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A RESEARCH HALF-LIFE: TWENTY YEARS OF STUDIES ON WATERSHED PROCESSES

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INTRODUCTION

Watershed processes are those individual and collective physical interactions and chemical reactions which control the movement of mass and energy through the biotic and abiotic components of a watershed. These processes are complex, interactive, and time and space variant. A thorough understanding of a watershed's function and health necessitates that researchers and natural resource managers have clear insights into the role and importance of each process and its interactions with other processes.

One framework for studying watershed processes is through development of conceptual and/or mathematical models of watersheds (Simons et al. 1979b; Simons et al. 1982). Once a model has been established, the role of each of the processes can be investigated with its importance to the model as a whole. Because the model is a symbolic representation or simulation of integrated watershed processes, there is always the danger that one or more processes' components may be neglected, or that the mathematical representation of the processes may be in error. Therefore, it is important for modelers to have a firm grasp on what is a reasonable outcome or result from a model simulation of watershed processes or the integration of several of those processes.

But how does a modeler acquire this firm grasp of what is reasonable? Typically, a modeler combs the literature to discover what others have found from actual field research or from laboratory studies. Although this is a reasonable approach, it is not necessarily the best approach. I believe the best approach is for the modeler to participate in field and laboratory studies so that the modeler can experience firsthand the complexity of real systems of processes.

At this point, I must confess that I am a "reformed" modeler. My first professional experience was with field data collection for a mathematical model of the Truckee River in California and Nevada. I drifted, however, and began dabbling in computer models of different watershed processes. Eventually, I came to realize that the feeble mathematical models that existed could never compare with the complexity and variability of the natural watershed processes which the models tried to simulate. That simple, but profound, realization has guided me in trying to understand processes as best as I can so that someday mathematical watershed models can better represent actual conditions.

I have spent over 20 years studying various watershed processes, and have been fortunate to receive funding from various federal, state, and local agencies to conduct my studies. One of the biggest contributors to my research has been the U.S. Department of Agriculture Forest Service, which is being honored at this conference. Other funding has come from the New Mexico Department of Game and Fish, New Mexico Water Resources Research Institute, U.S. Army Corps of Engineers, U.S. Environmental Protection Agency, and the National Science Foundation. I have also worked with many outstanding scientists, engineers, and undergraduate and graduate students over the years, all of whom have contributed to my understanding of natural systems. In this paper, I would like to share some of my observations and opinions about the natural processes I have studied. Many of my observations will not be surprising to field researchers who have studied those processes, but some may be of interest to all who have either investigated or modeled those processes.

OBSERVATIONS ON WATERSHED PROCESSES

General

There is a plethora of watershed processes that can be observed, studied, modeled, or incorrectly ignored. These processes include precipitation, evapotranspiration, infiltration, subsurface/groundwater flow, surface water flow, channel flow, erosion, transport of inorganic and organic particles and chemicals, water chemistry, mass wasting, and natural and human impacts. The reader might note that I have integrated a number of individual processes into a single process, such as water chemistry and human impacts. I have done so for brevity and as a way of organizing the rest of my comments. Note that I have organized the processes or groups of processes in a basic conceptualization of how water moves through a watershed. Not all the processes listed above will be reviewed as I will limit my remarks to those I have studied and about which I can offer some observations.

Precipitation

There are three basic truths about precipitation: you never know how much you will receive, where it will fall, or how long it will last. We call these truths "temporal and spatial variability" to make them sound more scientific.

The two forms of precipitation we are usually concerned with are rainfall and snow. The first because it tends to cause quickly occurring floods, and the latter because it is the source of almost all our surface water supply. The first professional paper I presented was about rainfall precipitation (Ward and Gupta 1973). That paper analyzed rainfall data from various USDA-ARS watersheds in New Mexico and Arizona with respect to depth, duration, and temporal variation. Over the years, the analyses have continued as new data and new sites were added to the data base. More recently, Bolin et al. (1989) examined data from the Jornada Long-Term Ecological Research (LTER) site north of Las Cruces.

