6 Space, Time and the Mountain - How Do We Order What We See?

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ABSTRACT

The spatial and temporal scales of the principal perceived phenomena have severely constrained the development of geomorphology as a science. The scales of ordinary human perception at which nineteenth-century naturalists attempted to understand the landscape gave way only after about 1950 to the scales of classical mechanics. This chiefly meant constraining space scales to make them commensurable with observable time scales, so that the subject in recent decades has been dominated by considerations of 'dynamical' or 'process' geomorphology There has been no confrontation of the basic question of scales at which we may expect to observe consistent patterns in data, how these patterns may be expressed, and what - consequently - constitute useful modes of explanation. In this chapter, I attempt to develop this theme. I recognise four distinctive modes of theory construction. At small space and time scales, phenomena are recorded in sequences which describe very large numbers of characteristic events. Descriptions are statistical, and processes are considered to be stochastic. At the scales of classical mechanics, deterministic theories are sustainable. At still larger scales, system evolution reveals contingent endogenous effects which cannot be predicted, even though the system remains deterministic. Nonlinear dynamical models, expressing chaotic behaviour, are appropriate. At the largest scales of space and time, landscape evolution is entirely contingent, and we adopt a narrative, particularistic model of explanation. Each level of theory construction must be consistent with the others if the subject is to present a viable construction of nature, but it is not obvious that phenomena described at each scale can be derived from theory at different scales. Scales are relative and are set by the resolution of measurements and by material virtual velocities. At high frequencies and high resolution, it is not clear that all information possesses coherent patterns of geomorphological

The Scientific Nature of Geomorphology: Proceedings of the 27th Binghamton Symposium in Geomorphology held 27-29 September 1996. Edited by Bruce L. Rhoads and Colin E. Thorn.

interest. At low frequencies (those over which landscapes evolve), the information available nearly always is highly censored. Significant elements of geomorphological patterns may not be decipherable.

INTRODUCTION

> We ... naturally hope that the world is orderly. We like it that way... . All of us, including those ignorant of science, find this idea sustaining. It controls confusion, it makes the world seem more intelligible. But suppose the world should happen in fact to be *not* very intelligible? Or suppose merely that we do not know it to be so? Might it not then be our duty to admit these distressing facts?
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> Mary Midgley, in *Science as Salvation: A Modern Myth and its Meaning,* quoted in *Science, 269 (28 July 1995): 567.*

Whatever the truth about the intrinsic orderliness of the world, it is obvious that the order scientifically imposed upon the world is a human invention, a means by which we sustain ourselves. Science is a product of the way we see the world. Our perceptions of the world around us are fundamentally constrained by the dimensions of space and time within which we inhabit the world. These constraints ultimately affect all of science, but they are perhaps most immediately evident within the geographical and historical sciences that directly describe the condition and history of the natural world. Striking evidence for these claims is available in the modern history of geomorphology. The evidence is arresting because of a significant mismatch between the spatial and temporal scales of ordinary human experience of the landscape, and those of geological processes which have created it. Despite the familiar nature of the principal features of the landscape, a virtually unprecedented range of scales must be invoked in order to explain them.

In this chapter, I propose to examine ways in which space and time scales have conditioned our construction of a scientific world-view, using the example of geomorphology to illustrate the discussion. I shall argue that scientific theories are essentially constrained by their associated scales of space and time, and that different kinds of theories are appropriate to describe phenomena at different scales.

An important *desideratum* in science is that theories at different scales be mutually consistent - at least if they are to be viewed as equally valid parts of the description of nature. But it is not obvious that the conceptual foundations for a theory at one scale must be entirely manifest in theories at other scales. Indeed, such often is not the case. An elementary reason for this is information loss through shifts of the scale limits of resolution, but there appear to be deeper reasons residing in the ways that theories are constructed.

I shall commence my argument by endeavouring to illustrate the issues from the history of geomorphology. Almost any other field science could serve as well. My examples will be drawn nearly entirely from the field of fluvial geomorphology; that is merely because it is the topic that I study. In what follows, the specifications of scale magnitude should be understood to represent the scale of resolution, that is, the lower end of the range of scales under consideration.

A SCANDALOUSLY BRIEF HISTORY OF GEOMORPHOLOGY

Chapter 1: Landscape History

Modern geomorphology was born just two centuries ago in the Huttonian revolution of geological thought. James Hutton was a Scottish doctor, landowner and natural philosopher who forcefully established the physical bases of modern earth science. The perceptually evident spatial scale at which Hutton and his successors attempted to understand the landscape was that of ordinary human perception - on the order of kilometres. (Which is not to say that they did not examine closely phenomena at smaller scales for what they could reveal about the landscape and its history.) Hutton's claim was that landscapes develop not by uniquely exceptional cataclysms, but by the same incremental processes of weathering, erosion and sedimentation that we observe today. Unfortunately, the time scale for significant changes in the landscape in this mode is many milleniums; well beyond the ordinary human sense of time. The consequence was an inferential, largely hypothetical (or speculative) discipline preoccupied with attempting to explain the historical particularities of specific landscapes. The underlying purpose was to extract a temporal pattern from such studies which could serve as a template for the interpretation of landscape. The theory, and the quintessential science, lay in the template.

This development is not surprising. To a greater or lesser extent it occurred in all of the nineteenth-century natural sciences, and it persisted until instruments were developed by which we could magnify or telescope our sense of scale. Arguably the most revolutionary development in all of nineteenth-century science is the theory of evolution, and it was subject to just the same temporal constraint as nineteenth-century theories of landscape. Both Huttonian landscape theory and Darwinian evolutionary theory challenged the credulity of scholars no less than lay people by stretching the bounds of time beyond all common reason.

Within geomorphology, the archetypal achievement was the 'geographical cycle' of WM. Davis, published in 1899. For more than half a century it remained the dominant template for landscape interpretation. It portrayed landscape as a staged sequence of erosional transformations of an initially elevated landmass. (A brief description of the geographical cycle is given in Chorley et al. 1984, pp. 17-22; notes from a lecture course given by Davis, compiled and annotated by King and Schumm 1980, give a detailed outline and commentary.) Davis's model incorporates a number of classical hallmarks of scientific theories. It postulates artificially simple initial conditions; tectonic uplift followed by essential stability. (So far as I can tell, isostatic compensation of erosion was practically ignored, even though it presents no significant complications.) In its abstract form, the theory adopts relatively simple boundary conditions, even though the influence of geological structure is prominently acknowledged as one of the principal determinants of landform. This is exemplary (and perfectly reasonable) reductionism. The theory also is remarkably sophisticated in some respects. It recognises contingency in the form of climatic 'accidents', in the possibility for tectonic rejuvenation, and in its acknowledgement of multicyclic landscapes. In seeking evidence to support his theory, Davis 'solved' the time warp by conflating contemporary conditions in different landscapes, by making a loose sort of 'space-for-time' substitution (see Paine 1985, for a modern discussion of this procedure).

Within the attempt to reconcile spatial scales of the order of kilometres with time scales of the order of many milleniums, Davis's theory is a notable achievement. But it lacks a sense of the mechanics of landform development - of the specific physical processes by which erosion and sedimentation proceed. That is because the paradigm of classical mechanics, the ostensible basis for describing and analysing the displacement of earth materials, is also constructed upon the ordinary scales of human perception, and consequently does not readily admit this combination of space and time scales.. Yet classical mechanics, which exemplifies the apparently deeply ingrained human wish to find a rationally ascribable cause (an action) to cover every observed result (reaction), is the foundation for our sense of order of the ordinarily observed world.

It is possible to quantify Davis's theory, but Davis did not proceed to that. He probably was too honest (or perhaps merely too blinkered by the conventions of his day) to admit the necessarily massive parameterisation. Only recently have such parameterisations begun to appear in numerical models of landscape development. I expect that the qualitative character of Davis's theory is the reason why it fell not merely into obsolescence, but into positive disrepute after the middle of this century.

