# 7 Samples and Cases: Generalisation and Explanation in Geomorphology

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ABSTRACT

Research in geomorphology employs a range of strategies, but one useful distinction is between extensive research methods based on large-N samples, and intensive methods employing small-N case studies. The former may lead to generalisation by empirical statistical means, while the latter generalise by theoretical reasoning. This chapter explores the relationship between these approaches, and some implications of adopting the latter. The case of the historical development of views on the nature of river meandering is used to illustrate that a broad shift occurs from extensive to intensive research as understanding improves. However, this necessitates a more detailed assessment of the rules governing case-study research than has hitherto taken place; while sampling theory for large-N studies is well established, theoretical bases for the selection of field areas for case studies are much less evident. In a case study, it is essential to identify the boundary conditions provided by the field location, in order that generalisation can proceed of the mechanisms inferred from observation. This in turn places great emphasis on the development of new methods for describing those local conditions in time and space. These general considerations are illustrated with examples drawn from fluvial geomorphology, glacial hydrology and slope hydrology.

## INTRODUCTION

Discussion of methodology in most disciplines, and geomorphology is no exception, is contentious because it often involves semantic devices of more or less dubious validity. For example, critics of 'positivism' often conveniently ignore the large number of its

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variants (up to 12 have been identified; Outhwaite 1987). Instead, they judiciously select the most convenient straw man for their particular purpose. A given position can most easily be defended (or attacked) by deploying arguments about one of its properties, when a different property has been the subject of attack (or defence). Phillips (1992) illustrates this by showing that 'naturalism' in the social sciences involves several distinct properties, and that refuting only one cannot undermine the whole notion. In geomorphology, as in other disciplines, methodological debate may resort to the tactic of reducing a complex issue to a dichotomous variable, with the most familiar being the evolution: equilibrium dichotomy. This particular case (of a dichotomy) has been entrenched metonymically, by symbolic representation through the attachment of the names of claimed or supposed historic authorities (in this case, Davis and Gilbert). As Sack (1992) has shown, detailed textual analysis often reveals that the symbolic representative provides no evidence of having been a true proponent of the methodological position assigned to, or chosen by, him or her.

These debating strategies often result in polarisation of views, and this in turn encourages belief in the reality of the various, often opposing, positions held. This is unhelpful, because it results in methodological statements being treated normatively, as a set of guiding principles or rules. In fact, most statements about methodology are no more than models themselves - that is, mental constructs that attempt to represent a degree of understanding of the process whereby knowledge is acquired, and judged as being adequate for some purpose. It is therefore important to acknowledge the range of circumstances and conditions within which a particular methodology is both developed and applied. For example, the experimental method is shown by Harré (1981) to be employed for a wide range of reasons and purposes (Table 7. 1), and in a wide variety of forms. This reflects the fact, among others, that as scientific knowledge about a phenomenon increases, so the methods required to extend that knowledge further are likely to be adapted.

In reality, both the specific explanation of particular geomorphological events (cases), and general explanations of geomorphological phenomena, commonly demand a methodology in which a complex migration occurs between the poles that are represented in

**Table 7.1** The uses of experiment as identified by Harré (1981)

| | |
|---|---|
| A. | As formal aspects of method |
| | 1. To explore the characteristics of a naturally occurring process |
| | 2. To decide between rival hypotheses |
| | 3. To find the form of a law inductively |
| | 4. As models to simulate an otherwise unresearchable process |
| | 5. To exploit an accidental occurrence |
| | 6. To provide null or negative results |
| B. | In the development of the content of a theory |
| | 7. Through finding the hidden mechanism of a known effect |
| | 8. By providing existence proofs |
| | 9. Through the decomposition of an apparently simple phenomenon |
| | 10. Through demonstration of underlying unity within apparent variety |
| C. | In the development of technique |
| | 11. By developing accuracy and care in manipulation |
| | 12. Demonstrating the power and versatility of apparatus |

typical dichotomies. These dichotomies can therefore be seen not to be truly dichotomous, but merely devices to simplify, summarise and misrepresent what are, in fact, continua. This chapter considers, and seeks to deconstruct some related, apparent dichotomies, and assesses their continually changing roles in the methodology and practice of geomorphology in particular, and the environmental sciences in general (of which geomorphology is a case).

