# Watershed Form and Process

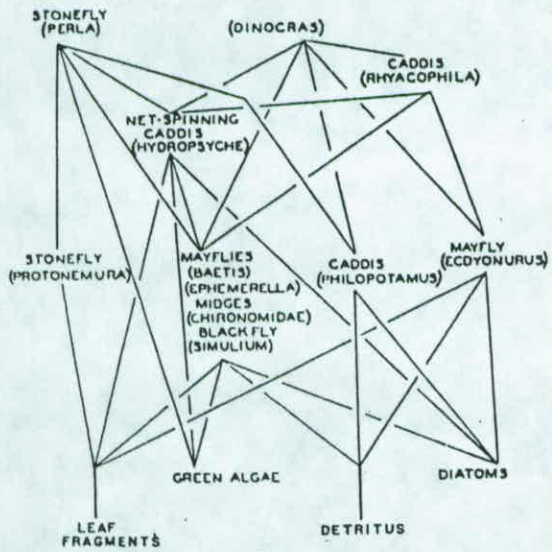
# The Elegant Balance

BY ROBERT R. CURRY

All of Earth is a manifestation of energy flow and ordering. The fundamental difference between organisms and non-living things is that living things can store and convert energy and can order its expenditure at times different from when it is received.

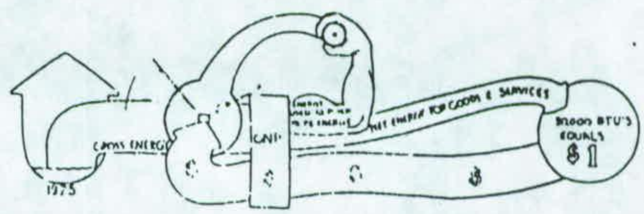
The stone cannot convert the sun's energy to carbohydrate and thus save that energy for later release during the coldest part of the night. Similarly, the potential energy of each drop of water cannot increase after that drop falls to the ground. It can remain constant momentarily in a lake or glacier but can only run downhill, decreasing its solar-derived potential energy while expending kinetic energy as work within the watershed.

Both the living and inorganic (rocks, soil) components of the earth's surface make up a single open thermodynamic system. Together, they are bound together as the pathways and equilibria of energy flow at the surface of the earth. Energy utilization by living parts of the landscape <u>and</u> the energy and material pathways in the non-living parts of the landscape <u>are</u> the essence of watershed science. In watersheds, nutrients and materials cycle through many inputs of solar energy while landforms are shaped by one particular kind of solar input — running water. In summary, despite the different ways energy moves through and is stored by rock, soil and life, they are all inextricably bound by the sun-driven cycle of water and by thermo-dynamic laws.




**Watershed vs. Ecosystem Thought**

*Watersheds have rarely been used as natural conceptual boundaries for ecosystems. Ecology as popularly perceived has focussed primarily on the biological end of the spectrum. Watershed science is the study of the biological* and *geochemical roots of life-support. In this essay, the ecosystem concept will be opened to accommodate the flow of energy and materials through time and space.*




**Watershed Energy and Economic Thought**

*It is true that man has learned to supplement the energy flux in his biologic niches through consumption of fossil fuels and it is likewise true that we consume ever increasing amounts of this supplemental energy. But albeit damaging, the human flux of energy is still but a fraction of a percent of the total solar flux at the earth's surface. Our world fuel consumption in 1975 is but one thirty-four-thousandth of the worldwide solar flux.*

*Fossil fuels primarily change the energy flux in the economic systems of the world, but not in the sum total of watershed ecologic systems of Earth. Fossil fuels are converted to goods and services to exchange for money to develop more fossil fuels. In most contemporary economics, materials and energy are not related to sun-power and thermodynamics. So, forget this contemporary sense of energy right now. See energy as it interrelates to watershed form and process. This will let us see watershed function — the Middle Way, the optimum way of energy flow on earth. As Gary Snyder says: "Electricity for Los Angeles is not energy." It is commodity. Earth's energy is much greater, bigger, sacred. As William Blake said: "Energy is Eternal Delight."*

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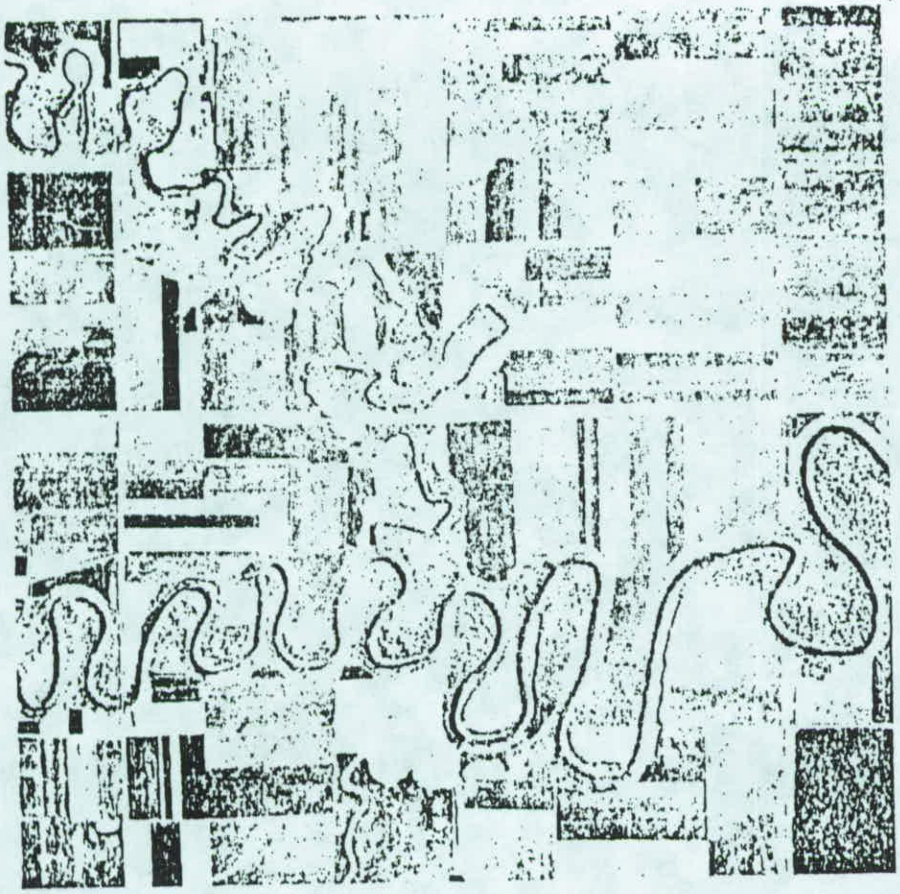
*Robert R. Curry has been one of the strongest influences in my life in recent years. Just walking a proposed logging road and hearing what he had to say about hillslopes and running water was sheer pleasure. He is a professor at the University of Montana, Missoula, advisor on earth science to the U.S. Senate Public Works Committee and was Director of Sierra Club Research.*

