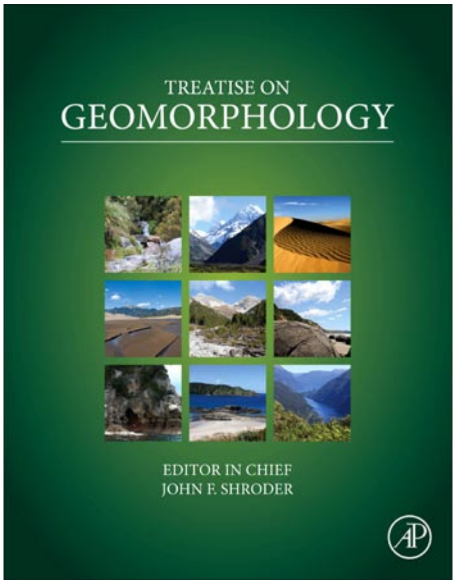

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# 9.2 A River Runs Through It: Conceptual Models in Fluvial Geomorphology

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## Abstract

Fluvial geomorphology has a rich history of conceptual models of river evolution. Underlying these models is a scaffolding of ideas drawn from Newtonian physics and fundamental geological principles. This history of fluvial geomorphological models can be viewed as a braided river of ideas beginning with a bifurcation in thinking between Gilbert's concept of landscape processes as a balance among pertinent forces, and Davis' concept of the geographic cycle. Concepts such as the graded river, hydraulic geometry, dynamic equilibrium, geomorphic thresholds, magnitude/frequency of geomorphic processes, landscape and channel classification, and landscape evolution all find their places in this river of ideas.

## 9.2.1 The Geomorphic Field Problem

Walking down the riverbank to the gravel bar, the curious geomorphologist will be entertaining a lively set of questions in his/her mind: Why does this river look the way it does? How did it get that way? How might it change if I build or remove a dam? What might happen if the climate gets wetter or drier? And so on…

Where to start? Does one consider all the forces acting on every single particle over time? Or does one survey in the bankfull level as an indicator of channel-forming process? Does one classify the stream or reach, or measure the diameter of pebbles under his boot? Does one assume that the stream is in equilibrium with its surrounding watershed, or does one assume that it is in a disturbed or transient state, perhaps due to climate or land use or some other cause?

In choosing where to start, what to assume, and how to proceed, the geomorphologist is making a set of judgments and decisions that have enormous consequence on where the investigation ultimately ends up. Consciously or not, the geomorphologist is choosing among a plethora of conceptual models that will inevitably guide and channel his/her inquiry. These models provide a foundation – the analytical map from which to begin to navigate the complexities of the fluvial system.

What is a conceptual model? One skeptic called it ''a fuzzy set of ideas without any math'' (Church, 2009, personal communication). Here we use the term to mean a 'persistent set of ideas that usefully organizes thinking.' We focus on

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conceptual models rather than just concepts, as such models provide representations or abstractions of complex systems that make them easier to understand. As Baker (2011, personal communication) put it:

> A model is a special kind of representation. Whether it is physical, mathematical, or conceptual (i.e., involving ideas), a model involves a representation that extracts from the full complexity of reality some elements that seem fundamental or essential such that one can see their pattern, form, or operation without having to deal with all the complex details.

Conceptual models are, of course, not unique to geomorphology. But this relatively young discipline has had more than its share of such models. In this chapter we develop a framework for conceptual models and examine how scientific progress in geomorphology has been both advanced and stymied by the manner in which some of these models have been adopted, the degree to which they have held intellectual sway, and the extent to which their application and limitations have been explicitly recognized. Our intent is not to provide a history of either conceptual models in geomorphology or the field itself; others have done a far better job of this than we could hope to do here (e.g., Chorley et al., 1964; Dury, 1983; Smith, 1977; Tinkler, 1985). Rather, our focus is on how certain conceptual models have guided understanding of geomorphic systems, with an inevitable bias toward conceptual models in fluvial geomorphology due to our disciplinary backgrounds.

## 9.2.2 Hierarchy of Analysis Frameworks

To better understand conceptual models, we begin with one of our own (**Figure 1**). We propose a hierarchy of frameworks that serve as the foundation for any attack on the geomorphic field problem. Beginning with the most fundamental level and moving toward those concepts that are unique to fluvial geomorphology, these frameworks are often implicit, unstated, or assumed at such a deep level that many practitioners are unaware of their import. The sequence of levels from 1 to 3 reflects moving from fundamental principles of physics that underlie all physical sciences toward core principles of geology (level 2) and finally key analytical ideas in geomorphology (level 3). These three levels can be viewed as uber-models, providing critical concepts that tie the fabric of the discipline together. Recognizing their role is useful to understanding how thinking in geomorphology has evolved over time and appreciating the underpinnings of conceptual frameworks that are currently in use or have fallen by the wayside.

### 9.2.2.1 Level 1: Fundamental Physical Frameworks

The most fundamental level represents the laws of physics. This can be stated simply as the Newtonian principles of force, motion, and energy applied to geomorphic systems. While perhaps obvious, this principle underlies all application of physical characterization, measurement, and modeling of geomorphic processes and provides the foundation for inferring process from observation of geomorphic landforms, not only on Earth but other astronomical bodies as well. But while Newton's Laws are typically stated in terms of the effects of one body or object on another and thereby emphasize behavior of 'closed' thermodynamic systems where forces and energy can be fully accounted for, geomorphic systems are notoriously 'open' (sensu Chorley, 1962) and do not lend themselves to such a strict accounting. Nevertheless, fundamental concepts of mass and energy balance, balance of forces, and by extension, concepts of equilibrium, thresholds, and steady state directly underlie key concepts in geomorphology (e.g., Howard, 1965; Langbein and Leopold, 1964). In particular, the concept of equilibrium is probably the single most important idea in geomorphology – not because geomorphic processes and forces are necessarily in equilibrium, but because the concept provides a reference point for assumptions, observations, and mathematical and physical characterizations of system behavior.

### 9.2.2.2 Level 2: Geological Analysis Frameworks

A second level of concepts primarily owes its origins to the field of geology. These concepts are the basis for interpreting landscape history, evolution, and change, and underlie key strands

| Level | Overarching principle | Key concepts |
|---|---|---|
| 1: Fundamental physical frameworks | Newtonian physics | Mass and energy balance; force balance; equilibrium; steady-state; physical thresholds |
| 2: Geological analysis frameworks | Uniformitarianism | Geological history; deep time; space-for-time substitution; “appreciate the pleistocene” |
| 3: Geomorphic analysis frameworks | Process/form correspondence | Geomorphic work; “nice adjustment”; basel level |

**Figure 1** Hierarchy of overarching concepts in geomorphology. Lower levels control and constrain higher levels.

of historical geomorphic thinking, including the relationship between form and time that anchors the contributions of William Morris Davis and many workers thereafter. The most important of these concepts were featured in a seminal early chapter by Thornbury (1954), who set forth 10 principles of geomorphic thinking, which remain highly relevant for modern workers. With some temerity, we abbreviate and recast Thornbury's dictums to five precepts that speak directly to the role of geological concepts in geomorphic thought:

- History is important. Geomorphic systems are fundamentally physical systems with a history, and an appreciation of that history is necessary to interpret their form and, to a lesser extent, their behavior.
- History can be long. The timescales that are relevant for interpretation of many geomorphic systems and forms are long (i.e., thousands to millions of years), and an appreciation of deep time is necessary in order to make sense of the Earth's present surface.
- Time is deep, but not that deep. While many modern landforms owe their origin to processes and rates that occurred during the Pleistocene, little of the Earth's surface is much older than the Tertiary. And as Thornbury goes on to argue, more recent events, including the effects of humans, are likely to play a disproportionately important role in influencing modern forms and processes.
- Uniformitarianism applies. In other words, Level 1 principles applied in the past as they do in the present. This is not to say that rates of present processes necessarily reflect rates in the past, nor that extreme or catastrophic processes do not play an important role in geomorphology (e.g., Baker, 1998; Dury, 1975; Dury, 1980). As Baker (2011, personal communication) put it:

> The pragmatically relevant concept here is the view that we can use our understanding of processes in operation today, that is, accessible to our direct observation and measurement, to derive at least an initial understanding of process operations in the (even remote) past (but we must be willing to toss this out when we encounter compelling evidence for causal phenomena of a magnitude that we do not observe today).