## DICHOTOMIES AND EXPERIMENTS

The linked 'dichotomies' defined in Table 7.2 form the basis for discussing the thesis that, as research into a phenomenon continues, a continual bidirectional, spiralling migration occurs between end members, represented by the left-hand and right-hand columns of this table. This has implications for the conduct of field research in geomorphology, affecting the research methods adopted by both individuals and research communities. Different individuals researching aspects of a particular problem may be simultaneously at opposite poles of the dichotomy, but as research questions evolve, communities may shift position in directions conditioned by the emerging research needs and paradigms. The left-hand column in Table 7.2 summarises a broadly empirical and 'positivist' approach to research, typically characterised as concerned with observational and experimental evidence. For example, a relationship between drainage basin morphometric variables and mean annual flood might be considered a typical outcome of such a research method, being a statistical generalisation of the relationship between operationalised and measurable variables. The research method employed in the construction of this relationship is extensive - it requires the sampling of a large number of drainage basins for which the independent ('causal') and the dependent ('response') variables are measured and related (an example of experimental method A. 3 in Table 7. 1). The variables employed are representative of both 'form' and 'product'. A 'realist' approach, on the other hand, employs methods appropriate to a world-view or ontology in which a distinction is drawn between three levels of a phenomenon (Bhaskar 1989; Richards 1994). These are the underlying mechanisms and the intellectual structures that represent them, events caused by those mechanisms in particular circumstances, and observations of those events. It recognises that observation is contingent on both the occurrence of observable events and the presence of capable observers (with appropriate technology), and that events are also contingent, in this case on an appropriate conjunction of mechanisms and the necessary space-time context to allow them to operate and create events. This construction of the world and our interpretation of it implies that empirical observation alone cannot reveal causal behaviour, and that theoretical analysis underpins realist research (Sayer 1992). Since identification of an association between observed and measured variables is itself no basis for the explanation sought by a realist methodology, this commonly requires intensive research of individual cases. A typical example is an investigation of the mechanisms of hillslope hydrology which seeks to uncover them by detailed study at a single site. The throughflow pit at a single point on the slope yields data, but the hydrological processes are interpreted for the upslope hillside on the basis of theoretical consideration of the behaviour of water flowing through the particular soils observed on the slope.

**Table 7.2** Some linked apparent dichotomies in the scientific methodologies employed by geomorphologists

| | | |
|---|---|---|
| Ontology | **'Positivism'** | **'Realism'** |
| Epistemology | Empirical | Theoretical |
| | Concrete | Abstract |
| | Extensive research | Intensive research |
| | Large-N | Small-N |
| | **Samples** | **Cases** |
| Subject | Form and product | Process and mechanism |

*Note:* The intention is to suggest that, in practice, research moves back and forwards between these poles, and that the labels attached to the methodologies are often semantic devices rather than rigid definitions; hence, the inverted commas,

These methodological distinctions are of importance in environmental sciences like geomorphology because they influence the way in which investigations in such sciences are undertaken in practice. If the 'model' for scientific activity is a conventional view of positivist experimentation, when applied to field-based sciences this leads to an emphasis on sampling theory, extensive 'large-N' studies, statistical methods and empirical generalisation. Laboratory experimentation involves physical isolation of the system being studied; this experimental closure allows manipulation of causal relationships so that the regular behaviour observed (constant conjunction) permits law-like statements to be made. However, this is subject to the charge that such law-like statements, derived from this form of experimental activity, only reflect the behaviour 'created' by the act of experimental closure, and are laws made in the laboratory rather than 'laws of nature' (Bhaskar 1989). Multiple causes operate together in 'open' systems in the natural environment, and their effects may be self-cancelling in certain contexts, so that no observable events occur, or so that events relate to causal processes inconsistently (as in the case of the variable stormrelated slope and channel responses described in the upper Severn catchment by Newson 1980). Thus there can be no simple link from a field observation to identification of a causal mechanism; extensive, large-N studies are therefore necessary in order that 'closure' can be statistically created, by methods such as partial correlation.