From these analyses, I have concluded that there is no relationship between the duration of a rainfall event and the corresponding depth of rainfall. It is only through radical massaging of the data that one can develop a design storm, which implies that for a selected probability of occurrence, such as 1%, there is a functional relationship between storm duration and rainfall depth. I believe that an appropriate rainfall event to use as a design storm is a thunderstorm event of one-hour duration and of a depth appropriate to some low frequency of occurrence, such as 1%. The event's time distribution should be such that most of the rainfall occurs early. A model of the temporal variation of rainfall can be written as:

$$V^*=\sqrt{T^*}$$

where V^* is a nondimensional depth of rainfall ranging from 0 to 1, and T^* is a nondimensional duration also ranging from 0 to 1. This equation implies that by half the duration ($T^* = 0.5$), 71% of the total rainfall ($V^* = 0.71$) will have occurred. This model of temporal variation is reasonable and based on a variety of storm depths from durations of two hours or less. This equation is what I use in developing design storms.

Snowfall and snowmelt are much more difficult to model as they require a thorough understanding of thermal properties of the snowpack over time. One interesting finding about snowmelt as revealed by a model study (Foltz 1987; and Foltz and Ward 1987) was that the total solar radiation at the top of the atmosphere worked just as well in modeling total snowmelt runoff as did the solar radiation adjusted to ground level by cloud cover and slope aspect corrections. This may have occurred because of the type of model used or the output modeled, but it may also be a short cut for further modeling efforts.

Infiltration

Much of my research has focussed on assessing infiltration and erosion characteristics with the aid of rainfall simulation (Sabol et al. 1982b; Sabol et al. 1982c; Ward 1983a; Sabol and Ward 1983; Ward and Seiger 1983; Bach et al. 1986; Ward 1986c; Ward and Bolin 1989a and 1989b; and Ward and Bolton 1991). My research associates and I have conducted rainfall simulation experiments at over twenty sites in New Mexico, Arizona, and Colorado for a total of over 1,000 experiments. A variety of vegetation-soil types were sampled for various reasons depending on the goals of a particular study. Recent activity has been in pinyon-juniper and desert rangelands.

A primary infiltration characteristic that has been sought is the steady-state loss rate which is taken to represent the hydraulic conductivity of the infiltrating zone. This characteristic is used by land managers in determining the health and hydrologic function of a watershed and by modelers in simulating the infiltration process. A desired outcome from infiltration studies would be the development of a simple, accurate equation or technique for estimating the hydraulic conductivity from site specific data. Although simple equations can be developed, the accuracy of such equations is not very good. I believe that the accuracy is affected strongly by the amount of natural variability or noise occurring when measuring infiltration of natural plots.

It is my observation, however, that a reasonable, conservative estimate of a steady-state loss rate for most natural vegetation-soil types is in the range of 25 to 50 mm per hour. The loss rate is much higher under a forest canopy, in the range of 75 to 100 mm per hour, and is about a factor of three lower in those areas denuded of vegetation.

We have also found a marked difference between the steady-state loss rates and whether the soil was initially dry, that is, in its typical field condition, or whether the soil had been prewetted by a previous experiment. This difference, which was larger for some vegetation-soil types and almost nonexistent for others, demonstrates that paired dry-wet experiments should always be conducted.

Another finding is that there is a marked difference in the loss rates of vegetation-soil types between seasons in rainfall dominated areas (i.e., not snowmelt). We believe that the surficial layers of soil become more porous (lower bulk density) over the winter and spring months because of physical and biological processes such as freeze-thaw and termite activity (Elkins et al. 1986). At the beginning of the monsoon season, the soils have a higher infiltration rate because of their higher porosity. By the end of the season, the soils have been compacted by rainfall and land-use activities and the loss rate has diminished. We have been able to create a similar response when we conduct the dry-wet experiments on a soil before the rainfall season begins. In this case, only the action of the rainfall and the subsequent overland flow is responsible for compacting the soil surface.