The glacial theory - another nineteenth-century theory which originated in geomorphology - illustrates in a different way the problems of spatiotemporal constraints. After about 1800, the (then) entirely hypothetical concept of former glaciers of semi-continental extent became a contender to explain the widespread stony soils - termed 'drift' - of north-west Europe. Although Hutton himself expressed some inklings about glacial action, the theory triumphed only in the years after 1840, when Louis Agassiz published an influential paper proposing a former great ice sheet in northern Europe. (A useful brief account of the origins of the glacial theory is given by Flint (1971, pp. 11-20).) Agassiz had been shown the efficacy of glacial action in high alpine valleys by colleagues in the Society of Natural History at Lucerne. A mechanism was thus demonstrated within commensurable space and time scales which could be invoked - if one possessed sufficient uniformitarian faith to make dramatic extrapolations in both space and time - to explain the widespread drift. Presumably, farmers in the Alps had known the mechanism for centuries, but they lacked the knowledge and motivation to make such unreasonable extrapolations. The theory continued to meet resistance for many years, and never completely captured the allegiance of Charles Lyell, the great nineteenth-century publicist of Huttonian earth science. The difficulty to envisage concepts outside the familiar spatio-temporal range in which they are mechanistically grounded is probably the reason for that. The subsequent history of the glacial theory has continued to be plagued by this problem. Today we remain uncertain about the mechanics of the unstable ice sheets of the Pleistocene Northern Hemisphere (cf. Clark 1994), and therein lies the crux of some of the more tantalising current problems of late Pleistocene earth history (cf. Bond et al. 1992; Lehmann and Keigwin 1992; MacAyeal 1993).

Chapter 2: Functional Geomorphology

In geomorphology, the nineteenth century ended in about 1950. The turning-point apparently was exasperation with the evident impossibility to reconcile the time scale of observable and mechanically explicable processes with the spatial scale of the classically considered landscape (Strahler 1952). A substantial consensus emerged, instead, to constrain the spatial scale of enquiry to match the time scales of observable processes. It probably is no accident that the most influential student of the new paradigm (L.B. Leopold, a hydrologist in the United States Geological Survey) was trained as an engineer. Considering practical problems of land management and public safety, engineers had been studying such landscape processes as field erosion, hillslope failure and river erosion at these scales since the time of Leonardo. Refocusing on new and *commensurable* space and time scales permitted fresh theoretical grounding to enter geomorphology. 'Commensurable scales' are ones which permit landscape phenomena to be described and ordered in terms of some more fundamental knowledge or familiar experience. In the present case, the methods and paraphernalia of applied physics (or engineering science, if you prefer) could now be deployed to measure landform geometry, applied forces and material transfers on time scales from seconds out to decades. The commensurable space scales are on the order of metres.

There has, in succeeding decades, been a preoccupation with 'dynamical' or 'process' geomorphology (influential textbooks include those of Leopold et al. 1964; Carson and Kirkby 1972; Ritter 1978; revised by Ritter et al. 1995; Chorley et al. 1984). Process geomorphology can be defined as the study of 'the erosional and depositional processes that fashion the landform, their mechanics and their rates of operation' (Chorley et al. 1984, p. 3). Major effort is directed towards analysing the equilibrium between the strength of earth materials and the applied erosional stresses on supposedly stable landforms. This focus of attention is dictated directly by Newtonian mechanical principles (cf. Ritter et al. 1995, pp. 7ff). In the field, observations are conducted at very local sites. There is even the possibility to move important observations into the laboratory. Within this paradigm, and the theories of landform development to which it has given rise, the evolving landscape of the nineteenth-century geomorphologists became a part of the fixed boundary conditions. Theories to explain large-scale landscape development have been quietly ignored.

A representative topic within process geomorphology is the theory of sediment transport in rivers. Achievement of a closed theory, it has been supposed, will lead to mechanical understanding of how the river shapes its channel in the short term and, since rivers are supposed (mainly incorrectly) to form the valleys in which they flow, of the erosional development of the landscape in the long term. Within the theory, it is supposed that the river moves loose granular sediment over the bed of the stream in proportion to the shearing force applied by the flow at the bed:

$$g_b = f\,[(\tau - \tau_o)/D] \qquad (1)$$

in which g_b is the bedload (traction load) transported per unit width of channel, $\tau = \rho gRS$ is the shear stress (tractive stress) imposed on the bed by a uniform flow of water, ρ is the density of water, g is the acceleration of gravity, τ_o is the threshold stress for sediment movement, and D is the diameter of the transported sediment. The sediment transport relation is nonlinear, very strongly so near the threshold for motion (Figure 6.1). This approach to sediment transport was initiated by European river engineers towards the end of the chronological nineteenth century, and it has endured ever since. Its appearance in geomorphology was accompanied by a host of other engineering results on the hydraulics of deformable channels which have proven useful to develop a level of understanding about rivers. Similar developments have informed almost every other topic in geomor-

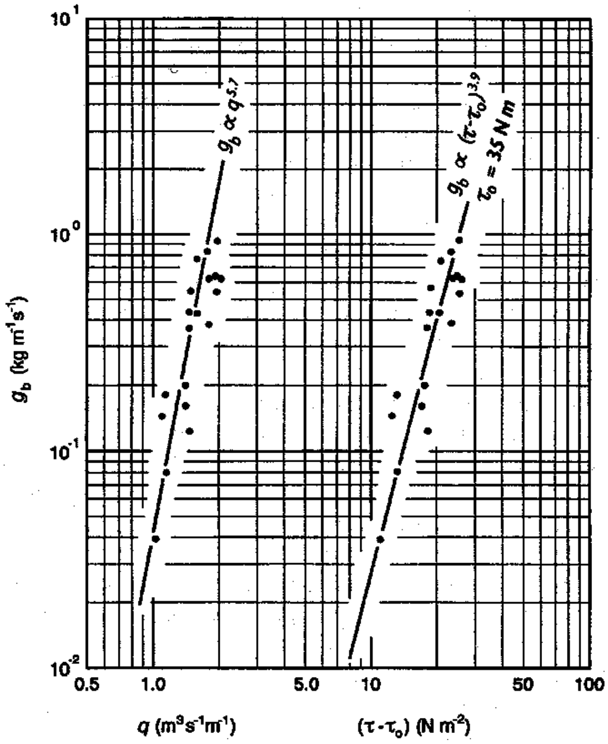

Figure 6.1 The relation between bedload sediment transport and hydraulic quantities in Elbow River at Bragg Creek, Alberta, a cobble-gravel stream. Data of A.B. Hollingshead (1971) obtained using basket traps and infilling of bed excavations, analysed in the theory-oriented paper of Parker et al. (1982b). On the right, the relation between sediment transport and effective shear stress at the bed. The shear stress is based upon section averaged flow depth. The transport rates are low and the relation is very sensitive to changes in shear stress. The sensitivity of the relation is based upon the rapidly increasing proportion of the bed that takes part in the sediment exchange process as the flow increases above the nominal threshold for motion. On the left, the relation between sediment transport and specific discharge. This relation is as good as the last one, although it is very sensitive. The mutual correlations amongst discharge, shear stress and sediment transport indicate that these relations should be regarded as scale relations of the flow

phology. Concomitantly the subject has adopted, in conformity with the rest of physical science, a thoroughly quantitative character. Perhaps the desire to conform drove much of this development. Certainly the desire for orderly and, within the scales, more precise explanation did.

