from the extraction of raw materials up to waste disposal. There is a growing number of software tools for LCA (MIET93). A general tool for modeling systems of mass and energy flow (at the company, production process, and product life cycle levels) based on Petri Nets was proposed by Schmidt et al. (SCHM94).

Other industrial applications of environmental information processing are found in logistics, where the ecological challenge has led to the concept of “eco-logistics”. In this new field, methods of modeling and simulation are used to assess the resource efficiency and the specific emission rates of alternative logistical strategies (HILT94a).

## 5. ENVIRONMENTAL INFORMATION PROCESSING SYSTEMS

There is a broad spectrum of environmental information processing systems which can be differentiated based on the nature of the information to be processed. This includes monitoring and control systems, conventional information systems, computation and analysis systems, planning and decision support systems, and integrated environmental information systems (PAGE92).

*Monitoring and control systems* interact very closely with environmental objects and processes. Monitoring systems serve in the automation of measurements (including remote sensing) in water, air, soil, noise, and radiation control. These also includes preliminary analysis: time series data need to be aggregated, environmental objects need to be classified (e.g., in satellite images), and chemical substances need to be identified based on the measured data. Computerized process control is either directly employed in environmental technology such as in air or exhaust gas cleaning, sewage, sludge, or refuse processing, or used in production process automation with secondary effects on environmental protection (e.g., energy conservation, emission reduction). Monitoring and control systems often require the processing of vague information, e.g., using the evidence theory of Dempster and Shafer, fuzzy logic, or artificial neural networks.

*Conventional information systems* are systems for input, storage, structuring, integration, retrieval, and presentation of various kinds of environmental information such as raw measurement data, descriptions of environmental objects (such as geographic objects or chemical substances), as well as formal, semi-formal and unformal documents such as environmental regulations or literature references. Spatial and temporal aspects often play an important role in the management of these kinds of information. Various kinds of software tools, including geographic information systems, hypermedia systems, thesauri, etc., are necessary for coping with all of these data.

*Computational evaluation and analysis systems* support the processing of environmental data using complex mathematical-statistical analysis methods and modeling techniques. This includes simulating and forecasting various environmental scenarios. Possible applications of these systems are the identification of possible causes of various kinds of environmental loads or the derivation of possible effects of different planning scenarios (e.g., causal models in forest damage research or forecast of emission loads over time and region).

*Planning and decision support systems* directly support decision makers by offering criteria for the evaluation of alternatives or for justifying decisions, e.g., for comparing eco-balances or approving eco-audits, for conducting environmental impact analyses, and for handling hazardous substances.

*Integrated environmental information systems*, as the last category mentioned, cannot be uniquely associated with a single system class, since they consist of multiple components serving various purposes. It can be expected that integrated environmental information systems will be increasingly designed as distributed systems. The integration of various concepts for information processing, which is required for building these kinds of systems, presents a special challenge to the discipline of applied computer science, with similar importance to other application fields.

## 6. FROM DATA TO INFORMATION

Environmental data differ from traditional data in many respects. Often the data are related to a certain location and time interval. Measurement data that are acquired for discrete locations and points in time belong to a special category; these data need to be interpolated if continuous profiles are required (e.g., air pollution data or elevation models). A special case is image data (e.g., satellite sensor data), which typically consist of very large raster data sets. NASA experts often handle terabytes of satellite data; this is more than two orders of magnitude greater than the amount of data managed today in large international financial transaction systems. This requires new storage models for environmental databases, e.g., the use of automatic tape archives and CD ROM jukeboxes as tertiary storage medium.

The most demanding problem concerns the derivation of the requested information from the existing data. Usually, the transition from data to information requires an appropriate application of algorithms on data, possibly in an iterative way, and supported by an appropriate model or theory of the application domain. Models may have to be calibrated, algorithms may have to be parameterized, and, depending on the results, these processes may have to be repeated. These tasks are very demanding and require massive knowledge processing and the availability of an appropriate model base. In addition, the translation of information into reports, documentations, balances, etc. needs to be supported by appropriate report generators and publishing tools.

In the ideal case, an environmental database contains all the necessary data which are needed to conduct these translation processes and to derive the information requested by the user. Apart from the raw environmental data, this requires the availability of additional information, known as *metainformation* (RADE91). In a broad sense, this includes information about location, time, precision, and revision dates of the data under consideration, as well as descriptions of the data structures and data formats used.