A spinoff from studying infiltration and erosion through construction and use of rainfall simulators is the knowledge gained about rainfall simulation and its appropriate application (Wilcox et al. 1986; Endebrock 1990; and Ward et al. 1991). A major problem facing hydrologists when they study watersheds, whether the watersheds are several hundred square kilometers or only one square meter, is that there is a tremendous degree of variability from one point to another with respect to hydrologic characteristics. Because loss rate, as measured through rainfall simulation, is calculated as the difference between rainfall rate applied to a target plot and runoff rate from the plot, the loss rate is an integration of all the point rates within the plot. The larger the plot, the more the point values are integrated. We have found that the loss rates over a large area can be estimated from small plot experiments (Ward 1986c; Ward and Bolin 1989a), a fact which was confirmed in other modeling efforts (Wicks et al. 1988). However, the effects of partial area contribution, that is, some areas within an experimental plot do not produce runoff from the applied rainfall, create a situation wherein increasing the applied rainfall rate appears to increase the loss rate. Therefore, it is necessary to apply a sufficiently high rainfall rate to produce runoff from all areas of a plot. My best estimate of that application rate for the vegetation-soil types we have studied is 75 mm per hour except for high-loss plots such as those in litter under forest canopy. Applied rainfall rates below 50 mm per hour will create a situation wherein partial area contribution will occur.

Although I cannot, I wish I could list a universal loss rate estimation equation. At this point in our knowledge of hydrologic processes, all I can recommend is that each watershed of interest be tested for infiltration rates before modeling commences.

Surface Water Flow

Surface water flow results from water not infiltrating and thus running across the soil surface. Channel flow is a specific case of surface water flow. The other specific case is overland flow whereby water flows across the vegetation-soil surface as either a broad sheet (rarely) or in tiny channels or rills (usually). Overland flow is affected by vegetation-soil surface characteristics on the bottom of the flow, and rainfall characteristics on the top of the flow. I have studied overland flow as a sideline to other experiments (Ward 1986c). Recently, Jorat (1991) used data collected from our small-plot experiments to explain some of the phenomena we have observed. One finding from his analyses was that the Manning's roughness coefficient, n, could be approximated by the total fraction of vegetation plus rock covering a plot. This implies that if a plot has 50% vegetation plus rock cover, then the Manning's n would be 0.50. Because overland flow helps control erosion and sediment transport, more research should be conducted in this area.

Erosion and Sediment Transport

At this point, I will discuss erosion and sediment transport as it relates to vegetation-soil surface interactions. Later I will discuss it again with respect to surface water (channel) flow. Rainfall simulation, if conducted correctly, can provide information on the erosion/transport characteristics of falling and running water when that water is applied to a vegetation-soil surface. For short plots, less than 3 meters in length, the erosion/transport measured is primarily from interrill processes of splash detachment and short distance, shallow overland flow transport. For plots greater than 3 meters in length, the erosion transport measured is a combination of rainfall splash detachment and shallow overland flow/rill flow detachment and transport. Measurements of erosion/transport are affected by the size of the plot and the applied rainfall. We have found that erosion/transport characteristics are typically higher for small plots compared to large plots (Ward 1986c; Ward and Bolin 1989a). This can be explained by the observation that material removed from a small plot has a much shorter distance to travel to the plot outlet (measurement point) than does material removed and transported across a larger plot. In fact, the point splash detachment of soils is much higher than the detachment inferred from plot studies (Ward et al. 1983; Ward 1983a).

The technique used to measure sediment concentrations in the runoff water from the plot can also affect the results. We have found that applying three different techniques for measuring suspended sediment concentrations produced three different values for the same runoff sample (Ward and Bolin 1989a and 1989b). Unfortunately, the techniques which produced the highest and lowest values were significantly different from each other. One technique which seems to produce a reliable result is filtration and drying of a subsample, a standard approach. Still, this technique appears to be a bit low if the subsample is not well mixed. The technique producing the highest values was drying the entire sample in an oven and then calculating the residue's weight. The problem we found with this technique is that dissolved solids were also part of the dried residue, thus increasing the apparent concentration of suspended materials.

