The ancient civilizations of Mesopotamia, in the Fertile Crescent made possible by the Tigris and Euphrates Rivers, were among the first cultures to explore the advantages and discover the costs of using watershed-based common pool resources (sensu Ostrom and Ostrom 1977). They produced bountiful crops with irrigation and plowing and in the process discovered water scarcity, salinization, and soil loss. In the generations since, access to water has been a key determinant in the evolution of human society. The cost has been that the cumulative impact of human use has altered Earth’s freshwater ecosystems profoundly, to a greater extent than terrestrial ecosystems (Vitousek et al. 1997).

Of all of the environmental security issues facing nations, an adequate supply of clean water is one of the most important. In developed economies, the water supply business has traditionally been very stable, but in the last two decades dramatic changes have occurred and supplies have become more difficult to obtain (Beard 1996). In developing economies, the task of providing adequate water supplies is almost overwhelming. Increases in resource demand rise directly with increases in population (fig. 13.1). Conflicts arising from the global use of water will be exacerbated in the years ahead, with a growing human population and the stresses that global changes will impose on water quality and availability.

Future management and optimization of water (and other common-pool resources) must emphasize demand management, efficiency improvements, and conservation. This will require increasingly sophisticated information on the functioning of the underlying physical and biological systems and how they are affected by socioeconomic and political institutions. Because these
resources are frequently distributed across multiple physical and political boundaries, it is imperative that a suitable paradigm be developed that can guide their more sustained use.

Hardin (1998) may have laid a foundation for that paradigm. He observed that “in the language of twentieth century commentators traditional thinking was magnificently verbal and deplorably non-numerate.” A consequence is that contemporary policy and laws are sparse on quantitative criteria with which complex trade-offs can be evaluated. Hardin continued, “One of today’s cardinal tasks is to marry the philosopher’s literate ethics with the scientist’s commitment to numerate analysis.” Such a marriage would produce what might be called a *numerate ethics*.

The underlying assumption for a numerate ethics is that, in the face of inevitable pressures on the environment, resources can be allocated and used with a higher degree of precision than is currently possible. Although it must be recognized that resource decisions will be made regardless of the depth of supporting information, the question here is whether a numerate ethics can rigorously contribute to that decision support process. A template allowing decision makers to consider rigorous scenarios of alternative futures could play an important role in making complex environmental decisions. Design of such a template will require a robust numerate analysis of the systematic dynamics of the landscape with sufficient detail to be relevant on a broad geographic
base. Contemporary earth system sciences, with their emerging capabilities in spatial and dynamic modeling coupled to such sophisticated observation systems as satellites, are now poised to provide the basis for numerate analysis. To bring ethics to the numerate analysis, the process must involve not only the scientists building the models but the policymakers and the citizenry of the region who use the analysis.

At least three problems must be resolved. The first is to understand and capture the characteristic dynamics and scales at which water moves across the landscape and into the ocean, under both intrinsic and human influences, into quantitative structures, or models, that can provide the basis for analysis. The second is to examine the key issues for a specific region (including recognition of the policy realities of cross-jurisdictional boundaries and ultimately politics at which resource decisions are typically made) and adapt the models to focus on these issues. The third problem is how to perceive and present the reality of the extremely complex information that would be derived through such a process. For another analysis of how water can be managed as a commons, see Schlager and Blomquist (chapter 6, this volume).

Capturing the Spatial and Temporal Dynamics of Watersheds

A watershed, as the landscape through which all waters flow from their highest source before draining naturally to the sea, can be considered a fundamental organizing unit of the land surface and its population (fig. 13.1). A watershed is defined by landforms, which do not necessarily correspond to political boundaries. Their edges are the ridges and hilltops that direct water into a stream or river, and their surfaces are the landscapes where communities grow. Rain or snow falls to the land surface. Some of this precipitation is returned to the atmosphere (through evapor-transpiration), some is stored in the soil (as soil moisture), and the balance drains into stream networks (where it provides river flow, or discharge). As streams descend, tributaries and groundwaters add to their volume, creating ever-larger rivers.

