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Watershed management and the Web

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Watershed analysis and watershed management are developing as tools of integrated ecological and economic study. They also assist decision-making at the regional scale. The new technology and thinking offered by the advent of the Internet and the World Wide Web is highly complementary to some of the goals of watershed analysis. Services delivered by the Web are open, interactive, fast, spatially distributed, hierarchical and flexible. The Web offers the ability to display information creatively, to interact with that information and to change and modify it remotely. In this way the Internet provides a much-needed opportunity to deliver scientific findings and information to stakeholders and to link stakeholders together providing for collective decision-making. The benefits fall into two major categories: methodological and educational. Methodologically the approach furthers the watershed management concept, offering an avenue for practical implementation of watershed management principles. For educational purposes the Web is a source of data and insight serving a variety of needs at all levels. We use the Patuxent River case study to illustrate the web-based approach to watershed management. A watershed scale simulation model is built for the Patuxent area and it serves as a core for watershed management design based on web applications. It integrates the knowledge available for the Patuxent area in a comprehensive and systematic format, and provides a conceptual basis for understanding the performance of the watershed as a system. Moreover, the extensive data collection and conceptualisation required within the framework of the modeling effort stimulates close contact with the environmental management community. This is further enhanced by offering access to the modeling results and the data sets over the Web. Additional web applications and links are provided to increase awareness and involvement of stakeholders in the watershed management process. We argue that it is not the amount and quality of information that is crucial for the success of watershed management, but how well the information is disseminated, shared and used by the stakeholders. In this respect the Web offers a wealth of opportunities for the decision-making process, but still to be answered are the questions at what scale and how widely will the Web be accepted as a management tool, and how can watershed management benefit from web applications.

Keywords: environmental science, decision support systems, dynamic spatial modeling, Internet.

Introduction

The watershed management approach has emerged as an holistic and integral way of research, analysis and decision-making at a watershed scale (Montgomery *et al.*, 1995; Perciasepe, 1994). It certainly implies more than just the regional scale of analysis. The method stresses the need to integrate not only physical and biological factors, but also political and socio-economic ones. The major impetus for watershed management stemmed from the understanding that science needs to be linked to planning, and that decision-making should be based on broad citizen involvement. Thus it is important that the information be shared between the stakeholders and that it be processed into a format readily perceived by wide and diverse groups, institutions and individuals. Moreover, the watershed delineates a physical boundary and not a political one, creating the need for methods which would allow management and communication between many administrative entities such as towns, counties and states. One of the problems that watershed management immediately encountered was the mismatch between the existing administrative hierarchies and the physical and societal boundaries and groupings that represented the watershed dynamics. Appropriate institutions were required that could operate in a flexible manner over alternative regional divisions.

As with the advent of any new technology, it took some time to realize all the benefits and advantages that the Internet and the

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Web can deliver. Until 1992 the Internet was the realm of a relatively small contingent of scientists and engineers, who were using it to communicate data among themselves, when both the sender and the recipient of information were usually personally defined. The Web opened a new page in the use and development of the Internet. Information was no longer personally targeted; once posted to the net it became open to any user who had the interest and time to view it. Basically the Web is to the Internet what radio is to postal services. Instead of mailing a letter to a definite addressee, information could be now aired as if it was broadcast over a radio or television network, and the sender no longer knew who the particular recipient was to be. In this way the audiences expanded dramatically and are still growing. A major advantage of the Web compared to other mass media is that it is relatively cheap. As a result, in addition to the businesses that were eager to employ another opportunity for advertisement and sales, the Web offered a whole new way of outreach and communication to governmental, academic and non-profit organisations. Even individuals could afford to establish their presence in this mass media.

Another advantage of the Web is that it provides for direct feedback from the recipient, who can now interact with the information displayed. Instead of just passively viewing information, web-site visitors can change and modify it remotely. Users are offered search engines that can direct them to the most relevant information available; they can revisit sites and refer others to them. Unlike other mass media, the Web is more stable and persistent. Even though copyright issues and authorship on the Web are still very much disputed, in the literature there is an increasing number of references to web publications, which means that there is an obvious trend toward acceptance of the Web as a valid media for display of copyrighted material.

In spite of these novel features, most of the use of the Internet does not seem to be much different from that of the traditional mass media or archived information (libraries, data sets, etc.). Business is driving a vast majority of web applications towards advertisement and sales in a way very much similar to what may be observed on radio, TV and in unsolicited mail and catalogues. There are just a few examples when the Web is used in an innovative way, that employ some of its unique features; electronic stock trading is probably one few such examples.

In this paper we review the concept of watershed analysis and management in brief and show how it can benefit from some of the advances in Internet development in general and the Web in particular. The interactivity and the hierarchical organisation of data displayed on the Web seems to offer a lot of potential in providing tools for watershed management. Users could be learning about the intricacies of environmental decision-making by running models to see what the potential outcomes of decisions might be. Planners and politicians would have an efficient manner of soliciting opinions about proposed projects from various stakeholder groups. This interactivity of the Web offers great potential for linking science, planning and public action. The access to information is crucial for the success of the watershed approach.

We first describe some of the basic features of watershed management. Next we focus on those features of the Web that can be instrumental for watershed management. We then present a case study for the Patuxent watershed, where the Web is used extensively to communicate data and modeling results to diverse groups of stakeholders, and offers an opportunity to solicit, process and organise citizens feedback on important watershed-related issues.