We have observed that large plots have higher sediment yields than do small plots, as one expects based on size alone. However, our data also showed that the small plots exhibit higher per area sediment yields, again reflecting the mode of erosion and transport. When the sediment yield is expressed as a concentration of weight per unit area per unit of runoff, such as kilograms per hectare per mm of runoff, the differences between plot sizes or amount of runoff from a plot essentially disappears. For this reason, we have been reporting erosion/sediment data in units of yield per area and yield per area per depth of runoff. I believe that what we are observing is an applied energy threshold (rainfall rate and resultant runoff rate) which limits the amount or concentration of sediment entrained in the runoff (Bolin and Ward 1986).

Equations to estimate the detachment coefficients (model coefficients that is) associated with rainfall splash and overland flow on plots have been developed (such as Simons et al. 1977a; Simons et al. 1979a; Ward 1986a; and Riggins et al. 1989b), but the predictive capability of such equations is poor (Serrag 1987). Currently, we do not have a reasonably good technique for estimating detachment coefficients for modeling purposes. More research should be conducted on this topic.

Channel Flow

Channels can be classified in numerous ways. One way is by the presence of flowing water in the channel some of the time (ephemeral), most of the time (intermittent), or all of the time (perennial). Channels also can be classified as to their steepness: less than 1% channel slope, channel slopes much less than the angle of repose of the bed material (about 30° to 35° or 60% to 70%), slopes on the same order as the angle of repose, and slopes greater than the angle of repose. Steep channels are those with slopes greater than about 1%. By this slope classification, most channels in upland watersheds could be termed as steep. Therefore, flow and sediment transport characteristics of steep channels become of interest to those wishing to model channel processes (Ward 1981).

Li et al. (1979a and b), Ward and O'Brien (1980), and Ward (1986b) are examples of analyses which can be conducted on steep channel flow. An interesting characteristic of steep channel sediment transport is that the maximum concentration of transported material in the flow becomes a constant at high energy conditions, for example high slope or flow conditions. I found (Ward 1986b) that this concentration was related directly to the square of the channel slope and inversely related to the mean size of the sediment. The experimental data did not support the hypothesis that grain-size distribution had an effect on this maximum concentration. Subsequent data analyses implied that the observed slope effect may be an artifact of the experimental design and cannot be supported by a lack-of-fit test.

Transport rates for channels of lower energy conditions have been modeled for years using standard sediment transport formula developed for conditions that were not necessarily like those encountered in actual watersheds.

I had the opportunity to participate in preparation of an analysis of expert witness testimony for the reserved water rights case *In the Matter of the Application of the United States of America for Reserved Water Rights* (Water Division No. 1), (Water Court, Colorado) wherein the U.S. Justice Department argued on behalf of the U.S. Forest Service. A primary point of dispute was that flows in Colorado mountain streams should not be decreased by further diversions because the reduced flows would lead to channel sedimentation and an increased flood hazard.

Data were collected from several different streams by the U.S. Forest Service and by consultants for the State of Colorado. When all the data were plotted on a graph depicting sediment transport rate versus water discharge rate, the two sets of data overlapped and intermingled to such a degree that the two sets were indistinguishable. The interesting aspect of this comparison was that one of the litigants claimed the data proved that there was an excess of transport capacity and lack of sediment supply in the channels and, therefore, the flows could be safely reduced by further diversion. Conversely, the other litigant claimed that the graph showed that there was a distinctive hydraulic relationship between transport rate and water flow which meant that any reduced flows would cause sedimentation. As of this writing, the judge has not declared which interpretation he believes is correct.

It is my impression that traditional techniques for estimating sediment transport in mountain channels are inadequate. Fortunately, the U.S. Geological Survey is actively developing a new technique for estimating sediment transport in gravel and cobble bed streams which will address this problem. After working on this case, I have come away believing that the concepts I was taught are not necessarily correct in light of what I have seen in the data sets.

In arid and semi-arid areas, ephemeral channels perform a function in addition to transport of water and sediment; they form zones of high transmission or infiltration losses. These zones then become settings for plants and animals which may be quite different than those found in the surrounding non-channel areas. Ephemeral arroyo channels are a major path for surface water to enter the subsurface. Sabol et al. (1982a) and Van Vactor (1989) have measured the infiltration rates of arroyos and found that the rates are about an order of magnitude greater than rates on soils in non-channel areas. Van Vactor used this fact to demonstrate (using a distributed parameter, single-event rainfall runoff model) that channel flow would seldom, if ever, transverse the bajada at the Jornada LTER and reach the valley playa. Hydrologists should devote more effort to studying the importance of ephemeral channels in arid and semi-arid watersheds.