Metainformation is missing today in most existing environmental information processing systems. Often the only data source consists of a magnetic tape containing the raw data (e.g., image data or measurement data) to be analyzed. All of the additional information which is necessary for the correct interpretation of the raw data is implicitly coded in the application programs or must be contributed by the user. Such a tape may become completely useless after a change of the personnel or of the data processing software. Therefore, environmental metainformation systems, also known - with a reduced scope - as *environmental data directories* (SCHÜ93), are currently being developed to overcome the prevailing lack of metainformation. They constitute one of the central scientific challenges to be adressed in this field, as does coping with heterogeneous hard- and software, as well as network environments.

## 7. SPATIOTEMPORAL ASPECTS

Environmental data often describe environmental objects with a spatial and temporal extent. These objects, also known as geographic objects, possess a geometry consisting of point-form (0D), linear (1D), flat (2D), or solid (3D) features. Often geographic objects also have a lifetime which is given by their dates of construction and destruction. During the lifetime of an environmental object, its attributes may change. That is, the values of the attributes are only valid during a certain time interval, and a given attribute (e.g., the population of a city or the land use of a parcel) may possess many possible values during the lifetime of the object. A special case is the change of the geometry of a geographic object such as the growth of a city or the shrinking of a lake or a forest.

The adequate representation of spatio-temporal environmental objects is a special challenge to applied computer scientists. Abstract data types are required for representing concepts such as the partonomy, the topology, and the spatio-temporal extension of geographic objects as well as the thematic information associated with these objects, such as alpha-numeric attributes and relationships to other geographic objects. An important task is also the (carto-)graphic presentation of these objects. In most cases, non-standard data types are required for representing these kinds of information and, therefore, a trend towards systems which allow the definition of such data types, such as extended relational or object-oriented databases (CACM91), can be recognized in current developments (GÜNT93).

The special nature of environmental data also requires a query language with special characteristics. Apart from typical SQL-like questions, the forthcoming object-oriented database management systems (CATT93) also allow navigational queries and queries that include user-defined predicates. In particular the latter allows the usage of spatio-temporal predicates in queries. The optimization of spatio-temporal query-processing is a scientifically demanding problem which concerns both storage models and indexing techniques for multi-dimensional data. The integration of these techniques with existing databases is a hard problem which will still require major research activities in the future.

## 8. OVERCOMING THE HETEROGENEITY

The harmonization of environmental information at national, European and worldwide levels is of central importance for gaining a reliable description of the environmental situation and, at the same time, is a basic requirement for any reporting system in this context. These requirements, however, are confronted with the existing heterogeneity of hardware and software environments, of database systems, of method bases, of network technology, and of various computer languages. Approaches for overcoming the heterogeneity, one of the major obstacles to open software solutions, can have a tremendous impact on the productivity in environmental management, and can also lead to a greater stability in system design and system usage.

The task of overcoming heterogeneity is a challenge which is mainly addressed to applied computer science and which must be tackled primarily by applied computer science. Doubtless the development and promotion of standards is of particular importance in this respect. Experience shows, however, that we will still have to cope with competing standards in the future. In addition, technological advances will always produce new heterogeneity problems and will require strategies for migrating the software towards new solutions. The proper handling of questions of this kind is very important for obtaining powerful solutions in the environmental domain. A pragmatic usage of the currently evolving architectures such as client/server architectures, object request brokers, hypermedia technology for identifying and accessing services and data, and remote procedure components are important in this field (RIEK94).

## 9. ENVIRONMENTAL INFORMATICS

The solution of the versatile, strongly interrelated, and highly interdisciplinary tasks in the environmental field requires the intensive use of modern information processing methods and techniques. This has led to a new scientific discipline, known as Environmental Informatics.

This discipline has been maturing since the eighties. In Germany this is nicely documented by the yearly conference series on “Environmental Informatics”. These conferences, which have been organized by the working group “Informatics in Environmental Protection” in the German Society for Informatics (GI) since 1987, have yielded a growing number of participants, projects, and publications (e.g., JAES93, PAGE94, HILT94b). Today, environmental informatics is an integral part of applied computer science. It provides methodological support for computer utilization in environmental protection by combining advanced research fields such as database systems, geographic information systems, modeling and simulation, computer graphics, user interfaces, neural networks, knowledge processing, and systems integration.

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