Watershed management

Watershed analysis and management inherit all the main concepts of ecosystem management. It embodies the greater ecosystem concept (Grumbine, 1990), which broadens the ecosystem definition beyond its original biological and physical meaning. The fact that ecosystem management is based on the principle of preserving ecosystem integrity while maintaining sustainable benefits for human population (Norton, 1992) implies that the decision-making process should be fundamentally restructured to take into account all the subsystems in their integrity and all the stakeholders who represent a wealth of potentially contradicting interests and concerns. As with sustainable development (Gale and Cordray, 1991; Voinov, 1998), ecosystem management has been defined in a variety of different ways (Lackey, 1998). There seems to be some obvious similarity in the two concepts since both require a systems approach that puts economic concerns within the framework of ecological options available. Both require that values of the society be brought into harmony with the carrying capacities of the environment. In both cases the existing administrative and sociogeographic boundaries and institutions become somewhat restrictive to take into account both the socio-economic and ecological features of systems.

In addition to scientific research and data acquisition by what Slocombe (1993) calls 'substantive methods', there is demand for new 'process methods' that refer to working with people, communities and businesses in describing, planning and managing ecosystems. As early as the beginning of this century Berdyaev (1916) called for an extension of the boundaries of scientific activities *per se*. According to Berdyaev, concrete sciences study the laws of nature and societies and can be included in the 'kingdom of necessity', which is determined by these laws. Intellectual efforts in search of new ways for the development of mankind must break away from these limits and restrictions. The 'scientific objectivity', which is indifferent with respect to good and evil, no longer is to be of prime importance. Values, as well as personal and social responsibilities, become prioritised. This does not preclude the significance of scientific knowledge, which is still a necessary component of human creativity. Yet being necessary, it should no longer be considered sufficient. Berdyaevs vision was that of a new creative epoch, when the main goal of human intellectual work will not be the search for new tools and methods, but rather it will be focused on the creation of a 'new heaven and new earth' (Berdyaev, 1939).

The fact that ecosystem management seeks alternative mechanisms to purely market forces based on the existing policy equilibrium seems to be very bothersome to traditional economists (Fitzsimmons, 1994). They argue that the ecosystem concept is inappropriate for use as a geographic guide for public policies. Mostly they are concerned that the ecosystem approach will significantly expand federal and other non-market control of the use of privately owned land, and lead to increased restrictions on the use of public lands for economic purposes.

In one respect the watershed approach seems to be more versatile than the general ecosystem management view. Well-defined boundaries are indeed an important prerequisite of a management strategy. Ecosystems and ecoregions (Gallant *et al.*, 1989) may be hard to define unambiguously and may be even harder to explain to the general public. The system boundaries associated with a watershed approach are objective. Instead of being the result of historical, subjective, oftentimes unfair, voluntary or contradictory processes, they are based on certain geographical characteristics such as elevation and flow gradient, which is difficult to change and makes little sense to dispute. The flow of water serves as an indicator of the relief and landscape characteristics, on the one hand, and as an integrator of many of the processes occurring within the watershed, on the other (NRMRL, 1999). The watershed approach is not intended to substitute the existing borders and regions, but rather it offers a superadministrative viewpoint to exercise consensus across economic, social and administrative bodies. It is also not perfect from the ecosystem point of view because 'drainage basins are not generally regarded as causal factors in the distribution of biota and are therefore of little value in determining ecosystem boundaries' (Omernik, 1987). In this sense the watershed approach offers a true compromise between purely ecological and purely administrative viewpoints.

A hierarchical context is another crucial component of successful management schemes. The implied hierarchical structure of superwatersheds and subwatersheds is instrumental for upgrading and downgrading, zooming in and out and changing resolution, depending upon the type and scale of the managerial problems to be resolved. This hierarchical approach adds flexibility to management, breaking the usual rigid connection between policy and scale. In most cases the scale is driven by the policy problem, and it is usually unclear who should formulate the policy question and at what scale (Lackey, 1997). With the hierarchy provided by the watershed approach, the scale of the targeted management object becomes less crucial, as long as it is presented as an element of the whole hierarchical structure. The smaller watersheds are embedded into the larger ones, and various policies formulated can be treated in the appropriate level. The hierarchy in this case is not imposed on the system from the outside, as in case of administrative divisions, but it is embedded in the physical characteristics of the system and offers a much larger variety of scales.

The potential of the watershed management approach may be illustrated by the fact that the US Environmental Protection Agency (EPA) has currently adopted it as its primary approach to addressing remaining water quality problems (NRMRL, 1999). The US Geological Survey (USGS) has defined a multi-digit classification system for watersheds based on the size of the stem stream and the Hydrological Unit Classification (HUC) system. There are 2149 watershed within the continental United States identified as HUC-8 systems, and they are often used as standards for the watershed approach. Groups of stakeholders may apply their efforts to the HUC-8 scale or may move up or down the scale, as appropriate to their local problems and their concerns. More than 20 states are known to be developing or implementing management frameworks that use watersheds as the organisational basis for integrating water resource protection and restoration activities. These frameworks address the process and procedures for coordinating activities—from public outreach to strategic monitoring and assessment to integrated management (EPA, 1997b).

Lackey (1998) identifies five general characteristics for ecosystem management problems: (1) public and private values and priorities are in dispute, resulting in mutually exclusive decision alternatives; (2) there is political pressure to make rapid and significant changes in public policy; (3) private and public stakes are high with substantial costs and risks (some irreversible) to some groups; (4) the technical ecological and sociological facts are highly uncertain; and (5) policy decisions will have effects outside the scope of the problem. He concludes that ‘solving these kinds of problems in a democracy has been likened to asking a pack of four hungry wolves and a sheep to apply democratic principles to deciding what to eat for lunch’ (p. 22). The outcome may seem quite obvious, except that with people there is always less certainty about how problems are resolved, and in the long run there is still a chance for the sheep to persuade the wolves to become vegetarians. The success of this endeavor becomes very much dependent on how efficiently the new technology is developed and used, since it is our scientific, cultural and social development which makes *Homo sapiens* special and leaves certain space for optimism. In this context we do not view technology as a panacea that can cure all the problems of environmental degradation and resource depletion, but rather as a means of understanding, educating and resolving conflict.