Water Chemistry

Overland flow and channel flow have a common characteristic in that they both transport sediment (albeit at different rates) and associated nutrients and other chemicals. Inorganic chemicals in runoff from watersheds are typically anions and cations of bicarbonate, chloride, sulfate, sodium, potassium, calcium, and magnesium. Concentrations of these chemicals are controlled by groundwater flow to the channel system and dilution by snowmelt (Ward 1973). Watersheds exhibiting low groundwater transmission rates (thus allowing more time for the groundwater to be in contact with geologic materials) or low snowmelt (less dilution) tend to have higher concentrations of the major anions and cations. Nutrients such as nitrogen, phosphorous, and volatile suspended solids (organic carbon) are associated with surface soils and do not exhibit the same dilution phenomena as do the major cations and anions. We have been measuring nutrients in runoff from rainfall simulators as part of several different studies (Sabol et al. 1982c; Ward and Bolin 1989a and 1989b; Cole et al. 1990b; and Ward and Bolton 1991). Much of the work has been to fulfill objectives related to a long-term, state-wide modeling effort focussing on fisheries in New Mexico (Cole et al. 1990a). A summary of the work can be found in Bolton et al. (1991a) and Bolton et al. (1991b, these proceedings). In general, it was determined that for upland areas, total volatile suspended sediments (organic carbon) were strongly related to total suspended sediments (about 10% of the total was volatile), phosphorous was related to total suspended sediment, and nitrogen was not related to anything. These results now give us a technique for estimating loadings of the nutrients to channels.

Bolton (1991) took the analyses one step further by comparing the relationships observed in the upland simulator data to those relationships which could be developed at stream gaging sites on ephemeral and perennial channels. She found that for phosphorous and organic carbon, the simulator data tended to be somewhat higher at the same suspended sediment concentrations. This was not the case for nitrogen. Reasons given for these differences were that the phosphorous and organic carbon were probably diluted or scavenged, whereas the nitrogen could easily be enhanced by other chemical reactions in the channel system.

Water chemistry, then, is not a process in itself but an agglomeration of different processes ranging from surface erosion to groundwater flow. Water chemistry is further complicated, as in the case of nitrogen, when biotic activity comes into play. At present, empiricism and statistical modeling may be the best way to estimate chemical concentrations in runoff water.

Mass Wasting

Another process, which is not as important in New Mexico as it is elsewhere in steep watersheds, is mass wasting, commonly referred to as landslides. Mass wasting ranges from the very slow creep of earth materials in a downslope direction under the influence of gravity to the extremely rapid and violent debris avalanches associated with the flushing of extremely steep chutes or channels. I have conducted numerous studies on landslides (e.g., Simons and Ward 1976; Ward 1976; Simons et al. 1978b; Ward et al. 1979; Ward et al. 1980; Ward et al. 1981a and 1981b; Ward and O'Brien 1981; Ward et al. 1982; and Ward 1985) as they relate to the overall mix of processes in watersheds and in the planning and management of watershed activities.

Landslides can destroy productivity at the site of the failure and add large quantities of sediment to existing channels downslope, or completely scour channels removing the sediments and vegetation which comprised the riparian system (Simons et al. 1977b). Recently, we had the opportunity to study the Aguirre Springs debris flow which occurred in August of 1991. This flow was initiated by a heavy rain on already wet soils. The resulting water flow eroded a steep channel near the top of the Organ Mountains, and the ensuing debris flow scoured the lower level channels and left extensive lateral deposits of large boulders and organic matter. Our site investigations indicated that this was not the first time that the scoured channel had experienced a debris flow, as evidenced by older lateral deposits. Measurements made of high-water marks (debris lines), cross sections and channel slopes suggest that the debris flow may have had a peak volumetric flow rate on the order of 300 to 400 cubic meters per second, occurring in a channel which typically had a capacity of less than one-hundredth that rate. Although rare, such an event can and does significantly alter the water and sediment carrying characteristics of the original channel and watershed.