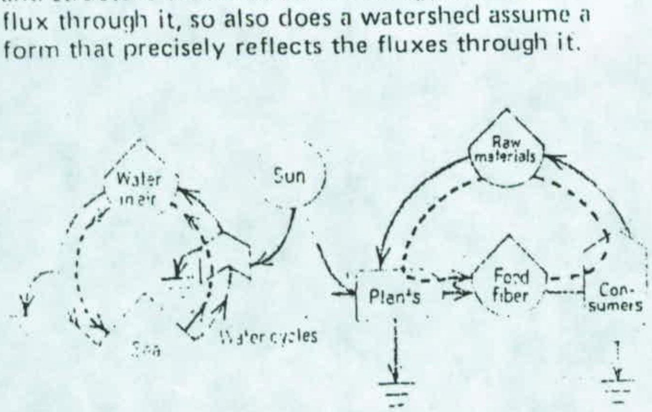
*There is a real need to liberate the imagination of scientists and give them space to trip out on their own work.* CQ *is a perfect magazine to allow loose and far-out science. Bob's article had to be drastically reduced because of limited space and I reworked it (I hope O.K.) so that more* CQ *readers could take his plunge into the wildness of entropy and landscape evolution. —PW*



*This airphoto (map) view of stream channel form in the midwest illustrates how form reflects process and stability. The main trunk stream is meandering in a smooth sinusoidal pattern while flowing from left to right. Note that after the tributary stream discharges into the main stream, its meander wavelength and amplitude increase to accommodate the increased water and sediment. But also note that the tributary does not have a smooth equilibrium channel pattern. Close inspection reveals that it is dammed and water is taken out for irrigation. Further, at some point in time, the riparian vegetation of cottonwood trees was removed or partly cut, increasing sediment load. All of these assaults have created a non-equilibrium form that indicates that the channel will meander in an unpredictable way. This has been important in limiting the farm use of the lands adjacent to the side tributary. More land is not tilled next to the small tributary than next to the larger stream. Disturbance of the watershed has cost in terms of stability and productivity of the side-stream tributary.*

## The Watershed

A watershed is a system. It has energy and material flux, dominantly through the solar-energy-driven hydrologic cycle. We all understand at least the basic concepts of the hydrologic cycle, but few perceive that the form of the watershed system, as well as its stability, its equilibrium, and its biologic productivity is precisely and accurately controlled by this energy and material flux. Just as an ecosystem, a tropical forest for example, takes a form and structure that reflects the energy and material flux through it, so also does a watershed assume a form that precisely reflects the fluxes through it.




*Flows of solar energy drive the material cycles of watersheds. The material is water (left) flowing between two energy "storage tanks" we call clouds and sea. The sun adds heat energy to water and evaporates it. This counters gravity creating the rain-runoff-evaporation cycle. The materials are nutrients/minerals (right). The sun energy feeds the plant "production" plant which flows through the food chain and back to soil/atmosphere when the living creatures die and decay. Both diagrams are greatly over-simplified.*

The fundamental lesson to be learned is: that a change in energy flow through a system will be reflected by a change in form in the system that was shaped by the flux. This is a most fundamental principle that must be understood to live upon the land surface of this or any other planet.

## Energy: The Flow and the Order

To repeat, all of Earth is a manifestation of energy flow and ordering. The Form of a watershed refers to its relative proportions of hillslopes, stream channels, flood-plains, and mountain tops, and the shape of these in terms of length, width, and relief. The watershed system is generally made up almost entirely of hillslopes. About one percent of the watershed area is made up of stream channels that serve to drain the system. Additionally, we must consider the factors like drainage density, slope shape and steepness, soil stability and development and relative dominance of various geologic erosional processes like gullies or landslides as all contributing to basin form.

Energy flux refers to the transformation from potential energy to kinetic energy that occurs when water flows downward through a watershed system and, on its way, does the work of erosion and transportation. Over 90 percent of the energy expended in a stream channel is dissipated as frictional heat, but the rest can do geologic work. Some energy is derived without the direct aid of the sun through movement of matter through a watershed system under the direct influence of gravity or wind. The ultimate source of gravity-transfer potential energy is the rotational energy of the earth manifest in mountain-building forces, and the indirect effects of heat-flow from within the earth. All of these energy sources together flow through watershed systems to modify those systems and transport materials within those systems.