- Space can be (cautiously) substituted for time. Because geomorphic processes can take long periods of time to imprint or mold landforms or landscapes, the short period of time available for observation is often insufficient to adequately record or measure their effect. To address this, one can legitimately, if carefully, assume that the modern landscape includes landforms in various stages of development and that '…we may therefore make inferences about changes through time based on the variety of forms we see at present' (Paine, 1985). Other substitutions (i.e., time for space, space for space) are also possible.

### 9.2.2.3 Level 3: Fundamental Concepts in Fluvial Geomorphology

Although the first two levels highlight concepts that could apply to any geological discipline, the third level introduces some of the underlying principles and key constructs of geomorphology. These are cornerstone concepts that lie at the base of interpretations of landforms and their evolution. Some of these concepts have served as the basis for the most important conceptual models in the field. The distinction we are drawing between 'concept' and 'conceptual model' is admittedly a fuzzy one, but essentially concepts are the bricks used to construct more elaborate and sophisticated conceptual models.

There have been various efforts to identify the most fundamental concepts in geomorphology. As summarized by Baker (1986):

> Most geomorphologists would agree that certain fundamental assumptions underlie all geomorphological investigations. Whether termed 'fundamental concepts' (Thornbury, 1969), 'philosophical assumptions' (Twidale, 1977), 'paradigms' (Ollier, 1981), or 'basic postulates' (Pitty, 1982), these ideas constitute a 'conventional wisdom' for the science. One such fundamental concept involves the inherent complexity of landscapes. This concept has impeded the development of grand theories that survive the test of explaining numerous local features. Another basic assumption involves climatic morphogenesis, emphasizing the role of climatically controlled processes of landform genesis. Several of these concepts have yielded major intellectual controversy, such as the role of cataclysmic processes in shaping the landscape. These concepts apply to geomorphology of all scales.

Perhaps the most fundamental concept in geomorphology is 'the correspondence between form and process.' The earliest references to this are thought to be Biblical and refer to efforts to relate surficial landforms to the Noachian flood (Baker et al., 1988, p. 1). It is probably fair to say that the Great Flood was the first conceptual model in geomorphology. Leonardo da Vinci's notebooks also contain keen observations of process/form relationships in landforms and rivers. By the late eighteenth century, the correspondence between rivers and their valleys was being noted, as were speculations on the causes of this relationship (Rudwick, 2005). But the formal recognition of the correspondence between process and form that underlies the origin of the science of geomorphology itself was probably first captured in the writings of Playfair (1802). As described by Newson (2002, p. 366):

> Playfair described 'a system of valleys, communicating with one another, and having such a nice adjustment of their declivities, that none of them join the principal valley, either on too high or too low a level' (Playfair, 1802). Playfair advanced 'nice adjustment' as a system property, a fundamental change from the religious view that order was evidence of a deity acting protectively to humankind, between punishing us with calamities such as floods.

Playfair's 'nice adjustment,' sometimes termed 'Playfair's Law,' represents the first published recognition of the empirical linkage between landforms and the processes responsible for their formation, although he did not describe the specific processes underlying these adjustments. But the idea that the form of the landscape reveals something about the physical processes that produced it remains a fundamental tenet of geomorphology and the well-chosen phrase 'nice adjustment' captures something of the essence of that underlying but often ill-defined relationship between process and form. Almost exactly 200 years later, Playfair's observation continues to be examined through numerical models (e.g., Niemann et al., 2001).

A related but equally fundamental geomorphic concept is that of geomorphic work. This is the idea that geomorphic processes and fluxes of water, energy, and sediment imprint themselves on the landscape to different degrees. Although a formal and quantitative definition of this concept did not really emerge until Wolman and Miller's (1960) classic paper on magnitude and frequency of geomorphic processes (discussed in Section 9.2.3.2.5), the underlying principle was certainly recognized by Playfair and Hutton, although the British geologist CG Greenwood is credited as being the first 'subaerialist' by Naqi (2005, p. 71) for his marvelously titled book: Rain and Rivers: Hutton and Playfair against Lyell and All Comers (Greenwood, 1857).

A third fundamental concept in fluvial geomorphology is that of base level. The origin of the term is widely credited to John Wesley Powell (Powell et al., 1875), who defined base level as the elevation 'below which the dry lands cannot be eroded.' The observation that the sea established the lowest point to which rivers could erode their valleys was noted earlier, however, by Dana (1849), who speculated about the origin of deep valleys adjacent to the Oregon Coast:

> Subaerial denudation is our last cause, the only other mode of origin to which we can appeal. And this implies that the land was higher above the sea when subjected to this wear; and also that the fjords were originally the valleys of the land. The subsidence of a country, continued till its alluvial region along the coast is submerged, will necessarily make deep bays of its long linear valleys; and this is a view to which we are directed by the investigation of the subject (p. 676).

Naqi (2005, p. 71) also credits CG Greenwood as the 'father' of the concept of base level, citing King (1966): "He put forward the idea of the base-level of erosion before Powell in America."

Although hardly a comprehensive list, the trifecta of process/form linkage, geomorphic work, and base level comprises the roots of modern geomorphic thought, and is reflected in much of the work that has followed over the two centuries since Playfair. Baker (1986, Tables 1 and 2) provides a more comprehensive table of fundamental concepts in geomorphology, which include some of our Level 2 and 3 concepts, among others. In his table, Baker considers both a concept (simplicity) and its opposite (complexity) as providing useful intellectual reference points for understanding geomorphology.

## 9.2.3 A Braided River of Conceptual Models in Fluvial Geomorphology

The hierarchy of analytical frameworks and fundamental concepts described in Section 9.2.2 are the basic building blocks of geomorphic thought. Now we examine how higher order conceptual models in fluvial geomorphology draw on and emphasize different aspects of this hierarchy. We offer the perspective that development and evolution of conceptual models in geomorphology arise out of different weightings of elements from the analysis hierarchy; models then evolve in response to other conceptual models, all of which increase over time in sophistication of measurement and analytical and modeling tools.

This evolution is neither linear in time nor unidirectional, and is perhaps most usefully envisioned as a genealogy in the form of a braided river with multiple intellectual channels, many of which may be active at any given time, but usually with one or two primary threads representing ideas that dominate thinking at any particular time (**Figure 2**). We build this genealogy or 'metaconceptual model' around what is perhaps the fundamental question in fluvial geomorphology: How do we understand the form and evolution of rivers? In a more restricted sense, this is much the same problem confronting our field geomorphologist standing on the river bank. The history of fluvial geomorphology can be viewed, at least in part, through the lens of the various conceptual models that have been developed to answer this overarching question.

### 9.2.3.1 The Master Braids: Gilbert and Davis

These models roughly align themselves along the two master braids of the intellectual history of the discipline: Grove Karl Gilbert's Balance of Forces (Gilbert, 1880) and William Morris Davis's Cycle of Erosion (Davis, 1909) (**Figure 2**). Here we consider how the ideas put forth by these two seminal geomorphologists have dominated and underscored different conceptual models in fluvial geomorphology up to the present and where the interactions and crossovers between models have occurred.

#### *9.2.3.1.1 The Balance of Forces*

Gilbert's greatest and most enduring contribution to conceptual models in geomorphology, drawn from a mere two field seasons (one mostly spent sitting on a horse), was the application of basic principles of energy and thermodynamics to the behavior of rivers. He did so with clarity of expression and an absence of mathematics that appeals directly to intuition, logic, and analog reasoning. His insights rely on principles of physics – equilibrium, balance of forces, and least work – rather than on historical geology. Consider his discussion from his 1877 'Report on the Geology of the Henry Mountains' (Gilbert, 1880) on how the equilibrium slope or graded river form arises:

> Let us suppose that a stream endowed with a constant volume of water, is at some point continuously supplied with as great a load as it is capable of carrying. For so great a distance as its velocity remains the same, it will neither corrade (downward) nor deposit, but will leave the grade of its bed unchanged. But if in its progress it reaches a place where a less declivity of bed gives a diminished velocity, its capacity for transportation will become less than the load and part of the load will be deposited. Or if in its progress it reaches a place where a greater declivity of bed gives an increased velocity, the capacity for transportation will become greater than the load and there will be corrasion of the bed. In this way a stream which has a supply of debris equal to its capacity, tends to build up the gentler slopes of its bed and cut away the steeper. It tends to establish a single, uniform grade (p. 106).

