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LANDSCAPE HYDROLOGY, A COMPONENT OF LANDSCAPE ECOLOGY

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ABSTRACT

A landscape is a three-dimensional mosaic of interacting environmental components or zones. Landscape hydrology—the movement and storage of water in landscapes—deserves to be seen in a broad view of environmental relationships. A framework is presented to make landscape patterns and environmental relationships comprehensible and manageable. It organizes the types of hydrologic components that exist in landscapes, the fluxes among them, and their implications for mankind's management of water and of the environment in general.

The water balance summarizes the fluxes of water through a land area. Within a landscape, different types of flows and storages occur in a series of layers or mantles. The dominant types of hydrologic structures and processes in different landscapes can be compared by relating the topography and permeability of the various mantles to the drainage base level. Artificial water supplies and dispositions amount to diversions into and out of the environmental mantles. Water management enables water to be used or disposed by stimulating the mantles to produce altered levels of water quantity, quality, time and place.

A unified concept of landscape hydrology, reflecting the interaction of environmental mantles, allows recognition of the implications of human management of water and landscape. Ecosystemic cycles are armatures on which to build future land and resource uses. Preservation of the hydrologic equilibrium in landscapes ought to be one of the objectives of resource use.

If the term ecology is used in its broadest sense to mean the totality of earth systems with all their biophysical interactions, then landscape ecology, at its broadest and most useful, is a convergence or synthesis of a range of natural sciences that interact in a geographic area. Hydrology is certainly one of those natural sciences. Hydrology interacts with other components such as air, nutrients,

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soil and biota to form landscape patterns with all their implications for habitat and sustainability.

Water has particular relevance in its direct relationship to man. The flux of water required to support modern cities is much greater than that of any other substance [1]. People manage water at all geographic scales for irrigation, flood control, industrial processes, cooling, hydropower, navigation, aquaculture, insect control, recreation, aesthetics, wastewater disposal, assimilation of pollutants, and control of soil salinization and subsidence. As a resource, water is limited in renewability and degradable in quality. It is part of the natural constraints upon economic development and quality of human life.

Landscape hydrology—the movement and storage of water in landscapes—deserves to be seen in a broad view of environmental relationships. Water has for too long been abused as a discrete substance that can be segregated from its environmental context and managed in isolation from the landscapes that spawned it and which it in turn sustains. One need not look exclusively at a stream, or an aquifer, or an irrigation head to think of water. In every environment from salt pan to mesic forest, from icefield to concrete city, hydrology interacts with every organism, every soil constituent and every tangible human activity in the landscape column.

To construct such a broad view, disparate pieces of hydrology need to be absorbed into a coherent framework where the continuity of hydrologic flows can be followed through landscapes. That hydrologic science has suffered from fragmentation of disciplinary approach is a familiar complaint [2, 3]. Too often such professionals as foresters, geologists, climatologists or engineers have studied water-related facets only of their home disciplines. The continuous, global circulation of water transcends boundaries of traditionally defined disciplines as easily as it does political boundaries. Scientists and designers who wish to work with the full complexity and relevance of hydrologic flows in the environment cannot rely on any one of the separate hydrologic disciplines, or any mere combination of them, to organize their thinking. They need a concept of landscape hydrology encompassing the full complexity of flows in landscapes while retaining an overview of how those flows fit together.

This article provides such a framework. It is an attempt to organize hydrologic information in such a way as to make landscape patterns and environmental relationships comprehensible and manageable. It examines the types of hydrologic components that exist in landscapes, the fluxes among them, and their implications for mankind's management of water and of the environment in general.

COMPONENTS OF LANDSCAPE HYDROLOGY

A landscape is a three-dimensional mosaic of interacting environmental compartments or zones. A specified locale can be considered, at a variety of scales in space, as a coherent entity where structure, function and development can be delineated.

The water balance is the simplest and most comprehensive expression we have for summarizing the fluxes of water through a land area. It describes the balance between all the inflows and all the outflows of water in a land area over a period of time [4]. Hence it is a fundamental unifying theme in landscape hydrology, organizing our thinking about how a landscape transfers and transforms hydrologic throughflows.