Among other innovative technology we see computer modeling and Internet communications as one of the most promising for the goals of watershed management. While computer simulations and data processing have been widely recognised and implemented, the advantages of the Internet for watershed management have not been adequately discussed.

Placing watershed management on the Web

Regional management implies a close interaction and linkage between the numerous agents acting in the region. The efficacy of this interaction is a function of the information that is shared among and used by all the stakeholders. In many cases it depends not as much on the quality and amount of the information available (what science has been mostly concerned with all this time), but rather on how well the information is disseminated, shared and used. And that is exactly the function that the Internet and the Web, as a substantial part of it, can offer.

In fact, up till now there has not been much progress in adapting the services of the Web for watershed management. The consensus building power of this 'informational superhighway' has been definitely underestimated. We argue that there are a number of features that make the Web an exceptionally important tool for watershed management in particular, and for regional management in general. The Web is:

Open

The Internet is one of the most readily available and reliable media providing information across geographical, administrative, social and economic boundaries. It is relatively cheap and can be accessed by all the stakeholders in a watershed and outside of it. The fact that it requires a computer (or advanced TV set—'Web-TV') and an Internet connection becomes less and less restrictive as more Internet Service Providers (ISP) enter the market. For example, in the UK, where Internet access has always been relatively expensive, just one ISP—Freeserve—is reporting a steady 55–65 000 new customers per week with more than a million already signed up (Dolley, 1999). For those who do not have Web access at home or at work there are public providers (libraries, 'webcafes') that also have become more available. This direct access to all the necessary information and, reciprocally, the ability to disseminate the facts that are of concern to particular stakeholders is an important prerequisite of watershed management.

Interactive

It is most important for management purposes that the user has the option of interacting with the provider of information and with other stakeholders. With the Internet this can be accomplished either via e-mail or directly through forms that can be filled in on web pages and transmitted to the server. These forms can be further manually or automatically processed and posted back on the Web. In this case information is not only passively perceived, as in case of the traditional media (radio, press, newsletter, etc.), but it also stimulates direct feedback. Moreover, users can modify the content and format of the existing pages by ordering excerpts from databases or providing scenarios for model runs, thus creating their own output to be viewed immediately on the Web. They may also provide additional information to the Web in response to the published requests or as a representation of their own findings and concerns.

Fast

Communications via the Internet are probably the fastest and the most economic since they do not require any intermediate carriers (as in ordinary mail) or materials (paper). Once the information is updated on the server it becomes immediately available for further use and processing. The feedback in many cases can be handled automatically and be directly channeled to the appropriate web link or interest group.

Spatially distributed

Internet access is offered over telephone lines and therefore covers almost the entire planet. The various nodes on the Internet can correspond and represent the spatially distributed data of different stakeholders both in the watershed and outside it. The web tools allow information to be linked together; search engines are created to find the necessary information and data. In this way concerns and awareness can be shared across different geographic localities. This gives a broader picture of the region within the framework of external systems and concerns.

Hierarchical

The hierarchical structure supported by the Web design allows organisation of the data in logical and efficient ways when various branches on the Web may present specific fields, domains and interest groups. The links on web pages can stitch the whole structure together offering cross-references and alternative views whenever necessary. The watershed hierarchy of subwatersheds and sub-subwatersheds can be easily mirrored on the Web with specific groups of pages representing each particular level. The hierarchical structure also offers levels of protection for the information, allowing certain domains to be completely open to all users, others being only read-permitted, yet others being accessible only to limited users and interest groups, providing the necessary extent of privacy and discretion.

Flexible

Additional benefits that are offered by the Common Gateway Interface (CGI) and the Java programming language allow the data to be processed by the users according to their own goals and interests. This is especially important for modeling tools because by employing the Web, they can be made directly accessible to the user, and with Java they can be made sufficiently flexible and user friendly to be used meaningfully and efficiently. Currently, web applications are being used at the high-school level to teach science and ecology (MVHS, 1998). The scope of potential uses ranges from running particular scenarios, which stakeholders can formulate based on their concerns, to adjustments in scale and structural detail of the model in response to special needs and projects.

All the important features and tools to augment and improve watershed management seem to be present, and it then becomes a matter of using them efficiently.

Web page design for decision support at a watershed scale

A watershed management web page can be considered as a *problem-oriented web page* that contains the state-of-the-art data and methods available for decision-making in a particular geographic region of a watershed (Figure 1). Web pages of this sort are driven by a particular problem and serve as a means of interactive communication rather than passive informing.

We argue that a watershed landscape model is instrumental as a core of web-based management. It brings together the geographic, ecological and socio-economic data about the watershed and its subsystems. It offers a conceptualisation of the watershed as a complex system, and it also helps identify the gaps in information available. The database used by the model becomes the reference book and repository for future research and measurements in the area. It is further linked to other models and methods that describe different processes or phenomena on the watershed in a variety of structural, spatial and temporal scales, all together helping process and understand the data.

The numerous stakeholders and interest groups in a watershed can represent themselves in separate web pages that are linked to the root page and cross-referenced when necessary. They are also invited to submit summaries of their activities and concerns that will be placed on the root page. This stage can be an important part of the consensus building process when all the varying concerns are summarised at one web site, are made open for discussion while monitoring a corresponding bulletin board that serves the purposes of exchanging current opinions and information on hot issues. Three immediate benefits of this clearly emerge:

- all discussions are documented and filed;
- they are open to the public and those concerned can immediately follow them and participate;
- participants do not need to travel to meetings and special hearings; all discussions are handled directly from office or home.