Gilbert's genius was his ability to recognize and succinctly articulate the fundamental mechanism by which rivers tend to work toward equilibrium. Because this mechanism relies

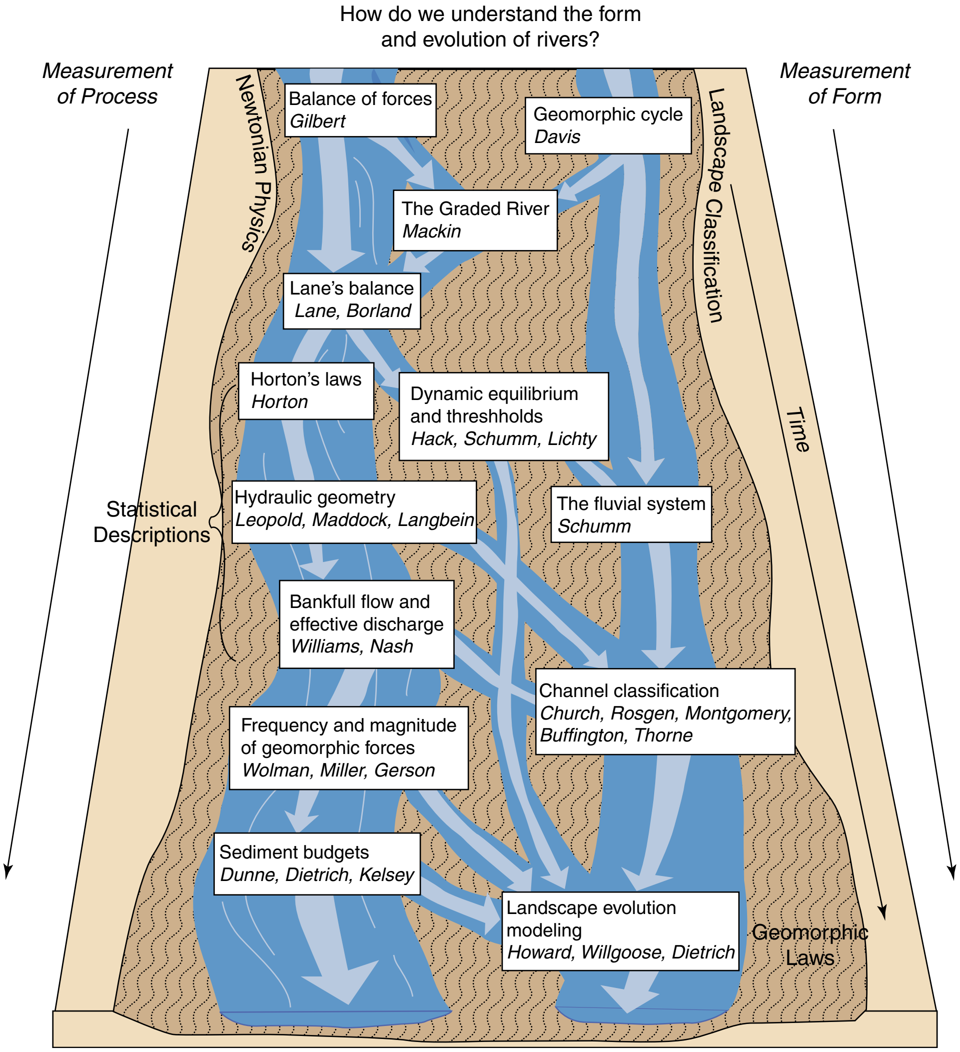

**Figure 2** Braided river of concepts and conceptual models in fluvial geomorphology.

solely on physics, it is 'timeless' in the sense that it presumes nothing about the state of the system, other than that the supply of water and sediment be balanced. Moreover, he described the process by which that balance is maintained. The form of the channel results from the interplay of forces that are inevitably balanced by their actions on each other. This profound insight into how physical forces operate to produce equilibrium forms pervades all of Gilbert's work, and provides a framework for viewing landscape processes that now dominates modern geomorphology (Baker and Pyne, 1978). The success of Gilbert's model is that it provides an approach as much as an explanation for understanding landscape form. As noted by Baker and Pyne (1978, p. 104):

> When Gilbert codified the processes of a graded stream he did for geology and hydraulics what the phase rule did for physiochemical systems – it not only rationalized the known data but it introduced predictability into the behavior of the systems. Both concepts now operate in geologic phenomena, and each describes a form of metamorphism. With a change in temperature or pressure, a change of phase reconstructs the chemical system, the rock. With a change of sediment load or water discharge, a change of grade reconstructs the fluvial system, the river.

#### 9.2.3.1.2 *The Cycle of Erosion*

Davis wasted no time in laying out his thesis. Under the heading 'The Genetic Classification of Landforms,' he began his essay 'The Geographical Cycle' with "All the varied forms of the lands are dependent upon – or, as a mathematician would say, are functions of – three variable quantities, which may be called structure, process, and time" (Davis, 1899, p. 481). With one sentence he linked the conceptual building blocks of form, process, geology, and history, and forever changed the way we look at landscapes. His contribution rests on bringing time into the equation, not as an idle bystander but as an inexorable driver of sequential landforms. Moreover, he posited that there is a discernible relationship between the form that the landscape takes and time. As Chorley et al. (1973, p. 160–161) gave Davis's account of how this realization occurred to him, the revelation was primarily from geologic observations – erosional features on the smooth plains of eastern Montana could only indicate great age. In Davis's words:

> It was thus forced upon me that the plains are old, not young; also that young valleys are now incised in the old plains because of revived erosion by the rivers. The scheme of the cycle of erosion, published in the following year, was a natural outcome of this summer's observations. The following years at Harvard I introduced the natural history of rivers into my course on physical geography, and thus enlivened what had been before a very dull topic.

By introducing the coupled ideas that the stage of a landscape could be read in its forms, and that most landscapes experienced a discernible evolution of form through time, Davis presented his students with a readily understandable even if not entirely accurate (as many would later point out) blueprint for landscape evolution. Set against the backdrop of other late nineteenth-century evolutionary thought by Darwin and others, Davis's conceptual model provided an appealing 'timebound' narrative of landscapes cycling through a sequence of youth, maturity, and old age only to be rejuvenated by uplift. This narrative formed the basis of a geomorphological trope that successive generations of geographers would repeat and refine. Its broad appeal lay in its simplicity, although Davis would spend many of his later years attempting to reconcile the wide range of 'inconvenient truths' of landforms and landscapes that were not well explained by this model. It also introduces an explicit 'space-for-time' substitution that offers an attractive way of describing temporal change.

Two elements of this simplicity, in particular, stand out. First is the obvious correspondence, emphasized by Davis's choice of terminology, between landscape and human evolution. This is a story we all understand, and its cyclicity is uplifting (in the emotional sense). More to the point, the concept of landscapes evolving in cycles, or at least along trajectories, has informed later work, including analysis of sedimentation associated with arroyo formation (Schumm and Hadley, 1957), urban development (Wolman, 1967), and ecosystem response to wildfire and disturbance (Reeves et al., 1995).

The second appeal is that the Davisian system is fundamentally about classification of landscapes. As noted by the mathematician Mirkin (1996; p. 2), "It is a common opinion that narrative becomes science when it involves classification." Davis (1899; p.367) emphasized and promoted the classificatory nature of his scheme as providing a general framework into which all landscapes could be fit:

> The structure of the land may be regarded as composed of a number of individual forms, whose general character depends on the rock-structure which the processes of land sculpture have worked upon, and whose more particular expression depends on the degree of advance in the degradation of the surface from its initial, constructional form to the smooth, low, baselevel plain to which it is finally reduced. Thus regarded, any geographic individual may be associated with certain others to which it is related by similarity of structure, and the whole group of similar individuals, thus related, may be idealized in a type, which presents all the essential, but none of the accidental features of the group that it represents.

Although Davis was speaking directly to forms that fit into his denudation chronology, his words foreshadow over a century of landscape classification that proceeds to this day and has sparked some of the more vigorous debates in the field of fluvial geomorphology.

