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WATERSHED FUNCTIONS[1]

Peter E. Black[2]

ABSTRACT: Watershed functions that dominate the hydrologic environment are identified and discussed. Hydrological and ecological functions are considered in relation to the storm and annual hydrographs, and to water quality. Two integrative watershed responses to these functions are also articulated. Since most of the Earth's water is in storage, consideration of the hydrologic cycle as movement between water storage sites enhances this functional and response characterization of the watershed which, in turn, suggests guidance and direction for the restoration of watershed functions.
(KEY TERMS: watershed; functions; processes; hydrology; wetlands; hydrograph.)

INTRODUCTION

This paper identifies and organizes watershed functions. The purpose is to suggest a framework for understanding and managing the growing move to "restore watersheds." A great deal of practical hydrological management activity has recently been directed at rehabilitation or restoration; that activity has often been focused on legal compliance to limit hazardous or toxic wastes, to achieve some water quality standard, or to please the eye. While those goals may be important, they ignore the necessity for restoration of the natural functioning of the aquatic ecosystem that consists primarily of watersheds, streams, and wetlands. The combined operation of these landscape components is referred to here generally as "watershed functions."

A considerable amount of research has been conducted on stream functions, values, and restoration. Wetlands restoration and preservation have been flawed by a lack of a sound scientific basis for characterization and identification of wetland functions and values. Major reasons include that wetlands are poorly drained and relatively flat, and that the hydrology is therefore difficult to assess. The administration and management of wetlands, driven by an intuitive need for preservation, has suffered from a neglect of the recognition of functions and values that should provide the basis for classification, delineation, and inventory, all of which are necessary intervening steps between identification and regulation. Watersheds need not suffer the consequences of similar misjudgment. The effective application of practical field measures to restore watershed functions must be predicated on a clear understanding of what those functions are.

PREVIOUS WORK

Scholars from Ecclesiastes to modern day hydrologists have been primarily concerned with the processes that dominate our perception of the hydrologic cycle, but have ignored the question with which this article is concerned: How does the watershed function? And perhaps rightly so, since the major processes – precipitation, infiltration, percolation, interception, evapotranspiration, and runoff – are normally of immediate and principal concern as humankind's surging population growth has come to dominate the landscape and create the need for, and interest, in restoration.

Marsh (1874) eloquently noted that . . .

> Nature, left undisturbed, so fashions her territory as to give it almost unchanging permanence of form, outline and proportion, except when shattered by geologic convulsions; and in these

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[2]Professor, SUNY College of Environmental Science and Forestry, 1 Forestry Drive, Syracuse, New York 13210.

> comparatively rare cases of derangement, she sets herself at once to repair the superficial damage, and to *restore*, as nearly as practicable, the former aspect of her dominion [emphasis added].

Marsh identifies the many forces that contribute to equilibrium conditions in the natural environment, and considers civilization developments as intrusions thereon. Marsh's approach is, of course, the first step in recognition of the need for protection and of the means of restoration.

In his wide-ranging introduction, Meinzer (1942) presents the hydrologic cycle in functional impression, but not in functional detail or language. His review of the role that water plays on the planet is comprehensive and lacks only to recognize the specific functions identified herein. Many subsequent authors do this as well; the ecological and engineering hydrology books are filled with eloquent breadth and content in their introductory sections, but revert to utilitarian discussion of the detailed hydrological processes that collectively and in various combinations make up the functions of the aquatic systems. One of the more comprehensive yet succinct modern presentations on processes is in the 1955 Yearbook of Agriculture Water (Ackerman *et al.*, 1955); yet it also neglects consideration of the functions in aquatic environments. In the less succinct but highly useful *Handbook of Hydrology*, Chow (1964) discusses the "hydrologic functions of vegetative cover" in terms of its "beneficial effects." These effects include the familiar (1) build-up of organic matter in the soil, (2) organic material on the soil that protects against soil erosion, (3) slowing the runoff process, (4) increasing infiltration, and (5) shading that causes reduced snowmelt rates and evaporation. Loucks (1975) points out that modeling methods benefit from "the systems approach [which] allows quantitative study of the entire complex of biological and physical entities, and interactions, as a *functional* unit" [emphasis added]. The approach is important for comprehension of expected hydrological (and biological) behavior. An educational film, *The Flooding River* (Brower 1974), presents a comprehensive functional analysis of the Connecticut River, especially in (1) the relationships between the river's physical characteristics and behavior; and (2) the numerous biological niches that depend upon and, in some instances, influence the river.

In an introductory article for the 1978 *Wetland Functions and Values* symposium (Greeson *et al.*, 1979), Odum identifies two levels of wetland values: fish and wildlife habitat as *component*-level values; and *system*-level values, which include hydrologic processes, productivity, waste assimilation, and the "role of wetlands in global cycling and atmospheric stability." These processes embrace the wide range of wetland values and, indeed, reflect the breadth of their functions.