The water balance applies the principle of mass conservation by saying that any difference between a landscape's inflow and outflow is taken up by a change in storage. If the landscape being considered is a drainage basin, where it is assumed that there are no hidden flows of groundwater or artificial transfers into or out of the basin, and errors of measurement are disregarded, the area's water balance can be expressed in the following simple form:

$$\text{Precipitation} = \text{Evapotranspiration} + \text{Runoff} + \Delta\text{Storage}$$

In this formulation, precipitation inflow is transformed into evapotranspiration and runoff outflows. Drainage basin storage occurs in some combination of surface, soil, groundwater and other compartments.

In many landscapes the simplifying assumptions of the above equation do not apply, and there may be many additional inflows and outflows, but the same principle of balance always holds. A balance can be constructed for any land area, no matter how arbitrarily the boundaries may be drawn, and to any selected time period or design condition. The water balance is the site-specific expression of the hydrologic cycle, in which water circulates on a global scale from land, to ocean, to atmosphere, and back to land, with temporary increase or decrease in storage balancing any difference between one end of the cycle and another.

The water balance offers insight to broader environmental processes. It integrates effective energy and moisture endowments to an ecosystem. It is analogous to and linked with nutrient budgets, where water is a powerful solute, and energy budgets, where water has high latent heat. Places with similar water balances bear similar life forms [5] and have similar levels of biotic productivity [6].

Within the simple overview of inflows and outflows presented by the water balance, water can follow myriad paths within a landscape. Some precipitation becomes runoff, while some infiltrates the soil and becomes available to plants. Some water is stored for a while in the soil, while some seeps down to groundwater. Some subsurface water reemerges to the surface. Some water is artificially diverted to cultural water supplies, to be discharged later as wastewater.

A way to break down the overall water balance into component parts in such a way as to express the full range and relevance of a landscape's internal processes, while continuing to make the hydrologic patterns comprehensible and tractable, is shown in Figure 1. The hydrologic landscape can be thought of as a series of

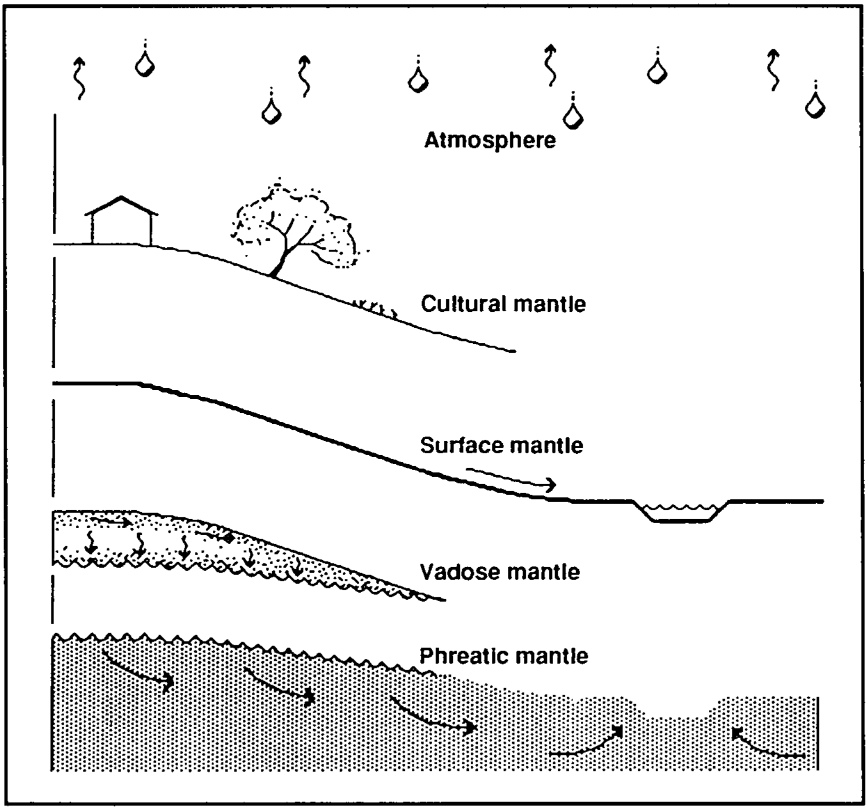

Figure 1. Five hydrologic mantles.