### 9.2.3.2 Secondary Channels: Conceptual Models from the Golden Age of Geomorphology

Gilbert's 'timeless' model focused on process and Davis's 'timebound' model (sensu Baker and Twidale, 1991) focused on form and sequence represent the two dominant 'braids' of our model genealogy, with most twentieth-century conceptual models fed by intellectual currents off one or the other (**Figure 2**). Most of these models arose during what has been termed the 'Golden Age of Geomorphology' (Baker and Twidale, 1991). A key distinction is the way in which the concept of the graded river was dealt with. Along the Gilbertian strand are arrayed a diversity of concepts and ideas pointed at understanding the processes and factors that underlie grade. By what mechanisms, for example, do channels adjust their dimensions to changing flow and sediment inputs and how can that adjustment be described quantitatively (bankfull flow, hydraulic geometry)? How and when does sediment move in rivers (magnitude/frequency)? In contrast, the currents fed by the Davisian strand support conceptual models of landscape organization and form. How is the fluvial landscape organized (the fluvial system, channel classification)? How does the landscape evolve over time (landscape evolution models)?

Here we discuss some of these more prominent and recent conceptual models, examining their relationship and hybridization with other models, and extract some useful lessons about the role of conceptual models in general in both driving and retarding scientific thinking. Rather than taking a chronological perspective, we have highlighted some of the more interesting pathways through our braided genealogy (**Figure 2**).

#### *9.2.3.2.1 The Graded River*

As we have seen, the concept of the graded or equilibrium river was clearly in play by the beginning of the twentieth century and used by both Gilbert and Davis in their thinking. It took Mackin (1948) to expand the Gilbertian concept, however, clearly linking it to thermodynamics as an application of Le Chatelier's principle: "if a stress is brought to bear on a system in equilibrium, a reaction occurs, displacing the equilibrium in a direction that tends to absorb the effect of the stress." More importantly, the concept was extended to include the full suite of potential channel adjustments (e.g., channel dimensions and caliber of bed material), but also considerations of scale (local versus broad-scale adjustments). Mackin also gave us one of the most famous and concise definitions in fluvial geomorphology:

> A graded stream is one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and the prevailing channel characteristics, just the velocity required for transportation of all of the load supplied from above.

The value of the concept of the graded river again lies in its simplicity and coherence, less in its applicability to real rivers. Demonstrating that a river conforms to Mackin's dictum has proven difficult, partly because of the loosely defined timescale ('…over a period of years') and partly because the driving variables of discharge and sediment are rarely constant and, in the case of sediment, difficult to measure. This emphasizes a key point about conceptual models: they are often more useful as general tendencies or heuristic devices rather than as rigorous guides for measurement or analysis.

### 9.2.3.2.2 Lane's (and Borland's) Balance

A closely related conceptual model that includes one of the two most recognized graphics in fluvial geomorphology is derived from Lane's (1955) physical relationship between available sediment and available energy. This relationship was succinctly illustrated as a literal balance by Borland (1960) (**Figure 3**). Mackin's 'delicate adjustment' is perfectly captured in this rich visual model that shows the proportionality between the discharge and slope (essentially stream power) on the one hand and sediment flux and bed caliber on the other. A change in any of these variables will tip the balance toward either aggradation or degradation; rebalancing can occur through compensating changes in one or more of the other three variables. This figure and the concepts that underlie it have stood the test of time, and provided the basis for more rigorous and quantitative models. Recent works to develop quantitative predictions of the downstream effects of dams on channels, for example, have explicitly used Lane's balance as the foundation for their analytical schemes (Schmidt and Wilcock, 2008).

### 9.2.3.2.3 Dynamic Equilibrium and Thresholds

As previously noted, the idea of equilibrium, which we introduced as a Level 1 concept, pervades much of the thinking in geomorphology and both braids of our genealogical river, but is not a conceptual model per se (see Thorn and Welford, 1994 for a review). Starting with Hack (1960), however, the concept was more explicitly defined as a fundamental tendency of geomorphic systems. As Hack (1960) defined it:

> The landscape and the processes molding it are considered a part of an open system in a steady state of balance in which every slope and every form is adjusted to every other. Changes in topographic form take place as equilibrium conditions change, but it is not necessary to assume that the kind of evolutionary changes envisaged by Davis ever occur (p. 81).

Hack credited Gilbert as the progenitor of the concept and, in keeping with the Gilbertian notion of interpreting landscapes with a 'timeless' perspective, went on to say:

> The theory of dynamic equilibrium explains topographic forms and the differences between them in a manner that may be said to be independent of time. The theory is concerned with the relations between rocks and processes as they exist in space. The forms can change only as the energy applied to the system changes. It is obvious, however, that erosional energy changes through time and hence forms must change (p. 94).

In essence, Hack took Gilbert's balance of forces and scaled them up to the entire landscape, acknowledging time only in passing in the last sentence.

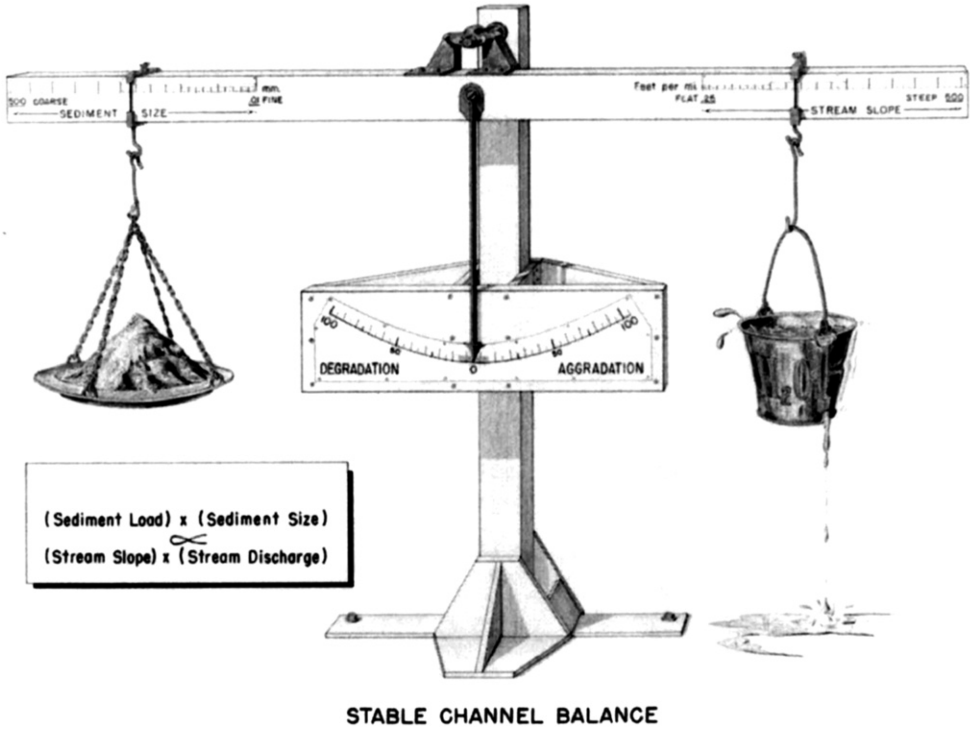

**Figure 3** Lane's balance. One of the most recognized conceptual models in geomorphology. Reproduced with permission from Borland, W.M., 1960. Stream Channel Stability. U.S. Bureau of Reclamation, Denver.

But how is any of this of use to our inquisitive geomorphologist, still standing in the creek? It took the insights of Schumm and Lichty (1965) to begin to bridge the gap between the timeless and timebound perspectives, and develop a framework in which concepts such as dynamic equilibrium could be used to understand the behavior of the fluvial system. They developed the concept of a hierarchy of controls on the form and behavior of fluvial systems that expresses itself over a range of explicitly if loosely bounded timescales. Defined timescales range from 'cyclic' (e.g., geological) to 'graded' (e.g., modern) to 'steady' (e.g., present), and processes that vary at one timescale (i.e., seasonal or annual variations in discharge or sediment flux) are seen as essentially constant at longer timescales of centuries to millennia. By developing an explicit framework for how processes express themselves across different ranges of time, they clearly introduced the concept of scale in geomorphology and brought together timeless and timebound perspectives. In doing so, the Schumm and Lichty conceptual model reconciles the Davisian and Gilbertian schemes: it is all a matter of scale used and question asked. Moreover, they give the practicing geomorphologist a 'roadmap' for distinguishing cause and effect across a wide range of processes and controls.