Withal, an interesting feature of the tractive force approach to sediment transport is that it is not mechanically rigorous at all. Some heroic attempts have been made to place the equation on a completely rational foundation (cf. in particular, Yalin 1972; more recently, work by Parker and colleagues, beginning with Parker et al. 1982a, b), but it remains stubbornly empirical. Whilst the formula above has the appearance of a classical Newtonian force-response equation, it must be recognised that conditions at the stream bed are much too complex to admit more than an empirical correlation at the specified scale of examination. The channel-scale measurements that underlie the assessment of shear stress are substantially averaged in time and, often, in space. The simple description of the sediment boundary ignores important structural characteristics of the sediment surface. It is a highly parameterised result. This is true of a substantial range of the results that have been imported into or developed within the 'process' geomorphology of recent decades. Many of the results are, indeed, no more than empirical scale relations (Church and Mark 1980; see also Figure 6.1). This has led to the criticism that process geomorphology represents merely a kind of functionalist thinking that - whatever its merit in the engineering arena - is not good science at all because it does not approach the 'true' phenomena.

I think that this criticism of functionalism is not very helpful. It ignores the fundamental constraint posed by the space and time scales at which observations, and the consequent theories, are pitched. Important mechanical constraints upon the nature of the sediment transport process occur at scales that are below the resolution of most of the observations made in geomorphology until very recently, and well beyond the descriptive capacity of simple mechanical models of the kind that underlies the engineering approach to sediment transport in rivers. The Japanese geomorphologist Eiju Yatsu - who dealt with the difficult topics of weathering and erosion - more than 30 years ago recognised the general problem that is represented here (cf. Yatsu 1966), but his teaching has been generally ignored. The space and time scales of observation constrain the structure and physical content of functionalist theories through their control of the resolution of information in the theory. Our theoretical construction of order in nature is bound by the tyranny of the scales. (Whether a particular scale of enquiry is enlightening or practically helpful is quite another question.) This, of course, opens the possibility that a coherent theory pitched at one scale may be subject to fundamental criticism in light of criteria derived at different scales (Montgomery 1991). Such was the criticism of nineteenth-century landscape science raised by functional geomorphology, and such is the criticism of ftinctionalist geomorphology raised by the realist school.

We are here broaching philosophical issues which run very deep in science. I suppose that the archetypal theory in all of science is Newton's theory of gravitation. Yet for more than two centuries it provoked nagging uncertainty in thinkers who were predisposed not to be satisfied with the appearance of mere functional order in the cosmos. How in heaven could celestial bodies separated by vast gulfs of space influence each other's motion in the formulated manner? Surely explicable order implied more than Newton's sleight-of-mind. It took Einstein, building upon the insights of James Clark Maxwell, to provide an answer. But none of this invalidates the practical utility nor destroys the intellectual satisfaction that Newton's achievement has provided during these last three centuries. Nor does it provide a basis to dismiss the description of fluvial sediment transport achieved within the bounds of tractive force theory.

Chapter 3: Competing Paradigms and Competing Scales

We must recognise that it is perfectly reasonable for more than one spatiotemporally delimited paradigm to be pursued within a science at any given time. A signal example occurs within geomorphology. At the same time that Davis was propounding and refining his geographical cycle, G.K. Gilbert was engaged in investigations, some of them not surpassed for nearly a century, which we would today recognise as quintessentially functional geomorphology. More than most investigators, Gilbert was conscious, as well, of the necessity for theories to be mutually consistent across different scales. That is the most startling feature of *The Geology of the Henry Mountains* (1877). Why, one asks, did it require another 75 years before a functionalist paradigm came to the fore in geomorphology? The answers that have been offered usually have referred to the character and situation of these major actors. But a thorough ransack of the literature reveals a steady production of functional studies from the mid-nineteenth century on. The spirit of the times and the general education of practitioners and public seem to have been much more important. Education, in particular, serves to define for most individuals what is a satisfactory standard for order in their world.

The last 20 years have witnessed the widest proliferation of programmes for study in the history of the subject. One must be careful about such claims. It is the propensity of every generation to declare that it is the grand historical exception. The basis for my claim is that geomorphology appears at present to be entertaining work on a wider range of space and time scales and - accordingly - within a wider range of paradigms than ever before. There appear to be several reasons for this. An important one in the present argument is that geomorphologists have lately become very good at adopting and importing into the field the advanced tools of physical science. One encounters everything from the more exotic atomic microscopes and mass spectrometers at the molecular end, to the satellites and sensors of space science at the global end. This has produced a dramatic expansion in the range of spatiotemporal scales that, through instrumental resources, are more or less directly available for study. Even geologically deep time is forced to reveal some of its secrets to modern absolute dating techniques based on isotope chemistry. Another reason is the increasingly diverse range of educational backgrounds of students drawn to the subject. These immigrants bring with them analytical tools with their own spatiotemporal scales and apply them to order geomorphological phenomena in original ways. Ultimately, the shear size of the discipline promotes diversity.

We may briefly illustrate the claim of diversity by referring again to sediment transport. In order to approach more closely the supposed real mechanics of sediment transport, geomorphologists have made studies of turbulent shear flows using high-frequency velocity probes (see Clifford et al. 1993, for a review). The underlying expectation is that sediment is actually entrained from the stream bed when high-velocity threads of the flow impinge upon it. They have also used advanced flow visualisation techniques in an attempt to establish this claim directly. At the other extreme, geomorphologists have used satellite images of the Amazon - the largest river in the world - to observe and attempt to understand aspects of sediment diffusion and sedimentation (Mertes 1994), not previously accessible to practical observation, that clarify the interaction between the river and its serially reconstructed floodplain and floodplain vegetation (Mertes et al. 1995).

The theoretical constructs into which these disparate observations lead have quite different foundations. Turbulent flows have classically been thought of as random phenomena, as processes with no evident coherent structure. More recently, the picture has been modified to recognise the occurrence of randomly recurrent structures within the turbulent flow. Whilst the phenomenological picture over boundaries of high roughness (i.e. river beds) remains decidedly murky, there appears to be little doubt that recurrent events of some description are centrally implicated in sediment entrainment. The time and space scales of turbulent motions and turbulent structures are seconds and millimetres.

The theoretical constructs are generic and *essentially* statistical. (I mean 'generic' in the sense that characteristic events are defined which are supposed to be repeated infinitely many times with only minor variation; I mean 'essentially statistical' in the sense that there is no means to specify unequivocally an individual event within the characteristic range.) Studies of regions as large as the Amazon floodplain reintroduce contingency. Contingency in this case is represented by the observed pattern of channel and floodplain configuration which is created by the erosion and sedimentation. The scales are decades and tens of kilometres, or greater, and these are consistent with the virtual -velocity (i.e. the time-averaged rate of displacement) of sediment movement in the system, hence are a commensurable set. The features observed have individually distinctive histories and contexts which are recognisable at ordinary scales of perception (which does not prevent summary for certain purposes of sets of features or events by *convenient* statistics). These two sets of scales lead to theories quite different in their character, and different again from those associated with functional investigations at the scale of ordinary human perception.

At that scale, recent work has attempted to understand the pattern of channel shifts and sediment storage in river channels. Channel shifting is a consequence of sediment transport and storage. To the trained observer, there is a clear pattern in the bar and channel structure in a braided channel, and in a meandered channel the pattern is evident to almost anyone. But what is the pattern of modification of the channel? Murray and Paola (1994) have created a cellular model of the process which generates a developing braided pattern with statistics similar to those of real braided channels. The model is based on a nonlinear sediment transport rule similar to that given in Figure 6.1. It is entirely deterministic and there is statistical stability in the characteristics of the pattern, but the developing configuration of the channels is unpredictable. Accordingly, the behaviour is chaotic (cf. Turcotte 1992, for a simple description of chaotic processes).

