River Morphology as an Analog to Darwin's Theory of Natural Selection

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River channels exhibit a remarkable similarity, regardless of size. There is a neat progression of shapes and dimensions from the smallest rill to the Mississippi or the Amazon. There are, of course, differences among rivers in various climates and geological settings, but such differences seem overshadowed by similarities.

For example, meander curves (see Figure 1)—the beautiful bends and loops of rivers seen most clearly from an airplane—appear similar in shape because there is a nearly constant ratio of wave length to channel width. The consistency of these relationships can be seen by the remarkable correlations shown in Figure 2. The plotted data represent individual locations on a wide variety of streams, rivers, and flumes where the radius, wave length and width could be measured on maps, photographs, or in the field. Comparable consistencies among different rivers exist in their hydraulic geometries, exemplified by the relations of water discharge to mean values of width, depth, and velocity.

Had these characteristics been widely recognized in the last century, they probably would have been used as arguments for the teleology widely accepted in biology at that time. The concept held "that everything in nature and its processes leads to a . . . predetermined goal, . . . and that the world was driven by some intrinsic force or directly by the hand of God which would lead it to ever-greater . . . perfection" (Mayr, 1991, pp. 125-29).

Indeed, the nearly perfect geometry seen in some river forms evokes a wonder comparable to that we experience in observing components of the biologic world. It has been difficult for scientists in the fields of geography, geomorphology, and hydraulics to assimilate into a coherent philosophy the several aspects of river channels that evade explanation by simple determinism:

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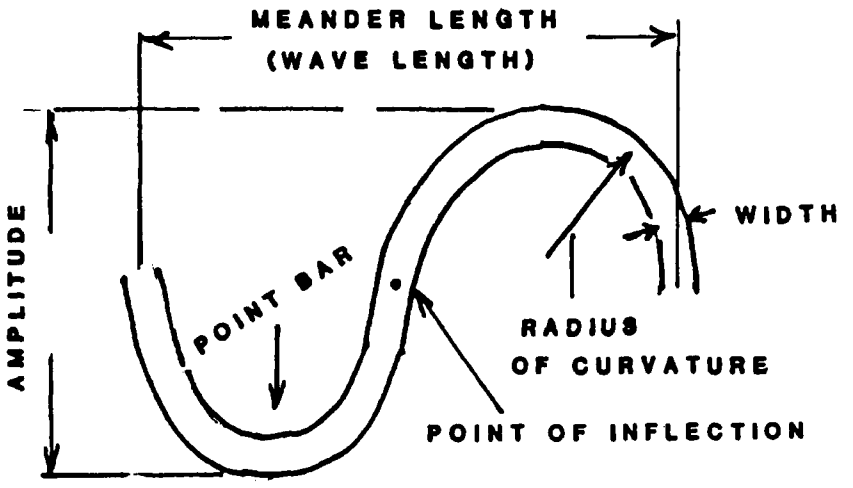


FIGURE 1. Definition sketch of a river meander.

River characteristics of paramount importance and great generality might be stated as:

1) similarity of forms without exact identicalness;
2) despite general similarities, uniqueness of each individual location along a channel that leads to scatter or intrinsic variability in relationships such as Figure 2;
3) reaction to change in environmental conditions such as climate and tectonic alterations;
4) tendency to assume forms that minimize expenditure of energy;
5) tendency to assume forms that make energy expenditure uniform along a segment of channel length;
6) dependence on random effects;
7) change of a river's form and pattern through time that often shows evidence of the influence of its past history.

These statements about rivers are reminiscent of a summary of Darwinian philosophy concerning natural selection that was analyzed in a most lucid manner by Ernst Mayr (1991). It was Mayr's stimulating essay that crystallized in my mind concepts with which I have struggled for some years as I continually return to *The Origin of Species*.

Mayr was concerned in his essay with the reasons Darwin's ideas were so vehemently resisted for at least half a century after initial publication. My concern is somewhat different. I seek ways of making more clear the relation of physical laws, tendencies expressed in the concept of entropy, and the influence of chance (stochastic processes) on the observed characteristics of river channels.

The educated reader has a general, though perhaps not detailed, understanding of the relation of DNA to the gene and the multitude of genes in any advanced organism—there are many thousands in a human being. Many specific traits of an individual can be traced directly to

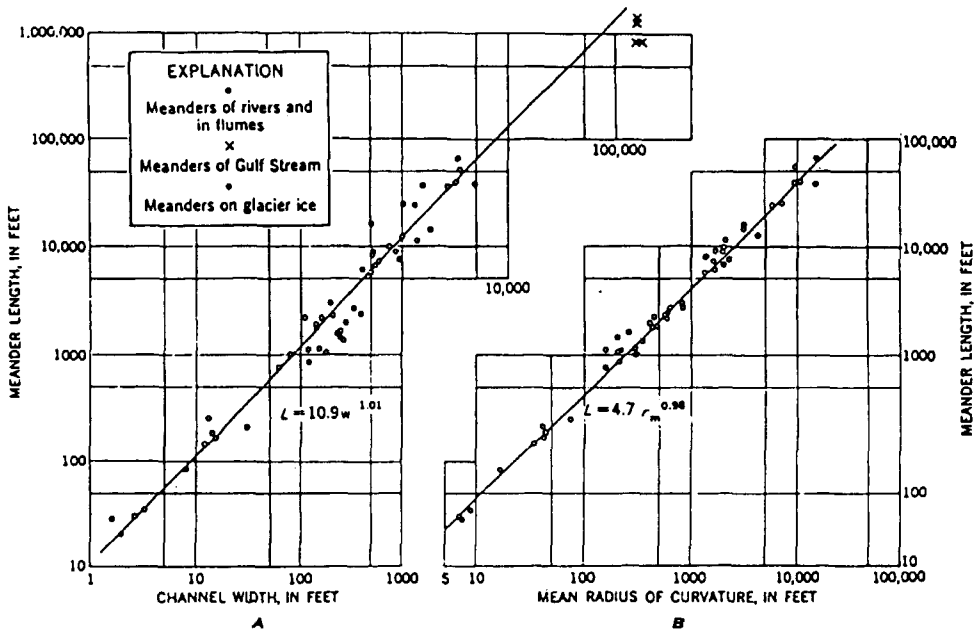


FIGURE 2. Relation of meander length to (A) channel width and (b) radius of curvature (from Leopold, 1962).

specific genes and the locations of those genes on the chromosome. He knows at least in a general way about the double helix, how the chemical structure of the gene may lead to duplication of cells, and the inheritance of traits as children are produced.