mantles or layers where different types of hydrologic flows and storages occur [7]. The atmospheric mantle includes fluxes of water vapor across, to and from the land surface. The surface mantle includes overland flows and surface water bodies; it involves urban flooding, aquatic habitat, aesthetics, recreation, hydropower, soil erosion, and surface water quantity and quality for cultural intakes. The vadose mantle includes soil moisture either being stored in soil voids or in transit toward groundwater, plant roots, or back to the surface; it is characterized by capillary tension and involves support of plant growth and stream base flow. The phreatic mantle includes water in any subsurface saturated zone, either being stored or in transit toward wells, deeper aquifers, or back to the surface; it is characterized by hydraulic pressure and involves subsurface quantity and quality for cultural intake, water table constraints on construction and farming, and support of stream base flow. The cultural mantle includes artificial diversions of water for human use, the consumption of water by growing crops, and the

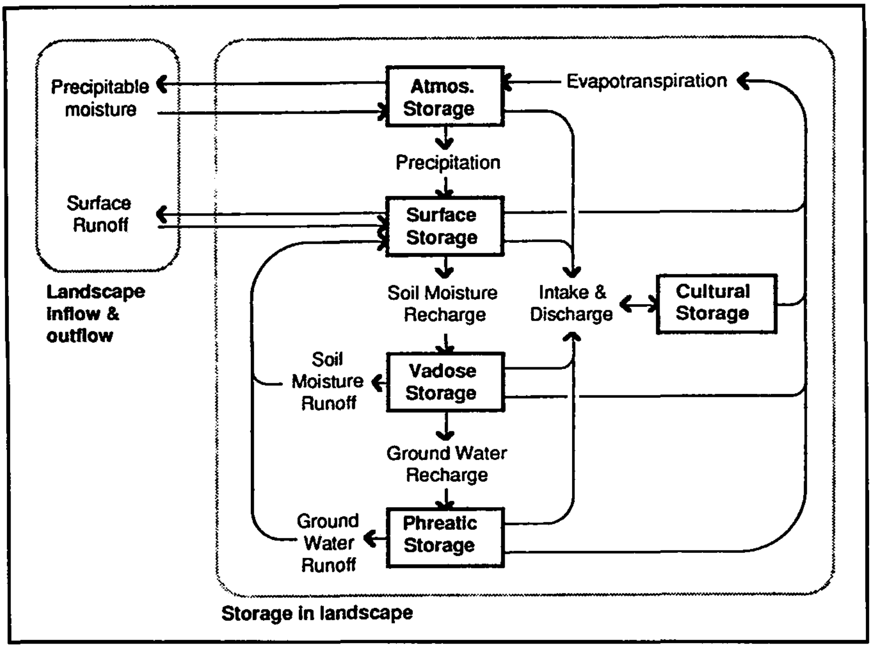

Figure 2. Interactions among landscape hydrologic mantles. Atmos., atmosphere.

disposition and recycling of wastewater; it is characterized by confined tanks and channels.

Each mantle has, directly or indirectly, imports from and exports to all the other mantles, and acts as a reservoir to take up any difference between them. A separate water balance can be constructed for each mantle, using terms corresponding functionally to those of the overall water balance: inflow, outflow and change in storage. The sum of all the mantles' balances equals the water balance of the whole area. In Figure 2 the mantles are arranged symbolically to bring out the hydrologic connections among them and their cumulation to overall landscape inflow and outflow. Through these connections, any change in throughflow in one mantle tends to ripple through the others and into the overall water balance [8].