Chaotic behaviour is radically different than classical mechanical theories admit. It incorporates an unpredictable sort of deterministic process. That is, the short-term and local trajectory of the system is clear enough, if sufficient information is collected about it (in the stream channel model referred to above, it is specified), but the overall structure of the system is sufficiently complex that predictive ability more or less rapidly disappears as the system develops. It is difficult to see whether the statistical aspect of such theories is essential or convenient. Systems subject to chaotic behaviour present, perhaps, one of the clearest examples of the scale-bound nature of theories. The pattern of behaviour that is evident in braided channel switching (or in loop development in a meandered channel) may not be derivable at all from characterisation of the microscale sediment transport events. Nor is it evident in the deterministic, mechanical description of channel hydraulics. In a sense, channel switching is 'emergent behaviour'. In fact, in the river channel example, the behaviour arises from the effect that the pattern of sediment storage has on the subsequent sediment transport. For the same reason, one expects - contrary to classical dogma - that the construction of the Amazon floodplain is not derivable from integration of sediment transport mechanics, even though viable theories at both scales must accommodate each other.

It is important to recognise that the theoretical constructs themselves are not tied essentially to scales. We can study eddies in classical mechanical terms; we can study ensembles of large landforms statistically. Theory selection follows from the way we isolate or aggregate events when we have freedom so to do within the scale metric we have chosen. But at the limit of resolution set by the metric, scale may indeed constrain the theoretical possibilities,

Whilst geomorphologists have embraced a very wide range of space and time scales to order - thence 'explain' - observations, there has not been (to my knowledge) any' organised attempt to construct the subject about those scales in conscious recognition that the character and quality of explanation will thereby be systematically affected. It is my claim that this is, indeed, what happens. In the next section, I shall attempt to demonstrate this by deliberate recapitulation of a linked set of topics; the flow of water and sediment in stream channels, and the fluvial development of landscape. I shall introduce arbitrary adjustments of scale in order to emphasise how that controls feasible explanation.

A SPATIOTEMPORAL HIERARCHY OF EXPLANATION

Consider the flow of water in a river channel. At the scale of casual observation, we observe a mass of water flowing downstream with some assignable mean depth and mean velocity. A closer inspection, still at the scale of ordinary perception, reveals the existence of eddies, swirling masses of water moving across the main flow in more or less organised and briefly persistent cells. If we abandon ordinary perception and obtain a photograph at an instant in time we observe a highly complicated field of fluid motions. How can we describe it?

Physicists and others, including geomorphologists, have placed velocity sensors with resolution of order 10^{-3} m 10^{-2} s in the flow field. What is observed is a record of apparently random fluctuations about the mean. The recent development of high-resolution sensors for sediment concentration has revealed similar characteristics in sediment flux (Figure 6.2). A.N. Kolmogorov's analysis of such signals represents the classical statistical characterisation of turbulence. The character of the motion appears to remain similar over a substantial range of scales. Instruments have improved to the point that physicists have identified coherent structures in laboratory flows over boundaries of low roughness (cf. Robinson 1991). Evidence has been sought for similar structures in highly sheared flows over rough boundaries (that is, in rivers) because of the conviction that herein lies the mechanistic key to sediment entrainment. The observations remain decidedly equivocal (Clifford and French 1993), probably because the locally conditioned eddy structure over boundaries of high roughness replaces the spontaneously generated structures found in the laboratory. In any event, the description of such phenomena remains essentially statistical and simple patterns of cause and effect cannot be traced. The classical equations of fluid motion have customarily been applied to such flows only through averaging procedures and arbitrary linearisation.

But suppose we accelerate our own time scale by several orders of magnitude and correspondingly shrink the spatial scale of our ordinary perception. (Or, alternately, suppose we magnify the scales of the flow dramatically. Readers unable to suspend reality in this way may imagine, instead, that they are swimming in the Gulf Stream.) The random velocity fluctuations of our turbulent flow will now appear to be well-defined eddies. They will persist for a substantial period (in our accelerated frame), and - with instruments of correspondingly increased resolution - we will be able to measure internal characteristics

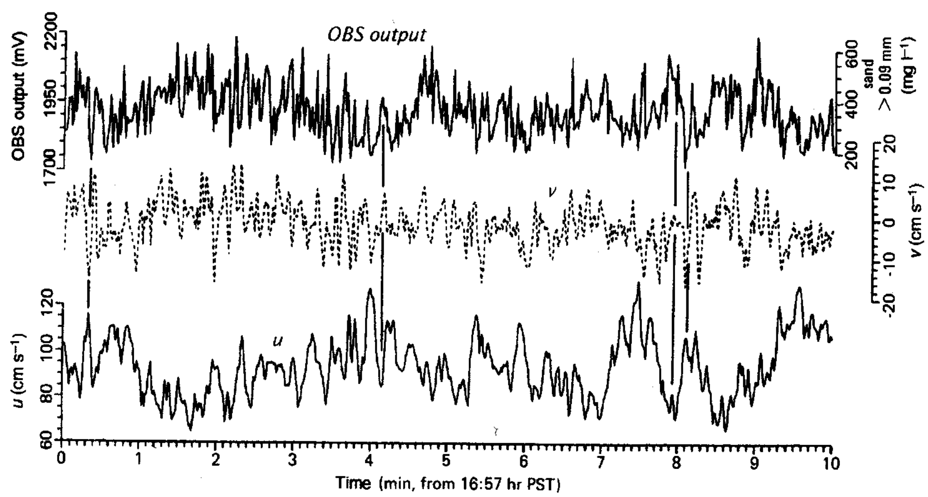

Figure 6.2 Ten-minute time sequence of downstream and vertical velocity components and optical backscatter (OBS) record of water turbidity at 1m above the sand bed of Fraser River, Near Mission, British Columbia, to illustrate the relation between suspended sediment flux and turbulent velocity scales in the flow. Peaks in OBS turbidity are characteristically associated with turbulent peaks in v and troughs in u. Peaks in v and in OBS turbidity are correlated with r = 0.31 (in a 2.2 hour record), a level that is typical of turbulent transfer of scalar properties. The displayed record also shows clear fluctuations lasting several minutes which can be interpreted as patchiness in the higher frequency regime. Data of 13 June 1986, recorded by M.F. Lapointe and presented in Lapointe (1992, Figure 8)

of the motion. These characteristics might include an Eulerian advection velocity, a rotation rate, radial velocity gradient, momentum, vorticity of the motion, and so on. A classical mechanical description of the flow becomes locally possible. Given some properties of the motion, we can predict others. If we know something about the neighbourhood of our eddy, we may also be able to calculate some features of its evolution, but we will not be able to extend our predictions for arbitrarily lengthy periods. This is, of course, just a thought experiment, except in large-scale geophysical flows. (The results in large-scale flows are distorted in comparison with those we would see in our river because intrinsic properties of the flow, such as viscosity of the fluid, will not be scaled, and certain exogenous parameters, such as the acceleration of gravity, will remain constant so long as we constrain our imaginations to the Earth's surface.)

Expand our scales by some orders of magnitude again. We are now embedded well inside our eddy, the dimensions of which are substantially larger than our 'ordinary' perception. We will perceive a large, slowly developing system within which we can track a specific history. To achieve that we will have to take into account the evolution of the system in the context of the even larger field of motion around it, with which there are continual momentum and energy exchanges. We will notice the contingencies that govern the evolution of our large eddy. We may calculate the fluid motion at places within the eddy in accordance with classical mechanics, and we may now be able to assume equilibrium conditions for substantial periods within our interval of observation. This, of course, is routinely done for Gulf Stream rings, and for large atmospheric disturbances.