No such detailed knowledge about river channel processes exists. There is no clearly expressed philosophy covering the factors that govern alteration, adjustment, and establishment of a quasi-equilibrium state in river morphology. Though it is understood that the processes of erosion and deposition are the causal factors leading to an observed result, the relation of these processes to underlying tendencies is far from clear.

I believe that the analogy to Darwin's theory of natural selection may clarify some of these obscure points and may lead toward a philosophical framework for viewing river mechanics. Drawing on Mayr's (1991) summary of the main ideas of Darwin's theory, I will attempt to word several of his points in such a form that their analogy to rivers may be illustrated.

a) "Inanimate nature is characterized by . . . large classes of identical objects. Each sodium atom is like any other. . . . Exactly the opposite is found in living nature. No two individuals . . . are identical with each other" (p. 137).
b) Species of animals and plants must be seen "not as a type but as a variable population in which variability is renewed . . . in every generation. . . . Evolutionary changes . . . must be gradual, not requiring any saltations. . . . A population . . . changes by a slow shift of its mean values" (p. 128).
c) "Every species and hence every individual was a product of his-

tory. . . . Every individual carried with him . . . the experiences of three and a half billion years of its evolutionary history" (p. 135).

d) Among the natural processes in living organisms there are goal directed processes. These may be exemplified by annual migration of individuals and by development of an individual from fertilized egg to adulthood. Such goal-directed processes are called teleonomic (p. 130).

e) Selection is a two-step process. The first step in every generation consists of production of an immense amount of genetic variation (every individual is genetically unique). It is largely a matter of chance whether the individual is physiologically or behaviorally best adapted to survive. The second step is survival, for it depends largely on the adaptedness of the individual to its surroundings. Those that are best adapted have the greatest probability of surviving (pp. 126, 133).