While extensive research reveals patterns through statistical manipulation, intensive research may involve a detailed study of a single, or a small number, of case(s); the objective is then to provide an explanation of the mechanisms generating the observed patterns in an extensive investigation (Yatsu 1992). The small-N case study (Ragin and Becker 1992) provides 'detailed examination of an event (or series of related events) which the analyst believes exhibits (or exhibit) the operation of some identified general theoretical principle' (Mitchell 1983, p. 192). Generalisation from a case study to other cases is not through empirical extrapolation using statistical inference; rather, 'the validity of extrapolation depends not on the typicality or representativeness of the case but upon the cogency of the theoretical reasoning' (Mitchell 1983, p. 207). However, this theoretical reasoning identifies intellectual structures that seek to represent natural mechanisms, and the degree of generality of these structures may vary. For example, the laws of conservation of mass and momentum represent highly general natural constraints within which fluid dynamic mechanisms operate, but when embodied in intellectual structures such as versions of the Navier-Stokes equations, certain assumptions are made that limit their applicability (constant density, steady flow, hydrostatic pressure distribution, depth averaging).

Experimental investigations of salt weathering provide a useful illustration of the differences between the approaches in the columns of Table 7.2. Climatic cabinets can be used to explore the different rates of rock breakdown under controlled conditions (rock sample size and shape, and temperature and humidity cycles). Appropriately controlled experiments (Goudie 1974) allow differential rates of rock sample breakdown to be measured, and permit ranking of the susceptibility of different rocks to salt weathering (by a given salt), and ranking of the efficacy of different salts (acting on a given rock). However, simple observation of differential rates of breakdown identifies neither the precise rock properties responsible for susceptibility to weathering, nor the actual mechanisms of destruction. These mechanisms can be identified by theoretical consideration of the stresses imposed by crystal growth, and stress-strain behaviour leading to crack-tip propagation (Whalley et al. 1982). They are then necessarily observed and measured by different techniques (and experiments).

The dichotomies in Table 7.2 are, however, somewhat artificial, and the implied characterisation of positivism and realism should not be treated as defining different sets of rules for scientific activity In the first place, it is not that positivism is a scientific method that eschews theory, but that positivist or empiricist models of scientific activity have erroneously implied that observation and measurement can take place without theory. The researcher who relates morphometric variables to mean annual flood in fact selects those variables on the basis of theory, implying that there is no such thing as pure empiricism. The dichotomies do, however, become useful initial guides in relation to certain practical aspects of research, particularly when distinguishing between 'samples' and 'cases' as both the objectives and the outcomes of field research. In summary, an initial dichotomy can be identified between large-N, extensive field studies whose outcome is often empirical generalisation. about forms or products; and small-N, intensive field-based case studies whose outcome is often a theoretical understanding of process-form relationships. However, these two styles of research, and the generalisations and explanations that they generate, are inextricably linked, and in any area of geomorphological enquiry there is a continual spiralling between them. This reflects the movement of the study from outside the case(s) in more extensive investigations, to inside a case in an intensive investigation (when new questions may be posed that require the embedding of additional extensive enquiries within the intensive case study).

In the case of extensive large-N studies, there are many familiar rules to guide the selection of the cases about which generalisation may subsequently be made - this is traditionally a matter of sampling theory (Son 1973). The theoretical basis for this allows errors to be accounted for and both estimated as uncertainties in prediction confidence, and protected against by the collection of a suitably large sample size. However, there is much less theoretical clarity about the process in which concepts, which are often 'chaotic conceptions' (Sayer 1992, p. 202), are converted into measurable variables. In intensive, small-N case studies the rules for case selection are even less clearly defined and well known, although the site-specific boundary conditions are critical for understanding of the case (because they determine whether the mechanisms being investigated will produce particular kinds of events). The selection of a field area for a case study therefore demands appraisals (i) of what it is considered to be a case of; and (ii) of those characteristics that may allow observable events, that are interpretable in terms of the mechanisms or processes about which understanding is sought. Otherwise, the choice of a particular case may predetermine the mechanisms the researcher can investigate.