VARIATIONS AMONG LANDSCAPES

That the hydrologic structure and function of landscapes vary from place to place is familiar. Some lands contain groundwater, others do not. Some lands contain significant soil moisture, others do not. Some lands have a water surplus, others do not. Some lands are the recipients of flows from elsewhere in the landscape.

One systematic way to compare the dominant types of hydrologic structures and processes in landscapes is by the landform's relationship to a local drainage base level [9]. The base level is marked by the groundwater table where one exists and elsewhere by the elevations of major streams. Its elevation changes from place to place due to stream and groundwater table gradients, so it is reasonable to think of it as a gently undulating plane.

Positive landforms, which rise above the drainage level, can be distinguished from negative ones, at or below the base level. The distinction between positive and negative environments is made strictly in relation to the drainage base level, not to other nearby landforms—for instance, although limestone tends to form topographic valleys or depressions relative to nearby shale hills or sandstone mountains, it is still hydrologically elevated and positive relative to the streams and groundwater tables that drain it. In Figure 1, the left side of the illustration shows a positive landform; the right side is negative.

In a negative landform water moves inward to the landform, possibly collecting flows from a large tributary region. Negative landforms are characteristically formed by recent fluvial processes. Examples are floodplains and all types of wetlands. They lace through all regions, collecting the runoff from adjacent positive landforms and often conveying it down regional drainage gradients. They are the only landforms with regularly occurring surface flows and storages. Vadose flows and storages are relatively insignificant; essentially all subsurface flow is saturated.

Water in a positive landform moves outward from the landform. Among positive landforms, three subtypes are easily recognized [9]:

1. **Water infiltrators** are entirely formed of permeable materials, including permeable bedrock (or its unconsolidated equivalent), with or without a significant mantle of soil. Examples are sandstone, carbonates, and most unconsolidated materials above the drainage base level. Infiltrating water is potentially able to reach a groundwater table, after being stored in and flowing through a significant vadose zone. These landforms can be the recharge areas of regional aquifers.

2. **Water spreaders** are formed of essentially impermeable materials throughout their depth, including impermeable bedrock with little overlying soil. Examples are many occurrences of shale and slate, and most occurrences of granite. They are familiar in arid regions, where soils may be shallow to absent. Drainage is mostly by surface runoff; infiltration and subsurface storages and flows are small.

3. **An intermediate type of landform** has impermeable, water-spreading bedrock, but a significant mantle of permeable soil. An example is the combination of crystalline rock and thick overlying saprolite, all above the drainage base level, in the southern Piedmont. Water infiltrates the soil, but seldom settles into a

significant mass of groundwater. By default, vadose moisture dominates subsurface storages and flows.

Landscapes that mix characteristics of permeability and impermeability, and even positive and negative hydrologic functions, occur. Many such environments are glacial in origin, because glaciation tends to disrupt drainage patterns and the sorting of earth materials. Another hybrid subtype is a dissected sedimentary plateau, where many layers of materials, permeable and impermeable, may be stacked between the drainage base level and the land surface. Still other kinds are anthropogenic: urban land cover might lead to a landscape with an impermeable surface, underlain by a permeable soil mantle, underlain in turn by impermeable bedrock, all above the drainage base level.

As suggested by the overall water balance, the most ubiquitous forces that drive the movement of water through a landscape are climatic: precipitation originates flows and storages, and evapotranspiration short-circuits the transformation into runoff. The difference between precipitation (P) and evapotranspiration (Et) is a landscape's water surplus if P exceeds Et, or deficit if P is less. Some of the hydrologic differences between regions with long-term water deficits and surpluses are soil moisture process (evaporation and accumulation of salts vs. leaching and groundwater recharge), soil depth, vegetation type, drainage integration (playa lakes vs. integrated stream systems), quality of ground and surface waters, annual runoff, potential for local water supplies, and potential for increasing crop growth by irrigation. Hydroclimatic distinctions exist at both regional and local scales: local differences in radiation and temperature with slope orientation and position lead directly to differences in Et and the water surplus, commonly manifested in different natural vegetation types. The hydroclimatic surplus or deficit can be altered by management: in a given location, any land or resource use is associated with some level of Et, so different uses lead to different balances between precipitation and evapotranspiration.