Natural Impacts

The flood/landslide discussed above is just one natural impact which can alter a watershed and channel system. Floods alone can have a significant effect on the total amount of water and sediment leaving a watershed. Ward (1983b) and Ward and Baker (1984) present data which show that for a managed pine watershed in northern Arizona, most of the sediment yield over a twenty-year period of record was associated with one or two storms with low frequencies of occurrence (one storm was estimated to have a return period of one in 100 years). This supports the observation that it is the low frequency-high energy events doing the most work in ephemeral watersheds.

Another natural impact is that caused by wildfire. At one time, before fire suppression became standard operating procedure, wildfire cleared out deadwood and understory growth, thus reducing the fuel source for subsequent fires. Fire suppression, in contrast, increased the fuel source. Subsequently, fires burned hotter and did more damage to the vegetation and to soil productivity. Wildfire, like floods and landslides, are episodic events which occur infrequently, cause damage, and then allow the watershed and channel system to heal. Bolin and Ward (1987a) documented this healing process following a fire in northern New Mexico. Within about three years following the fire, water and sediment yields returned to prefire levels. Similar recoveries were observed in the data presented by Ward and Baker (1984) for a major flood event, and is also evident in the renewal of Yellowstone Park after the great fire and the slow return of the area devastated by the eruption of Mount St. Helens.

Human Impacts

Human impacts, unlike natural impacts, tend to be continuous and pervasive throughout the watershed. The two major impacts inflicted by man on watersheds are timber harvest operations and cattle grazing. Timber harvest operations require that roads be built in places that may be unsuitable. Over the years, we have studied the impact of roadways in forested watersheds (Simons et al. 1978a; Li et al. 1979c; Simons et al. 1980; Ward and Seiger 1985; Ward 1985; and Riggins et al. 1989a). It is estimated that between 70% and 90% of the suspended sediment found in channels of forested watersheds is derived from roadways.

Reduction in canopy cover from timber removal and disturbance of vegetative and litter cover by grazing and logging activities are two other severe impacts on a watershed. Ward et al. (1990) and Bolton et al. (1992b, these proceedings) clearly show the effects of cover removal on the hydrologic function of the vegetation-soil complex in the pinyon-juniper zone. Bach et al. (1984) and Bolin and Ward (1987b) had previously described the effects of cover in desert grasslands/shrublands. It is my observation that if ground cover is reduced below 50%, erosion and runoff will increase significantly. It is with these studies and observations in mind that I question the wisdom of the "new perspectives" approach to removing canopy cover (pinyon and juniper), which is really an old idea and practice, in an attempt to increase grass growth to encourage more grazing. Canopy removal will not in the long run add any more water or any more biomass than carefully controlled or restricted grazing practices. Ward and Baker (1984) make a similar statement about watershed treatments in Arizona which were conducted to improve water yield.

CONCLUSIONS

In this paper, I have attempted to summarize concisely some of the observations and findings my research associates and I have found or developed over the last twenty years of studying watershed processes. Watershed processes are complex, highly interrelated, and vary in space and time. Although we have learned a great deal about the processes, we have not yet achieved a level of confidence in our modeling to guarantee accurate predictions. Some of the errors we find are related to our inability to estimate accurately watershed and channel characteristics/parameters useful in modeling. Other errors are related to our failure to represent correctly the processes involved with our mathematical surrogates. Probably most of the errors we find in our watershed modeling is inherent in our attempts to try to make a complex system simple.

As scientists and engineers, we need to transmit our ideas and findings into concepts and rules which are useful to land managers. Although models are one way to achieve that goal, simple rules-of-thumb based on common sense and supported by good science will find greater use.

After twenty years of sampling, measuring, analyzing, and modeling, I have answered many of the questions I started with, but I now have more questions than when I began my career. In the next twenty years, I hope that my colleagues and I will be able to answer some of those questions.

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