The relationships and trends between extensive and intensive, large-N and small-N studies, and the problems of experimental design in the latter, are illustrated in this chapter in three main ways. Firstly, the general historical development of approaches to the explanation of a particular geomorphological phenomenon, based on a commonly occurring shift from large-N to small-N studies, is highlighted by the example of river meandering. Secondly, some detailed characteristics of intensive research are illustrated through a review of a research design for the investigation of the seasonal evolution of the character of subglacial drainage (Richards et al. 1996), an example of a geomorphological research project in which the role of direct observation is severely circumscribed and innovative methodology is essential. What emerges from analysis of this case study is that intensive research frequently demands study of interaction and coincidence, and therefore is crucially dependent on simultaneous study of several related phenomena and processes. Finally, the importance of establishing the boundary conditions for the investigation of earth surface processes is considered, in terms of both the need to evaluate carefully the choice of field location, and the need to develop innovative methods of observation and measurement.

## FROM LARGE-N TO SMALL-N: INCREASED KNOWLEDGE AND CHANGING METHOD

One context for a move from the left- to the right-hand column in Table 7.2 is historical; extensive research is commonly necessary in the early stages of an investigation, but may give way to intensive research later, as observation and empirical generalisation about form and product necessitate theoretical consideration about mechanism. This is demonstrated clearly by the changing modes of investigation of channel pattern, especially river meandering.

Rivers are diverse and spatially variable, but our appreciation of this seems to have diminished over the years. Indeed, the tendency has been to emphasise the similarity of river meanders over a broad scale range, particularly on the basis of bivariate plots of morphometric variables displaying statistically linear relationships across several orders of magnitude (Figure 7.1(a)). One of the consequences both of these simple quantitative relationships derived by extensive, empirical research employing large-N sampling designs in fluvial geomorphology, and of traditional river engineering methods such as channelisation for flood control, has been to emphasise, and even create, similarity among rivers. The empirical generalisations which reinforce this are those such as the channel width-meander wavelength relationship (Leopold and Wolman 1960), which seems to imply that all rivers have bends of similar shape. These relationships are supported by early notions which account for meander development from initially straight river reaches (e.g. Dury 1969). In reality, rivers rarely evolve thus except when straightened artificially; rather there is continual adjustment from variable and arbitrary states by varying combinations of erosional and depositional processes as discharge regime and sediment supply

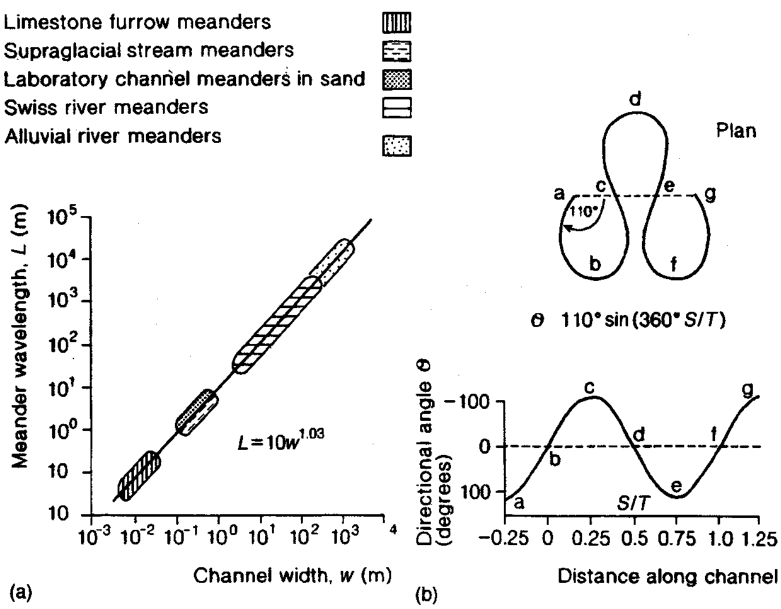


Figure 7.1 Examples of morphometric models of river meanders. (a) The classic regression of meander wavelength on channel width (after Leopold and Wolman 1960); (b) the sine-generated curve model of meander shape (after Langbein and Leopold 1966)

alter. In contrast to these geomorphological and engineering traditions, any focus on aesthetics and ecology in river management is liable to emphasise the conservation value of uniqueness. This is illustrated by the failures - and expensive restorations - of river engineering schemes, such as the straightening and subsequent renaturalisation of the Kissimmee River in Florida (Boon 1992). There appears to be a contradiction in these different emphases on similarity and difference, but one which is being rapidly eroded by new approaches to the study of river morphology which are more sensitive to the local contexts within which generally occurring processes operate, and which recognise that similarity lies in the fundamentals of process (hydrodynamic and sediment transport) and not in the morphologies of meander bends.