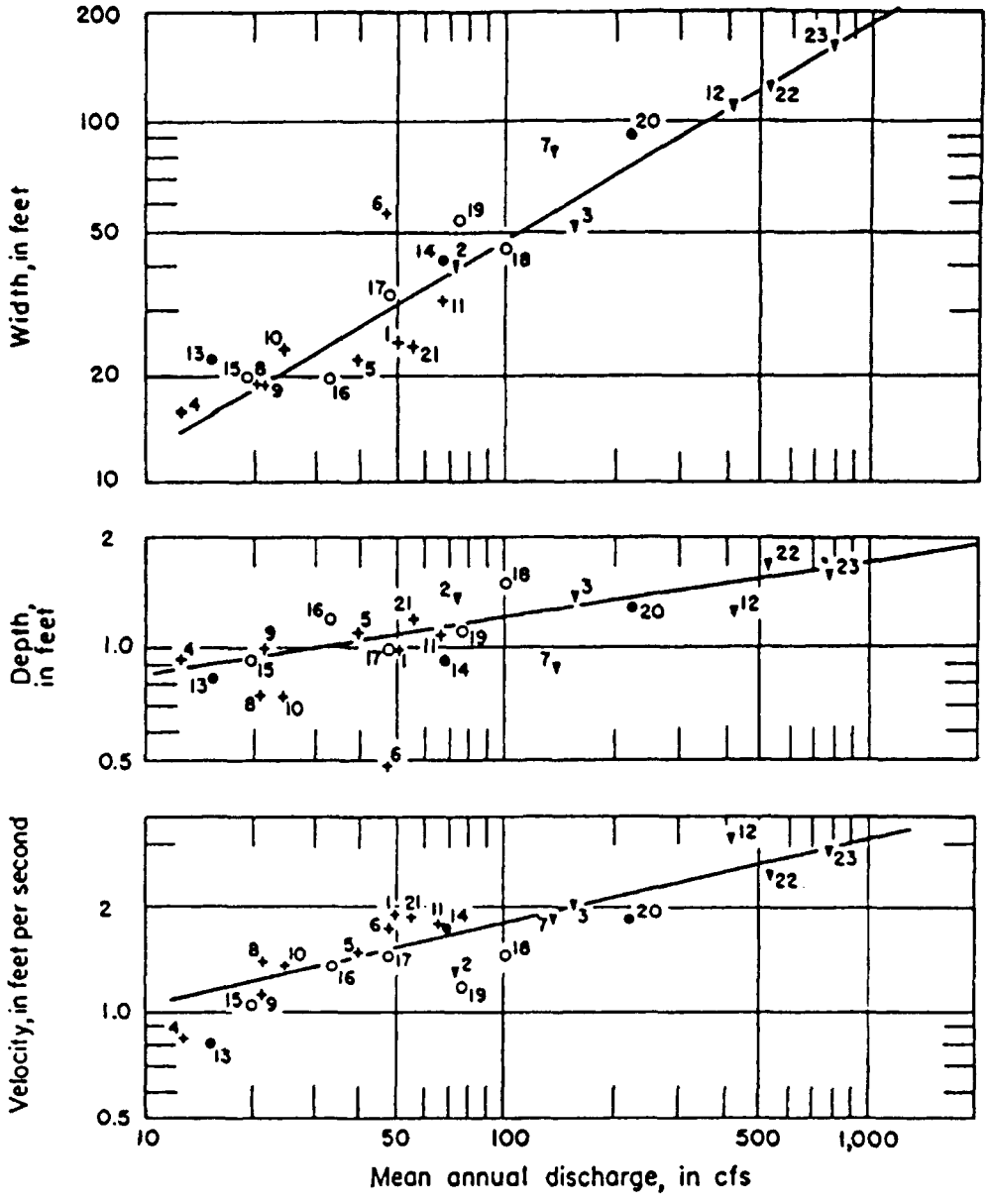
Population and Species

Species of animals and plants consist of a variable population in which evolutionary changes occur gradually rather than by discrete jumps. A population changes by a slow shift in its mean value. Consider the river data included in Figure 3 for the Powder River and its tributaries in Wyoming and Montana. For each of the twenty-three tabulated locations there is a specific mean annual discharge at which recur specific values of channel width, depth, and velocity. The latter parameters are related to mean discharge by a power function in the form $y = ax^n$, where x is mean discharge and the other parameters can be represented by y. The correlation is not perfect, as can be seen by the scatter of individual values about the mean regression line.

This system, the various locations along the river channels of the Powder River and tributaries, can be visualized as a species, including many non-identical individuals that exhibit uniqueness but yet are closely related in an orderly manner as discharge changes.

If one walks along this river, each bend seems similar, each gravel bar looks generally the same, but every location is unique in form, vegetation, and cross section. The scatter of points on the graph indicates an internal variability. This uniqueness of every individual location in the river system fulfills one of the specifications of a species. Other features of speciation will be explained below.

River systems differ because they may be in different geographic locations, have different climate, geology, and vegetation, and different histories. Yet the organization of each system with regard to its width, depth, and velocity in relation to discharge is comparable. Figure 4 shows various river systems in the world in which the mean annual discharge at a given location is related to its principal hydraulic parameters. The figure shows that various river systems increase in size downstream in a comparable manner. The lines for the various river systems are essen-



EXPLANATION

1. Red Fork near Barnum, Wyo.
2. Middle Fork Powder River above Kaycee, Wyo.
3. Middle Fork Powder River near Kaycee, Wyo.
4. North Fork Powder River near Hazelton, Wyo.
5. North Fork Powder River near Mayoworth, Wyo.
6. South Fork Powder River near Kaycee, Wyo.
7. Powder River at Sussex, Wyo.
8. Middle Fork Crazy Woman Creek near Greub, Wyo.
9. North Fork Crazy Woman Creek near Buffalo, Wyo.
10. North Fork Crazy Woman Creek near Greub, Wyo.
11. Crazy Woman Creek near Arvada, Wyo.
12. Powder River at Arvada, Wyo.
13. North Fork Clear Creek near Buffalo, Wyo.
14. Clear Creek near Buffalo, Wyo.
15. South Fork Rock Creek near Buffalo, Wyo.
16. Rock Creek near Buffalo, Wyo.
17. South Piney Creek at Willow Park, Wyo.
18. Piney Creek at Kearney, Wyo.
19. Piney Creek at Ucross, Wyo.
20. Clear Creek near Arvada, Wyo.
21. Little Powder River near Broadus, Mont.
22. Powder River at Moorhead, Mont.
23. Powder River near Locate, Mont.

FIGURE 3. Width, depth, and velocity in relation to mean annual discharge as discharge increases downstream, Powder River and tributaries, Wyoming and Montana (from Leopold and Maddock, 1953).