The social, physical and ecological domains become essentially linked and interacting. To make a case, a stakeholder needs physical, socio-economic or ecological data, which is readily provided by the watershed database. These are supplemented by the stakeholders own experience and visions that he can share with the rest of the community. If there is need for modeling or data-processing techniques

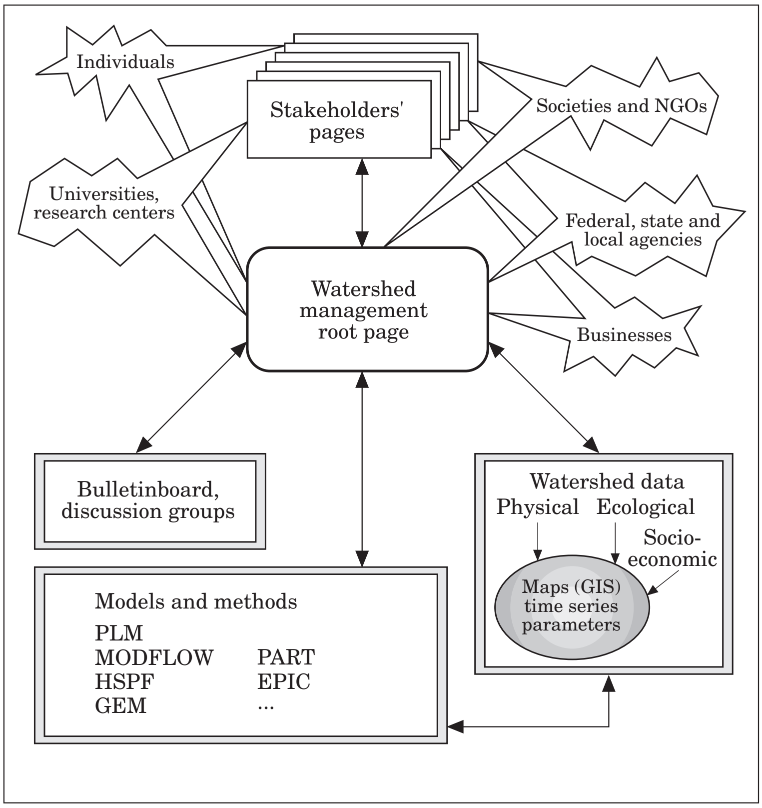

Figure 1. Conceptual structure of a watershed management web page. Three major components of the watershed management process are the data, the analytical tools and the stakeholders involved. The problem oriented web page serves to represent these components and to provide interaction between them.

to illustrate one's point, these methods also can be obtained from the Web, with applets that accompany data for simple evaluations or forms that can be filed, and scenarios that can be ordered from the full-scale model or its submodules. The results are immediately posted on the Web and made available for discussion and decision-making. The Web serves to integrate knowledge and data from different institutions and sites, and to offer it to the potential user.

Since the EPA has adopted the watershed approach, a wealth of information on watersheds and watershed management has become available over the Web. A group of sources such as the 'Watershed Academy' at http://www.epa.gov/owow/watershed/wacademy.htm was created to disseminate information that can be useful for managing the watershed or organising stakeholders on a watershed basis (e.g. EPA, 1997a). The 'Surf Your Watershed' service (http://www.epa.gov/surf) helps the user find and share information about any watershed in the USA. The watershed can be easily located from a map, by a geographic name (river, city, county, state, zip code, etc.) or by a name of a large ecosystem. For each watershed one can get information on water quality and quantity (via links to other EPA and USGS sites), citizens groups and other stakeholders, integrated information on watershed health, and specific data on land use, toxic releases, hazardous waste, etc. Another web site (http://www.epa.gov/OST/BASINS/) may be used to download an analytical modeling tool—the BASINS model (EPA, 1998), together with an appropriate data set for any watershed in the USA. Once again we see all the major components for watershed management now offered over the Web, however, the flow of information is mostly directed from the server, to the user; feedback is not encouraged and the interactivity of the Web is yet to be put to work. The next logical

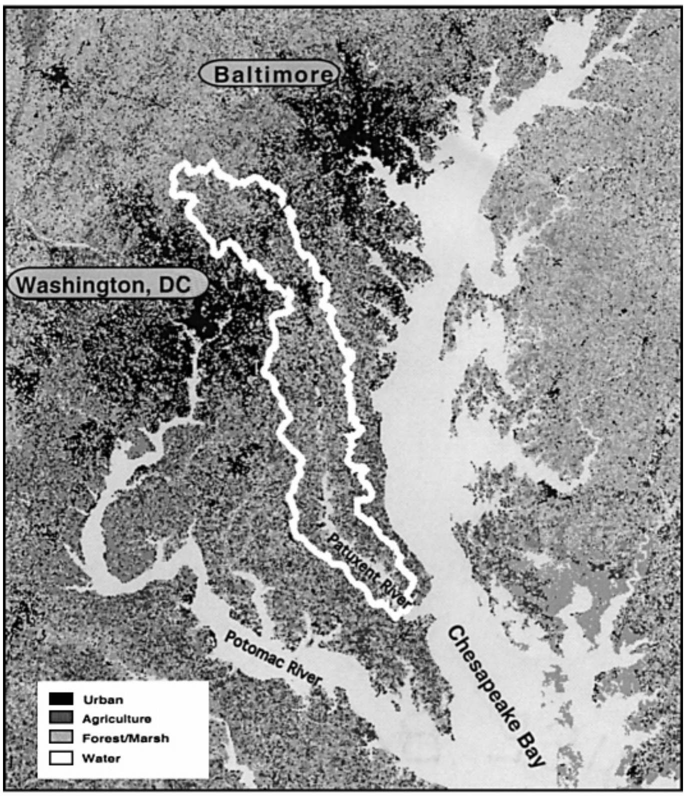

Figure 2. Geolocation of the Patuxent watershed. The drainage basin covers an area of 2356·2 km^2 and stretches for about 150 km from the Piedmont area of the Appalachians to the Chesapeake Bay. It is represented by a mix of land use and land cover types.

step would be to attempt to integrate web resources of this kind in an interactive way that could be incorporated into the decision-making process on a watershed scale.