### Watershed Equilibrium

This watershed system works so remarkably well and is so perfectly integrated no matter what its size, geologic history, vegetative cover, or region of the world, that there must be some underlying principles of form and process that control its origin and development.

The hillslopes provide runoff and sediment to the stream channels in just the right proportions so that the river may carry them out of the watershed over the gradient (steepness) that must be traversed. All of the tributary watercourses discharge into the main streams at precisely the elevation of the main stream. Each side stream is accurately scaled to its individual watershed.

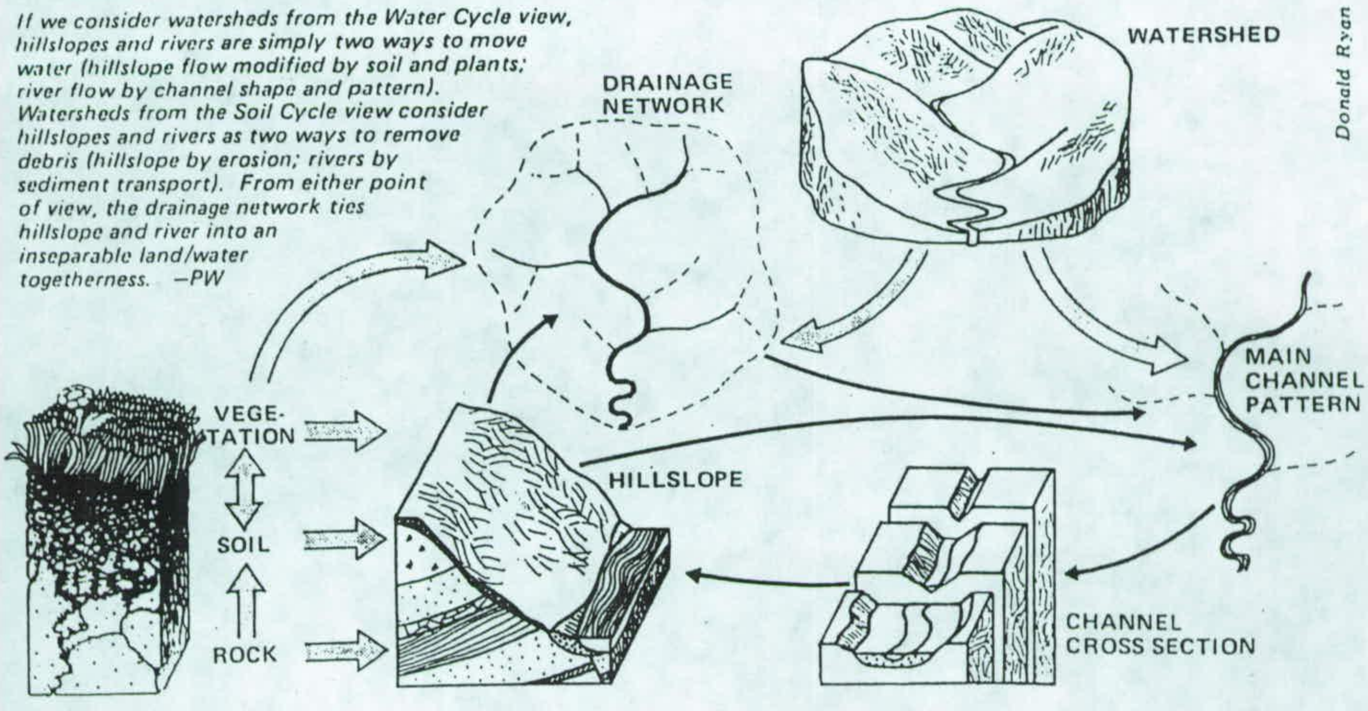
The critical thing to remember about watershed systems is that the rivers, the hillslopes, the mountain-tops, and the flood-formed bottom-lands are really all part of one watershed system. All are integrated with each other. The shape of the hillsides controls the rate of energy expenditure of water flowing over and through them, and are thus themselves a function of the local energy flux. *All biotic elements in the watershed interact with and modify the energy flow through the watershed system so it therefore clearly follows that the shape of a watershed is a function of what lives there.* This perfectly fundamental and very simple fact has seemed to escape mankind's segmented and regimented thought. We seem to believe that the non-biologic portions of a watershed can be changed to suit our perceived needs without a concommitant change in the physical system. But energy ties both together. If we remove a forest cover that earlier had stored and converted a portion of the solar energy falling upon that system and that had intercepted and transpired a portion of the water falling on that system, then it follows that the energy flux through that watershed is changed and the very shape of the hillside and stream channels in that watershed must adjust as rapidly as possible to accommodate the change.

An equilibrium state is one in which the many variables of a watershed system are dynamically balanced. On slopes, for example, the profile is the result of a balance between runoff, infiltration, and erosion. All of these are modified by the degree of soil development since that in turn controls what grows on the hillside and thus controls runoff, infiltration, and erosion. Soil development is in turn determined by the age and stability of the surface. Age and stability are in part a function of the history of runoff, infiltration, and erosion at the site; which are themselves in turn a function of the history of climatic and biotic activities on the hillside. Each integrally intertwined loop rests within a larger loop and all determine the state of equilibrium. Upset of the balance can be compensated only to a certain point, and then disequilibrium occurs.