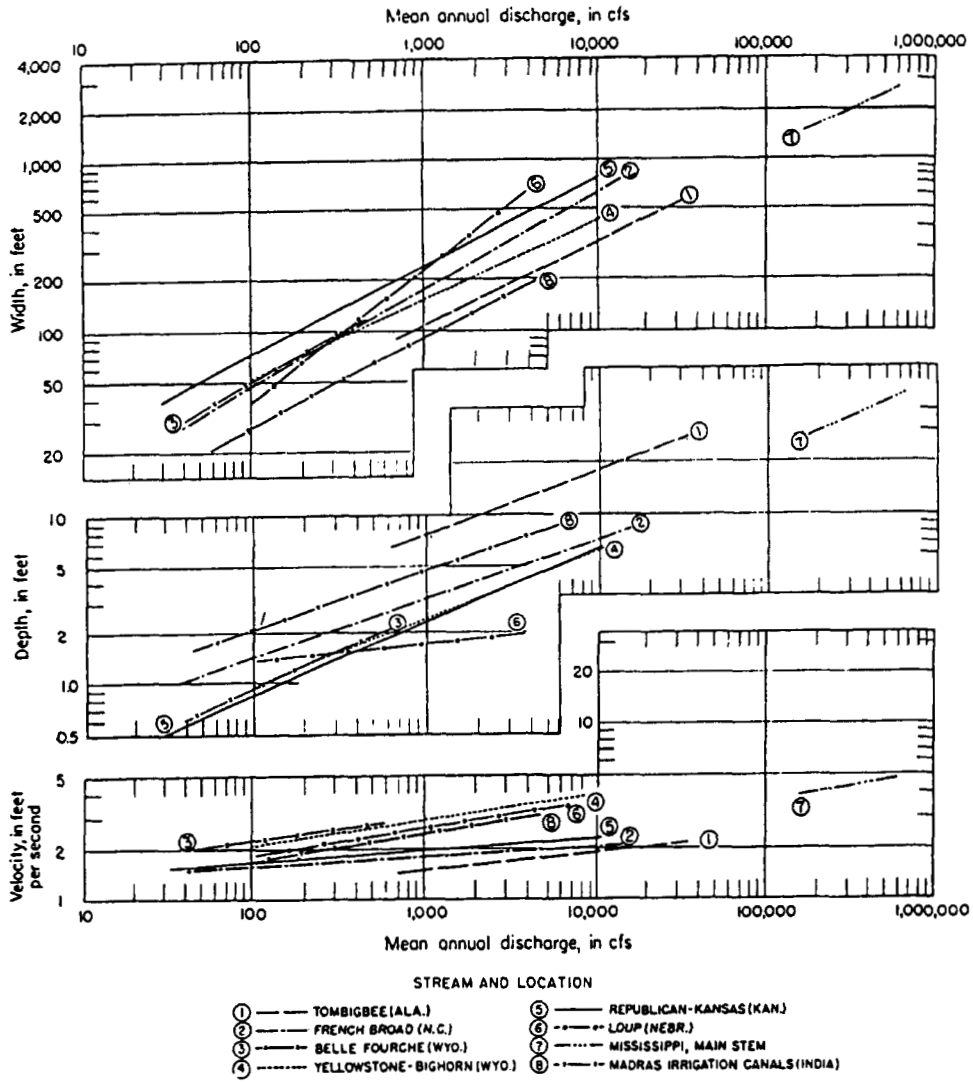


FIGURE 4. Width, depth, and velocity in relation to mean annual discharge as discharge increases downstream, for several river systems and some canals (from Leopold and Maddock, 1953).

tially parallel, indicating that in each, the hydraulic characteristics change at the same rate with respect to discharge as it increases downstream. These systems or river basins may be considered different species owing to the uniqueness of individual locations along the channel system, but at the same time each exhibits an orderly progression distinct from other river basins.

Each of the locations along a river system is not only unique, but may gradually change with time due to local erosion or deposition resulting from floods, from local heterogeneity of the bank, from absence or presence of vegetation. Thus the whole system, like a species, must be seen "not as a type but as a variable population." (Mayr, 1991, p. 128) The erosion or deposition at a particular place is ordinarily by gradual accretion or removal of sediment. But avulsion or sudden change is also common

when meanders cut off, when stream capture occurs, when banks collapse, and in the presence of other geomorphologic dislocations. Changes in the whole system occur as a result of climatic change and usually these are gradual. The river system, like a species, tends to change gradually, though interruptions do occur.

A Heritage But No Beginning—A Product of History

I have previously written that a river has a heritage but no beginning. The relation of a species of river, a river basin, to its history may be illustrated by the Green River, which rises in the Wind River Mountains in Wyoming and flows south where it joins the Colorado River in Utah. One part of the past history of this river can be read from physiographic relations in Sublette County, Wyoming. Figure 5 is a generalized cross section across the valley of the New Fork, a major tributary of the Green River. Bordering the valley on the east is the Wind River Range uplifted at the end of the Mesozoic, and not diagnostic in the history of this river. But exposed on both sides of the valley are Wasatch Formation horizontally bedded sands, clays and some gravel deposited in mid Tertiary time. Truncating the Wasatch is a layer of gravel (level A) 10 to 20 feet thick, laid down by the early ancestor of the present river as it moved back and forth, planing the Wasatch beds and forming a nearly flat surface at least ten miles wide, sloping gently to the south-southeast. Many square miles of this now dissected plain exist. The deposits of sand and gravel left by this ancient river and presently exposed at the surface show a plethora of individual channels suggesting a braided pattern. In Pleistocene time, a million or more years ago, it followed essentially the same course as the present river.

Subsequently, probably 1.3 million years ago, the river cut downward, eroding away much of the plain it had planed on the Wasatch beds. This downcutting was as much as 300 feet deep, 100 feet below the present valley floor (level B). The progenitor of the present river must have been large in volume and was incised in a fairly narrow gorge that gradually

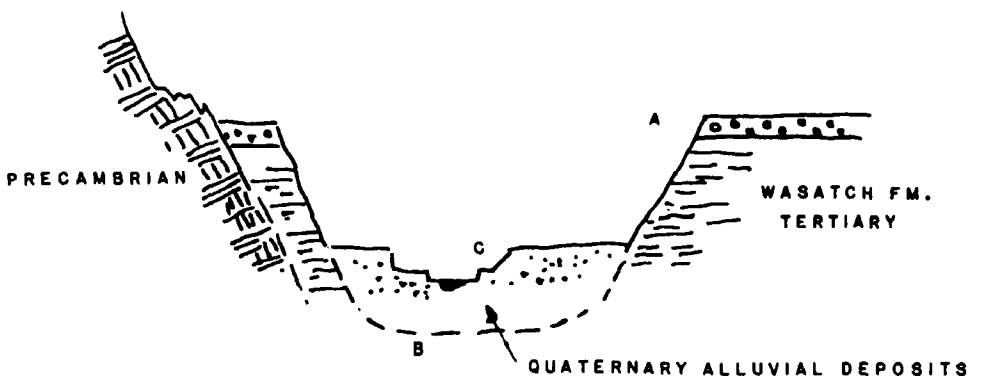


FIGURE 5. **Diagrammatic cross section across New Fork Valley, Wyoming.**

expanded laterally to develop a valley perhaps two miles wide. This was followed by the melting of glaciers, more than once in the late Pleistocene. Finally in the most recent and last Wisconsin glaciation, melt water deposited about 100 feet of gravel and sand, building the valley floor to its present level (C). The present river is a sand and gravel trout stream of modest size, meandering through a valley flat of willows, sage brush, and hay meadows.

This example shows by its geomorphic remnants a long history of change and its heritage of millions of years. The analogy to species seems obvious.