Patuxent watershed case study

A prototype Watershed Management Page is currently under development as part of the project on 'Integrated Ecological Economic Modeling and Valuation of Watersheds' and can be viewed at http://iee.umces.edu/PLM/WMA. The Chesapeake Bay watershed has been a model of watershed-based ecosystem restoration (Costanza and Greer, 1995), and the Patuxent River is one of the most important tributaries of the Chesapeake Bay (Figure 2). Its drainage basin covers an area of 2356·2 km^2 and stretches for about 150 km from the Piedmont area of the Appalachians to the Chesapeake Bay. It is part of the 'tributary strategy' adopted by multistate/federal Chesapeake Bay Program, in which the sources of pollutants are estimated for each tributary watershed, fluxes are modeled, loadings are related to ecological conditions and living resources in the receiving subestuary, and goals are set for reduction of contaminants by generating sector (e.g. sewage treatment plants, agriculture and dispersed residential) and location in the watershed. Thus the focus came to be on watersheds and individual tributaries to the Bay.

Model

Within the framework of the project a watershed scale simulation model is built for the Patuxent area and serves as a core for watershed management design based on web applications. The Patuxent Landscape Model (PLM) (Voinov *et al.*, 1999) is an integrated ecological economic spatial model that combines general models of ecological and economic site-specific processes with

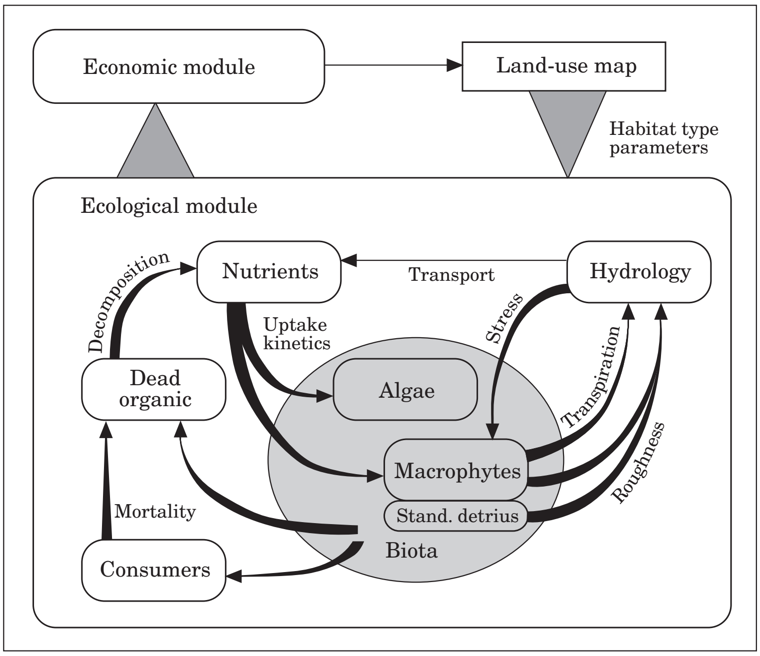

Figure 3. Major modules and ecological processes that are considered in the Patuxent watershed model. The model integrates knowledge about the physical, ecological and socio-economic subsystems on the watershed, and helps explain the interaction and feedbacks between individual variables and processes.

remote sensing and GIS data on changes in land use and management, and field monitoring measurements in both aquatic and terrestrial environments in a unique spatial modeling framework for broad applications linking science and policy. This allows simulation of detailed spatial dynamics of the Patuxent River watershed, including the interaction of the ecological and economic components (Bockstael *et al.*, 1995).

What makes a landscape scale model especially useful for the purposes of watershed management is that it integrates most of the knowledge available for the area in a comprehensive and systematic format (Figure 3). The extensive data collection and conceptualisation required within the framework of the modeling effort stimulates close contact with the environmental management community. The model also provides a conceptual basis for understanding the performance of the watershed as a system, which is especially important in identifying the gaps in our knowledge about the economic processes that drive the land use and land cover change in the area, the social factors that define the human activities and priorities, and the ecological foundation that provides natural resources and sinks for unwanted products.

The Patuxent modeling approach provides for a variety of spatial, temporal and structural scales over which the model performs. As a result we actually talk about a modeling hierarchy rather than a single simulation model. The ability to switch easily from one resolution to another is an important feature of our approach, one that gives much insight into the overall ecosystem dynamics and allows matching particular management problems with the correct level of detail and complexity.

For Patuxent watershed we identify two spatial scales at which to run the model—200 m and 1 km cell resolution. The 200 m resolution is more appropriate for capturing some of the ecological processes associated with land-use change, but may be too detailed and require too much computer processor time to perform the numerous model runs required for calibration, scenario evaluation and decision support. The 1 km resolution reduces the total number of model cells and makes multiple runs over longer time periods feasible.

Secondly, we identify a hierarchy of subwatersheds. The smaller subwatersheds (approximate 100 km^2) are used for initial calibration and model debugging. Even though additional tuning is usually required when going from one watershed size to another, still the amount of calibration needed is significantly lower. Moreover, these smaller subwatersheds occupy their specific niche in the hierarchy of watershed management. Regional concerns can be treated both on a local scale and within the framework of the whole watershed.

The temporal scale for landscape models of this type is very much defined by the resolution of the existing data sets. In most cases there is hardly any data measured more often than on a daily routine. Therefore 1 day is chosen as the basic time step for the model. Internally there are smaller time steps employed (e.g. some hydrologic processes are modeled on an hourly basis), but the input/output is handled on a daily basis. This sets certain limits to what the model can mimic. For example, flash flood events that occur on an hourly resolution and need climatic data at better than daily resolution are currently outside of the scope of the model. But they can be still considered at the smaller spatial scales of subwatersheds provided the input data exists.