Bivariate empirical relationships among wavelength, width and radius of curvature are static descriptions of morphology involving simple, discrete, quantitative parameters. These simple parametric descriptions of meander bends developed into attempts to represent meander morphology more continuously, for example by employing a single-parameter sine-generated curve model of the bend shape which implies that bends are symmetrical about their axes (Figure 7. 1 (b): Langbein and Leopold 1966). Processes (for example, of energy dissipation) were then inferred from the bend geometry, which is, however, still represented in a static manner. Since maximum bank erosion tends to be displaced downstream from the apex of a bend, symmetrical forms are improbable, and a variety of evidence suggests that bends are more generally asymmetric in plan shape. This focus on bank erosion has in turn demanded greater emphasis on bends as dynamic, migrating forms, and a wide range of modes of bend migration has been identified.

Understanding of bend development requires an examination of processes such as secondary circulation, bank erosion, sediment transport from the base of eroding banks and across point bars, and deposition of point bar sediments. Study of these phenomena emphasises meanders as dynamic features having a diversity of behaviour. For example, many become asymmetric in shape as bank erosion occurs downstream from the apex, although there are many other styles of migration. Such study also links meander migration with the structuring of floodplain sedimentology, and implies that the classic model of inward-directed flow at the bed because of secondary flow, leading to fining upwards of lateral accretion deposits, is only one of several such relationships.

Bends therefore display a wide range of migration styles which result in shapes that are far from uniform and symmetrical (Figure 7.2). There are delayed inflection bends (Figure 7.2(a)) in high-power rivers with rapid bank erosion and strong secondary circulation, and with sandy bedload. In these, erosion occurs on the outer bank, the flow hugs the bank, evacuates products of bank erosion rapidly, scours along the base of the bank, and a delayed switch of the flow across to the opposite bank occurs. The bend is therefore strongly asymmetric, and may become a gooseneck bend which bends back up-valley (Lapointe and Carson 1986). However, there are also premature inflection bends (Figure 7.2(b)) in steep rivers with very high stream power and coarse gravelly bedload. These rivers develop over-widened bends, in which the point bar is deposited as the flow spreads across it without displaying any inward-directed cross-stream flow, and a deeply scoured pool is formed against a resistant bank out of which the flow 'squirts' across against the opposite bank again (Carson 1986). There is also the bend characterised by concave-bank bench deposition (Figure 7.2(c)), in which confined meanders on narrow floodplains in rivers carrying heavy suspended sediment load but little bedload develop a sharp bend in which erosion occurs on the inner, convex bank, causing over-widening at the apex and a dead zone against the concave bank. Silt deposition occurs on the outer, concave bank, and the inner convex experiences erosion, and the floodplain accretes by silt deposition (Page and Nanson 1982). This richness in the behaviour of meander bends is also reflected in an increasing awareness that bends in different environments - especially different sedimentological environments - may have shapes that by traditional standards are extremely irregular, but which in terms of the flow and sediment transport processes that both create the bend shape and are modified by it, are perfectly explicable.

This development of a more diversified view of the nature of meander bends reflects a change in the method of investigation, to small-N case studies involving meticulous observation of sediment transport rates and paths, three-dimensional flow dynamics, and their interdependence with channel form (a typical example is the work of Dietrich and Smith 1983). Additionally, it is evident that small-N studies involve comparative assessment of the effects of mechanisms at different times and places. Carson's (1986) study of premature inflection bends on the Canterbury Plains in New Zealand is typical of the combination of detailed observation of site characteristics and in-depth understanding of general processes that case studies require. Indeed, Carson criticises reliance on mathematical approaches, implying that they have helped to preserve the myth of uniform circular motion. However, increasing use of computational fluid dynamics numerical modelling programs based on two-and three-dimensional solutions of the shallow-water (Saint Venant) equations now allows numerical simulation of flow in channels with arbitrary plan geometries and bed topographies, ranging from what have been called 'non-