Mayr (1991, p. 135) says that an organism has a genetic program that "has a history of billions of years. The existence of this program is the fundamental difference between the inanimate and the living world." In a different sense, the history of a river represents successive changes of form, pattern, and discharge. In this respect, present river character has been dictated by the past circumstances of river history. And in the landscape, remnants of past conditions are common and, if carefully observed, yield clear indications of both the history of and conditions surrounding ancestors of the present river.

The landscape indicators of past conditions are not only ubiquitous but in many areas they control or constrict the location and action of present rivers. As an example, over broad regions in the western United States rivers and streams flow through landscapes characterized by three terraces, flood plains now abandoned, formed by the ancestor of each present river (Figure 6). The present river is building its flood plain at level D in the diagram. At one time the river flowed at level A and wandered laterally over a broad valley floor. Later a change of climate resulted in downcutting and the river stabilized for a time at level B, moving laterally again. At a still later stage it stabilized at level C, and again at the present level D. This sequence is prominently displayed all over northern Arizona, northern New Mexico, in much of Utah, many places in Colorado, and in all of eastern Wyoming. The three terraces are not everywhere preserved but can be seen in many places over the region just mentioned.

The importance of this history as influencing present streams can be seen by noting in Figure 5 that the river now forming the flood plain is

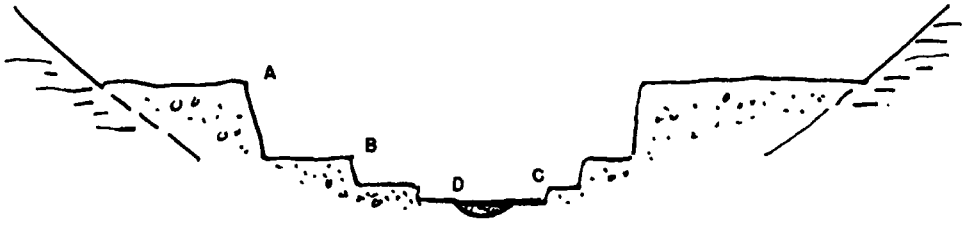


FIGURE 6. Alluvial terrace remnants consisting of three terraces, typical of many alluvial valleys in the western U.S. Terrace heights above present streambed tend to be respectively 20 feet, 8 feet and 3 feet.

constrained by remnants of the abandoned plain of level C. Given time and a continuation of the present climate, the river may be expected to widen its present level, even eliminating remnants of some or all of the previous levels it once occupied.

The examples illustrate that rivers have characteristics analogous to the first three traits of biologic forms mentioned above: they may be grouped into populations composed of like but not identical individuals; these populations resemble species in that ordinarily they change gradually by slow shift in mean conditions; they are the product of their own history and may be characterized as having a heritage but no specific beginning.

Variability and the Role of Chance

In a large population of river reaches within a given river system or including many systems, straight reaches are few in number and short in length, seldom if ever exceeding a length twenty times the channel width. Statistically, curved channels are the most frequent. The explanation of this tendency must begin with the fact that all river channels having heterogeneous material on the bed (mixture of cobbles, gravel, sand) develop alternating deeps and shallows along their length (Leopold, Wolman, and Miller, 1964, p. 207). The alternation tends to have a spacing equal to five to seven times channel width.

Over the shallow portions or riffle bars, the water flows at a relatively steep slope because of several factors, including the friction offered by the bar. Over the deeper pool the slope is flat or gentle. There is, then, an alternation of local water surface gradient, flat over the pool and steeper over the riffle bar. The water surface gradient is a direct measure of the rate of energy dissipation from potential energy to kinetic form, and thus into heat. These alternations of steeper and more gentle water surface gradients reflect greater and smaller rates of energy transformation. This variation in rate over a short distance along the channel leads inexorably to reaction among hydraulic parameters, velocity, depth, roughness, shear, and the distribution of these factors along and within the channel. The magnitude and distribution of these factors operate on sediment by erosion and/or deposition. Moreover, all of these same factors are rapidly and materially changed as the water discharge and the sediment it carries vary through time, as low flow is followed by flood followed by low flow, each of different duration depending on the nature and location of rainfall or snowmelt. To accommodate these various changes the interdependent hydraulic variables will change. A particular change in discharge and sediment may be accommodated by several combinations of values of these dependent or adjustable factors.

There is not merely one way these factors will change. The immutable physical laws of conservation of energy and conservation of mass can be satisfied by many combinations—in fact, the particular values that will exist at any moment of time and place are greatly influenced by random

or chance circumstances. Moreover, the adjustment to the initial perturbation takes time and may not be complete before another chance event disrupts the condition and readjustment begins anew. Thus, a number of individual cases will differ among themselves, although the average is reproducible in different samples: in any individual case (location in place and time) values of the interdependent variables cannot be forecast or specified except in a statistical sense. The individual case is indeterminate.

Indeterminacy is a principle long recognized in physics but not much discussed in geomorphology. It is strikingly analogous to one aspect of Darwin's theory of natural selection.

Darwinian selection is a two-step process. "The first step in every generation consists of the production of an immense amount of genetic variation; . . . it is largely a matter of chance. Every single step that precedes the production of an egg or spermatozoan is a chance event" (Mayr, 1991, pp. 132–33). Darwinism "rejected both essentialism and determinism. Predictions could only be probabilistic-statistical . . ." (Mayr, 1991, p. 134). "In many and perhaps all evolutionary processes one can only operate by postulating probabilities" (Mayr, 1991, p. 136).

Teleological Processes

A teleological process is one that is goal-directed, or purposeful. Many processes in biology appear to be of this nature and were believed to exhibit the hand of God. In centuries past, so strong was this belief that even some prominent scientists were convinced of a teleological world. When it was believed that the world was 6,000 years old, the explanation was that God created individually everything we observe on earth. Though some occurrences in nature, including some aspects of rivers, appear teleological, there are clear reasons why they are explicable without calling on divine direction.