Subject to some constraints about approximate similarity of the phenomena (which need not be very strict) our thought experiment has demonstrated how we may describe a geophysical phenomenon on quite different theoretical bases, depending upon the scales (read resolution) of the enquiry. It also hints at how reasonable assumptions and approximations allow us to embed one theoretical description within systems of phenomena drawn on significantly different scales. A key to understand the changing theoretical basis is to recognise that resolution governs what we can observe about structures in the system and what we can record about the evolution of those structures. When we have many, more or less rapidly evolving structures we know relatively little about each one - certainly too little to appreciate the individual nuances of its development and to assign specific antecedent causes. We adopt a statistical characterisation of what we observe. At the other extreme, we may observe only an interval in the evolution of a major structure. Our description becomes highly contingent. We observe a different sort of order at different scales.

It is useful to remind ourselves that, whilst at each step in the foregoing sequence of scale transitions new explanatory modes become feasible, previously sketched modes remain accessible. The essential constraint upon the character of information resides in the interaction between the resolution of the observations and the information requirements for the particular mode of explanation.

Let us return to our river and perform the scale transformation instead by focusing upon larger scale features of the flow. At scales of 10^0 m 10^0 s (1 metre, 1 second), we again observe eddies. But this time, particular eddy configurations persistently recur. Using appropriate velocity meters, hydrologists accordingly measure secondary currents in the river (Figure 6.3). Our spatial scale is now well within an order of magnitude of that of the channel itself, and we observe the shaping effect of the channel upon the flow. If the boundary is compliant (alluvial or, at least, erodible by the ambient currents), the configuration of these flows will eventually reshape the channel. This is what we observe in an evolving meander bend, or in the successive zones of flow convergence and divergence in a braided channel. This is the scale at which classical sediment transport theory, as exemplified in equation (1), is straightforwardly applied. We obtain measurements at individual points on the bed of velocity, shear stress, and sediment flux over the adjacent boundary. The *eddy scale* phenomenon varies sufficiently slowly to permit classical mechanical descriptions based on averaged quantities, even though the individual flow structures remain transient. We do not resolve the turbulent scales, but this does not entitle us to ignore them conceptually since sediment fluxes depend upon the turbulent-scale correlation of sediment concentration and flow velocity. At the large eddy to channel scale, we also observe the contingencies of the recent history of flows and of the morphological development governing eddy production and the evolution of the averaged secondary flows. We incorporate these effects into the mechanical description in the form of initial and boundary conditions. Our ability to predict their further evolution remains, however, limited. The use of different explanatory modes to order phenomena which interact across a broad range of scales - hence the necessity for mutual consistency between explanations at different scales - is particularly well illustrated here.

Let us expand the space and time scales again to order 10^1 m 10^4 s (about 3 hours). Much of the functionalist geomorphology of recent decades resides in these scales of normal human perception (at least, of rivers). We now consider the mean flow and

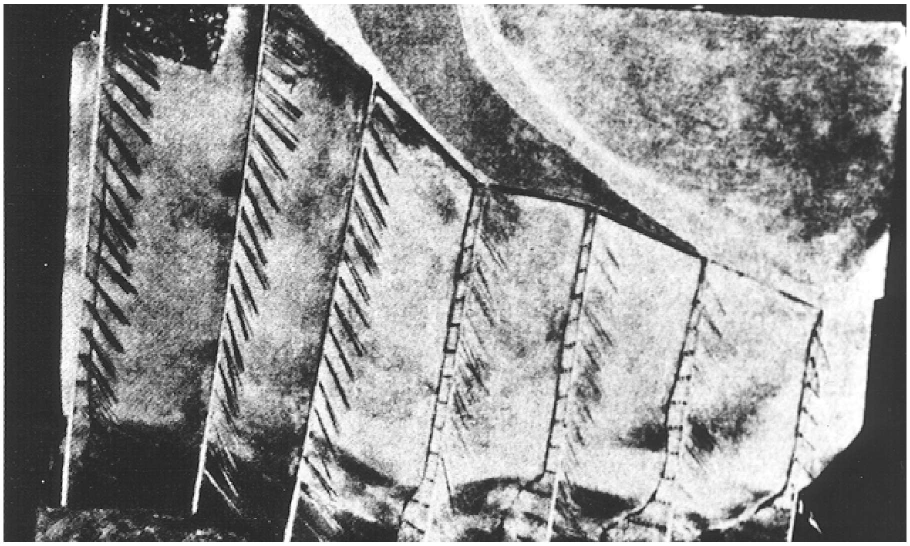

Figure 6.3 Illustration of secondary currents in a section of the Dniepr River, Ukraine, based on measurements of N. de Leliavsky. Flow is left to right (Figure 33 in Leliavsky 1959). De Leliavsky's measurements, taken around 1890, represented the first measurements of secondary currents. Leliavsky (1959, p. 98) notes of these data, 'the principle of non- parallelism of the flow lines in natural rivers, is not merely a matter of turbulent disorder.. .. It refers to temporal average velocities ... the general pattern of which was capable of being interpreted as and consistent with, an original scour theory.' Leliavsky is asserting that a distinctive theory emerges at this scale, and with the achieved resolution, which reflects the observed persistence of the flow configuration

sediment transport in a reach. This is the scale of usual application of hydrological and hydraulic measurements. At this scale, we are close to a mechanistic view of river channel evolution, a result of intense geomorphological interest. It is also the scale at which most attempts have been made to apply classical sediment transport theory to understand river channel evolution. Moreover, it is now possible to obtain information about the sediment transport process by examining sequential changes in channel morphology (Ashmore and Church in press: see Figure 6.4). This may be much more relevant, geomorphologically, than direct flux measurements. However, the further averaging that is inherent in the observations can introduce bias into the results if they are viewed only at this scale, since we no longer see the mechanistically conceived transport process. Nesting of measurements in adjacent scales is a means to minimise this problem which represents an important connection between scales of enquiry. The averaging arises from the space and time limits of resolution; the bias may arise when changes beyond the limit of resolution are not reflected in the average. An example may be compensating scour and fill in a river bed.

If we again expand our scale of attention, we begin to consider the river as an extended system, in which locally contingent events are happening at many places. Consider scales between the channel scale, above, and 10^4 m 10^9 s (the latter is 30 years). At these scales, styles of explanation and the structure of theories can be seen clearly to depend upon the way in which information is marshalled. A major achievement of L.B. Leopold and his