As rivers leave the highlands, they slow and start to meander and braid. In the lower stretches of unmanaged rivers, water moves between the river’s mainstream and its floodplain, modifying the flow regime and creating critical ecological niches. River and floodplain ecosystems are closely adapted to a river’s flooding cycle. The diversity of a river lies not only in the various types of land surfaces (or land uses) it flows through but also in the changing seasons and the differences between wet and dry years.

Disruption of the linkages between the landscape and rivers and between rivers and their floodplains through human intervention fundamentally alters the nature of riverine ecosystems. Waterways have always been, and will continue to be, used for irrigation, transport, flood control, industrial and domestic
consumption, and dilution of chemical wastes. The most disruptive influence on watersheds has been dams. Starting about fifty years ago, large dams were seen as a solution of water resource issues, including flood control, hydroelectric power generation, and irrigation. Now some 40,000 large dams obstruct the world's rivers. In the United States, only 2 percent of the rivers run unimpeded, and 5,500 large dams make it the second most dammed country in the world (Vitousek et al. 1997). But the time when large dams constitute a realistic answer to solving water problems probably is over.

The overall balance of energy over a watershed affects how water is partitioned between the atmosphere, soil, and river channel. Globally, human beings now use about a quarter of total terrestrial evapotranspiration and more than half of the runoff water that is fresh and reasonably accessible (with about 70 percent used in agriculture). Local or regional climate change may alter rainfall patterns. Irrigation increases atmospheric humidity in semiarid areas, often increasing precipitation and thunderstorm frequency. Changes in the landscape also have significant impact on watersheds and river flow. Converting a forest to a field or parking lot will change the flow pathways from rain to the river. Land transformation from forest to agriculture or pasture increases albedo and decreases surface roughness, which has the net regional effect of increasing temperature and decreasing precipitation.

**Intrinsic Spatial and Temporal Scales of Watersheds**

In terms of management, individual small stream segments are often the unit of concern to a local agency and are often observed by simply “walking the stream.” But the hydrosphere of that stream is determined by the larger watershed that stream is nested in, which probably has its headwaters in another county or even country. Impacts of land-use change on an entire river basin cannot be defined simply by summing up the impacts observed on individual streams; extrapolations based on scaling must be made. Overall, we must recognize the spatial and temporal relationships between dynamic ecosystems within river basins, where a landscape is composed of ever-changing elements, according to how the system is observed.

So what are the scales at which watersheds and their models can realistically be represented? Ultimately, this is a trade-off between how finely individual processes can be described, the data that are actually available, and the ability of computers to make calculations. Theoretically, there is a continuous range of scales represented in a watershed. In practice, the nature of how observations can even be made imposes some serious constraints. For example, an observer flying over a section of the Amazon floodplain will see a series of discrete and recognizable landscape patches, made up of streams, main river, pastures and forest, and open and closed lake environments (fig. 13.2). The
processes occurring in each patch can be readily be measured directly. A landscape of this scale can best be described by satellites of the LANDSAT Thematic Mapper (TM) type, which can “see” up to 180 km in extent. But the distinction of what can be observed is reduced to 30-m homogeneous patches (pixels) in fewer spectral bands than the eye itself will observe, resulting in a more blurred view of the landscape. When we move to larger scales yet, which is necessary to characterize regions, our ability to observe distinct features is degraded further. For example, the Advanced Very High Resolution Radiometer (AVHRR) satellite can “see” for hundreds of kilometers but with no better than 1-km pixels, in fewer bands yet. As a result, for example, the Rio Xingu in the Brazilian Amazon is barely distinguished, never mind details of the floodplain. In moving from the AVHRR-scale view to the global scale, pixels of 1° latitude/longitude (about 100 km on a side in low to midlatitudes) render large regions essentially uniform (for instance, Taiwan becomes 2 pixels). At these larger scales, specific objects in space are less important than the general “pulse” between longer temporal patterns and larger spatial extents. Time and magnitude of spatial variance are perhaps the most important variables at these scales. Issues of data aggregation and temporal phasing drive the modeling requirements.