Recent literature on ecosystem, environmental, or aquatic restoration tends to focus on the rehabilitation, reclamation, or restoration of biological components rather than nonbiological functions. Two works treating aquatic ecosystem restoration are (1) the *Restoration of Aquatic Ecosystems* (National Research Council, 1992), which defines "restoration" as "reestablishment of predisturbance aquatic functions;" and (2) *Freshwater Ecosystems and their Management: A National Initiative* by Naiman *et al.* (1995), which states that "we must understand how our natural systems – from molecular to watershed scales – operate." However, no discussion of how a watershed, or a fresh water system does in fact operate – or *function* – is present or identified. The National Research Council report states that "wetlands provide essential functions, including flood control, soil and nutrient retention, and wildlife habitat." In fact, there is in the report considerable useful coverage of wetlands; most of the discussion concerns the ecosystems that thrive on the physical and chemical regime of wetlands. But that is only part of the story, and not the central issue of watershed function. More recently, a comprehensive geomorphic classification of river systems – including wetlands – has been effectively utilized as a basis for practical stream restoration (Rosgen 1994). The system highlights how habitats are based on different geomorphic characteristics.

In short, the study of water in natural and disturbed environments has focused on the processes whereby water moves from one specific type of storage to another, or is stored therein, with little regard to (1) the role of water in Earth's overall environment; (2) the implications of the relationships between regional environmental components; and (3) the natural functions of the individual units of aquatic systems, especially wetlands, streams, and watersheds.

Restoration of hydrologic integrity without considering the context of the processes is difficult, if not impossible. It is this consideration that has led to the necessity of identifying and organizing the watershed functions. Indeed, restoration as a social goal seems to have fostered the need to illuminate stream, wetland, and watershed functions. As local community and national interest in aquatic environments grew during the 1960s, 1970s, and 1980s, it became necessary to articulate the specific goal(s) of restoration: What do we want of this stream? How would we like it to operate? How did this stream operate prior to the disturbance that now demands control? How does this wetland work? What are the behavioral characteristics of this watershed? What are their functions?

HOW A WATERSHED OPERATES

Five clearly identifiable functions are exhibited by watersheds, though not necessarily all at the same time. *Hydrologically*, there are three fundamental watershed functions: (1) ***collection*** of the water from rainfall, snowmelt, and storage that becomes runoff, (2) ***storage*** of various amounts and durations, and (3) ***discharge*** of water as runoff. In fact, the first and last of these functions have, long been incorporated in the commonly-used terms, "***catch***ment" and "water***shed***;" storage is the inevitable consequence of water being detained within an area between "catching" and "shedding."

Ecologically, the watershed functions in two additional ways: (4) it provides diverse sites and pathways along which vital ***chemical reactions*** take place, and (5) it provides ***habitat*** for the flora and fauna that constitute the biological elements of ecosystems. The latter, of course, constitute the more familiar ecological *niches*. The former were organized and presented in greater detail by Albert H. Todd in an unpublished plenary session address at the symposium for which this paper was prepared, in which he suggested that water bodies function as *sources, sinks, transformers,* and *filters*. Todd added a sustainer function, but that is already included as the essence of habitat.

Two integrative responses to these five functions are especially important to virtually all aquatic environments. First, the watershed hydrologically ***attenuates*** the energy inherent in the irregular and often abrupt delivery of precipitation or snowmelt as reflected in storm or annual hydrographs. These runoff events are usually uniquely typical of the watershed in which they are produced.

Second, the regulated movement of water out of the diverse storage sites, especially on the rising limb of the (storm or annual) hydrograph, ***flushes*** a water body, an action that is also a universal characteristic of natural aquatic systems. This flushing action in turn regulates the movement of mobilized chemicals. Its effect is manifested in the concentration or load of materials in suspension or solution in aquatic environments. These measurements, of course, are dependent upon the flow regime. Thus, the critically important linkage between hydrology and water quality is captured through characterization of watershed functions.

While the organization that follows reflects the content of the previous paragraphs, the intricate relationships between watershed functions and the factors that affect and characterize them impart a high degree of overlap; it is difficult to completely isolate the discussion of each. In order to properly assess runoff behavior from different watersheds and varying conditions, it is assumed in the following discussion that the watershed is instantaneously, completely, and uniformly covered by a rainfall event, unless specifically stated otherwise.

The Collection Function

How runoff is collected within the watershed depends upon storm position and size relative to basin size, storm proximity to runoff source areas within the watershed, and precipitation type and intensity. Ultimately, these are critical issues of relative scales of the watershed and the runoff-producing event. Two of these issues are particularly relevant. The first is whether the event completely covers the watershed (Figure 1), and the second is where on the watershed the storm is located if it is smaller than the watershed. This, in turn, is dependent upon the type of runoff-causing event because storm type and areal extent are related. If the watershed underneath a typical summer thunderstorm is subjected to a "direct hit" by a mature storm (Figure 1A), the resultant runoff event is likely to be the maximum flood for the year, perhaps even the flood of record. If the storm's area is less than that of the watershed, the peak runoff will be lower, although the proximity of the storm to the watershed outlet becomes an important factor (Figures 1B, 1C, and 1D). If the storm centers on an area of the watershed that is remote, the peak runoff will be small. (Here "remote" refers to the location of the storm relative to the *variable source area* of the watershed). If the storm is larger than the watershed, the primary factor affecting runoff is the rainfall distribution *within* the storm. Drainage efficiency (actually a characteristic of the discharge function) becomes paramount, suggesting that under varying collection function conditions different processes may dominate runoff behavior. If the storm strikes a "glancing blow" to the watershed, the effect is similar to that which would be observed if the storm were smaller than the watershed.