The flows in many local landscapes are connected to those in regional rivers, which then supplement and link the flows among many local landforms. Runoff records reflect the different degrees of surface runoff and subsurface storage of the landforms they drain [9]. Some rivers also put water into landforms, such as those that seasonally recharge shallow aquifers in the southeastern Coastal Plain. Artificial river intakes and outfalls accelerate connections among landscapes.

Like rivers, aquifers drain water out of landforms. Landforms overlying a shallow (unconfined) aquifer discharge into the aquifer during times of water surplus. As the water in a shallow aquifer moves laterally through the bases of similar landforms, the outfall from one landform becomes the inflow into another, as in the sand hills of Nebraska. A groundwater-supplied wetland can form where the topography dips low enough. Confined aquifers are distinct from shallow ones: they are in materials hydrologically segregated from those at the surface, and may underlie many surface landscapes at once. When an aquifer is artificially pumped or injected, the outflow from the outcrop area becomes the inflow to new landscapes.

WATER MANAGEMENT

Water management comprises all the great variety of steps that enable water to be used for given purposes, in given amounts, and in given times and places, or to be disposed afterward [10]. The demands that beneficiaries may require of water, and therefore of water management, can be described in fundamental terms of quantity, quality, time and place (perhaps energy is a fifth fundamental characteristic of water). Management of water before use enables water to be used by converting its characteristics in nature to those it will have during use. Management after use gives water characteristics necessary for desired types of discharge.

Artificial water supplies and dispositions amount to diversions into and out of the environmental mantles. Each of the mantles produces flows and storages which can be described in terms of quantity, quality, time and place, and which might be useful to human society at the levels at which they are found in nature. In Table 1 are listed the ranges of quantity, quality, time and place that are commonly found in unaltered nature.

The environmental mantles can be induced to produce altered levels of quantity, quality, time and place. Consider, for example, a stream valley. A natural stream characteristically has little storage volume or duration, so its flow fluctuates widely in response to weather in its watershed. However, a stream has a potential capacity for storage, fixed by the overall topography of its valley. When a dam is built across the valley the stream's storage volume and duration are enlarged; stream flows are relatively stabilized, with likely consequences for downstream ecosystems and human societies. The artificial dam by itself has no storage capacity; the dam's role is to induce the natural valley to fulfill more of its potential for storage. A dam is the final wall of a reservoir which had been partially shaped by the preexisting valley walls. The reservoir is neither entirely natural nor entirely man-made. It is an integrated system, encompassing dam and valley together. The qualitative types of flows and storages in a dammed valley are the same as under natural conditions, but their quantitative rates have been modified.

The same type of thing happens when man irrigates a soil, recharges an aquifer, erects snowfences, treats sewage, constructs impervious land covers, diverts floods or manages water in many other possible ways, advertent and inadvertent. Man's water and land management technologies provide stimuli, to which the mantles of the environment respond according to their native properties. The mantles' responses are governed by such principles as the saturation vapor-pressure relationship in the atmosphere, the Manning and stage-storage-discharge relationships in the surface mantle, and the Darcy relationship and cation

Table 1. Measures of Hydrologic Characteristics Typically Found in the Unaltered Environment.

	Atmosphere	Surface Mantle[a]	Vadose Mantle	Phreatic Mantle	Cultural Mantle[a]
Quantity	Precipitation 1 to >10,000 mm/yr; evaporation 0 to >3,500 mm/yr	Streamflow <10 to >2,000 mm/yr	Specific yield 2 to 45% by volume	Specific yield 2 to 45% by volume	1 to 0.5 cu.m/cap/day
Quality (ppm)	Precipitation about 3 salt; Evaporation 0	Streamflow <500 to >2,000 TDS; Seawater 35,000 salt	0 to >30,000 salt	300 to 30,000 salt	Domestic supply 20 to 500 TDS; Domestic sewage 100 to 500 TDS
Time:					
Occurrence (day/year)	Precipitation <20 to 300	Streamflow 0 to 365	Flow 1 to >300	Flow 1 to >300	Flow 365
Average residence time (days)	10	Streamflow <10	About 70	About 200	1-3
Place:					
Occurrence (% of land area)	>99	Ordered streams 1; wetlands about 10	Unsaturated soil about 85	Significant groundwater about 75	About 5
Travel distance (km)	10-20,000	<5,000	<0.5	<1,000	<700

[a] TDS = Total Dissolved Solids

exchange capacity in the vadose and phreatic mantles. Each relationship measures the rate of response of a mantle to various types of loads or stimuli placed upon it.