The temporal scales of watersheds cover as much range as do the spatial
scales. Although the shape of the landscape itself (hills, valleys) will evolve (on geological time scales), these changes occur much more slowly than the seasonal and yearly evolution of the land cover and land use. These seasonal changes in turn occur much more slowly than a rainstorm, whose characteristic time scale is on the order of minutes to hours. The processes with which we are concerned, such as the translation of rainfall into runoff across different types of landscapes, are themselves described differently at different space scales. The overall ensemble of these landscape features, which we can observe at multiple scales, can be thought of as the physical template on which the more rapidly dynamic processes can operate.

**Toward a Spatially Explicit Model of the Landscape**

To bring this multiscaled physical template into a computational environment, the template can be thought of as being made up of a series of multiple elements (called grid cells or drainage basin elements), each of which has uniform attributes that can be characterized (fig. 13.3). These attributes (themselves spatial models) must include representations of the landscape that subsequent dynamic models require (such as the hydraulic properties of soil imparted by soil texture). A region is then made up of multiple grid cells, according to the resolution desired and what data it is feasible to acquire. The ensemble of these

*Figure 13.3. Schematic of the physical template basis for a geographic information system (GIS) representation of the land surface and climate.*
Chapter 13. Spatial Techniques for Understanding Commons Issues

Values can be represented in a computer format with which calculations can be made. The emergence of geographic information system (GIS) computer software allows such an organization of information.

The physical template is more than a GIS database of thematic layers. It is the explicit geographically referenced statement of the relationship between these data layers over both space and time. The template captures the multiplicity of time and space scales over which the watershed environment changes and to which humans must respond. The template is restricted, of course, to the data available to describe it.

Within the template, the slowly changing elements of the landscape (topography, river networks, soil texture) can be derived and left alone because they change much less frequently than the more dynamic components of the system. Land cover and land use (often determined through satellite imagery) may need to be updated on their characteristic time scale of seasonal to annual (depending on the objective). The next level of temporal resolution is that of changes in rainfall, solar radiation, humidity, and surface winds, which are the inputs (biophysical drivers) for the dynamic models themselves.

Dynamic Models of Basin Processes

With a physical template specified, models of dynamic processes of the environment, from the atmosphere to the land surface to marine circulation and productivity, can be developed, coupled, and used to evaluate resource issues. Models consist of the scientific theory of physical processes affecting a region, embodied in a computer program. While imperfect and at risk for misuse and misinterpretation, such models do summarize the cumulative understanding of a problem in ways that can be tested.

Contemporary models of land surface processes can be divided into several major components (fig. 13.4). As can be represented in a regional-scale climate model, the atmosphere's climate communicates with the land surface by distributing rainfall, temperature, and wind. A vertical component calculates the water balance of a grid cell. The water balance model is applied at each individual grid cell over the defined region and separates precipitation into evapotranspiration (a calculation that requires knowing solar radiation, temperature, and ideally surface winds), soil moisture change (a calculation that requires information about soil texture and how much water reaches the soil surface, after being intercepted by the tree canopy), and runoff from the land surface to streams. The actual rates at which these processes occur fundamentally depend on such attributes as soil texture, rooting depth, slope, and other physical characteristics, which must be described for each cell.

A horizontal component then takes the runoff generated by each grid cell
(as the surplus from the tipping bucket) and routes it (transports it) downstream. The combined surface and subsurface flow generated at each individual grid cell is routed to the stream network according to, for example, assumptions about how long the water should take to reach the nearest stream. Once the water enters the stream reach, it is routed to the ocean through the stream network (represented by the stick diagram). Downstream discharge is then compared (but not calibrated) against observed data from stream-gauging stations. Water storage in reservoirs, and withdrawals from reservoir and channel reaches, can be included in routing models. Water for irrigation can be withdrawn from the appropriate reach or reservoir and added to the grid cell as throughfall.

Application of a Numerate Ethics to a Specific Region: The Puget Sound Basin of Washington State

For a numerate ethics to be relevant to a specific region, such issues as the following must be addressed:

- What is important to the region?
- What is required of an integrated modeling system to provide decision support at the scales required by managers and decision makers?
- What are the trade-offs between those requirements and information availability?
As a test case, the general framework sketched out in the previous section will be applied to the Puget Sound basin (Pacific Northwest, USA). The application is based on the PRJSM (Puget Sound Regional Synthesis Model) project. The central metaphor for capturing the interactive and dynamic knowledge bases and the issues of the region is via the creation and execution of a “virtual Puget Sound.”