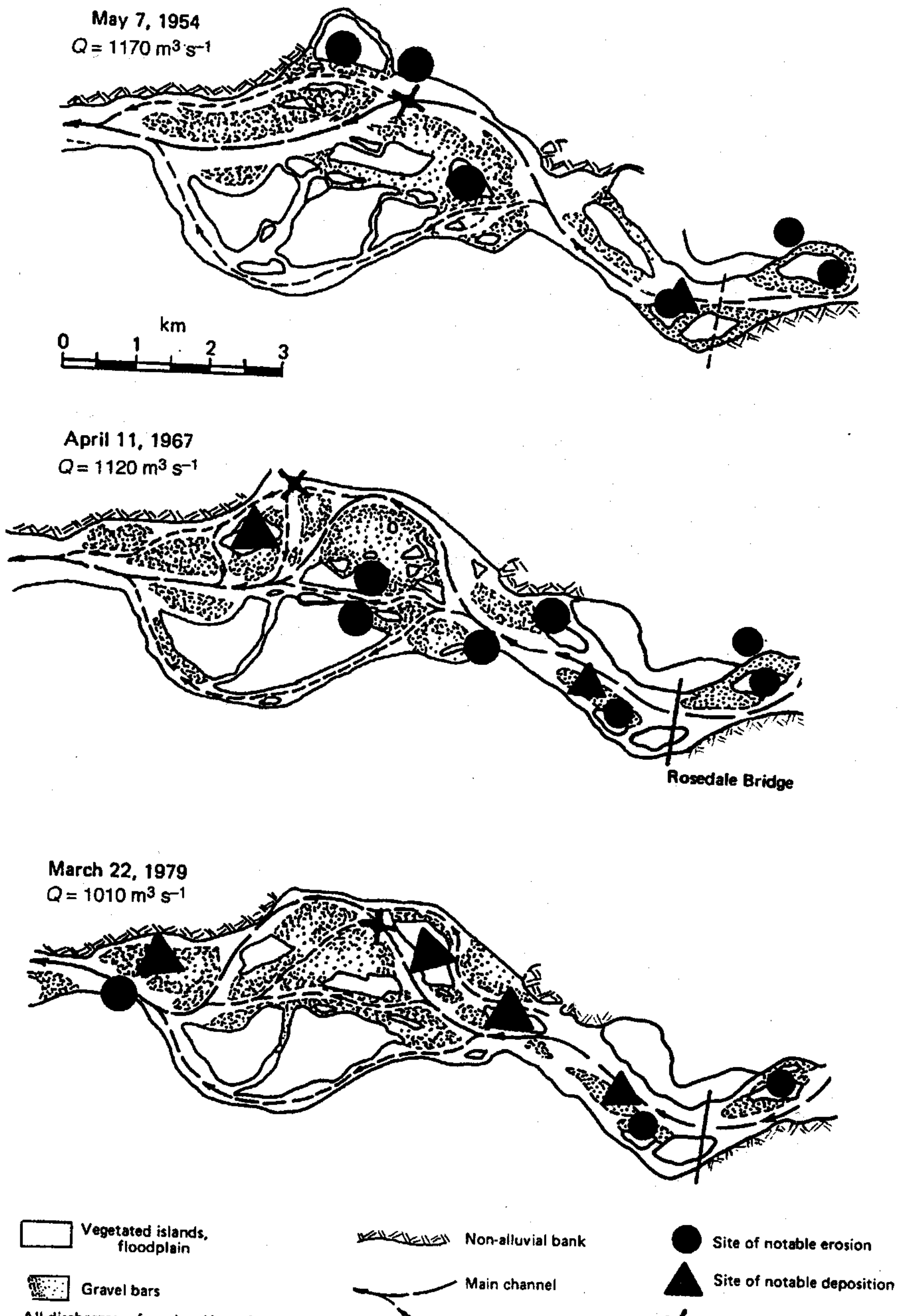
May 7, 1954
$Q = 1170\ m^3\ s^{-1}$
km
0 1 2 3
April 11, 1967
$Q = 1120\ m^3\ s^{-1}$
Rosedale Bridge
March 22, 1979
$Q = 1010\ m^3\ s^{-1}$
Vegetated islands, floodplain
Gravel bars
All discharges referred to Hope Gauge
Non-alluvial bank
Main channel
Secondary channel
Site of notable erosion
Site of notable deposition
Notable channel shift

Figure 6.4

associates was to notice that if measurements of mean flow and geometry in river channels are averaged and compared over time and throughout the river system (that is, over the current scales), then a functional description of mean behaviour of the river system known as the hydraulic geometry - becomes available (Leopold and Maddock 1953). These scales are identical with engineering regime scales, and so the coincidence of hydraulic geometry with engineering regime theory of unlined canals (cf. Blench 1957) is not surprising. If, on the other hand, we choose to examine the historical sequence of channel development within these scales, we observe contingent behaviour of two kinds. In the first kind, developments at one place in the system are constrained by endogenous developments elsewhere in the system. The result is the kind of deterministic but unpredictable development that is represented, for example, by braid switching or by meander loop extension and cut-off. In the second kind, exogenous constraints, such as the configuration of the even larger-scale landscape, impose conditions which remain constant (hence, trivially predictable). Climate, the forcing function for runoff and so for river hydrology, imposes an exogenous control that is particularly interesting because climate itself fluctuates significantly (and not yet predictably) on time scales similar to those of the river.

At the very largest scales (up to 10^6 m 10^{12} s), we are within the realm of development of those exogenous constrains. Macklin et al. (in press) have shown that at time scales between 30 and 9000 years a river is a complex system subject to both endogenous and exogenous controls. Short-term observations of channel regime may yield a quite misleading picture of long-term river behaviour because of instabilities associated with longer-term trends or a protracted period of relaxation after a major perturbation (see also Church 1981).

Within the last 30 years, some notable attempts have been made to model landscape geometry and development which provide insight into scale constraints. I shall consider two problems. Modern approaches to the description of the drainage network began with R.E. Horton (1945). The most prominent contribution was made by R.L. Shreve (1966, 1969), and some recent developments are presented by Stark (1991) on evolution and by Peckham (1995) on structure. There is essentially a single thread of development. The drainage network is modelled statistically on the basis of the theory of rooted tree graphs. The aim of modelling is not to describe the history of configuration of any particular drainage network, nor to predict the development of particular drainage networks, but to reproduce salient network characteristics of many or all such networks as means to test our

Figure 6.4 *(opposite)* Sequential maps of the channel configuration in Fraser River near Agassiz, British Columbia. Bed material transport has been estimated by measuring the volumetric changes in the channel over a number of years. The calculations yield a highly averaged view of river channel changes. Comparison of the results with bedload transport measurements at the Rosedale Bridge shows that the morphological changes estimate the bed material transfer very well. The observations are unbiased in this river because it is very large, so that episodes of erosion or deposition persist at individual sites along the river for a number of years and there is little compensating scour and fill (see Church and McLean 1994, for more details). Although consistency can be demonstrated between the sediment transport and channel evolution, it would not be possible to predict the long-term evolution of this particular channel from sediment transport theory, since details of erosion and deposition would remain inaccessible. Short-term predictions may be accessible via numerical models of flow and sediment transport. The problem is entirely analogous with the weather prediction problem understanding of how they might have arisen in general. So it is a reduced model. An interesting issue in the present context is that drainage networks are not particularly microscale phenomena in the landscape. None the less, they represent a (practically) undenumerable phenomenon at regional landscape scale and they extend to rather small scales. Statistical representation seems inevitable. This constrains the nature of the predictions that are to be had. This example shows very clearly that there are no absolute scale limits associated with theoretical representation of the landscape. But an important constraint compounded of scale and information is effective: we can practically analyse far too little information about individual drainage basins to permit more detailed, mechanistic modelling.

Models of the evolution of the entire fluvial landscape encounter the same problem. Early models (cf. Ahnert 1976, 1987, and Kirkby 1986) tended to be explicitly mechanistic. By this, I mean that they incorporate statements about the supposed actual driving forces (soil creep; slopewash; mass failures, and so on) and material resistances. Realistically, such models are constrained to simulate landform changes at the synoptic scales of these processes. Beyond that, they might indicate idealised landscape developments. More recent models have recognised the need to parameterise most sediment transfer processes in some manner appropriately generalised to cover integral effects which occur over the long time spans during which landscape development actually occurs. Topographic gradient-driven diffusion processes on hillslopes and scale correlations (cf. Figure 6.1) for fluvial sediment transfers are the usual models. Because of the difficulty to match development scales for slopes and rivers, slope-base sediment storage commonly has been ignored: the models are, in effect, debris supply limited. No doubt problems such as this will be resolved nearly as rapidly as they are properly defined (see Howard et al. 1994, for a recent discussion which appeals to physical principles). The possibility to model the development of particular landscapes appears nevertheless to remain remote. Uncertainty about driving forces in the long range, and the impossibility to reconstruct endogenously emergent events defeat the issue. The purpose of modelling remains similar to that of modelling the drainage network. The problem that can be tackled is not unlike that faced by WM. Davis. The useful purpose of model development is to simplify consideration of mechanics which occurs on more local scales than that of the overall system in order that features of landscape system development can be clearly defined and studied. But it is not clear, at the scale of landscape history, that useful simplification is to be had. Landscape development appears to be largely a matter of cumulated history. We have arrived back at the scale of nineteenth-century landscape science.