In a complex region many actors may be involved in completing management sequences, with different public or private agencies involved in withdrawing, treating, storing and distributing water to large regions or individual users. In a free market the money value of water tends to reflect the aggregate types and intensities of demands for quantity, quality, time and place, providing a means of establishing an equilibrium among competing water uses and between demand and supply. When the system works, each management step brings water closer to the quantity, quality, time and place of intended use or benefit.

TWO LANDSCAPES

Two landscapes in the Piedmont region of Georgia illustrate the application of landscape hydrologic concepts to specific sites. The region is underlain by impermeable crystalline rocks with a thick mantle of saprolite, and densely vegetated.

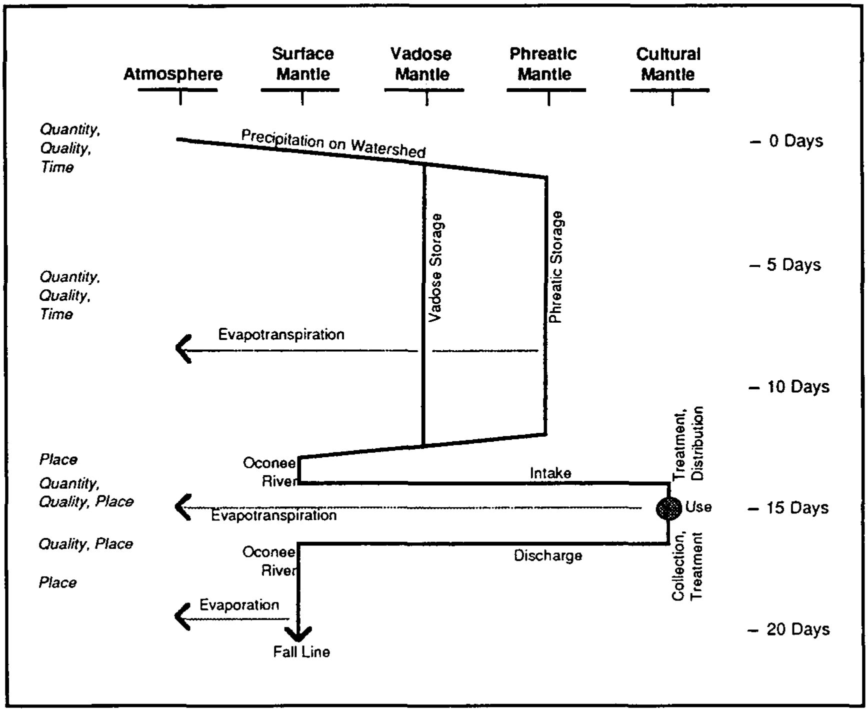

Figure 3. Flow through the hydrologic mantles of the Oconee River watershed, Georgia.

The watershed of the Oconee River exemplifies common types of flows in this region. The diagram in Figure 3 follows a typical drop of water through the hydrologic mantles of the watershed's landscape. The verticle scale is elapsed time in days. Along the left side are noted the fundamental characteristics of water that are altered substantially at each step. Sporadic, intense pulses of precipitation on the water shed mostly infiltrate the soil and are stored in the subsurface, where plants and soils evapotranspire more than half the water. The remainder exfiltrates to surface streams relatively steadily. The integrated stream system concentrates tributary discharges into higher-order rivers. The city of Athens takes its water from the main river; within hours the water is artificially filtered, distributed through pipes and used by city residents. Wastewater is collected to sewage treatment plants and is discharged back to the river a day or two later. The river carries the effluent over the Fall Line, into the Coastal Plain region where it begins to participate in a different set of dominant hydrologic processes. Thus from a broad environmental viewpoint, the combination of mantles in the Oconee landscape work in concert to create a balanced system of flows and storages in equilibrium with its hydroclimatic inputs and outputs. From a resource viewpoint a combination of relatively natural mantles in Athens' drainage area acts as water catchment, collection system, storage tank and treatment medium.