The Region: Its Issues and Jurisdictions

The Pacific Northwest is a region of extreme contrasts in physical geography, land use, and rainfall. Water is the unifying theme across most sectors of the Pacific Northwest economy and culture, from the traditionally important sectors—forestry, fisheries, agriculture, energy—to the recreation and quality-of-life issues that have become central to the explosively growing non-resource-based sectors. Salmon are not only an icon of the region but a reminder of how integrally linked climate, land surface processes, and the oceans are.

The most populated sector of the Pacific Northwest is the Puget Sound basin, a region of about 30,000 km², with a classic partitioning of multiple jurisdictions crossing drainage basin boundaries (fig. 13.5). There are eleven

Figure 13.5. Puget Sound basins overlapped with county boundaries.
primary river basins divided among eight counties, which in turn are made up of numerous municipalities, which themselves fall under state and federal government. These governing bodies are then responsible for enforcing a set of laws and regulations with regional consequences.

Stewardship of this region poses a series of interrelated questions, typical of those raised in many other regions, which must be confronted by current and future managers:

- What are the responses of the land surface to changes induced by urban pressures and overall population growth and from climate variability on seasonal to interannual and decade time scales?
- What impacts are discernible with respect to freshwater and marine water quality, agriculture, forestry, fisheries, and coastal erosion and hazards, and what management capacities and policy response strategies are needed?
- How can water resources best be accommodated to meet flow needs for agriculture, endangered species of salmon, and domestic and industrial consumption?

Under the Washington Growth Management Act (GMA) of 1990–1991, most of the state’s counties and their constituent municipalities are required to do comprehensive land-use planning for management of urban growth and protection of prime natural resource lands and environmentally critical areas. The GMA also requires monitoring of growth, including the spatial and temporal concurrency of urban growth and infrastructure improvements. These monitoring requirements have been among the most difficult for local and regional governments to accomplish.

Responsibilities for water resource planning and management are divided. User agencies include the Washington State departments of ecology, natural resources, and fish and wildlife, with their mandates for basinwide water resource planning, administration of water permits, and protection of instream flows. At a regional level, the Puget Sound Water Quality Action Team is responsible for implementing the Puget Sound Water Quality Management Plan and the federally approved Comprehensive Conservation and Management Plan under Section 320 (the National Estuary Program) of the Clean Water Act. The plan identifies activities for implementation at the local government level. Local government agencies include the Tri-County (King, Pierce, and Snohomish) coordination for salmon recovery, the Hood Canal Coordinating Council, and planning offices of the twelve basinwide counties.

The joint growth and water resource issues are accentuated with the listing of chinook salmon as threatened under the Endangered Species Act (ESA). This will require significant changes in urban development, pollution control, forestry, farming, and fishing activities, with major implications for resource management and land-use planning throughout much of the Pacific.
Northwest. Listing species under the ESA will increase information requirements, including the need for monitoring forest and agricultural practices, urban growth, and land-cover or land-use change. Players in the ESA arena are many, including the U.S. Fish and Wildlife; NOAA/National Marine Fisheries Service; Washington departments of natural resources, fish and wildlife, and agriculture, local governments throughout the region; and habitat restoration groups.

A Virtual Puget Sound: A High-Resolution Integrated Model

The virtual Puget Sound (VPS) centers on coupling dynamic ecosystem simulation models with models of human behavior and socioeconomic forecast (fig. 13.6). Each model performs its own predictions based on its own input data. The time and space scales of each submodel then provide, essentially by definition, what the relevant and feasible space and time scales of each set of processes are.