There are several categories of teleological processes (Mayr, 1991, p. 130), of which one, called teleonomic, consists of those phenomena controlled by a genetic program. As Mayr has stated, this type of teleology does not exist in inanimate nature where genetic controls do not exist. But, as in the analogs being here developed, some aspects of river behavior can be described as appearing to be directed toward a predetermined end, in the sense that physical laws govern behavior. These aspects are exemplified by the character of the curves and meanders of river channels.

The ubiquitous curves in river channels have special characteristics. Their length is directly related to the channel width, which is proportional to the square root of the bankfull discharge. The relation among width, radius of curvature, and wave length is illustrated in Figures 1 and 2. The correlations in Figure 2 are so excellent over four orders of magnitude that one might be led to believe that the processes causing the relation are goal directed. Moreover, the curves are not merely segments of

a circle but are more unique. They can be gentle wave-like undulations (Figure 7), similar but not identical to a sinusoidal wave, or so convoluted that the channel nearly meets itself in a cutoff. The three examples appear at first glance to be parts of the same river because the widths are the same in the diagram. But inspection of the scales indicates they are of vastly different scales, a very large river, the Mississippi, and a laboratory channel. At these different scales, natural channels tend to produce curves similar in form because of the close relation among width, radius, and wavelength, even though the amplitude of the waves is different. These different amplitudes of the waves all tend to approximate closely a special kind of curve we called "sine-generated" (Langbein and Leopold, 1966). This special form has the characteristic that the deviation angle from the mean down valley direction is a sine function of distance along the channel. Figure 8 is an example. The plan view of the Popo Agie River near Hudson, Wyoming, is shown. For many positions along the channel the direction angle of the channel was measured relative to the down-valley direction. These angle measurements are plotted as open circles in the lower diagram as function of distance along the channel. The solid line is a sine curve constructed with the same amplitude and wave length as the plotted circles. It can be seen that the field measurements of channel direction closely follow a sine-curve.

Meander curves in rivers tend to approximate closely this sine-generated form, but departures that appear random are caused by the natural heterogeneity of the stratigraphy and its associated vegetation, both influenced by the particular history of each locality. But so many individual curves or portions of a meander display a shape closely approximating the sine-generated form that one might say each curve is reaching for or tending to adopt that form, and would do so were the stratigraphic and biologic environment completely isotropic. The forms and tendencies operating to produce "many seemingly end-directed processes or movements in inorganic nature are the simple consequences of natural laws." These fall in the category of teleomatic processes (Mayr, 1991a, p. 67).

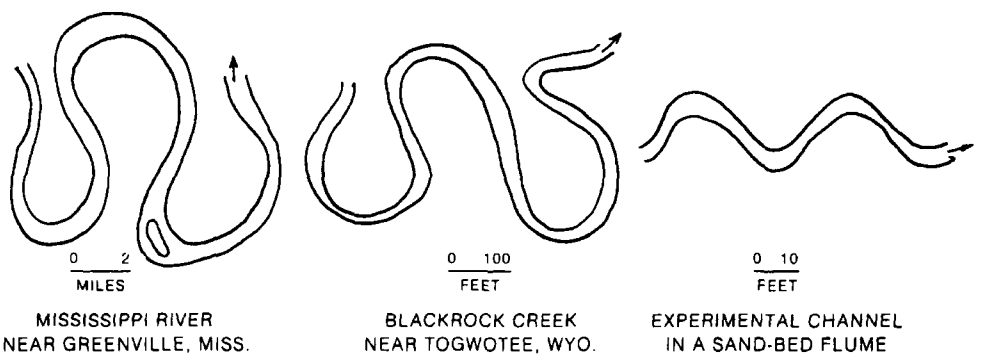


FIGURE 7. Meander curves of three channels of different size showing the similarity in form regardless of river magnitude.