More active human management is evident in the headwaters of the Flint and Ocmulgee Rivers in the rapidly growing suburbs of Atlanta. For many years management for urban water supply focused on the small rivers, but the surface resource is so limited that it has threatened the area's capacity for further urban development. However, the soil mantle, holding a significant reservoir of vadose moisture, has opened up new management potentials of the landscape. In 1981, one of the county water authorities began irrigating with wastewater upstream from its own water supply reservoir. The soil mantle infiltrates the water, renovates its quality, and steadily discharges it into the stream system for recapture and reuse. The irrigation also supports the growth of trees, which are harvested to remove effluent constituents from the treatment area and to supply fuel for the pretreatment plant. Thus fuller recognition of the landscape's hydrologic capabilities has allowed augmentation of small natural stream flows, enhanced the landscape's ability to support human development, and evolved toward a combined human-ecological system of high sustainability.

IMPLICATIONS

The hydrology of the landscape is not limited to streams, nor to reservoirs of phreatic groundwater. Water is one of the mobile substances that connect things together. Like energy, nitrogen and other mobile constituents, water can be used as a "tracer" to follow paths of environmental connections. Water flows through intricate but orderly sequences of mantles, whether in the uplands or the lowlands, the surface or the subsurface, the atmosphere or the earth. The various mantles mark distinctive types of processes but there are powerfully continuous flows among them. The various components of hydrologic systems are interactive and symbiotic.

Through water management, man and nature, too, are interactive and symbiotic. The environment is not just left behind when water is abstracted from it; the cycling of water through nature, through cultural systems, and back into nature is a single system. Many of the steps of man's water management happen in the soils, streams, vapors and aquifers of the "natural" landscape. Man modifies and interacts with natural flows and storages of water in a manner analogous to agriculture's modification of and interaction with "natural" soils and plants. When the landscape is managed, water is managed, and vice versa.

The interaction of environmental mantles, one of which is cultural, is the context within which choices in environmental ethics must be made. In every human management of water and landscape there are external relationships. None of our intended results can be achieved without taking into account the feedback mechanisms that exist outside ourselves. An integrated concept of man and nature does not mean that everything that man has done or could do is environmentally sound. On the contrary, the past is full of human blunders of ignorance, self-service, and vindictiveness, and an integrated concept helps us to see how blatant and far-reaching some of those errors were. An integrated concept is a tool which can help us to evaluate proposals and to direct our future actions. The cycles of nutrients, energy and water through ecosystems are armatures on which to build future land and resource uses [11]. Even when a planner is interested in only one management application at a time, management of any one mantle can be viewed as access to all the flows and reservoirs of the landscape.

The simplest theory of natural systems is the most unitary one. Under the Gaia hypothesis, earth systems interact through feedback mechanisms to operate homeostatically as would a single organism [12]. A hydrologic component of connected, interacting mantles, flexibly regulating their responses to stimuli, is consistent with such a hypothesis. The Gaic system is an extension of landscape hydrology, as it is of any other landscape system.

Hydrologic form and process interact to assure a dynamic equilibrium in which the system has the flexibility to adjust through changing circumstance. If our sense of the hydrologic continuum is fragmented, then our land and water management will follow in the same path; it becomes divorced if we do not see the consequences of neglect of connected systems. Preservation of the integrity of the continuum ought to be one of the objectives of resource use [13].

Every geographic area suggests a community of interrelated, interdependent organisms. We need to manage geographic areas, along with all that is in them, as well as or instead of discrete resources segregated from their environmental contexts.

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