The base physical template on which the VPS is built consists of layers of different temporal resolution (fig. 13.7). Digital elevation data, from which river networks are derived, change only on geological time scales. Soils and their attributes are then distributed across the elevation models. River networks are set by the elevation but may wander on decade time scales (particularly with human intervention). Vegetation may respond on an annual basis (as well as seasonal cycles), and is represented through LANDSAT time series data (e.g., fig. 13.2). With the template in place, the more dynamic properties of how water and energy are transferred from the atmosphere to the land surface and across the land surface can be represented. This template is also being

*Figure 13.6. Linked models of the virtual Puget Sound.*
Figure 13.7. The physical template basis for the virtual Puget Sound, illustrated here for the Snoqualmie River basin.

shared with regional agencies as the most complete land-cover source in the region for purposes ranging from habitat inventories to assessing extent of impervious surfaces for calculating taxes.

Meteorological forcing for the surface hydrology model is provided by a so-called mesoscale atmospheric model (the MM5), designed to predict regional-scale atmospheric circulations and surface exchanges. The MM5 produces 48-hr weather forecasts at 12-km spatial resolution for the entire Pacific Northwest and at 4-km resolution over Washington state (e.g., fig. 13.8). This model is initialized using both observations (satellite and in situ) and large-scale output from National Weather Service models. Model outputs are being used in regional weather forecasting. Past “climates” will be assembled and used as the basis for seasonal to annual climate alternatives for water resource models and for global change assessment.

Finer-scale surface water movement is represented via the Distributed Hydrology-Soil-Vegetation Model (DHSVM), a physically based, spatially distributed hydrologic model that explicitly solves the water-and-energy balance over a topographic grid with cells typically 30–200 m in dimension. A hydrological model routes the output of this spatially explicit data through a model landscape generated by a three-dimensional land-surface, elevation, and river network, and the output arrives at the coastal interface in the form of estimated volumes of water and chemical constituents. DHSVM uses as inputs spatial image data and meteorological forcings from the MM5 (e.g., fig. 13.9).
Immediate output from the model is starting to be used for flood forecasting and for generating in-stream flow alternatives for salmon.

This hydrology process model is then linked to a water resource model (CRYSTAL) predicting the availability and potential uses of water in Puget Sound (fig. 13.10). This model integrates the separate water supply systems to better use existing regional resources by viewing Puget Sound as a single watershed. The goal of the model is to illustrate the value and opportunities of a regional approach to water management, particularly in meeting the needs of both fish and people. Answering this challenge is becoming increasingly important as in-stream requirements are modified to address the impending salmon listing under the ESA. The model simulates water system response to different scenarios (e.g., “How will increased flow requirements for the salmon affect the reliability of the urban water supply? When might water use curtail-

Figure 13.9. Application of the DHVSM (D. Lettenmaier, pers. comm.) to a snowstorm in the Snoqualmie River basin, followed by rapid melting and rapid river rise.
Figure 13.10. The CRYSTAL water resources model (R. Palmer, pers. comm.) for allocating water between the principal utility districts of Seattle, Tacoma, and Everett.

ments be necessary? Can water in one basin be used to support fish production in another?""). With such tools, regional decision makers and the public can better understand the consequences of important policy and infrastructure decisions.

Changes in the land surface affect nearshore marine waters. Increasing sediment flow, altered flow regimes of rivers, and nonpoint source runoff from agricultural areas affect shellfish beds. Effluent from treatment plants can affect plankton communities. A numerical ocean circulation model (the Princeton Ocean Model, or POM), used extensively by coastal and estuarine researchers, captures the circulation of Puget Sound. The model, simulating Puget Sound
circulation and stratification for a model year, is forced by realistic tides and river flows from the hydrology model (fig. 13.11). An immediate application for the model is assessing the best location for a proposed major sewage treatment plant.

The coupled model is driven by not only the biophysical system dynamics but by explicit links to human alteration of the land surface by projecting environmental pressures of urbanization under various management practices. These human pressures are reflected in the state of land cover, air and water quality, and application of management programs in forestry, agriculture, and fisheries. At various time steps, a variety of feedback loops in the coupled model simulates socioeconomic responses to environmental changes and predicts the dynamics of the altered landscape (fig. 13.12).

The aggregate of the specific submodels, each of which addresses its own specific issues, is the value added by an interdisciplinary synthesis that provides the basis for a regional numerate ethics.