Structural scale is the level of detail about the processes that the model represents. The modular and icon-based interface allows changes in the model structure, depending on the particular problems to be analysed. The existing, fairly detailed landscape representation is important for a better systemic view over the whole watershed and collection of data in a consistent and comprehensive fashion. Particular model implementations assume simplification of the overall scheme with modules plugged in and out and variables added and removed from the model structure. Additional modules and data can be easily added to the system, if needed to simulate specific conditions or serve particular management purposes.

Central to the approach developed is a General Ecosystem Model (GEM) (Fitz *et al.*, 1996) which is replicated in each of the cells that compose the landscape (Figure 4). A study area is divided into a grid of square cells linked to GIS files. The unit model simulates fundamental ecological processes with hydrology as its core. The hydrologic sector module of GEM, for example, simulates the availability of water and its movements, determining the hydrologic head of surface and ground water within each cell. Primary production, nutrient fluxes, organic/inorganic sediment suspension and deposition, basic 'consumer' dynamics and decomposition are also simulated. The GEM model is simulated for each cell with parameters unique for each ecosystem type. If land-use type changes due to external (human induced) or internal (ecological succession) factors, the parameter sets are changed as necessary.

The dynamics of various ecological processes are expressed as the interaction between state variables (stocks) and flows of material, energy and information. After the vertical or within-cell dynamics have been simulated, the results of the unit model are processed by the spatial modeling program. The model calculates the exchange of material between cells (horizontal fluxes) and simulates the resulting temporal changes in water availability, water quality and habitat/ecosystem type.

The ecosystem functions and the parameters of those functions that are simulated for any given cell in the landscape are dictated by the cells land use or habitat designation at the beginning of any simulation time step. Then, conditioned on that land use and the stocks of the state variables at that point in time in the cell, the processes and fluxes are calculated. Conceptually, there are two levels at which human behavior could be expected to affect the simulation. One is in the land-use designation of a cell; the other is in the nature of ecological processes that occur within a cell conditioned on its land use.

The models are constructed using the Spatial Modeling Environment (SME) (Maxwell and Costanza, 1995), which links icon-based modeling environments (such as Stella™) with distributed computing resources. It offers links to database (Postrgres) and GIS (GRASS) data structures. The Java-based SME graphic interface is used to run and configure the model; it is further used to output and analyse results. The interface has the ability to run SME simulations remotely through a network, and extends the SME functionality by providing user-definable data analysis and

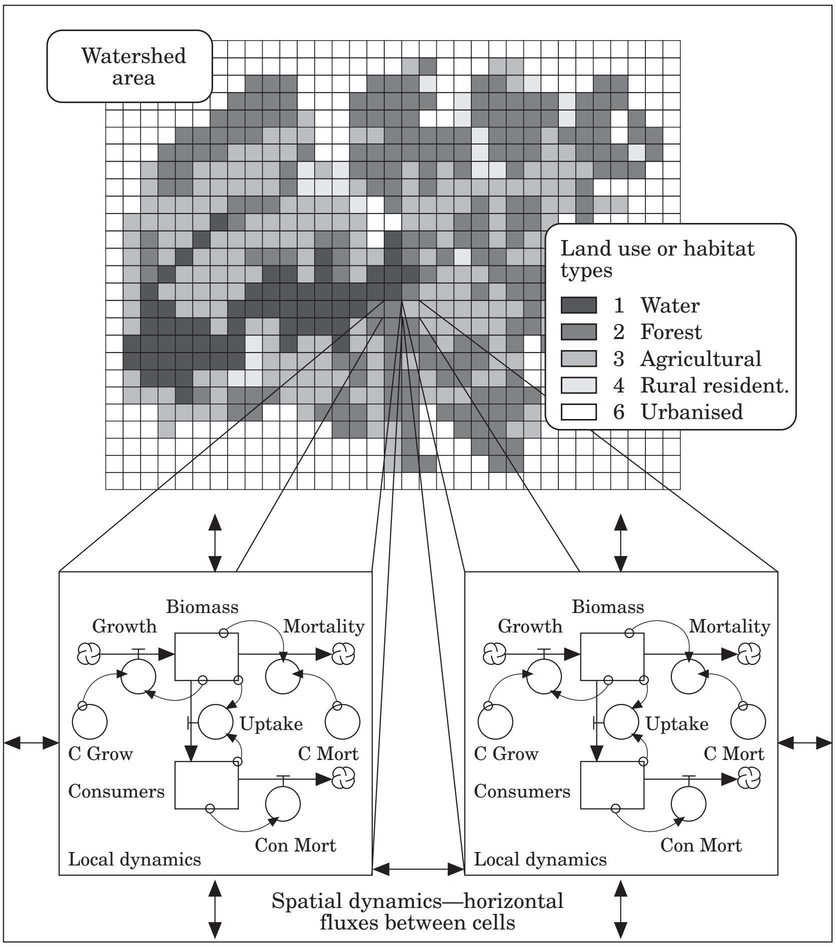

Figure 4. Spatial organisation of the Patuxent watershed model. For each cell of the rasterised landscape a unit ecological model represents local 'vertical' dynamics for variables shown in Figure 3. Different land-use cells have different sets of parameter values (growth rates, mortalities, uptake rates, etc.). Hydrologic fluxes link variables in cells horizontally across the landscape.

visualisation tools in addition to the more straightforward simulation control and data retrieval features.

There are three modes of model performance that are to be made available over the Web: batch runs, on-line runs and applets. The full PLM is considered a maximum model that tends to integrate all the knowledge available for the watershed system. Running it over the Web is cumbersome and time consuming. Therefore only limited scenarios are offered for web users. These are run in a batch mode when the server is not busy with other tasks. The user is notified by e-mail when his scenario is performed and results are made available over the Web. They are stored for only a limited time and usually translated into some integral characteristics. A library of performed scenarios is maintained, so that every newly formulated scenario is first checked against the set of previously performed scenarios and the available integral information is offered immediately.