We are most familiar with disequilibrium through the interactive reactions in a watershed following logging. Runoff intensity usually increases, thus causing erosion of hillslopes. Simultaneously, flood waters reach watercourses faster due to denser and more effective integration of rills and ephemeral channels on the hillslopes, and flood heights increase. Increased sedimentation and increased flooding lead to increased lateral erosion of stream channels that

**WATERSHED SHAPE**

*If we consider watersheds from the Water Cycle view, hillslopes and rivers are simply two ways to move water (hillslope flow modified by soil and plants; river flow by channel shape and pattern). Watersheds from the Soil Cycle view consider hillslopes and rivers as two ways to remove debris (hillslope by erosion; rivers by sediment transport). From either point of view, the drainage network ties hillslope and river into an inseparable land/water togetherness. —PW*



must change their channel geometry to accommodate a greater percentage of sediment load to water discharge. This results in a wider, shallower stream channel flowing at a somewhat steeper gradient. A wider channel will undercut adjacent hillslopes downstream from the area disturbed by logging. These undercut hillslopes are steeper and thus erode faster, thus further adding insult to injury in the already sediment-choked stream. Aggrading channels result that plug free-flowing watercourses with braided changing streams, and side slopes continue to ravel and erode until the slope steepness is once again reduced to an equilibrium profile that extends to the drainage divides. In this fashion, a headwater change in biota can effect a change in the shape of the whole watershed below it.

### Law of Minimum Variance

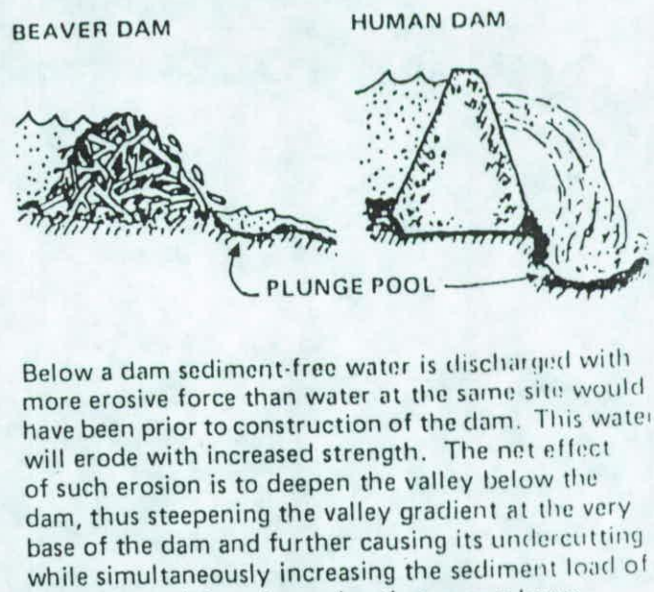
Stream channels and hillslopes assume a form that is adjusted very delicately to optimize two different tendencies. The first tendency is: watersheds will tend to assume a form in which the rate of energy expenditure remains constant through time and space. This means that the longitudinal (descending) profile of a river or the steepness of a hillslope will adjust itself so that the water flow will not become more erosive or less erosive as discharge (runoff plus rainfall) increases. The system will respond to minimize the effects of the agents causing the change, but some change will occur.

For example, what if the slope is made less steep? Someone cuts a road into the slope and locally breaks the equilibrium slope profile. The stream now has less sediment to move. It has increased energy. It uses that energy to downcut. That downcutting locally makes the slope immediately adjacent to the stream steeper. The material eroded in the channel becomes sediment in the stream and replaces that previously supplied from the altered hillslope. Each of these reactions work against the action resulting from the disequilibrium and work to reestablish a balance. This is LeChatielier's Principle and is manifest in all natural systems governed by basic thermodynamic law.

Similarly, compare a watershed dammed by a beaver vs. man. The hillslopes above the dam continue to function as if the dam were not there. The river above the dam continues to carry water and sediment as before. But when the flowing waters reach the quiet water impounded behind the dam, the river gradient suddenly becomes zero and sediment transport essentially stops. Water continues to pass down toward the dam, but sediment forms a delta at the point of contact between the reservoir and its inlet. This deposition goes on to build up a wedge of sediment extending upstream well above the reservoir level so that the gradient of the feeding river increases to better carry the sediment into the reservoir and toward the dam. Ultimately, as any old beaver knows too well, the river constructs what amounts to a sediment bridge across the reservoir and over the dam, thus reestablishing sediment transport and rendering the reservoir ineffective.

> **"Niagara has power and it has form and it is beautiful for thirty seconds, but the water at the bottom that has been Niagara is no better and no different from the water at the top that will be Niagara. Something wonderful and terrible has happened to it, but it is the same water and nothing at all would have happened if it had not been for an aberration in one of nature's forms. The river is the water's true form and it is a very satisfactory form for the water and Niagara is altogether wrong."**
>
> *— Gertrude Stein, 1935*

To pursue our example, what of the water that has been passing over the dam all this time? At the spillway or point of overflow, the local stream gradient has been greatly oversteepened and the water has been deprived of its sediment load. At the base of the dam or waterfall this higher velocity sediment-free water has great erosive force and forms a plunge-pool, undercutting the dam and tending to remove it to reestablish longitudinal equilibrium of the watershed system. If beavers rather than the Corps of Engineers constructed the dam, long experience has taught that a leaky dam will hold more water than a tight dam that overtops and erodes at a concentrated spot. Thus beaver dams can be quite effective sediment traps for long periods (most human dams no matter how large cannot be expected to remain unplugged for more than about 100 years, yet some mountain-meadow beaver communities have effectively trapped sediment for millenia).[1]




Below a dam sediment-free water is discharged with more erosive force than water at the same site would have been prior to construction of the dam. This water will erode with increased strength. The net effect of such erosion is to deepen the valley below the dam, thus steepening the valley gradient at the very base of the dam and further causing its undercutting while simultaneously increasing the sediment load of eroded materials and carrying that over a lesser gradient since the incised stream cannot lower its ultimate baselevel. All of this tends to balance the system while working to remove the obstacle.