Later, Schumm (1979) expanded on the concept of dynamic equilibrium, which he expanded and defined as a system that, while varying around a particular state (e.g., interannual variation in floodplain thickness) over shorter timescales, experiences progressive change in that state (e.g., overall valley elevation due to aggradation or degradation) over longer timescales. To this concept, he then introduced the concept of thresholds: Thresholds (another Level 1 term) can be either intrinsic (i.e., due to the evolution of the system itself) or extrinsic (i.e., imposed by a change in external forces). Schumm was more interested in the former and defined a geomorphic threshold as:

> …one that is inherent in the manner of landform change; it is a threshold that is developed within the geomorphic system by changes in the morphology of the landform itself through time. It is the change in the landform itself that is most important, because until it has evolved to a critical situation, adjustment or failure will not occur (p. 487).

Because thresholds represent an abrupt change in system behavior for a small increment of applied stress (either internal or external to the system), they introduce the potential for rapid change and nonlinear behavior in geomorphic systems – a potential that is not clearly expressed in the prevailing model of geomorphic equilibrium. Schumm pointed this out:

> It is inherent in the threshold concept that a landscape is not always in a condition of grade, balance, or equilibrium. The existence of the threshold suggests an inability of the landform to adjust readily to a new equilibrium condition (p. 493).

Adding the concept of thresholds introduces a rich but confusing cosmology of new conceptual models of landscape evolution, that is, metastable equilibrium, dynamic metastable equilibrium, etc. It also presages the field's short and inconclusive flirtation with catastrophe theory (Graf, 1979; Sherman, 1996).

But most importantly from the standpoint of our field geomorphologist, these newer conceptual models that explicitly recognize a hierarchy of control acting over different timescales with the potential for abrupt changes in system behavior offer hope that future states of the river can be predicted, at least empirically. From Schumm (1979, p. 513):

> The concepts advanced here provide, it is hoped, a basis for truly predictive and applied geomorphology. The fact that, at least locally, geomorphic thresholds of instability can be defined quantitatively suggests that they can be identified elsewhere and then used as a basis for recognition of potentially unstable landforms in the field.

#### *9.2.3.2.4 Analysis of Hydraulic Geometry*

Gilbert's perspective and later work suggested that the forms that the river and drainage system take are essentially independent of history, owing instead to the interactions among the driving variables of water and sediment supply and energy expenditure. This history-free view lends itself directly to describing river form and processes in statistical terms. The earliest statistical descriptions in geomorphology were probably those of Horton (1945), who developed morphometric characterizations of drainage basin structure (Horton's laws). These provided a powerful description of the fundamental architecture of drainage networks, and opened the door to the prospect that geomorphic systems could be rigorously represented in mathematical terms. Although later work has demonstrated that there is a certain 'statistical inevitability' to Horton's laws (Kirchner, 1993), the concept of mathematically and statistically describing the central tendencies of geomorphic systems has become a fundamental tenet and approach in geomorphology (see Clément and Piégay, 2003 for a review). Current drainage network studies now emphasize theoretical understanding of optimal network configurations and fractal models of self-organized criticality (e.g., Rodriguez-Iturbe and Rinaldo, 1997).

The statistical description of the form of the channel has been termed hydraulic geometry and development of this concept provided a cornerstone for moving fluvial geomorphology into the modern age (Leopold and Maddock, 1953). The idea is simple enough: empirically and graphically relate the measured geometry and hydraulics of the river channel – its width, depth, velocity, slope, etc. – to the 'master' variable of flow or its proxy, drainage area, and build a statistical description (typically power relationships) of how that geometry changes with flow. This can be done to describe the variation in channel parameters for a particular location (at-a-site hydraulic geometry) or, for a specified flow frequency, with longitudinal distance along the channel (downstream hydraulic geometry) (Leopold et al., 1964).

Rarely has a conceptual model had as much impact as that of hydraulic geometry. Workers now have a common language and tool for describing variation in individual channels (e.g., Wolman, 1955), examining unexpected trends in system behavior, that is, the counter-intuitive increase in stream velocity as rivers grow larger (Carlston, 1969; Leopold and Maddock, 1953) – more on this later, comparing channel forms across physiographic regions (e.g., Knighton, 1975; Park, 1977b), and analyzing effects of human activities, such as dam construction, on channel form (e.g., Park, 1977a). Moreover, the statistical description of rivers now provide a means of testing theoretical, analytical, physical, and numerical models of river evolution. Langbein and Leopold (1964), for example, used hydraulic geometry to argue for underlying 'least work' explanations of river channel form. Yang et al. (1981) did the same for the theory of minimum rate of energy dissipation. Parker (1979) tested mechanistic arguments of controls of channel form against hydraulic geometry relations in gravel bed rivers. Hydraulic geometry underlies one of the most critical and widely cited (4000 at last count) concepts in stream ecology: the river continuum concept (Vannote et al., 1980), and is used as the basis for habitat assessments around the world (e.g., Jowett, 1998).

Given the acknowledged simplicity, apparent sagacity, and demonstrated longevity, of the concept of hydraulic geometry, it would seem to be blasphemous to challenge it. Nevertheless, that is exactly what Mackin (1963) did, just as the idea was beginning to flourish, and we consider his criticism at some length, as it points to how conceptual models can conceal as well as reveal. His concern was not with hydraulic geometry per se, but with what it represented in terms of what he called 'blind empiricism' in geological thinking, the trumping of careful geological reasoning with uncritical quantification. In Mackin's words (p. 137):

> At least a part of the confusion in our thinking comes from a failure to distinguish between the evolutionary quantification, which is good, and the mechanical kind of quantification, which I think is bad when it takes the place of reasoning. It is not easy to draw a line between them because the empirical procedures may stand alone, or they may function effectively and usefully as parts of the classical geologic method; that is, they may replace, or be combined in all proportions with, the reasoning processes that are the hallmarks of that method. When this distinction is recognized it becomes evident that the real issue is not qualitative versus quantitative. It is, rather, rationality versus blind empiricism.

Mackin described that rationality (which he attributed in part to Gilbert) as a 'habit of thought' that:

> ...checks reasoning against other lines of reasoning, evidence against other kinds of evidence, reasoning against evidence, and evidence against reasoning, thus testing both the evidence and the reasoning for relevancy and accuracy at every stage of the inquiry (p. 139).

He contrasted this with what he termed the empirical method, which in his view drew heavily from the engineering approach to interpreting data:

> This method reduces to a minimum, or eliminates altogether, the byplay of inductive and deductive reasoning by which data and ideas are processed in the scientific method; this means that it cannot be critical of the data as they are gathered. The data are analyzed primarily by mathematical methods, which make no distinction between cause and effect; understanding of cause and effect relations may be interesting, but it is not essential, and if explanations are considered at all, there's usually only one, and it is likely to be superficial (p. 140).

So where does hydraulic geometry fit into this scathing critique? Mackin used it as one of his examples of 'blind empiricism' and deconstructed **Figure 6** from Leopold and Maddock's (1953) classic analysis to show that their plotted downstream trend between mean flow velocity and discharge, whose positive slope the authors interpreted as supporting their interpretation that rivers flow faster downstream, is actually a statistical average of individual curves that show a wide disparity of downstream trends in velocity (Mackin, 1963; **Figure 2**). His point was that by removing the geographical context associated with the data attached to individual rivers, an empirical relation is obtained that, although statistically valid, obscures the underlying forms, processes, and trends, and cannot be considered an adequate scientific explanation.

Other examples having to do with longitudinal profiles, meanders, etc. are similarly developed. In the end, Mackin's point was not about the value of quantification (which he accepted as here to stay) or the downstream velocity of rivers. He wished to remind us that as geomorphology inevitably becomes more quantitative in both its approaches and models (conceptual and otherwise), that we not lose sight of the value of rigorous rational thought. He concluded:

> As stated at the outset, the real issue is not a matter of classical geologic methods versus quantification. Geology is largely quantitative, and it is rapidly and properly becoming more so. The real issue is the rational method versus the empirical method of solving problems; the point that I have tried to make is that if the objective is an understanding of the system investigated, and if that system is complex, then the empirical method is apt to be less efficient than the rational method. Most geologic features – ledges of rock, mineral deposits, landscapes, segments of the river channel – present an almost infinite variety of elements, each susceptible to many different sorts of measurement. We cannot measure them all to any conventional standard of precision – blind probing will not work.… It is only by thinking, as we measure, that we can avoid listing together in a field book, and after a little while, averaging, random dimensions of apples and oranges and apple crates and orange trees (p. 161).