SOME CHARACTERISTICS OF SCALE-DELIMITED THEORY

In the foregoing sections, the relation between scale and resolution has been emphasised as a control upon the feasible representation of order in the landscape. In this section, this relation is explored more systematically and some additional characteristics of observations are introduced that further affect our choice of explanatory mode.

The foregoing paragraphs have essayed a systematic view of geomorphological scales on the basis of the fluvial system. I introduced a range of scales which I have called 'commensurable scales'. Beyond indicating that these are scales at which theory construction is feasible, I have not explicitly defined what commensurable scales might be. They are scales at which, within the resolution set by the dimensions and by our observing methods, information transfer can be detected within the landscape (or, more generally, 'within the system under study'). It is upon the basis of observed information transfer that theory can be constructed about the behaviour of the system, that causes and effects can be assigned, and that we can detect satisfactory order.

For geomorphological systems, information transfer is synonymous with the transfer of earth materials and, to a lesser degree, with the transfer of certain kinds of energy. Commensurable space and time scales are matched by consideration of the velocity for material transfer in the landscape. In the fluvial system at very local scales, this is the characteristic velocity of water (and entrained sediment), about 1 m s^{-1}. But even at the channel scale (the scale of 'ordinary' perception), the velocities of water and sediment have diverged significantly. Since sediments spend most of their time in storage - during which they constitute the visible morphology of landscape which we endeavour to explain - the 'virtual velocity' of the earth material is the critical scale-matching velocity. The virtual velocity is the average transfer rate for material on the time scale of resolution. (For landforms which can be defined by the linear dimension along which sediment transfer occurs - such as a river channel - virtual velocity is equivalent to linear dimension/residence time.) Virtual velocities rapidly decline as we move to larger spatial scales, whence commensurable time scales expand even more quickly. Within stream channel virtual velocities on the order 10^{-4} - 10^{-7} m s^{-1} are typical for bed material (these values are the same as 1 m to 1000 m yr^{-1})

It is probable that a good deal that happens on shorter time scales and more restricted space scales than those of sediment virtual velocity is not of direct interest geomorphologically. For exarnple, Macklin et al. (in press) have shown that the space and time scales of long-term sediment transfer and storage hold the key to understanding river morphology. But most of the change actually happens within a relatively short time, so the relevant time scale for observing geomorphological processes is that of ordinary perception of events, 10^1 m 10^4 s. From the geomorphological viewpoint, shorter-term phenomena that occur within such human synoptic scales are effectively averaged. They may, of course, remain intensely interesting in the context of environmental physics, and they may hold the key to mechanistic understanding of the system (as in the appearance that turbulent scale phenomena control sediment entrainment). At these shorter scales statistical modes of explanation dominate. Geornorphologically, there are no coherent patterns of essential interest. Event patterns are random with respect to the geomorphological structure of the landscape and averaged summary quantities are, for strictly geomorphological purposes, appropriate.

Conversely, at low frequencies and over large areas, the customary resolution of measurements (which usually is set by the resources available to collect information within the domain of interest, and by ability to analyse it) creates a more or less highly censored view of geomorphologically significant events. This is especially true at the scale of landscape history, which requires a long retrospective view that is often recovered only from the surviving sedimentary records. Significant elements of geomorphological event sequences remain inaccessible, especially in the temporal scale. In such circumstances, conjectural reconstruction of history, using inference as the evidence permits, is unavoidable. Significant elements of geomorphological patterns may remain inaccessible. Our characterisation will remain particularistic until we have gained sufficient experience to identify a representative class of phenomena, when we seek a mechanistic explanation (that is, one which maximises our appreciation of order in the most parsimonious way). At the landscape scale, models - both conceptual models such as that of Davis and more recent numerical models - serve this purpose.

Between these extremes lies the domain of classically ordered, mechanically tractable phenomena. Provided our time frame is sufficiently short, we use linear or linearised arguments to obtain relatively robust explanations. But on the outer margin of this realm we find a class of phenomena in which nonlinearities come to dominate the mechanistic behaviour and predictive ability decays rather quickly (Figure 6.5). This is the class of so-called chaotic processes. Chaos occurs in a wide range of mechanical systems and is detected when the observing time exceeds some characteristic event time by a substantial margin. Event times in geomorphological systems may, then, define the scale range for chaotic processes. River systems are driven at synoptic or seasonal scales by runoff, so the domain for chaotic behaviour of the channel may reasonably be expected to fall in the range of years to decades.

A significant feature of geomorphological systems is the occurrence of substantial, yet clearly bounded, accumulations of material in the form of sediment deposits. These are generated or consumed over many events. Such stores are repositories of information about the history of the system. Stores introduce significant nonlinearities into system behaviour by modifying force-flux relations (such as equation (1)), They can achieve this by modifying the bounding geometry of the system. Processes are then controlled by the current geometry of the system. This is nothing new. It appears, however, that very detailed features of the geometry, such as sedimentary structure, are of major importance in determining the further development of the sedimentary system. Sedimentary systems are extremely sensitive to current configuration. This claim is new. The phenomenon is a source of deterministic, unpredictable behaviour. The time scale for such behaviour to

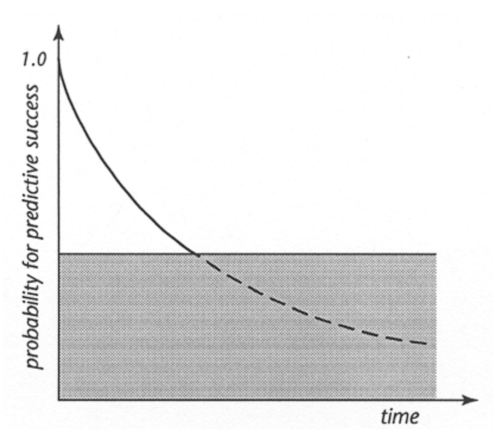

Figure 6.5 Illustration of the deterioration of predictive capability in systems subject to chaotic dynamics. The stippled zone represents probabilities not usefully different from zero

become manifest is consistent with the estimates given above and Figure 6.4 shows an example in which the effect occurs.

The passage of material through stores also creates persistence in the record of material flux (Klemes 1974; Kirkby 1987). Persistence provides an effective short-term memory for the system. The effect of persistence is to suppress the full range of variability in relatively short records of a process. In view of the discussion in the last paragraph, this seems to be a paradox. The limit of practical predictability in chaotic systems is, however, a way of viewing persistence. Persistence identifies a scale within which the controlling conditions remain sufficiently consistent to permit useful predictions to be made. Processes subject to storage effects are ultimately dominated by a sequence of increasingly rare, extreme events which are apt to be revealed only by taking a very long view of the process. It follows that the window of available observations may yield a quite misleading picture of the long term. What constitutes a long view, however, is determined by the commensurable scales of space and time. Intuitive recognition of this circumstance (or, at least, intelligent speculation upon the nature of the evidence left behind by dominant events) has probably influenced our tolerance for particularistic and narrative (hence contingent) 'theories' of large-scale processes, even though our sense of order is best served by reductionist, mechanistic theories of local processes, and may be provisionally satisfied by statistical (and still reductionist) theories of microscale processes.

Patchiness is a phenomenon in space which is homologous with persistence in time. Just as we must have a long view in time in order to detect persistence, in order to detect patches, we must enjoy a view that is far larger than the characteristic dimension of a patch. So we are most apt to detect patchiness in very local phenomena, and to detect it only when the resolution is very much finer than the domain of the study. We can find examples in the river. In an advecting system (such as flow down a river), persistence and patchiness are the same phenomenon. Low-frequency variance in turbulent signals (which is characteristic in rivers; cf. Figure 6.2) indicates the presence of patchiness. But a limit is imposed on the scale range of patchiness at one end by the size of the container (the channel) and at the other end by the onset of dissipative effects - in this case because of viscosity. Sediment accumulations in stream beds exhibit patchiness at the channel scale. The range of patches is delimited by the channel and by the elementary character of the sediments. Another way of viewing alternate theoretical frameworks is to consider that if we possess the means to survey the range of patch characteristics, then we are apt to construct a statistical theory as the only tractable way to digest the quantity of information and to appreciate its essential structure. At the other extreme, if we can scarcely see the structure of the patch system, we are apt to focus on local and particular elements and to construct mechanistic or particular explanations.