For a large, cyclonic storm associated with frontal events, the areal extent is much greater than is the individual thunderstorm. Thus, the size of the watershed that can be completely covered is correspondingly larger. However, the large-area storms generally have lower intensities and longer durations than small-area storms and, as a consequence, it takes a greater length of time for the watershed to discharge. Collection of runoff water within larger watersheds takes longer because (1) there is a greater distance of travel; and (2) for larger watersheds average slopes and stream gradients are lower, thereby reducing average runoff velocities. Both factors specifically

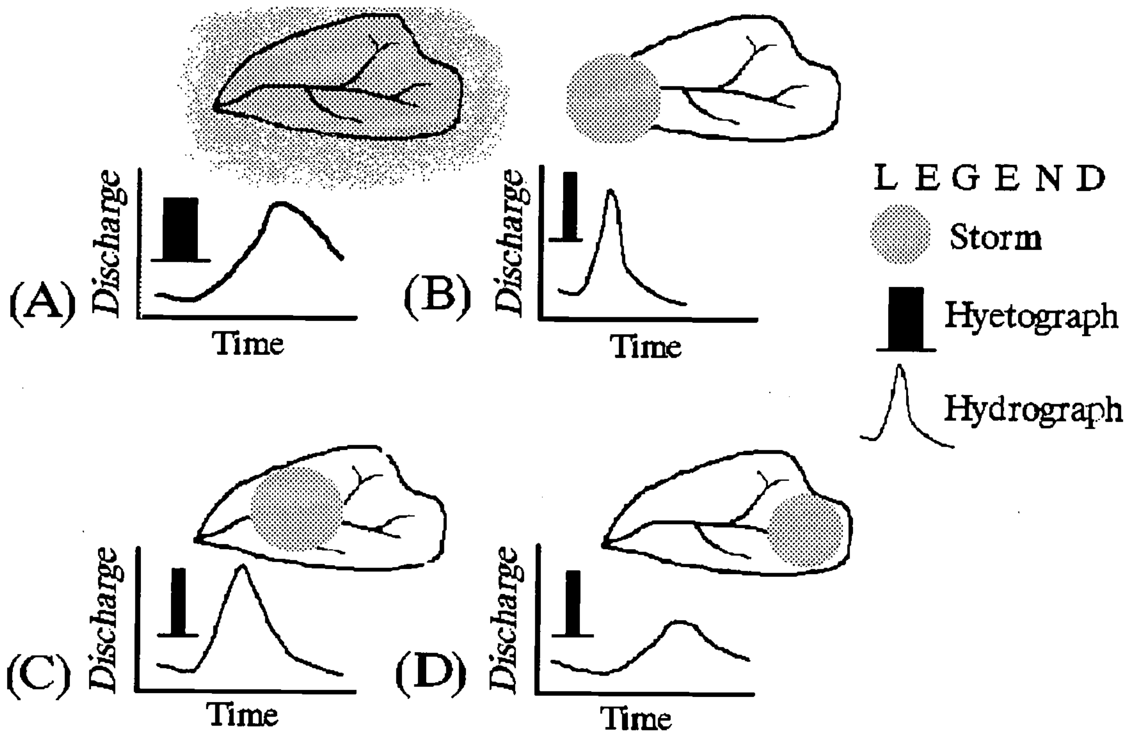

Figure 1. Hypothetical Hydrographs and Hyetographs from Rainfall Events on Different Portions of a Watershed: (A) Covering Entire Drainage; (B) At Outlet; (C) In Center of Variable Source Area, and (D) Remote to the Variable Source Area.

increase the time of travel and therefore lengthen the time of concentration. As a consequence, peak flows in rate per unit area on larger watersheds are lower and later than on smaller watersheds.

The concept of the variable source area is shown in Figure 2. Observation of both real watersheds and models reveals zones of the drainage that appear darker (owing to higher moisture content) in the immediate vicinity of the stream (Hewlett and Hibbert, 1967; Abdul and Gillham, 1984; Black, 1970). These zones may, in fact, be saturated. During a runoff-causing event such as rainfall or snowmelt, these zones expand to include areas farther and farther from the live stream. Streamflow increases during this expansion, and conversely, contracts during recession. By definition, the size limits of this variable source area are erratic and normally incalculable. Runoff from this zone may be supplied from ground water, from other storage sites within the watershed (mostly subsurface flow), and channel storage. Thus, during the runoff-causing event, storm flow (often equated with quickflow) may actually be a combination of surface runoff (often equated with overland flow), subsurface runoff (often equated with interflow), base flow, and channel interception. The variable source area demands synoptic, critical analysis of all the relevant factors affecting runoff from the drainage basin. Of especial importance is consideration of the watershed's response to water input under a given set of antecedent moisture conditions.