Many more examples could be given, but one more will suffice to illustrate the range of adjustments possible. Suppose a watershed is urbanized. Homes are built, roads are paved and compacted, areas are

1. The beaver didn't just build a dam, it changed the energy flow in the watershed. Other components of the watershed such as the river and alders or aspen will try to balance this by removing water on the reservoir.

roofed-over and the general permeability of a part of the watershed is impaired. In this case runoff is provided to the watercourse faster than it would have been in an undisturbed situation. In a greatly urbanized case, total volume of runoff may increase since moisture that previously filtered into the groundwater system or previously was transpired or evaporated directly from the watershed will now run through a gutter or street and enter watercourses more directly.

But the real change is not in the volume of water but its routing to the stream. More rapid routing means faster rise of the runoff flood peak. In essence, it means that the shape of the watershed is wrong in comparison to the geometry of the stream draining it. A natural watershed would respond by increasing the number of overbank flows that occur. In other words, a flood height that occurred once every hundred years now will occur once every twenty years or less. Floods become bigger and more frequent. This is so because the passage of water into the rivers is faster and the watershed shape cannot adjust to equalize the rate of energy utilization all along the drainage network, so flooding and sediment movement increase to locally balance the system.

The attempts of the drainage network (now pipes, gutters as well as streams) river channels and cement aquaducts and hillslopes (both pavement and soil) to re-equilibriate may progress for centuries. Parts of the Susquehanna watershed have been rapidly urbanized. Recently, following a rare but not unpredictable incursion of a tropical hurricane, sudden catastrophe ensued. A single 100-year rainfall yielded a 1,000-year flood. Eastern U.S. flood victims defined and zoned flood-plain areas based upon a historic record of flooding that no longer bears much direct causal relationship to suburban land use in the Susquehanna watershed. No wonder they feel eligible to apply for disaster-relief funds. Similarly, the Big Thompson Canyon in Colorado has experienced a flood of inestimable "rarity" of on the order of a one-in-ten-thousand-year event associated with only a once-in-300-or-so-year precipitation intensity following the paving and urbanization of a critical part of that watershed adjacent to Rocky Mountain National Park. LeChatelier's Principle seems to govern the removal of those very human agents perturbing the watershed systems.

Hillslope form and man-made obstructions make energy distribution unequal for different stretches of the watershed. Waterfalls are eroded by the river to equalize the energy flow rate. Dams are undermined for the same purpose. The watershed "wants" to vary minimally (not erratically) and will change its form (hillslope, drainage pattern, river channel, vegetation) in order to govern its energy flux.

### The Principle (Elegance) of Least Work

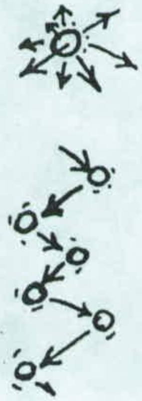
Watershed equilibrium is not just a result of a constant rate of energy spent in erosion, deposition and transportation of materials in the system. It is also, the result of energy doing the least work possible at each stage of the river and hillslopes.

For example, we may wonder why rivers are not sloped straight down from headwaters to mouth. A straight river, after all, would minimally vary its slopes. But, a river that has a straight slope would have a high variance in the amount of work done along the profile.

There is so much more water downstream (more tributaries and more collection of rainfall), streams and slopes become progressively less steep downstream. That is, streams and slopes tend to be concave upwards. The concave profile is necessary to adjust the work expenditure to minimum variance. Consider: One hundred cubic feet of water falling one foot per mile can do as much work as 10 cubic feet of water flowing down 10 feet per mile over the