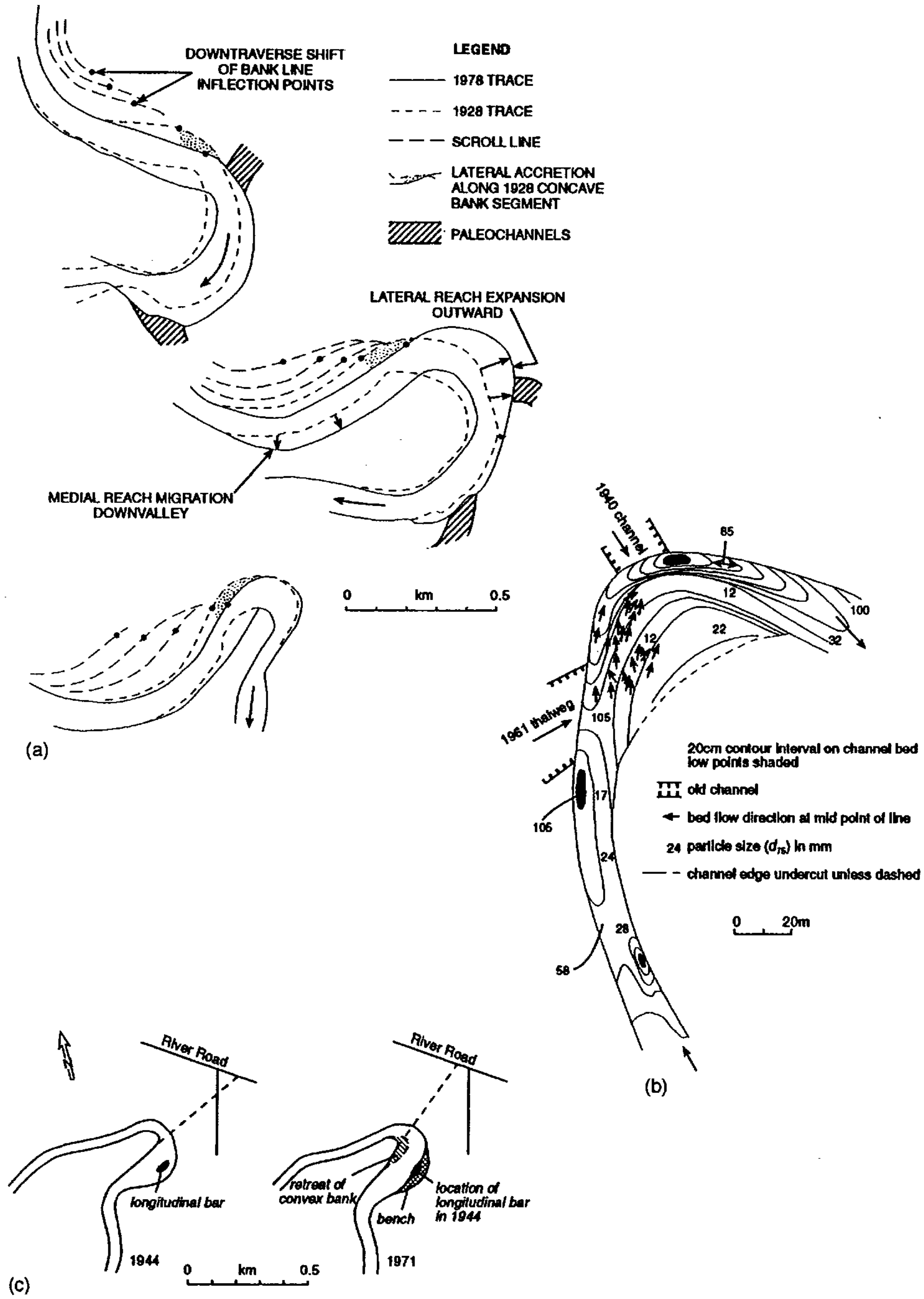


**Figure** 7.2 Different kinds of meander bend in different environments. (a) Delayed-inflection bends on the Rouge River, Quebec (after Lapointe and Carson 1986); (b) a premature-inflection bend on the Waireka Stream, Canterbury Plains, New Zealand (after Carson 1986); (c) a bend on the Murrumbidgee River, New South Wales, Australia, characterised by outer-bank deposition (after Page and Nanson 1982) classical meander bends' (Hodskinson 1995) to even more complex braided channels (Lane et al. 1994, 1995; see below). These approaches demand intensive, and generally very detailed field measurement of the channel bed topography, depending on the channel size and sedimentology, to form the boundary condition for the application of the numerical models. This necessitates the shift from large-N studies in which the many sampled cases are represented by simple parameters, to small-N studies in which the single (or few) cases are represented by complex sets of measurements, representing three- and even four-dimensional boundary conditions. Thus, a wide variety of bend shapes, migration styles and floodplain sedimentologies exists depending on local conditions of stream power, floodplain width, floodplain sediment and sediment load. This diversity has critical implications for river management, demanding greater attention to the local conditions of an individual site. What proves to be a suitable management strategy in one place will not, necessarily, be equally successful elsewhere. Channel changes, both natural and designed, must be interpreted in relation to the spatial interaction between flow and sediment transport processes and the bend morphology.

## A CASE OF A CASE STUDY: EXPLANATION CONFIRMED BY COINCIDENCE

In a large-N study, measurements are external to the individual sampled 'cases'; cases are sampled according to some variant of a random sampling strategy, and a simple measurement is performed on each one. In a small-N study, the case is selected, and is then the subject of a large number of observations and measurements internal to it. However, this case may also become a variate in a large-N study. The distinction between extensive and intensive research in Table 7.2 is fuzzy, since an intensive case study can also involve extensive monitoring. The distinction therefore rests less on the quantity of observational evidence than on the procedures involved in generalising the results of the study; as noted above, it is not the empirical evidence of form or product that is extrapolated, but the theoretical understanding of processes that allows explanation of the behaviour of the systems of which the case study is representative.

Traditionally, great stress is placed on random sampling in order to justify statistical inference, or on replication in order to validate conclusions based on sampled cases. Both have the effect of reducing the level of detailed observation with which the individual cases can be treated. In an in-depth single case study, the loss of inferential power arising from the absence of multiple cases may be compensated by considering the inter-dependency of different but related phenomena observable within the case. This basis of an explanatory investigation in interdependency can be seen particularly in research fields where