It should be noted that the variable source area concept was conceived of in an area of rather deep soils that were widely and uniformly distributed over tight bedrock (Hewlett and Hibbert, 1967). However, under contrasting conditions of thin, nonuniform soils, and perhaps fractured parent material, the variable source area model does not satisfactorily describe runoff behavior, as subsurface flow paths appear to be dominated by what is termed "preferential flow." Here, drainage water follows animal burrows, rotted root channels, solution pipes, and soil-rock interfaces. One might resolve the different models by application of the variable source area to smaller and smaller facets in the watershed within which soil storage is uniform. The definition of a watershed is thus dependent upon the existence of identifiable storage-runoff components as well as the existence of a defined drainage system. Different models for runoff behavior may need to be developed for watersheds with differing characteristics.

A classic example of the effect on runoff behavior of a storm that was small (relative to watershed size) striking a portion of a large watershed occurred in the summer of 1993. The three months of rain at the

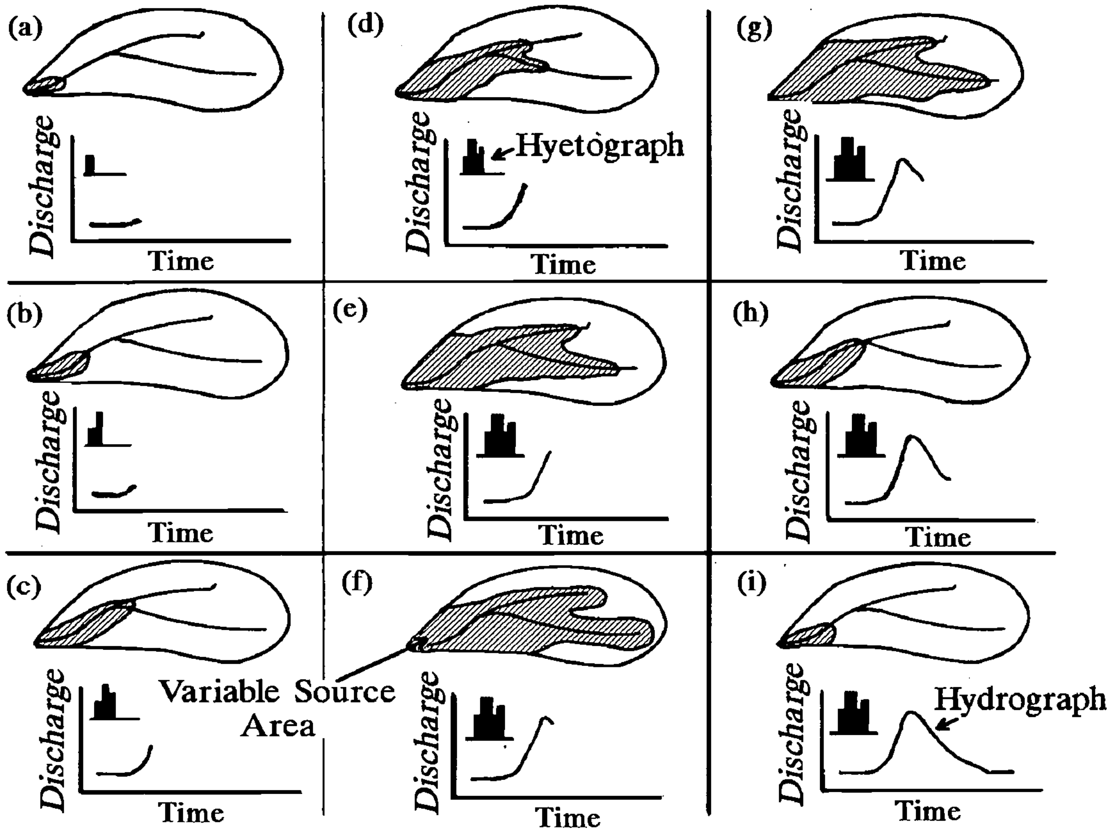

Figure 2. A Theoretical Example Illustrating the Variable Source Area Concept. The several stages of the variable source area are coordinated with a storm hydrograph. Precipitation ends at (e).

confluence of the major tributaries of the Mississippi River system were concentrated on a critical portion of the variable source area. That same, prolonged runoff-causing event, if focused on the interstream plains of eastern Colorado, for example, would not have produced the same effect at St. Louis, although it certainly would have produced local flooding in eastern Colorado.

Change of land use within the watershed, especially within the variable source area, greatly affects the collection capacity and consequent runoff behavior of the watershed. The extent of land use change over the watershed has effects that are similar to the relationship between areal storm extent and watershed size. If the land use changes are local, then the impact of such changes are especially apparent in the storm hydrograph; the storm hydrograph is dominated by local characteristics. For land use changes that cover larger portions of the watershed, the impacts may also be observed in the annual hydrograph. Watershed size plays a role here, as it interacts with the extent of land use changes, as well as factors that affect weather and climate. On smaller watersheds, the predominant interaction is between weather-scale runoff-causing events and the storm hydrograph; on larger watersheds, the predominant interaction is between climate-scale runoff-causing events and the annual hydrograph. While large-scale events or land use changes may impact small watersheds and even the storm hydrograph on large watersheds, smaller, localized runoff-causing events tend to produce more intensive precipitation over restricted areas, thus having a greater impact on the storm hydrograph on small watersheds or on small tributaries to larger watersheds.