The asymmetrical structure of space and time influences how these concepts inform our knowledge. Whilst we have no evident limits in the time dimension - hence the chance always to detect larger-scale persistence - the space domain on the surface of the earth is limited. The domains of specific processes may be even more severely delimited, as the examples of channel-scale phenomena given above demonstrate. For large-scale features of the landscape, we may never arrive at representative domains, and our explanation of the landscape is apt, then, to remain particularistic. What is 'large scale' must be interpreted in terms of the resolution with which we view the world. At turbulent scales, large eddies are large-scale phenomena. One might suppose that absence of representative domains leaves no constraint upon interpretations in the time domain, but the temporal limits for humans to collect information become very effective domain delimiters. Since information is far less readily accessible through time (especially deep geological time) than it is over space, particularistic explanation continues to play a dominating role at the large scales in time as well. In short, history matters.

A final important feature of landscape which must be acknowledged is that different sedimentary systems operate with different virtual velocities and with distinctive phenomenological scales. Furthermore, the relation between phenomenological scales and human scales appears to exert a substantial influence over our construction of order in the system. The contrast between the hillslope system and the fluvial system provides an obvious exarnple. Most hillslopes have quite limited space scales and very small characteristic virtual velocities, which is to say that time scales are very long. Hillslopes are also very sticky systems (friction is high), so that events are exceedingly episodic. On hillslopes, patchiness very quickly becomes evident both spatially and temporally. Interestingly, classical mechanistic theories almost completely dominate work on hillslope development. I guess that is because of the extreme difficulty to observe very local processes in any consistent way (not least because they are apt to be very boring for protracted periods), and - since they are largely erosional systems - because we usually cannot recover information to characterise the behaviour of hillslopes through very long periods, when changing climate and cumulative weathering of earth materials are apt to be dominant considerations.

SUMMARY

In this chapter, I have attempted to argue that our construction of rational order in the world around us is essentially constrained by the scales of space and time within which we examine the world. That is a remarkably large theme, of which the chapter presents only a sketch. I have tried to show that an important element of the constraint is the information that is accessible via the observing techniques at our disposal. Classically, two important domains of theory were recognised. The first summarises human experience in terms of a spatiotemporal narrative in which contingency plays a dominant role. Orderly explanation is couched in terms of recognised contingencies. Space and, particularly, time scales may be large. The second recognises the recurrence of characteristic, classifiable events which are subject to general, mechanistic explanations.

It has been common, since the advent of classical mechanical science, to deny that the first domain is even 'scientific'. So far as the earth sciences are concerned, at any rate, this claim scarcely seems tenable; in the end, we have only one earth to consider. But it appears, more generally, that the scales of enquiry determine the most appropriate mode of explanation, and its seems unreasonable to limit science only to that which is accessible to mechanistic theory. Within contingent explanation, the canons of science are observed in terms of the phenomena that may be admitted, and their expected behaviour at smaller, embedded scales (see Simpson 1963). 1 have endeavoured to show that the switch in modes of explanation might occur over a wide range of scales, depending upon the resolution of the observations.

This century has seen the accession of two new modes of theoretical organisation of phenomena. Around the turn of the century, statistical explanation entered the purview of science. Whether statistical abstractions of phenomena are a matter of convenience or a reflection of essentially stochastic processes remains a matter of controversy, at least in macroscopic science (see Smart 1979). There is no doubt, however, that the mode of explanation to which they give rise is distinctive in that the quality of the information that is summarised in theory is different than is found in classical or historical modes of organising knowledge. In statistical explanations, we at best know some information about a class of phenomena, within which we may be able to assign probabilities for the appearance of particular outcomes.

The final mode of theoretical organisation is very new, although its foundations also were laid around the turn of this century. It arises in the zone between mechanistic and contingent explanation; it may even emerge as a way to subsume contingency more acceptably into scientific method. It describes the phenomena that emerge in ostensibly well-behaved systems when sufficient time elapses for information to accumulate from remote parts of the system, or for significant information stores to experience systemmodifying changes. In this circumstance, highly novel and unpredictable developments may occur which we characterise as 'chaotic behaviour'. In geomorphology, this appears to occur in landform systems over time scales for significant changes in material storage, hence in the configuration of the system.

The domain of relevance for each mode of explanation provides a fundamental connection amongst them. I find it useful to consider these domains in relation to the virtual

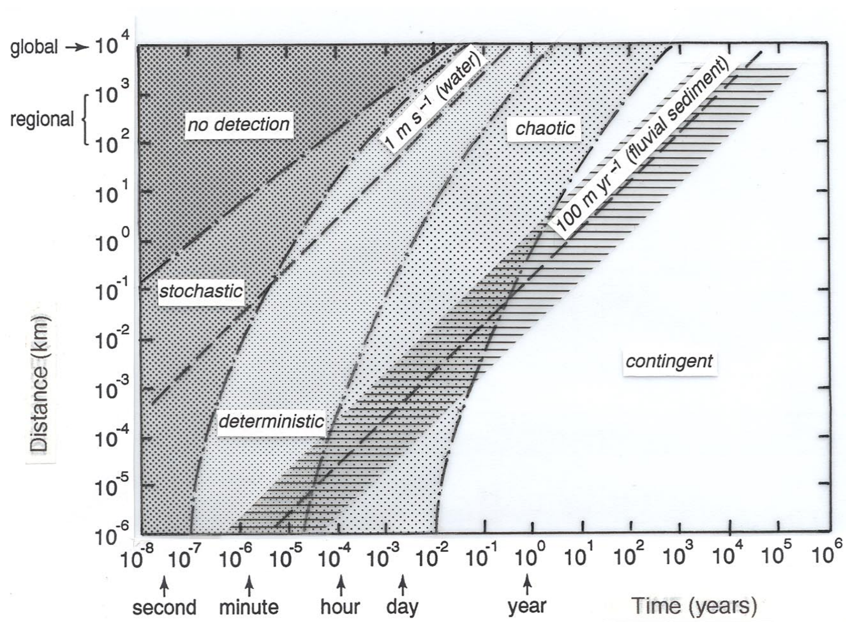

Figure 6.6 Conjectural division of characteristic spatiotemporal domains of four modes of theory construction, specified for fluvial system virtual velocities

velocity for material (or information) transfers in the system under consideration (Figure 6.6). This appears to set scales for theory, because it sets the information requirements to be able to make coherent statements about nature. However, it appears that feasible modes of explanation may change as instruments (hence, the resolution of measurements) and analytical capabilities change. Thus, numerical methods and large-scale automatic computation render a much wider range of phenomena open to classical mechanical description today than was possible only a few decades ago. Preferred modes of explanation appear, however, to be systematically related to customary human scales of perception of the world. These modes of explanation appear to be sufficient for us to construct an orderly picture of nature. It is not clear to me whether or not there is, in addition, an absolute order in nature which establishes as necessary ones the distinctions I have drawn. I am not sure it matters. Either way, we arrive at the possibility to ground theories of landscape (and, I would claim, of all else) in some concept of order at various distinct scales. This is what humans seek.

ACKNOWLEDGEMENTS

I thank two apparently perplexed and disappointingly anonymous referees for their persistence with my text, and editors Rhoads and Thom for their patience with my procrastination. I hope that the chapter will eventually repay their investments of good will and good advice.

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