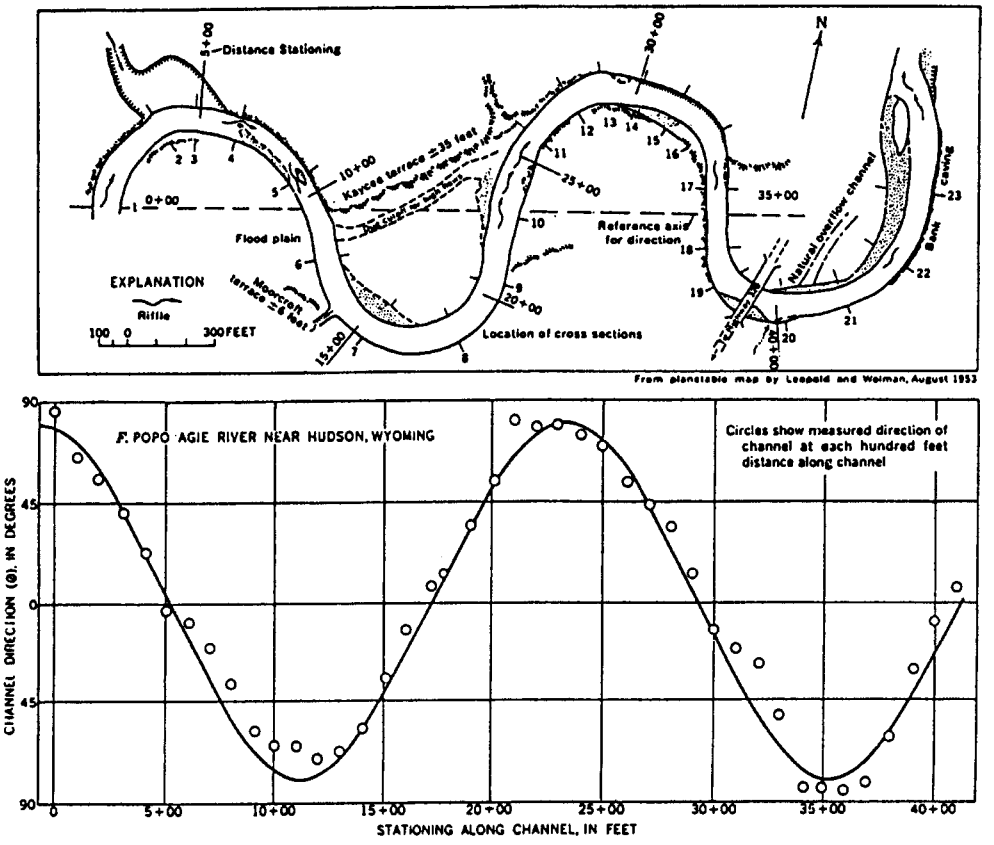


FIGURE 8. Meanders of the Popo Agie River near Hudson, Wyoming, that demonstrate the coincidence with a sine-generated curve. At 100-foot intervals along the channel the channel direction in degrees was measured. These direction angles are plotted in the lower diagram against distance as open circles. The solid line is a sine curve of similar amplitude and wave length.

MAXIMUM PROBABILITY

Complex systems are characterized by a large number of interacting forces, constraints, or structures. An example is flow of a fluid in three dimensions such as motion in the atmosphere or flow in a river. Air flow is affected by temperature and pressure and their gradients, by the Coriolus force, by differential heating and cooling, by radiation, by advection and all the physical laws relating to these parameters. As a result the conditions at any one place and time are quite unpredictable and only in the average can be quantified. There are many examples.

In geomorphology with respect to the shape of hills, the development of rills and channels, and the erosion of landscape, we expressed the stochastic influence in the following way:

Where a large number of interacting factors are involved in a large number of individual cases or examples, the possibilities of combination are so great that physical laws governing forces and motions are not sufficient to determine the outcome of these interactions in an individual case. The physical laws may be completely fulfilled by a variety of combinations of the interrelated factors. The

remaining statements are stochastic in nature rather than physical (Leopold and Langbein, 1963, p. 189).

The most general physical laws that must be satisfied require that matter and energy be conserved. These laws must characterize each reach of a river, each unit of any path and each instant of time. These laws, however necessary, are insufficient to explain either paths of particles or the interrelation of paths. Thus, they are insufficient to treat the surface form of the landscape or its change of form with time. Other considerations are necessary.

Another kind of principle is operating that can best be expressed by the concept of entropy (Leopold and Langbein, 1962). Entropy is an expression for the degree to which energy has become unavailable to do work. The closed system, usually visualized in introductory texts on physics, has clearly defined boundaries across which no import or export of materials or energy occurs. But a river basin is comparable to an open system that has a supply of incoming energy and that is maintained by removal of material and energy as the water and sediment move downstream.

In the open system of a river basin, potential energy is added to the system as precipitation falls at high elevations. This energy is changed to kinetic form as water flows downhill, and the kinetic energy is dissipated into heat, doing some mechanical work during the transformation. An important property of such an open system is the ability to attain a steady state in which the "import and export of energy and material are equated by means of an adjustment of the form, or geometry, of the system itself" (Chorley, 1962, p. 133).

The steady state has also been called quasi-equilibrium; as a philosophy for landscape evolution it was best developed by Hack (1960) in his "dynamic equilibrium." Among many authors' definitions, perhaps one of the more cogent is Hack's (1960, p. 86):

> The concept [of dynamic equilibrium] requires a state of balance between opposing forces such that they operate at equal rates and their effects cancel each other to produce a steady state, in which energy is continually entering and leaving the system.

The idea of dynamic equilibrium was first proposed in geomorphology by the great geologist G. K. Gilbert (1877). He applied this concept not merely to rivers but to the whole landscape, including hillslopes. An important part of his concept was interaction (1877, pp. 123–24):

> The tendency to equality of action, or to the establishment of a dynamic equilibrium, has already been pointed out . . ., but one of its most important results has not been noticed. . . . in each basin all lines of drainage unite in a main line, and a disturbance upon any line is communicated through it to the main line and thence to every tributary. And as any member of the system may influence all the others, so each member is influenced by every other. There is interdependence throughout the system.

In the condition of dynamic equilibrium or steady state, the rate of

output of entropy equals the rate of internal generation of entropy (Prigogine, 1955). The rate of generation of entropy is represented by the energy gradient—that is, the measure of rate of utilization of energy. The rate of outflow of entropy is measured by the dissipation of heat. The generation of heat is equal to the energy expended—transferred from potential through kinetic to heat form.

Entropy can also be defined as the logarithm of the ratio of the probability of a given physical state to the probability of all other possible alternative states. In the evolution of the steady state or dynamic equilibrium, maximum probability represents the condition of least work. In rivers, "the principle of least work is one of several ways in which the condition of maximum probability may be satisfied. The river channel has the possibility of internal adjustment among hydraulic variables to meet the requirement for maximum probability, and these adjustments tend also to achieve minimization of work" (Leopold and Langbein, 1962, p. A7). But in rivers, some other factors such as geologic structure, lithology, and history may constrain the system and minimum work may not actually be achieved; but the tendency still operates.

The concept of entropy has another aspect. In an open system in steady state the most probable energy distribution is one in which the rate of energy dissipation is uniformly distributed. The condition of minimum work and uniform distribution of work cannot simultaneously be achieved, and in many aspects of river morphology it is observed that the opposing tendencies lead to a compromise. For example, to maintain uniform expenditure of energy along a river would result in a nearly straight, moderately concave longitudinal profile. Minimum work in the river system would result in a very concave profile. Observed profiles are intermediate between these extremes (Langbein and Leopold, 1964, p. 786).