For example, hurricanes generally lie between thunderstorms and large cyclonic storms in size and are the runoff-causing event for the flood of record (and usually for all major floods) on intermediate-sized watersheds in the Northeast United States. Snowmelt events are usually even larger in areal extent and are often the cause of the flood of record on larger watersheds. Thus, the collection function is profoundly affected by the factors of size, timing, and type of runoff-causing event; size of watershed; and the complex interactions among those factors. Our understanding of the relationships between the runoff-causing event and runoff behavior characteristics such as flow duration relations, low flows, half- and quarter-flow intervals, seasonal runoff distribution, peak flows, and flood frequency curves for watersheds of different size and in different geographic locations can benefit from analyses that take these fundamental relationships into account.

The collection function of a watershed is thus confounded with the nature and location of the runoff-causing event; its type, size, and distribution over the watershed; relationship to climate and weather patterns; and interactions with land use and land use proximity to the variable source area. Drainage pattern also plays an important role, since the effect of other factors on runoff behavior can be masked by areal distribution of streams (Black, 1970). Consideration of any fewer factors and interactions in characterizing, describing, evaluating, and predicting runoff behavior falls short of fully characterizing this function.

The Storage Function

The type, amount, and distribution of storage are the primary watershed characteristics that affect the storage function. As the function that is intermediate between the collection and discharge functions, some storage characteristics play an intervening, complex, and interacting role among all three functions. Any given factor's significance may be different under different hydrologic circumstances. Further, resistance to leaving storage and antecedent moisture conditions are additional factors that affect the attenuation and discharge functions. It is difficult to discuss any of these functions or the factors in complete isolation.

The *stream-watershed system* may include some or all of the storage types that occur on the landscape (Figure 3), with emphasis on the storage in soil, stream, vegetation, and wetlands (including both depression and channel storage). Water stored in the soil is usually divided into capillary and noncapillary portions, also referred to as retention and detention storage. Retention storage water, which is held at high tensions in the soil capillary pores, cannot flow out at all. Only a portion of the water in retention storage can be removed from the soil by evaporative processes. Water temporarily detained in the noncapillary pores flows out during the first 24 hours following the runoff event by definition (Chow, 1964). Residual storm clouds and high atmospheric humidity

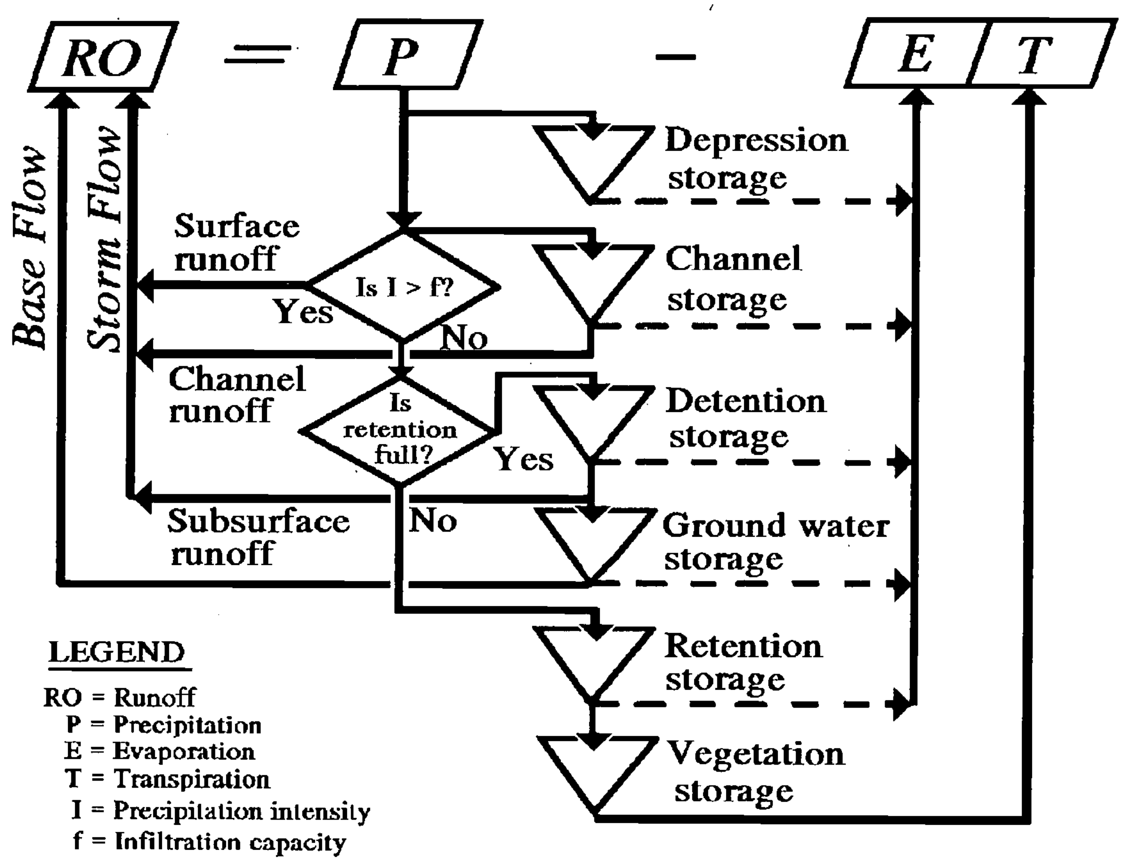

Figure 3. The Hydrologic Cycle Components Arranged by Storage Location and Function Within the Watershed.