Certain modules (submodels) of the full PLM require less computer capacities and can be run online. Such is the hydrologic module for subwatersheds of $\sim 100\,km^2$. Choosing among the set of subwatersheds, the user can identify the one he is interested in, and mimic the patterns of surface water runoff in response to the specified changes in climatic data, land-use patterns and soil characteristics. A model run for 1 year takes about 5 min; animations are made available at run time and charts that show the comparison of the generated output with the base scenario are displayed at the end of the model run.

Applets are created for even simpler jobs such as statistical evaluations for the already existing spatial and temporal data sets, both observed and simulated. These are transmitted to the users browser to do the simple data processing and interactive modeling that is needed. For example, an empirical erosion model can be presented as a Java applet and provided to test how erosion is defined by slope, soil properties, vegetation type, water flow, etc.

Data

The structure of the data sets that are offered over the Web for purposes of watershed management is another important part of the overall decision-making process. Providing data in a natural and accessible format can significantly facilitate understanding of socioeconomic and ecological interactions in the area and promote better interaction and consensus among the stakeholders. A hierarchical and structured design of data offers a standardised approach to watershed analysis and management.

We structure the watershed data along several dimensions. The choice of these dimensions is stipulated by three ongoing and interrelated processes:

1. data collection and acquisition;
2. data storage and processing;
3. data retrieval and use.

These three tasks have fairly different demands on the design of data sets. Requirements of task (1) are predominantly concerned with data input procedures and linkages to existing databases and archives. For task (2) we are mostly concerned with technical problems of data organisation in a database format, compressing, archiving and designing formats to link to models and analytical methods. Task (3) is closely related to classification problems that need to be solved to present the whole array of data in a user-friendly way, providing various search and query mechanisms to those who are looking for particular information and offering guidelines and hierarchically structured descriptions to those who need general information at a certain level of detail. Only a uniform approach to data structures can ensure that they will be internally consistent and complete. Feedback from tasks (2) and (3) can ensure that there will be no major gaps in the information field, while task (1) actually defines the extent of data available for the other stages.

Generally, a data unit is a spatial array (map) that evolves over time. This is the type of output that a spatially articulated model such as the PLM generates. Strictly speaking, this is the kind of data one needs to make decisions about regional spatial dynamics. However, the volume of these temporally evolving spatial data sets is immense and they are hardly appropriate both for storage and evaluation. In most cases the output data is characterised by information aggregated over space or time or over both space and time. As a result the more common data sets in the database are the spatial maps for the watershed, time series for variables measured at certain localities, or constants that represent rate coefficients or indices.

People

Within the framework of the project a series of policy dialogue workshops involving federal and state management agency and academic participants have been staged. The major goal was to both drive the research agenda and communicate results to major stakeholder groups. The workshops were instrumental in identifying the major stakeholders and their role in the watershed and in the decision-making process. We have identified the major stakeholders on the Patuxent web page and cross-referenced the various data sets and analytical tools that they could offer. A list of public organisations with vested interests in the watershed has been compiled and their URLs, when available, were added to the web site.

Two basic decision support tools have been implemented. One allows the user to initiate a discussion by providing some seed information describing the topic of interest. By submitting this information the user automatically creates an additional link to a new discussion page. Further comments are automatically added to the discussion and posted on the Web.

The other tool initiates a voting mechanism. A user can formulate a question that needs to be polled, and a new page is automatically generated which collects public opinion on the topic raised. The results are recorded in a database and may be viewed on the Web. Additional tools to generate statistical analysis of the results are under development.

Conclusions

After more than a year in which the Patuxent Watershed Management page has been on the Internet we can make one general conclusion: unfortunately the inertia among Web users is still quite considerable and the participation of the public is very limited. The reasons for this are threefold:

1. Web feedback and participation in the management process requires certain skills that are yet to be acquired by the stakeholders. The options offered are new and unfamiliar. There is little or no experience in online discussions, and the whole concept of web-facilitated consensus building needs to be well-explained and understood. There is also no proven history of success of decision-making over the Web with wide participation of the public.
2. Efforts to guide stakeholders towards the newly available web tools were inadequate. Commercial web sites are advertised and cross-referenced on a multitude of media outlets, increasing the number of visitors to their sites. No advertising has been undertaken for the web sites developed here. As a result the stakeholders in the watershed are hardly aware of the existence of the new tool.
3. For the Patuxent watershed in particular there is really no hot issue that needs a wide discussion among a multitude of stakeholders. There are no environmental controversies that would put jobs and the well-being of a significant body of citizens at risk. Therefore there is really no search for an outlet of opinions and no strong desire to become part of the decision-making process.

Nevertheless, we argue that the potential for web-facilitated decision-making and watershed management is great. The limited feedback that was generated, was unanimously positive and stressed the importance of further development of web-based decision support tools. More effort is needed in promoting the concept and tools among local and federal agencies. The benefits of public discussions and broad citizens participation that can be achieved through the Web are yet to be realised. It also remains unclear to what extent the modeling and other analytical tools need be made available to the public. The full Patuxent watershed model is clearly too complex for an average user to operate it efficiently and to interpret the results meaningfully. Further experiments with the model are underway to identify how the model can be simplified or aggregated in time, space and/or structure, and how it can be decomposed to separate units that can be better explained to the public and that are simpler to handle.

The terms ecosystem management and watershed management are somewhat misleading, because they seem to imply that humans can actually manage an ecosystem or a watershed. It should be noted that it is only the human-made systems that we can manage, and even with them the success is not always guaranteed. Ecosystem management in reality is still management of human made systems, by the humans, but with ecological factors taken into account. In most definitions (Lackey, 1998; Grumbine, 1994) the authors eventually conclude that ecosystem management is primarily about integrating theory and practice, science and people. In this process of integration value systems are refined and decisions are made over specific geographic areas and time periods. The success of ecosystem management depends on the efficacy of this link between science, which provides knowledge, and people, who make decisions based on their values, and who modify their values based on knowledge. The Internet offers a much-needed opportunity to deliver scientific findings and information directly to the stakeholders in an interactive fashion that provides for most of the needs of the watershed management concept. The benefits fall into two major categories—methodological and educational.