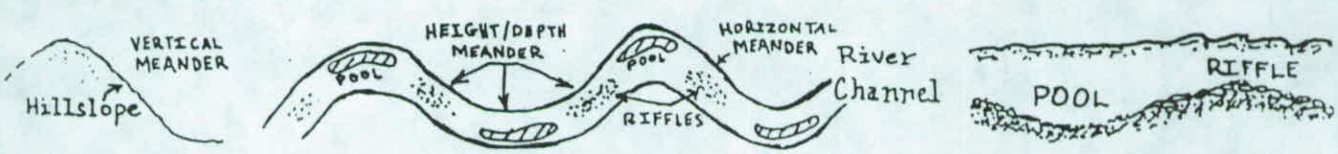
## Entropy and Landscape

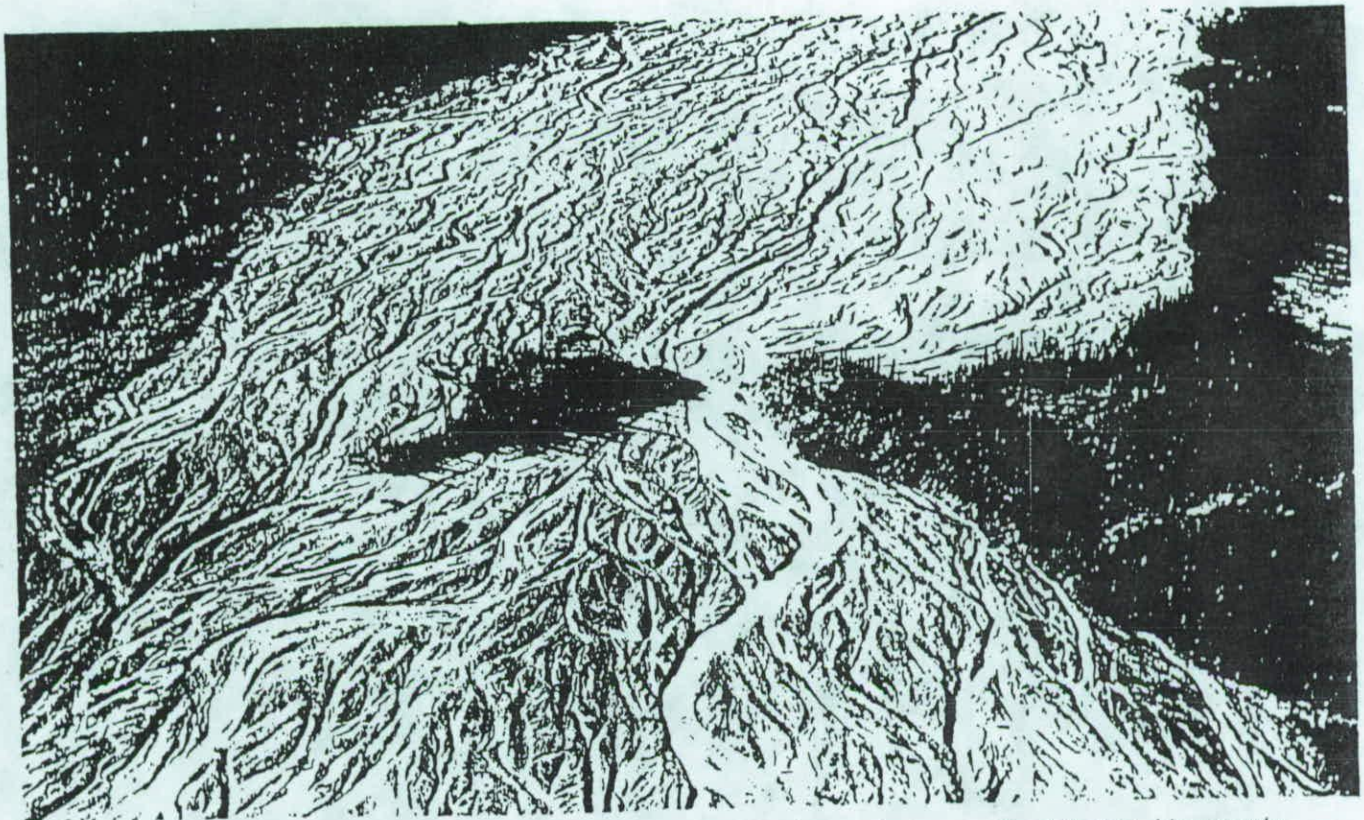
While it is true that on a flat surface, the shortest distance between two points is a straight line, this is not true for a point (like a water droplet) in motion. At any moment along the line, the droplet can theoretically go in any direction. In a space capsule, without gravity, water droplets do, in fact, have this "total" freedom of possibilities. Possibilities of going in any direction are limited on Earth by the constraints of gravity. Under the influence of gravity the shortest distance of a free moving particle between two points is a meandering (sinusoidal) curve. This is the path of a rather inebriated man attempting to go from the bar to the restroom but unable to keep his goal completely in focus. The vertical slope of a river as well as the horizontal meander of a river as well as the pools (deep water) and riffles (shallow water) inside the channel all approach a meandering line.



In theory, these are called "random walk" models constrained by gravity. They relate to entropy in that entropy always increases as potential energy is used up. Think of the rain drop on the mountain top. It is full of possibilities and potential energy. It can flow down in any of 360 degrees (any slope of the mountain) and can do all kinds of work as it flows to the sea. It has low entropy. By the time the droplet is in the ocean it has used up all that potential: it can only float (unless given new energy by the sun-driven water currents or evaporation or moon-driven tides) and has no work potential. Entropy has increased. Lakes half-way down the slope temporarily remove possibilities of movement but retains potential energy. Waterfalls eliminate possibilities of movement (the droplet essentially falls straight down) and uses up potential energy fast.

Rivers "try" to make the transition from maximum possibilities of movement and maximum potential energy (mountain top) to minimal possibilities of movement and minimal potential energy (the sea) as even as possible. Thus, we say a river tries to gain entropy equally along all its stretches (parts). This is the foundation of the Law of Minimum Variance and the Law of Least Work.





*Braided flow on gravelly bed of Muddy River a short distance above its junction with the McKinley River, Alaska. Most of the sediment is stored in the channel, so the channel changes its position continuously to flow around the load of sediment (mid channel bars) it cannot handle. Braided rivers have erodable banks so that the bars can be circumvented rather than washed away. Braided rivers, like meander rivers, are an equilibrium river form -- having a particular bank material and a debris load too large to be carried by a single channel. In itself, braided rivers are not "overloaded" with sediment but, if the river bed is building up, braiding may result from upstream disruption of the watershed*

same horizontal distance (100 ft-lbs of work). If more volume of water lower in the watershed can do more work, the slope must be less to balance the work load.

This is a second thermodynamic principle for open, steady state systems: a watershed tries to do the least work possible, it tries to minimize work at each point along the river. In other words, hillslopes and streams try to maximize the efficiency of energy through time and space.

Instead of the descending pattern of a river, now consider the horizontal pattern. A straight channel like an irrigation ditch or channelized stream can transport water and sediment efficiently only for given ratios of water and sediment. If the proportions change in space or time, sediment is temporarily stored within the channel and the river must be able to swing around the gravel bars during low flows. In addition to meandering, the river may alternate deep pools and shallow riffles. These forms of channel pattern do the least work as well as minimize variance in the rate of expenditure of that energy as work.