can impede evaporation and transpiration, as can low night-time energy. Therefore, most of the detention storage is not available to plants, and contributes primarily to the storm hydrograph in the absence of percolation to ground water reservoirs. Clearly, the balance of soil storage that is held in capillary and noncapillary storage impacts the discharge function by direct influence on subsurface flow.

The total amount of storage available in an undisturbed soil can be prodigious; a three-foot soil profile can store more than a third of a million gallons of water per acre in the 33-percent retention storage alone. The remaining noncapillary pore space of about 17 percent in a typical loam provides for the temporary storage of more than 166,000 additional gallons.

The distribution of this large volume of detention storage on the watershed profoundly affects the ease with which water both enters and is discharged from storage. Normally, natural or undisturbed watersheds will not become uniformly saturated during a runoff-causing event; however if soils are shallow, cover is sparse, slopes are steep, and/or rainfall is intense, local saturation may in fact occur. Watershed saturation is identifiable by the fact that the storm hydrograph will reach a peak and then level off for as long as the rainfall lasts, a clear indication that output is a function solely of input; that is, storage is no longer a factor affecting runoff. Of course, depending upon storm location over the watershed and the proximity of storage to the stream gage, runoff can commence prior to saturation. On disturbed watersheds, reduced storage and infiltration capacities mean earlier saturation and potential substantial impacts on both the storm hydrograph and total annual runoff.

The resistance to water leaving storage is affected by storage characteristics and outflow constraints, and temporal conditions that affect both of these. First, the balance of detention and retention storage plays the principal role in determining how much water is stored and released to streamflow. Second, physical blockage of the drainage passage(s) out of basin storage sites, such as at pond, lake, or wetland outlets, and stream channel roughness, e.g., a debris- or boulder-strewn streambed, may limit streamflow releases.

An example of a temporal condition that affects outflow is temperature. Such was the situation on the Columbia River in 1948: excessive Fall 1947 rains were rapidly followed by early cold weather that froze the water in the soil. Subsequently, a larger-than-normal insulating snow pack persisted under the influence of a cold winter until late Spring when unusually heavy warm rains caused frozen soil water and snowpack to melt and run off in a short time period, thus causing the river's flood of record.

In sum, the specific sequence of runoff-causing events, antecedent moisture (storage) conditions, and the factors that affect them complicate hydrologic analysis and forecasting of watershed behavior, even when based on a clear understanding of basic watershed functions.

The Discharge Function

The ultimate fate of runoff waters within a watershed is to be output from the basin, as depicted in the hydrograph, the record of the discharge function. Discharge takes place as the functions of collection and storage are played out over time scales varying from that of a runoff-causing event to a hydrologic year. Clearly, factors that affect the collection and storage functions also affect the discharge function, and are represented in both the storm and annual hydrographs.

Having been collected by and stored in the watershed system and in streams, lakes, ponds, and wetlands, the water is poised to run off. The principal factor that affects the discharge function is the resistance to leaving storage. This resistance is inherent in and intricately involves (1) characteristics of the drainage network, (2) proximity of the storage site thereto, and ultimately (3) interactions between the two. Drainage network efficiency is primarily determined by the number or miles of stream per unit area of the watershed. Drainage pattern may override the effects of these standard measures of drainage efficiency. So may watershed shape, especially if that characteristic is related to storage site location and amount, as it often is.

Watershed shape and orientation with respect to the direction of storm movement can profoundly impact the shape of the storm hydrograph. Concurrently, the amount and areal distribution of water stored in the riparian zone are likely to override the impact(s) of basin shape and orientation on hydrograph behavior.

As with the collection and storage functions, there are numerous parameters of stream behavior that may be the objective of management. Manipulation of environmental conditions to achieve restoration of some watershed function needs to be conducted in light of how that particular stream behavior might be impacted by the specific management practice adopted.

The Chemical Function

Water is the principal medium in which most chemical reactions occur; watersheds provide diverse aqueous sites in which those chemical reactions take place. Over time, these reactions have ranged from those preceding beginnings of life on Earth to those affecting the movement of pollutants and unwanted nutrients in the modern aquatic environment.

The importance of the interactions between water and life throughout Earth's lithosphere, energy sphere, and atmosphere are identified and discussed by Lovelock (1988). The reactions provide the fundamental relationships that support the concept of homeostasis that leads to the long-term stability of ecosystem elements and the relationships among those elements. In his thorough review and analysis of the natural aquatic environment, Hem (1970) points out that "the chemistry of natural water is concerned for the most part with impurities . . . Although . . . in a more dilute solution than most specialists in solution chemistry are accustomed to working with, the general principles of solution chemistry are certainly applicable to natural water."