Although written almost 50 years ago, Mackin's caution not to be blinded by our methods and models rings true to this day.

### 9.2.3.2.5 Frequency and Magnitude of Geomorphic Processes

Although the junior author might have demurred, along with Lane's balance, arguably the other most influential graphic in fluvial geomorphology is the frequency/magnitude graph of Wolman and Miller (1960) (**Figure 4**). Eschewing numbers on the axes, the graph shows the relation between an applied stress on the abscissa whose magnitude or rate of doing work is assumed to proceed exponentially, the frequency distribution of those applied stresses, which is assumed to be log-normally distributed, and the resulting product of magnitude and frequency, whose bell-shaped curve has a peak to the right of the frequency distribution of applied stresses but not at the far right extreme. Wolman and Miller interpreted the shape of this curve and its diagnostic peak as indicating that events of moderate frequency and magnitude are more effective in doing geomorphic work (defined in terms of mass transfer of sediment) than the extremes. This interpretation is supported by examples drawn from suspended sediment transport, channel

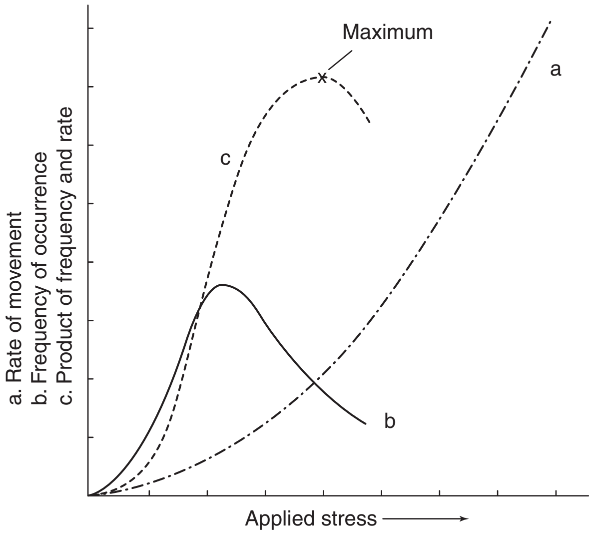

**Figure 4** The well-known magnitude and frequency curve. Reproduced from Figure 1 in Wolman, M.G., Miller, J.P., 1960. Magnitude and frequency of forces in geomorphic processes. The Journal of Geology 68, 54–74, with permission from The Journal of Geology.

form, and wind transport. Adopting a rational reasoning that even Mackin would accept, they concluded with a story:

> Perhaps the state of knowledge as well as the geomorphic effects of small and moderate versus extreme events may be best illustrated by the following analogy. A dwarf, a man, and a huge giant are having a wood-cutting contest. Because of metabolic peculiarities, individual chopping rates are roughly inverse to their size. The dwarf works steadily and is rarely seen to rest. However, his progress is slow, for even little trees take a long time, and there are many big ones which he cannot dent with his axe. The man is a strong fellow and a hard worker, but he takes a day off now and then. His vigorous and persistent labors are highly effective, but there are some trees that defy his best efforts. The giant is tremendously strong, but he spends most of his time sleeping. Whenever he is on the job, his actions are frequently capricious. Sometimes he throws away his axe and dashes wildly in the woods, where he breaks the trees or pulls them up by the roots. On the rare occasions when he encounters a tree too big for him, he ominously mentions his family of brothers – all bigger, stronger, and sleepier (page 73).

This fanciful story is also a conceptual model, capturing the essence of an idea that usefully organizes thinking. The concept of frequency and magnitude is fundamental to modern geomorphic thought and has sparked enormous discussion and debate within the field. It underlies our efforts to rigorously and quantitatively relate process and form, to reconcile the effectiveness of multiple processes of varying effectiveness operating over wide-ranging time and space scales. It has spawned other critical concepts, such as the idea of a dominant or effective discharge. This was originally taken as the peak of the Wolman and Miller curve, and interpreted as the discharge and its associated frequency or return period responsible for the maximum amount of erosional work done on the landscape. Alternative interpretations have emerged, such as the peak of bedload transport or the discharge that just fills the channel (Pickup and Warner, 1976), and other work has emphasized that the concept may differ in alluvial versus nonalluvial channels (Baker and Pyne, 1978; Carling, 1988). Later work called into question whether sediment transport can be well described as a power function, the importance of thresholds, whether the frequency distribution of effective events is truly log-normal, and whether the recurrence interval suggested by Wolman and Miller of approximately 1 year for bankfull events is a useful predictor of the recurrence interval of the effective discharge (Nash, 1994).

The concept of effectiveness was expanded by Wolman and Gerson (1978) to include the idea of persistence, with effective events being those responsible for creating or modifying landscape forms that persist over time. The absolute magnitudes of such events vary markedly across climates and in different parts of the drainage basin. Discussions such as these show no signs of diminishing in the present as considerations of nonstationarity in climate introduce an entirely new set of considerations in interpreting geomorphic work. What is remarkable is how a single simple model, capable of being captured in storybook form, has so firmly held our collective imagination.

### *9.2.3.2.6 Bankfull Flow as an Indicator of Channel-Forming Processes*

The concept of bankfull flow – that discharge just necessary to fill the channel – emerged out of considerations of frequency and magnitude. We include it here as a separate conceptual model primarily for the enormous impact it has had in shaping applied geomorphology and channel classification. Although Wolman and Miller used bankfull flow solely as a reference point for examining the correspondence between effective discharge (as defined by **Figure 4**) and channel form, it rapidly took on a life of its own as an assumed proxy for effective discharge and for comparisons of channel dimensions normalized to that discharge exceedance.

It certainly would be convenient if the geomorphic work of the complex sequence of flows represented by the long-term hydrograph could be represented by a single index flow and if that index flow had an approximately uniform recurrence interval across the landscape (e.g., the 1.5 year return flow). Although later work has shown these attributes as elusive (Hey, 1998; Williams, 1978), bankfull flow continues to be used as a reference point for stability and sediment transport analyses, since it provides a reasonably useful and measureable reference point common to many channels (i.e., Olsen et al., 1997). But one does wonder whether the term 'bankfull' has been taken far past its clear merit (and roots) as a nonquantitative communication device.

### 9.2.3.3 The Fluvial System

Most of the discussion so far has taken us far down the 'timeless' branch of our genealogical river. As discussed, this branch has been, by far, the dominant thread of modern geomorphic thinking. Much of the work along this thread has been to explore the various factors underlying the concept of grade or equilibrium in rivers. But another view, more closely allied with the 'timebound' or Davisian strand, is that of using the concept of grade or equilibrium to explore landscape evolution. This distinction is, as noted previously, a fuzzy one at best, and there are many examples, some shown in **Figure 2**, of hybrid or cross-over concepts. Nevertheless, our journey down the river would be incomplete if we do not consider some conceptual models from this second braid. Perhaps the concept that has held the most sway has been that of the fluvial system, as provided by Schumm (1977) in the title of his book of the same name. In contrast to the earlier work by Leopold et al. (1964), Schumm tackled the problem of providing a geographic context for forms and processes in fluvial geomorphology. He did this by building his analysis around a conception of the drainage basin as being divided into three process zones: sediment production, sediment transfer, and sediment deposition (**Figure 5**). Each zone is represented by a dominant process (erosion, transportation, deposition) with characteristic forms and behaviors. The overall landscape functions as a system within the constraints imposed by gravity; what happens upstream influences what happens downstream. The overall behavior of this system according to Schumm can be described in terms of concepts of uniformity, thresholds, landscape evolution, and complexity, concepts we have already seen to be extremely useful in understanding geomorphic systems. But the remarkable aspect of this scheme is that it essentially recasts Davis's sequence of fluvial forms through time (young mountain rivers, mature floodplain channels, old peneplains) as a longitudinal sequence of forms in space, through which water and sediment cascade. We can now talk about process domains, as defined by Montgomery (1999) as "… spatially identifiable areas characterized by distinct suites of geomorphic processes." This concept of distinctive zones where particular processes and forms link together is a distinctively different perspective than that embodied by hydraulic geometry relations or the river continuum concept, which posits a more or less linear change in the underlying drivers of water and sediment flux.