conventional observation is difficult, and field glaciology is the classic example considered below. Much scientific activity aims to facilitate observation, and the visual sense appears to have such primacy that 'seeing is believing'. Accordingly, science is often employed to develop technologies to enable visual observation. As Hacking (1983) has argued, the existence of a coincidence among the images obtained by, for example, optical and electron microscopes and the forms predicted by the scientific theory of the thing observed is enough to lead to belief in the reality of that thing. An alternative form of coincidence that strengthens belief in a theory arises when multiple properties observed in a case study coincidentally lead to similar conclusions about the behaviour of the system of which the case is a representative. Thus, the replication of similar measurement of supposedly similar samples (cases) that characterises large-N investigation is replaced in small-N case-study research by a research design which employs a multiplicity of different observations of related phenomena. Replication *per se is* replaced by forms of comparative assessment, of the conclusions developed from one case study with those derived in other case studies where the boundary conditions are different (at different times or in different places).

Field observation of glacial processes is fraught with difficulty, and interpretation of subglacial processes, for example, has always employed indirect indicators, such as the quality of outflow meltwater (Collins 1979). However, recent research has begun to employ the methodology of intensive case studies in which several phenomena are monitored together (for example, Hooke and Pohjola 1994; Richards et al. 1996; Lawler et al. 1996), with their interdependence being used to assist interpretation, and with numerical modelling providing both a predictive and testing role. Thus instead of monitoring electrical conductivity alone, as a surrogate for total dissolved solids, several water quality properties (cation, anion and suspended sediment concentrations, pH, PC02 and stable isotopes) are all monitored, together with dye-tracing experiments and water balance studies. Interpretation of aspects of the temporal covariation of these variables permits explanation of the seasonal evolution of subglacial drainage from a distributed form (e.g. linked cavities) to a channelised system, in terms of the up-glacier retreat of the transient snowline. When the surface snow cover has melted and glacier ice is exposed, the reduced albedo (coupled with higher energy inputs later in the summer) increases the amplitude of diurnal melt cycles, which destabilises the subglacial drainage. Suspended sediment and cation concentrations reveal when water chemistry is non-conservative because of rapid chemical interaction of meltwater with freshly abraded and finely divided sediment. The open- or closed-system nature of the subglacial weathering environment in the subglacial drainage system can therefore be interpreted. Dye-tracing experiments provide another check, distinguishing slow routing in distributed drainage from fast routing in subglacial channels, and water pressures monitored in moulins (or in boreholes drilled by hot-water drills) distinguish pressurised from free-surface flow in conduits.