Bormann and Likens (1979) developed the basic biogeochemical and nutrient cycling processes in forest ecosystems, and cited the utility of the watershed as a working unit. The primary value of utilizing the watershed as the basic unit of ecosystem management to control water quality lies in the need to manipulate hydrologic processes that are defined by the local drainage unit concurrently with the biological and physical characteristics, and systems that interact with them. The connections between land use and water quality have been known in general, at least, for years. Most of our present watershed management activity is devoted to the protection of water quality, especially in mitigating the impacts of land use changes at the rural-urban interface where nonpoint sources of pollution can be controlled through judicious use of (often watershed-based) best management practices.

In combination with the other peculiarities of water such as its high specific heat, moderate viscosity, and high surface tension, the H_2O molecule is, along with the versatile element carbon, a primary planetary buffer against the normally-occurring excesses of and variations in energy, pH, solutes, and gases (Black, 1995). Frequently, the aquatic environment is the cushion that absorbs the impacts of what otherwise would be life-threatening events.

The sites and pathways within which interactions between the physical and chemical characteristics of water take place are as varied as are the number of interactions and reactants, and their combinations. Certain water quality characteristics are likely to be similar between separated but similar ecological niches. For example, downstream of a riverine wetland, pH is likely to be low owing to high concentrations of carbon dioxide resulting from decomposition of organic matter; silica is also likely to be lower than in the inlet to the wetland owing to uptake by hydric vegetation for cell wall construction.

The Habitat Function

Life on Earth takes place in the presence of water. The fluids of living organisms are like that of the oceans. One popular theory (Morgan, 1972) is that the "higher" living organisms on Earth developed in an aqueous environment. The evolution of humans most likely occurred at diverse and protective seashore environments (as opposed to the rather hostile savannah). Wherever the human species evolved into its current form, other mammals thrived and made similar dramatic changes in appearance and behavior. At the seashore, an abundance of the universal solvent promoted nutrient mobility and opportunities for a wide variety of life forms in different habitats or niches that complement and support the complexities of human life.

The watershed and its fundamental hydrologic functions define the characteristics of freshwater aquatic habitat; they are further influenced by inputs from other systems. The amount of atmospheric fallout, washout, and biological waste products that are inputs to the aquatic system are affected by watershed size, elevation, proximity to oceans and related features. These impart the shaping of the flood frequency and flow duration curves, seasonal distribution of runoff, and characteristics of other hydrologic parameters in addition to impacts on water quality.

Human disturbances to the functions affecting physical and biological water characteristics often have a deleterious effect on ecosystems and their floral and faunal inhabitants. Acid rain, ozone depletion, global warming, forest decline, contaminated water supplies, sedimentation, smothering of spawning gravels, and declining populations of fish and wildlife all can be attributed in some way or other to the mismanagement of, or direct insult to, the natural chemical (and intricately related physical and biological) processes in watersheds. As noted earlier, much of the interest in environmental restoration is based on the belief that ecosystem health affects human health. A corollary is the presumption that essential environmental functions have been restored if habitat is restored. These presumptions may be correct, but they are not guaranteed. Thus, it may be erroneous or misleading to evaluate functional restoration as measured by success of habitat restoration.

The Attenuation Response

The integrated *physical* response to the three hydrologic functions is to attenuate the extremes of the storm hydrograph (e.g., the peak discharge) as the runoff pulse from a rain storm or snowmelt event courses downstream (Figure 4). This is a naturally-occurring phenomenon that is evident on any watershed. It results from the built-in storage processes and concomitant time delays (discussed earlier).

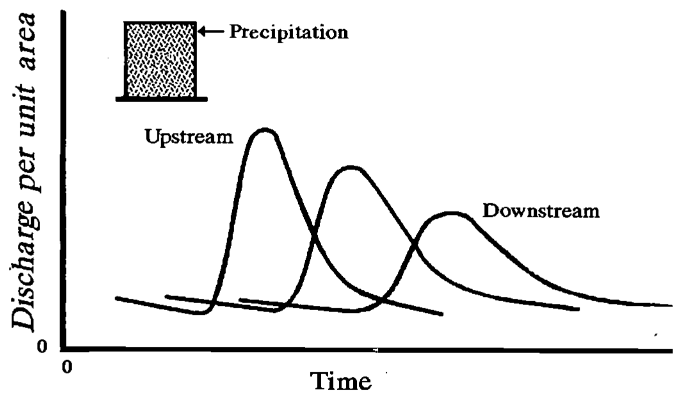

Figure 4. Runoff Attenuation as Illustrated by Storm Discharge Per Unit Area at Successive Downstream Locations.

The degree of attenuation can be impacted by changes in watershed characteristics that alter storage or time parameters, such as distribution or amount of different storage types, and by the lag time and time of rise. Led by the observation that peak flows are lower and later on larger watersheds (in discharge per unit area), other hydrologic characteristics are also mitigated by the runoff waters having to pass through soils with varying permeabilities, sinuous channels, alternating pools and riffles, wetlands, and even lakes. The effects may show up in either the storm or annual hydrographs. Alterations in watershed characteristics may be manifested in dramatic changes in flood frequency and flow duration curves, half- and quarter-flow intervals, seasonal distribution of water yield, relative types of runoff waters from different types of storage, and so forth.