In summary, unlike living creatures, running water cannot store up energy accumulated in its downward fall so it must use it up as soon as it acquires it. Water acts by erosion and transportation and deposition of hillslopes. As it moves, hillslopes and channel create a form that "tries to" minimally vary its shape and minimally vary the expenditure of [illegible] energy throughout time and space.

## The Middle Way

In a river watershed, equilibrium is manifest by balancing the tendency to do the least work necessary in a particular place in the river and the tendency to expend energy at a constant rate through the system.

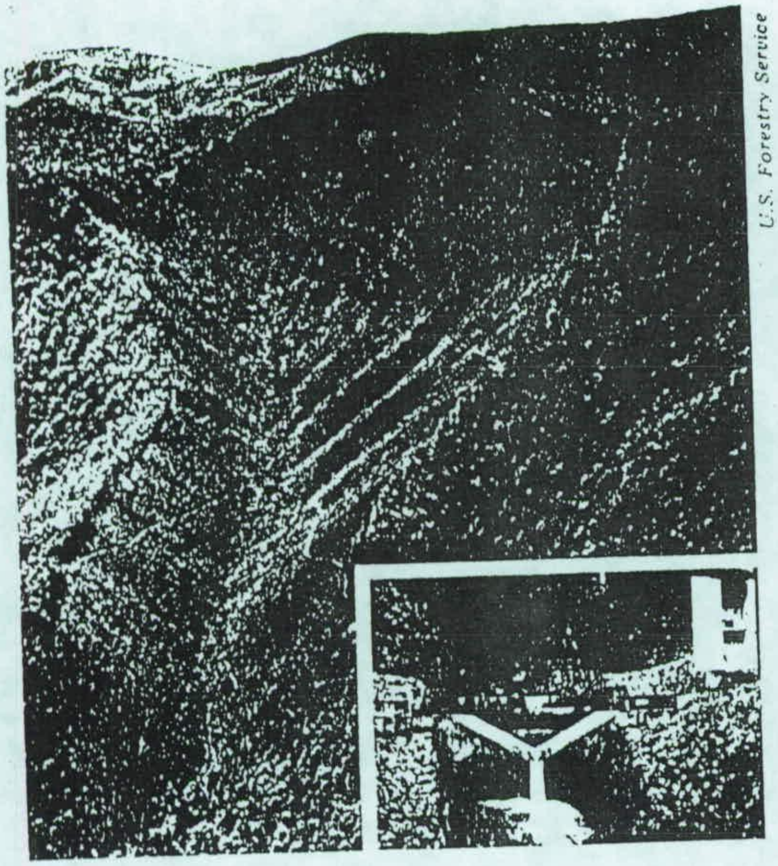
Since the system is itself formed as a result of energy flow that is in turn controlled by these separate but interactive tendencies, it follows that rivers achieve a balanced form. Flowing water seeks a middle way -- a dynamic equilibrium between these two tendencies.

Stream and slope profiles are neither straight nor exponentially concave, but generally are a combination of the two. Some slopes are straight where discharge may remain constant downstream or other hydraulic variables may adjust to compensate for increased discharge. Some slopes are even convex such as near the summit of a hill where runoff may seldom if ever occur due to the permeability of the soils. Each slope reflects the balances that result from the flux of energy through it.

*(more →)*

**"Do you think you can take on the universe and improve it? I do not believe it can be done. The universe is sacred. You cannot improve it. If you try to change it, you will ruin it. If you try to hold it, you will lose it."**

– *Lao Tsu*
Tao te Ching



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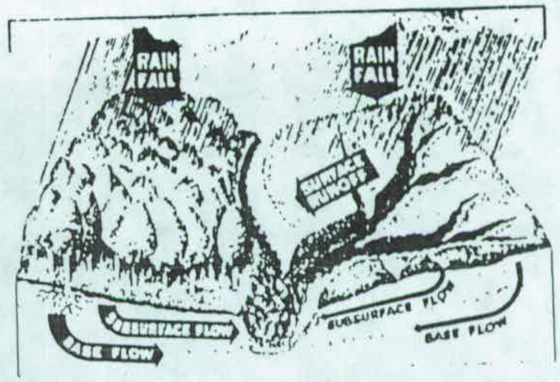


*Distribution of rainfall on vegetated and bare areas into surface runoff, sub-surface flow, and base flow. Width of arrows indicates the relative amount of each component.*

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*Experimental watersheds at the Coweeta Hydrologic Laboratory in the mountains of western North Carolina. All the trees have been cleared upsetting productivity of plant life but not hill-slope form. Nevertheless, rain-fall follows a new path as it traverses the hillslopes. This is shown in the top diagram. Below surface water flow decreases (narrow arrows) while surface runoff increases. This increase in surface runoff may lead to disequilibrium and a new drainage network.*

*Insert shows V-notch weir used to measure water flowing out of watershed. Experimenters are comparing this watershed to an undisturbed forested watershed.*

The optimization of balancing tendencies in a watershed system is "sacred." When the form of a watershed is changed through physical manipulation of the non-biological components of the system, the flux of energy through the system must change and this will affect both the living and inorganic components of the system. When the ecosystem is changed, then the energy flux will change and the energy distribution and rate of transfer will change resulting in a change in the physical form.

## Ecosystem/Watershed Productivity and Stability

An important corollary to the principle that a change in flux = a change in form is that a change in watershed form results in a decrease in site productivity and/or stability. This is the single watershed concept that most affects mankind and other organisms living in or below watersheds.