Numerate Literacy: End-to-End Information Networking and Visualization

The virtual Puget Sound raises some difficult technical issues. Modern society is increasingly confronted, if not characterized, by requirements to generate, process, and, it is hoped, understand high volumes of digital information representing extremely complex phenomena. Determining the overall sequence of acquisition, processing, use, and communication of such information is a fundamental challenge for a new generation of managers.
Data Management

How to solve the information management and computational issues of linking such complicated models and observations and then making the products accessible to a wide variety of users constitutes a significant challenge in information technology (fig. 13.13). There are approximately 6 million grid cells across the Puget Sound domain, with thirty-eight levels of atmosphere, three layers of soil, and thirty-two layers of marine environment, on which dynamical calculations are performed. The data, even for one specific submodel, come in many different formats and resolutions: spatially, from cm (rarely) to 10 m (often) to ~1 km (common); temporally, from every second to once per year or less. Adding to the problems, data come from many sources. This produces more possible variations of collected data, processed forms of collected data, transformed submodel outputs, and hypothetical data constructed by users who want to see how some process works or to test a hypothesis. The challenge is to efficiently store and analyze data from multiple data sources in metadata-referenced mass storage and knowledge bases.

The Visual Interface

Such complex information must be conveyed to multiple parties, from the student and the scientist involved in developing the information systems to the
end user making decisions (fig. 13.14). Recent advances in visualization technology combined with the dramatic increase in computer communication, including the World Wide Web, are making this possible. For example, the virtual Puget Sound is being brought to life by the wrapping of linked models with a visual interface, creating a user-friendly, interactive virtual environment. This resource can then be made available to many different types of users via the Internet. Interface development will include Web-based tools to access database structures, create interactive visualizations, and extract customized information from the models and data.

**Toward a Sustainable Future**

Water is one of the foremost examples of a common-pool resource in which sustainability cannot be accomplished by individuals acting out of self-interest alone; there must be intergenerational commons institutions to ensure sustainability. The vitality of watersheds is the result of all the day-to-day decisions of their inhabitants. How to do it? We can indeed generalize from one scale to the next. The new generation of earth system science provides necessary capabilities for addressing cross-scale issues in a quantitative way, which can allow improved capabilities to provide scenarios of future
outcomes. But these capabilities alone are not sufficient. Other requirements also must be met.

*Tools for systematic synthesis of information leading to a coherent information base that can be applied to regional evaluation must be developed.* A large amount of data is available in many regions, but there are few synthesis tools to bring it together. To sustain a numerate ethics, there must be a systematic identification of what information is needed, where it is, and how it must be brought together.

*A predicative capability and scenario generation across multiple time and space scales is necessary.* Though critical, synthesized information alone is not sufficient. The capability to use such information to evaluate resource and policy options is critical. This must be done with models and should include economic values and benefit/cost ratios for managers at levels of evaluating specific actions. As an end product, building a scaled modeling environment that addresses cumulative effects and allows adaptive management is being increasingly called for.

*A process for communication between scientists of different disciplines (the model developers) and especially between scientists and policy makers must be established.* Bringing together information from multiple sources, analyzing it with models, and ultimately conveying it not only to other scientists but also to policymakers are not trivial or common tasks. They require an explicit commitment to the process of communication and display. Solutions involving building the capacity of interdisciplinary scientists (including recruiting young scientists trained in the tools of synthesis), developing means for communication, and
Targeting how to involve policymakers in the process must be proactively sought. Technical issues of information transfer and visualization must be incorporated into the process.

Hardin (1998) concludes that the tragedy of the commons is well tailored for contemporary resource issues, as expedited by interdisciplinary synthesis. But the difficulties should not be underestimated: "The more specialties we try to stitch together, the greater are our opportunities for mistakes, and the more numerous are willing critics." Large teams of specialists have had considerable difficulty communicating the causes and long-term implications to each other, let alone to the general public. The melding of contemporary earth science tools specifically focused on legally mandated resource issues has enormous potential to effect a managed commons. Numerate literacy, executed by the interdisciplinary capabilities of today's science community and mediated by social and political scientists and practitioners, empowers the viable commons of tomorrow.

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