In addition to the initial characteristics, then, the opportunities for hydrologic regime modification are influenced by the fundamental temporal and storage features of the watershed that determine the attenuation response.

The Flushing Response

The second integrative physical response to the combined ecological and hydrologic functions is the characteristic flushing of the aquatic system. Soluble and suspended solids in excess of the flowing water's transport capacity are deposited at and moved between storage sites, dependent upon fluctuations in total discharge and velocity as well as properties of the substance being flushed.

The flushing response can be observed when monitoring the concentration of sediment, nutrients, waste products, or dissolved gases during a runoff event. The record, a *pollutograph*, is probably different for solids, gases, and physical characteristics such as temperature; however, the sequence of dilution, intensification, and restoration of concentrations (as generalized in Figure 5) appears to be fairly universal. Ultimately, substances are washed completely out of the watershed system, but until that time, concentrations are continually changing, reflecting fluctuations in local accumulation controlled by normal hydrologic behavior.

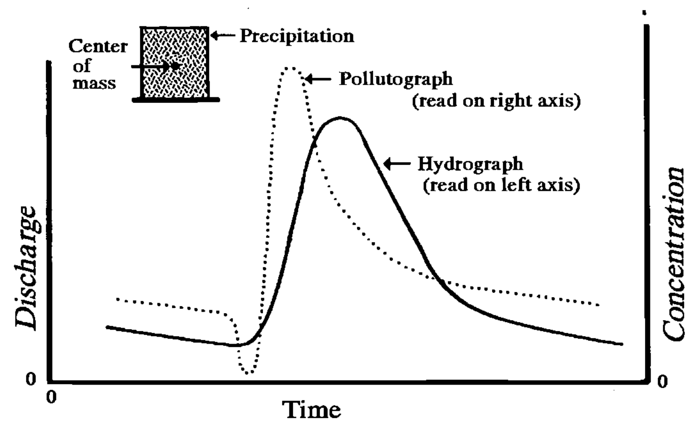

Figure 5. A Typical Pollutograph for Sediment Concentration Illustrates the Complexity of the Flushing Response.

Summary

Together, the three hydrological and two ecological functions, and the two natural responses thereto comprise the essence of watershed hydrology and water quality. The functions are elementary and, as a consequence, have been overlooked. It is important to consider them as the context for evaluating the impact of land use and water management practices. Human developments have made many intrusions on hydrologic behavior, often with disastrous and unanticipated consequences. If such disturbances are to be recognized and eliminated or controlled, it is essential to first understand the nature of the affected watershed functions that need to be restored.

LAND USE IMPACTS ON THE WATERSHED

Examples where land use changes have wrought havoc with the watershed functions and responses are common. Since the attenuation and flushing responses are integrative, land use impacts can be organized according to how these two primary responses are affected. The effects of changes in these watershed responses (and the functions that influence them) may impact water quality of on-site or downstream habitat and, as a consequence, can dramatically affect local ecological integrity as well as humankind's beneficial uses of water resources.

Whenever aquatic systems are going to be (or have been) affected by some practice, it is appropriate to ask the question: ***Have the aquatic system functions or responses been lost or impaired to the point where environmental or human values are adversely affected and where restoration is necessary in order to sustain the desired water use?*** In order to give a clear response to this question, a watershed analysis needs to be undertaken.

Watershed analysis requires a team approach with a soil scientist, a hydrologist, a geologist, an engineer, an ecologist, and other specialists as needed for the area under study. As with environmental impact analysis, the process consists largely of the group members asking questions until they are satisfied that they have determined the level of information necessary to restore the desired sites, conditions, and functions. As a start, restoration actions – and the disturbances that necessitated them – might be generally characterized according to critical management issues, such as (1) land operator goals; (2) whether economic or health (ecological and/or human) concerns are paramount; (3) effectiveness of proposed practice to restore site, condition, or function (e.g., eliminate negative land use impact); and (4) who is going to pay for – and benefit from – the practice.

From such an analysis, appropriate best management practices to restore or protect watershed functions can be planned that are based on sound strategies for the identification, sequencing, application, and evaluation of mitigation measure effectiveness and costs. Field checklists that guide these analyses for stream, wetland, and watershed environments are already available in many states and for specific localities.

Restoration of the conditions that promote natural watershed functions is costly and its success is often difficult to predict. It is imperative, however, that the waters of the Earth are in a condition to continue functioning as the medium for fundamental chemical reactions and ecosystem support, and as a natural buffer against the extremes and exigencies of the environment on which we depend.

SUMMARY

This is a rather simple – perhaps even completely obvious – synthesis of a considerable amount of complex material that has largely been described elsewhere, albeit without the foregoing organization or articulation. Nevertheless, it is of vital importance to maintain perspective on watershed functions as one considers the manifold opportunities and consequences of specific watershed management practices.

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