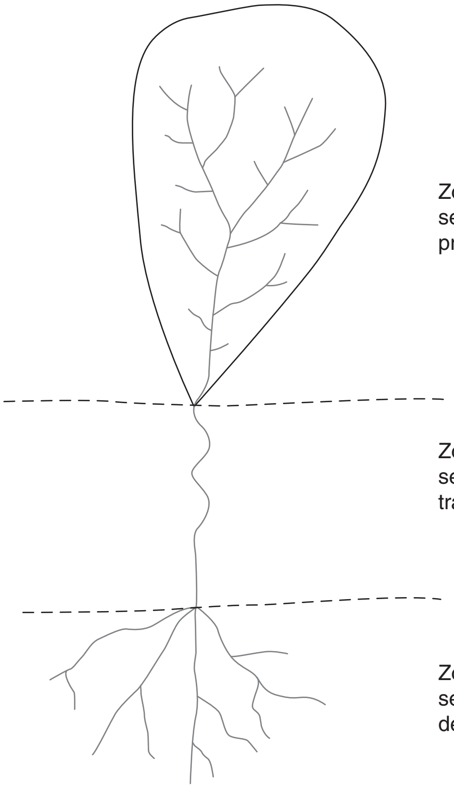

**Figure 5** Schumm's model of the fluvial system. Reproduced from Figure 1-1 in Schumm, S.A., 1977. The Fluvial System. Wiley-Interscience, New York, 338 pp.

### 9.2.3.3.1 Channel Classification

Both of these perspectives can be true simultaneously, of course, but they offer different opportunities for elaboration and application. The concept of the fluvial system underlies a new and, in some quarters, rather contentious development in the field: the classification of river channels for various purposes (*see* Chapter 9.36). Although this might seem to be more an approach than a conceptual model (see Kondolf et al., 2003, pp. 171–204 for review), the concept that channels that occupy different parts of the landscape are fundamentally distinct, and can be classified, interpreted, and managed based on that distinctiveness represents a major conceptual framework for viewing geomorphic systems. Classification in and of itself is not a new concept; as noted above, its pedigree in geomorphology runs straight to Davis. As noted by Kondolf et al. (2003, p. 170):

> Regional variability in river processes and river characteristics imparts a fundamental tension between development of generalizable and regional characterizations of river systems. It is not surprising, therefore, that attempts to classify rivers have resulted in a wide variety of classifications schemes, serving a wide range of purposes from typologies for interpreting and understanding landscape evolution over geologic time to those attempting to aid in the development of engineering designs for channel restoration projects.

Key classification schemes in use today include those developed by Church (1992), Rosgen (1994, 1996), Montgomery and Buffington (1997), and Thorne (1997), among others. Inevitably, the classification schemes reflect the underlying purposes, perspectives, and geographical biases of their authors. Just as inevitably, this has led to schisms in this arena that are particularly noteworthy for the enthusiasm with which proponents argue their cases (see Lave, 2009, for an excellent summary of aspects of this debate).

But beyond the classifications themselves, the concept that all channels are not created and do not behave equally has given rise to a resurgence of geographically focused fluvial geomorphology. The emphasis has been on identifying and describing types of rivers. Recent books, for example, have focused on mountain rivers (Wohl, 2010), bedrock rivers (Tinkler and Wohl, 1998), varieties of rivers (Miller, 1999), large rivers (Gupta, 2008), and even peculiar rivers (O'Connor and Grant, 2003). This trend seems likely to continue as recognition of the diversity of fluvial forms extends to other locales and even other planets.

Yet an unresolved problem with channel classification is its downplaying of the role of history in controlling form. How much of the channel form that we see today is inherited from some prior regime or condition, and hence not just a simple function of stream power or bankfull geometry? Integrating geology into classification remains a challenge for the future.

#### *9.2.3.3.2 Sediment Budgets*

As with channel classification, sediment budgets are both an approach and a model. A sediment budget is a rigorous quantitative accounting of the production, transfer, and storage of sediment within a landscape. It is a quantification and grounding of the concept of the fluvial system in time and space. An early and influential quantitative sediment budget was developed by Dietrich and Dunne (1978) for a small coastal watershed in Oregon. They provided a conceptual framework and suggested a range of approaches for estimating fluxes of sediment by various processes through the landscape (Dietrich and Dunne, 1978; **Figure 6**). The conceptual model was a flowchart with storage, fluxes, and outputs represented by geometric figures; estimates of rates were specified in the text (**Figure 6**). Publication of this paper was quickly followed by sediment budgets from other regions (i.e., Kelsey, 1980; Swanson et al., 1982; Trimble, 1983). Although the published number of detailed sediment budgets has declined in recent years, in part because of the difficulties of conducting a rigorous budget, the concept is still very much with us, particularly as a framework for understanding longer term erosional systems. Coupled with new dating techniques, such as cosmogenic nuclides, sediment budgets for large river systems have been developed that demonstrate the role of episodic events in long-term erosion and continental shelf sedimentation (i.e., Page et al., 1994; Sommerfield and Nittrouer, 1999), local variations in sediment storage and flux (McLean and Church, 1999), changing contributions of different sediment sources over time (Kesel et al., 1992), effects of human activities on the landscape (Reid et al., 1981), and long-term landscape evolution (i.e., Kuhlemann et al., 2002). This is another example of wholesale returns of analysis from a simple conceptual frame.

### 9.2.3.4 Landscape Evolution Modeling and the Search for Geomorphic Laws

Our last conceptual model is an open-ended one that does not have a simple graphic to support it. But it represents one of the leading edges of today's field of geomorphology. Landscape modeling of various processes over various scales by different approaches (numerical, physical) is an exploding area of fluvial geomorphology, and we do not even attempt to cover it here (see recent reviews by Darby and Van de Wiel, 2005; Wilcock and Iverson, 2003). In the present context, we draw attention to the concept of the search for geomorphic transport laws that underlie the development of these models. No one has been a more effective proponent of this idea than William Dietrich and colleagues (Dietrich et al., 2003).

> A geomorphic transport law is a mathematical statement derived from a physical principle or mechanism, which expresses the mass flux or erosion caused by one or more processes in a manner that: (1) can be parameterized from field measurements, (2) can be