Bear in mind that all life is a storage/transfer medium for energy. Life exists in energy flux niches. Solar energy is trapped by the plants that live on the surface of the watershed. It is held in storage by plants, converted to other energy-bundles by being eaten or by the plants themselves. The efficiency of trapping solar energy by a watershed is measured by the time delay (length of storage) that is possible in the living systems inhabiting that place. Inanimate energy storage such as water in a reservoir or heat in a rock cannot be controlled by all life forms in an ecosystem. There is no way that the energy can be stored for very long in these inanimate media and much dissipates before a living creature can utilize it. Efficient energy utilization in a natural system is the result of a great many conversions and storages of energy as it passes through that system. Many available energy flow niches are filled with living subsystems that can use the flowing energy. The energy "ages" in the system. The system is "mature."

But, despite much popular literature, natural communities are not just a biological system. The ecosystem is a chemical and physical system too. The efficiency and maturity of the ecosystem is largely dependent on the degree of chemical weathering of the rocks and soil and the biological availability of the nutrient portions of the system. In simplest terms, the soil status controls the efficiency of energy use by the ecosystem. Living organisms require both nutrient and energy fluxes.

Stability in natural communities means that the "system" has developed an inherent resistance to change. It is to some extent self-governing. Thermodynamically, stability must be seen as the ability of that system to sustain stress without loss of potential thermodynamic efficiency. This is really a very simple concept, if viewed from the perspective of geologic time. A stable system can withstand a fire or insect infestation or drought without so great a loss of its "nutrient capital" in both biomass (plants and animals) and soil/rocks that the watershed community's ability to trap and convert solar energy is impeded beyond the community's response-time to that stress.

For example, after a prairie fire, nutrients are washed out of the system and many are lost in the fire. A prairie fire in the fall greatly curtails energy fixation by the ecosystem for a year or two but by then a mosaic of species would exist that could trap energy and maintain nutrient cycles with a degree of closure or retention that is at least equal to that before the fire. From then on, the prairies system increases its nutrient capital and biologically-stored energy until the time of the next major stress. The net result through time is a maintenance or gain of stress-resisting nutrient capital in the soil of that ecosystem. In an unstable system, long times are necessary to replace those nutrients. Plant succession reflects the intervening less-stable state.

The more "mature" soil systems provide for greater nutrient reservoir storage to permit wider adaptability and niche utilization by the biota. This leads to maximization of energy capture and use efficiencies. Optimization of watershed equilibrium balance leads to land surface stabilization which in turn permits maximal soil development. Optimization in biologic systems results in the maximization of both site stability and site productivity. As Garrett Hardin has stated, you cannot simultaneously maximize both productivity and stability in natural systems.

An eutrophic pond uses more solar energy to fix more organic carbon than a mixed woodland. That is, the eutrophic pond captures more solar energy which makes it very productive but pond life is unstable because of the "run-away" production of algae which may, in extremes, kill off fish. The mixed woodland uses less solar energy but is more stable: the amount of tree flesh (biomass) doesn't fluctuate wildly, the number of species doesn't vary greatly, the productivity is less than the eutrophic pond but varies minimally.

One can imbalance toward greater stability or toward greater productivity, but one cannot achieve a higher combination of the two than that of Lao Tsu's "universe." Over time, and through the changes that are the rule through time, natural communities achieve a balance of maximum productivity and stability when their watersheds are in dynamic equilibrium. Once a hillslope begins to erode differentially to adjust to different runoff and infiltration conditions, its soil mantle is degraded. Such soil loss or structural change will result in a decreased ability of that soil to sustain a stable, diverse group of life forms that will utilize the energy flux as fully as is potentially possible.

We thus have an ecosystem/watershed theorem of behavior. Perturbations in watershed equilibrium will decrease system efficiency in trapping energy and will thus decrease long-term productivity. This theorem is critical to understanding man's agricultural and silvicultural interactions with watersheds. Forests on public lands are managed according to a "multiple-use sustained-yield" act which states that yields must be maintained in perpetuity. Watershed manipulations must not cause a physical change in slope profile equilibrium, nor increase the rate of physical soil erosion, nor break the nutrient/materials cycle to the extent that it will upset the community's efficient use of solar energy. Any time mineral nutrients stored in soil or litter are no longer demanded by plants and animals (e.g., clearcutting), these nutrients may be lost from the system through runoff into the water courses. A natural floodplain may trap the nutrients and keep them nearby, but they are lost from the hillside sites. Thus, site productivity and stability will decrease until very slow geologic mineral weathering returns the nutrients to the soil reservoir over future millenia..

## Watersheds and History

The watersheds are our energy mediators. They are our life support. They provide for ecosystem support. To maintain their energy trapping effectiveness under increased stress, we must supplement energy and nutrient storage such as through fertilizer or tractor-power in agronomic systems, and these are unstable systems. We cannot make the watersheds work better in temperate geologically evolving regions of the earth.

We must learn to respect the watershed because it comprises the very roots of our life support system. It is the great tributary system that reaches out to collect material and energy which it feeds to its biota. It is really the root system for life.

Watersheds have built-in historically "learned" responses that are adaptable to major changes at the earth's surface. They have response characteristics to optimize energy flow and nutrient retention following fire and flood. No fire is "bad" in the sense of destroying a watershed. Change may go on rapidly after a fire as a new equilibrium state is reached, but the watershed has gone through this before and will probably reoccupy old flood plains long abandoned or move sediments that have been waiting long for this large flux event. The key is that the shape of the system reflects the history and thus the adaptability of the site. The great river terrace sequences of the Connecticut River valley or the Missouri reflect past periods of enormously increased flows with even greater increases in sediment loads. These discharge events occurred during the past periods of major glacier advance into headwater areas. These glacial episodes will occur again and the rivers will readjust to them and begin once again to move sediment left beneath Hartford or Great Falls on a blustery afternoon 20,000 years ago. It is all going according to perfect natural plan. ■


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