Methodologically this approach furthers the watershed management concept, providing an avenue for practical implementation of watershed management principles. The framework developed can be replicated for a variety of watersheds and ecoregions, serving as a hierarchical tool for multivariate decision-making. By involving a multitude of stakeholders in all stages of the decision-making process, we may attempt to endogenise the policy development, so instead of being imposed from the outside by certain parties and interest groups, it develops from within the group of stakeholders interactively exchanging knowledge, information and ideas, and collectively searching for solutions. It may take time for the public to become aware of the new advantages offered by the web decision-making. This may be seen as a new level of democratisation of the society, and time is needed for the public to perceive it.

The approach provides a wealth of data and insights for educational purposes at all levels, and serves as a tool for consensus building and public involvement. The system can incorporate various levels of complexity ranging from simple applications that can be useful as visual demonstrations in schools (MVHS, 1998) to sophisticated decision-making tools such as the full Patuxent Landscape Model, which can be instrumental in resolving controversies over ecosystem valuation and zoning.

By sharing the data and concepts over the Web potential users are invited to join in collaborative research and analysis of the future trends of watershed development. Their feedback is solicited for further dissemination and improvement of knowledge about the watershed system. The management and decision-making are disclosed to the public, offering a broad spectrum of views and values and inviting stakeholders to become participants in a truly democratic process of decision-making.

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References

Berdyaev, N. (1916). *The meaning of creativity*. Moscow.

Berdyaev, N. (1939). *About the servitude and human liberty*. Paris: YMCA Press.

Bockstael, N., Costanza, R., Strand, I., Boynton, W., Bell, K. and Wainger, L. (1995). Ecological economic modeling and valuation of ecosystems. *Ecological Economics* **141**, 143–159.

Costanza, R. and Greer, J. (1995). The Chesapeake Bay and its watershed: a model for sustainable ecosystem management. In (L. H. Gunderson, C. S. Holling and S. Light, eds), *Barriers and bridges to the renewal of ecosystems and institutions*. pp. 169–213. New York: Columbia University Press.

Dolley, M. (1999). Its Free, Baby. *Business 2.0* **3**, 75–78.

EPA (1997a). Designing an Information Management System for Watersheds. EPA841-R-97-005, Information Transfer Series. US, EPA. Available online at: http://www.epa.gov/owow/watershed/wacademy.htm

EPA (1997b). Statewide Watershed Management Facilitation. EPA841-R-97-011. Office of Water (4503F), pp. 58 US, EPA. Available online at: http://www.epa.gov/OWOW/watershed/wacademy/its08/index.html

EPA (1998). *The BASINS Version 2.0 Users Manual*. EPA-823-B-98-006.

Fitz, H. C., DeBellevue, E., Costanza, R., Boumans, R., Maxwell, T., Wainger, L. and Sklar, F. (1996). Development of a general ecosystem model for a range of scales and ecosystems. *Ecological Modelling* **88**, 263–295.

Fitzsimmons, A. K. (1994). *Federal ecosystem management: a 'train wreck' in the making*. Washington, DC: Cato Institute.

Gale, R. P. and Cordray, S. M. (1991). What should forests sustain? Eight answers. *Journal of Forestry* **89**, 31–36.

Gallant, A. L., Whittier, T. R., Larsen, D. P., Omernik, J. M. and Hughes, R. M. (1989). *Regionalization as a tool for managing environmental resources*. Corvallis, EPA/600/3-89/060.

Grumbine, E. (1990). Protecting biological diversity through the greater ecosystem concept. *Natural Areas* **10**, 114–120.

Grumbine, E. (1994). What is ecosystem management. *Conservation Biology* **8**, 27–38.

Lackey, R. (1997). If ecological risk assessment is the answer, what is the question? *Human and Ecological Risk Assessment* **3**, 921–928.

Lackey, R. (1998). The seven pillars of ecosystem management. *Landscape and Urban Planning* **40**, 21–30.

Maxwell, T. and Costanza, R. (1995). Distributed Modular Spatial Ecosystem Modelling. *International Journal of Computer Simulation: Special Issue on Advanced Simulation Methodologies* **5**, 247–262.

Montgomery, D. R., Grant, G. E. and Sullivan, K. (1995). Watershed analysis as a framework for implementing ecosystem management. *Water resources bulletin* **31**, 369–386.

MVHS (1998). Maryland Virtual High School Project. Available online at:http://mvhs1.mbhs.edu/mvhs.html

Norton, B. G. (1992). A New Paradigm of Environmental Management. In (R. Costanza, B. G. Norton and B. D. Haskell, eds), *Ecosystem Heath* pp. 23–41. Washington D.C.: Island Press.

NRMRL (1999). *Watershed Management as an Integrating Theme for NRMRL Risk-Management Research* White Paper. EPA NRMRL.

Omernik, J. (1987). Ecoregions of the conterminous United States. *Annals of the Association of American Geographers* **77**, 118–125.

Perciasepe, R. (1994). EPAs watershed approach to ecosystem management. *Fisheries* **19**, 4.

Slocombe, S. (1993). Implementing ecosystem-based management. *BioScience* **43**, 612–622.

Voinov, A. A. (1998). Paradoxes of sustainability. *Journal of General Biology (Zhurnal Obshei Biologii)* **59**, 209–218.

Voinov, A., Costanza, R., Wainger, L., Boumans, R., Villa, F., Maxwell, T. and Voinov, H. (1999). Patuxent landscape model: integrated ecological economic modeling of a watershed. *Journal of Ecosystem Modeling and Software* **14**, 473–491.