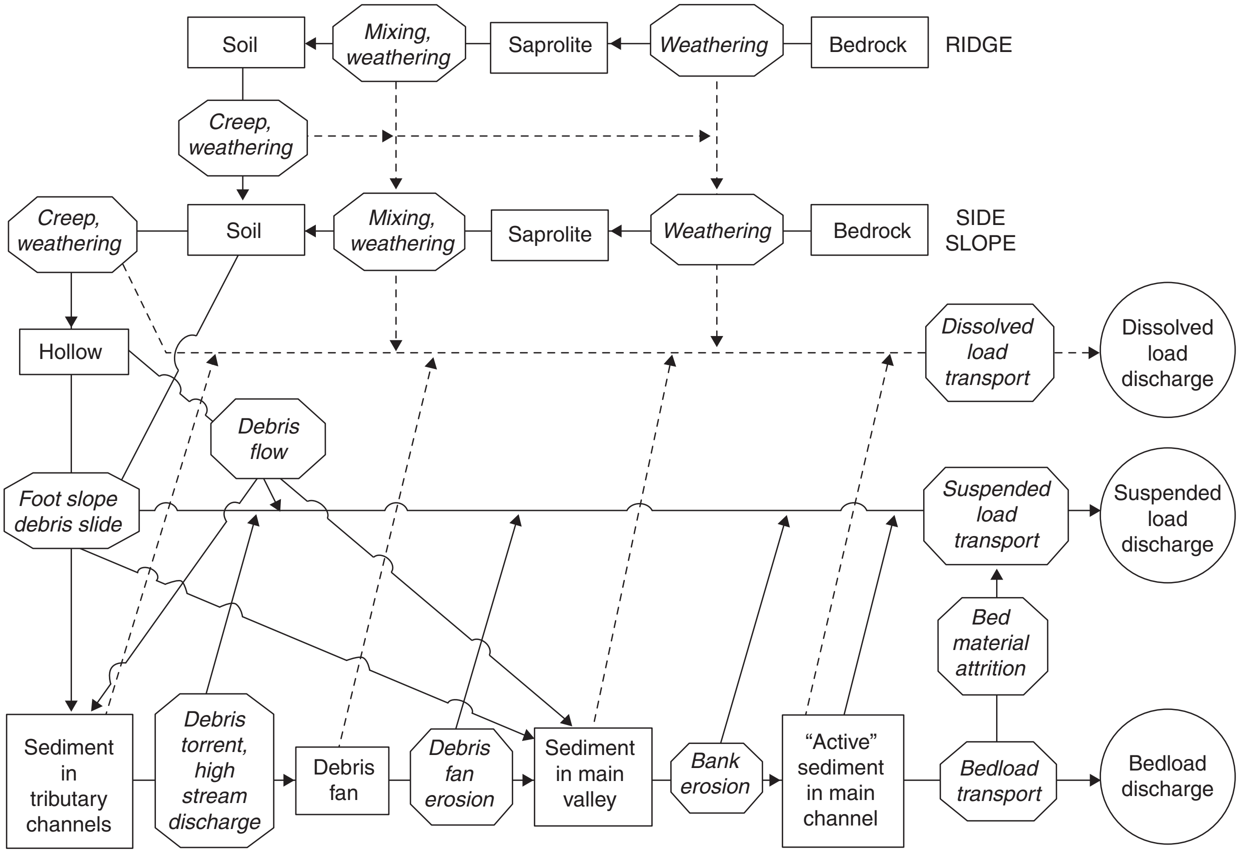

**Figure 6** Sediment budget for Rock Creek, OR. Reproduced from Figure 6 in Dietrich, W.E., Dunne, T., 1978. Sediment budget for a small catchment in mountainous terrain. Zeitschrift fuer Geomorphologie 29, 191–206, with permission from Zeitschrift fuer Geomorphologie.

> tested in physical models, and (3) can be applied over geomorphically significant spatial and temporal scales. Such laws are a compromise between physics-based theory that requires extensive information about materials and their interactions, which may be hard to quantify across real landscapes, and rules-based approaches, which cannot be tested directly but only can be used in models to see if the model outcomes match some expected or observed state (p. 1).

On the one hand, geomorphic transport laws, such as the stream power law, are solidly on the Gilbert braid of the river, grounded as they are on fundamental physics and first principles. But they are also rooted in the landscape, at least to the extent that they can be tested and quantified. Bringing the physics and field together is an intrinsic theme woven throughout the history of geomorphology, and it continues today as expressed in the plethora of landscape models that attempt to recreate by computer what Davis and Gilbert saw from their mountain perches.

The evolving field of landscape evolution modeling is generating new conceptual models, particularly in the coupling of tectonic geomorphology to climate (e.g., Burbank and Anderson, 2001). Chief among these is the 'steady-state' model of mountain-building, wherein erosion and denudation from glacial or fluvial processes is balanced by isostatic uplift and tectonic deformation (e.g., Whipple, 2001; Willett et al., 2006).

Crucial questions remain, however. First, how will we know if the models are right? As all honest modelers know: 'All models are wrong but some are useful' (Box and Draper, 1987). There is no single answer to this question, although some would argue that models that need to be extensively parameterized reflect a fundamental lack of understanding of the underlying system. Recent movement toward physical models that have no adjustable parameters is an exciting development in the field (i.e., Iverson, 1997). But perhaps more importantly, how do we bring history to bear on our landscape evolution thinking? Landscape evolution modeling captures two of Davis's trifecta of structure, process, and time – how can geological structure and sequence be incorporated? And can the models be used to explain as well as predict? Geomorphologists in the middle of the twentieth century were fond of their own classifications, in this case of drainage network architecture and pattern. Despite these elaborate taxonomies, we still have no explanation for why trellis patterns evolve in some landscapes whereas dendritic networks form in others. One test for our landscape evolution models should be whether they can answer these fundamental problems posed by the watershed structures we observe.

### 9.2.4 The Field Problem Revisited

So what do we tell our curious geomorphologist at the end of the day? What lessons emerge from consideration of this incomplete potpourri of conceptual models in fluvial geomorphology? Conceptual models help us by providing an intellectual toehold from which to get started with the field problem. They mean we do not always need to go back to first principles in order to make progress toward answering a question posed by the field: why does the river look the way it does and what will it look like in the future? They give us a conceptual 'hat' to wear when attacking complex problems (Figure 7).

But quickly seizing on a conceptual model to gain purchase has its own limitations. It may provide the safety of an answer, when what is needed is a more open-minded inquiry in the spirit of Mackin. There may be times when thinking through from first principles leads to greater insights, as it forces the mind to pay close attention to details that might otherwise be glossed over. And the history of conceptual models shows that because they are invariably biased by deeply rooted assumptions of cause and effect or hierarchy of controls, settling too soon on a model may obscure more than it reveals.

Moreover, one must be cautious of overly relying on conceptual models, as they may lead to lazy thinking. For example, concepts of both bankfull flow and dominant discharge are useful and simplify some geomorphic problems by providing a single index flow to use as a reference. But we should not fall into the trap of believing that any one particular flow has disproportionate weight when it comes to establishing and maintaining channel form. Focusing on a single flow (because it is easy) at the expense of recognizing the geomorphic work and role played by the full distribution of flows can lead to misleading results.

In short, the roads to both heaven and hell are paved with conceptual models. The course of our genealogical river reveals that the current of geomorphic thought swings back and forth in response to the problems and intellectual fashions of the day. Although master braids emerge, many individual threads of this river are active at the same time, and the current is forced around by fixed ideas and episodic turbulence. In looking at the river, we are struck that some combinations of models and themes seem under-represented at present, and these may be where the field needs to go in the future. Chief among these is a more explicit incorporation of geological history into process-based models and classifications. It may also serve us well to acknowledge the long shadows cast by the field's intellectual fathers – Davis and Gilbert – and directly consider how to better meld a physics-based conception of landscape behavior with a geologically based perspective of landscape evolution. New technologies for measuring form (e.g., LiDAR), process (i.e., sophisticated sensors), and time

**Figure 7** Three geologists wearing different conceptual hats. Photo courtesy of Noel Potter (on right). Hats courtesy of Robb Jacobson.

(e.g., cosmogenics) in ways that Gilbert and Davis never imagined are captivating, but ultimately it is Mackin's 'habits of thought' that will enlighten our geomorphologist's trip to the river.

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## Biographical Sketch

Gordon Grant is a Research Hydrologist with the US Forest Service at the Pacific Northwest Research Station in Corvallis, OR, USA, and also professor (Courtesy) in the Department of Geosciences at Oregon State University. Born in New York, he moved to Oregon at the age of 13 and promptly fell in love with the landscape. Following a decade-long career as a whitewater river guide, he received his PhD from Johns Hopkins University in 1986. His research since then has focused on the geomorphic response of rivers to changes in stream flow and sediment transport due to land use, dams and dam removal, volcanoes, and climatic variation.

Jim O'Connor is a Pacific Northwest native, long interested in the processes and events that shape the remarkable and diverse landscapes of the region. Following this interest with a Geological Science major at University of Washington and MS and PhD degrees at University of Arizona, he has spent the past 20+ years focused on fluvial geomorphology and quaternary geology in the western North America, for the past 15 years with the US Geological Survey Oregon Water Science Center in Portland, OR, USA.

M. Gordon (Reds) Wolman (deceased) grew up in Baltimore, MD, USA, where an early fascination with cows led to him being the only member of the Baltimore chapter of the 4H club. He received his BA in geology from Johns Hopkins where he also garnered All-American honors in lacrosse. Following his PhD in geology from Harvard, he worked as a hydrologist for 8 years for the US Geological Survey before returning to Hopkins as Chair of the Department of Geography and Environmental Engineering, a post he held through 1990. Over the course of his career, he contributed fundamental insights into the behavior of rivers, water quality, environmental health and engineering, interdisciplinary research and education, and the connection between science and society.