Possibly the easiest example to visualize without mathematical proof is the form assumed by river meanders introduced earlier in this essay. The sine-generated curve, as explained, is defined by the change in channel direction along the meander as measured by its angle of deviation from the mean downstream direction. The totality of the curvature can be expressed by the total variance, defined as the sum of the squares of deviations from the mean value. In the case of a curve, the total variance is the sum of squares of the deviation angles measured at uniform distances along the curve. The sine-generated curve differs from other forms having the same wavelength and amplitude—half circle, parabola, sine curve—by having a smaller total variance than that of the other forms. Because the forces of erosion on the concave bank of the river curve are governed by the sharpness of the bend (radius of curvature), the total variance is a measure of the total erosion ability. Because energy is expended in merely forcing the water into a curved path, the sine-generated curve is a minimum erosion curve and a minimum work curve. Thus the form of the curve constructed by a river is of a shape that minimizes energy loss.

But there is also the tendency toward uniformity of energy expenditure. Energy expenditure is directly measured by the slope (gradient) of the water surface. A channel that is more or less straight has a longitudinal profile that is steep over the riffle bar and less steep over the pool, so the profile is stepped or irregular. This deviates from the most probable form. One might expect, then, to see a tendency to straighten or make more uniform the water surface profile. If the straight channel has a stepped profile, the profile could be made more straight by increasing the slope over the pool, and this could be done by making the channel curved in the pool reach. But this would tend to make the profile as a whole steeper or would increase the total energy expended. Indeed, that is exactly how rivers act, for the meandering river achieves a straight profile at bankfull discharge; but in doing so it has a steeper slope than a comparable straight reach (Figure 9). The profile of the water surface in the meander at high flow in Baldwin Creek, shown in Figure 9, is practically straight, whereas in the straight reach of the same river the profile is stepped.

Thus, the meander curve of a river shows the results of the various tendencies. The meander assumes a sine-generated shape, which is a minimum variance form, a tendency for smoothly allocating energy expenditure while minimizing total energy loss. Its profile at high flow when most of the channel modification is done, shows a uniform rate of energy expenditure. Recalling that the dynamic equilibrium, least work, is one of the ways maximum probability can be satisfied, we see that rivers show form and pattern that approaches the most probable state.

The most probable state appears in Darwin's theory of natural selection in several ways. "The probabilistic nature of the evolutionary process was . . . alien to the thinking of the physicists" (Mayr, 1991a, p. 49). "Selection is a two-step process. . . . [In the second step] those individuals that are

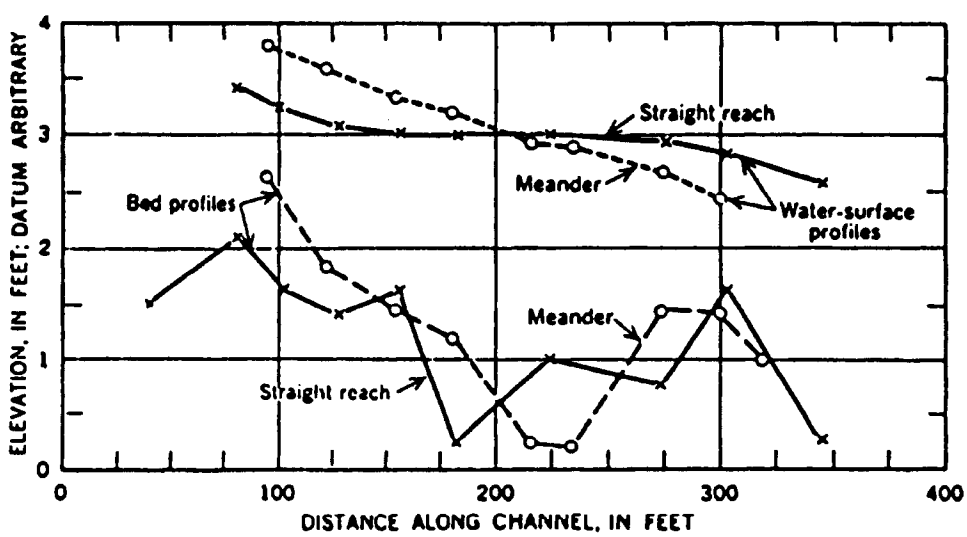


FIGURE 9. Profiles of bed and water surface in a meander curve and in a straight reach, Baldwin Creek near Lander, Wyoming (from Langbein and Leopold, 1966).

physiologically or behaviorally best adapted have a higher probability of surviving than other individuals of the population" (Mayr, 1991, p. 132).

I point to several ways in which river morphology is an analog to the theory of natural selection:

1. the analogous characteristics of species and river channels;
2. the uniqueness of individuals in a population and of locations along a river;
3. the reaction of a population to changing environmental conditions is also seen in the reaction of a river to changes in climate, tectonic movement, or human activities;
4. the individuals and the species are products of history; rivers similarly reflect the past, even through geologic time;
5. variability is a feature of populations and chance has an important role in survival; variability in rivers is characteristic because of the inhomogeneity of the environment, but probability plays a strong role even though individual actions and reactions are deterministically controlled;
6. teleology appears to be a trait of animal life but development is not goal directed; some river characteristics give the appearance of goal directed process but in fact are the expression of the most probable state.

The similarity of traits of animate life and inanimate but highly organized forms of rivers leads one to think that a better understanding of rivers may result from contemplation of these similarities. Rivers represent the result of operation of conflicting tendencies, the tendency for minimum work and the opposing tendency for uniform distribution of work. The average of the actual resulting forms is the most probable form.

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