Such a multivariate research design demands highly labour- and capital-intensive monitoring of the several indicators that allow testing of hypotheses suggested by one set of data against another, but it results in rigorous, detailed understanding of processes at a glacier bed. An example of such research is the study of glacial hydrology undertaken at the Haut Glacier d'Arolla, in Valais, Switzerland, outlined by Richards et al. (1996). This began by establishing the surface and bed topographies of the glacier by conventional survey and radio-echo sounding. Digital elevation models (DEMs) were then used to estimate the subglacial drainage network structure from the maps of the contributing area draining over the subglacial potential surface (Sharp et al. 1993). Dye-tracing experiments (over 500 in this case) permitted reconstruction of the subglacial catchments of the outlet streams, and therefore provided a check on the drainage system structure. In addition, the dye travel time from the moulins into which the injections were made to the outlet stream varies seasonally, and the shapes of the dye return curves distinguish rapid throughput in a conduit system from delayed flow in distributed drainage. Multivariate hydrochernical data (particularly the cation sum, pH and $pC0_2$) discriminate between open-and closed-system waters, interpreted in terms of both access to atmospheric $C0_2$ and chemical kinetics during the mixing of quickflow and delayed flow, and confirmed by water balance data which distinguish periods of net water storage and drainage. Finally, the data were integrated by a physically based numerical model. This simulates spatially distributed melt over the glacier surface using a surface energy balance submodel with hourly meteorological data inputs, and which accounts for surface albedo variations and topographic shading. A coupled conduit flow submodel then routes the simulated hourly meltwater input to moulins and crevasses, through the subglacial drainage network defined by the DEM and confirmed by dye-tracing data. Conduit dimensions in this submodel are varied by simulation of the seasonally changing balance between closure under overburden pressure and wall melting by the energy dissipated by the flowing water (Figure 7.3), and water pressure data provide a check on the validity of the model's predictions of the occurrence of surcharging in the conduits.

This example illustrates how understanding of subglacial hydrology is revealed in a detailed case study, involving an integrated, multivariate, multi-process programme of data collection and analysis. This provides what might be considered to be a realist interpretation of glacier hydrology, through a mutually reinforcing explanatory system, although it is clear that it contains elements of both columns in Table 7.2. Nevertheless, it illustrates an important methodological trend in physical geographical research - towards in-depth case-study research involving multiple, simultaneous investigation of a wide range of interdependent phenomena in order to improve process understanding. Returning to Harré's (1981) classification of the uses experiment in Table 7.2, this kind of investigation appears to be closest to B.10, although not identical to this type. Open-system, field-based experiments in realist environmental science appear to need a new category in this typology, emphasising interaction.

## BOUNDARY CONDITIONS: CONTEXTS FOR MECHANISMS

Small-N case study research is invariably set in a particular location - at a field site, for example. The principles that underpin selection of the site - the object of the case study -are much less clearly formulated than those that guide sampling design in large-N investigations. Often, selection is based on convenience, and on logistic rather than scientific grounds. Furthermore, if small-N research seems logically 'weaker' than large-N research, this may also reflect the fact that the phenomena of which the selected case is at first considered to be representative may change as the case study progresses, and accumulated knowledge acquired during the study reveals aspects of the case that were unknown at the outset. For example, in the study of glacial hydrology the substrate conditions may not be known initially, but may become apparent during the research programme. Interpretation of data may then have to be adjusted in the light of this information.

The philosophy of realism implies a structuring of the world in which observable events are contingent on appropriate circumstances for mechanisms to act. Methodologically, this means that interpretation of the nature of mechanisms from observation of events demands an understanding of the role played by local conditions in time and space. In laboratory science, the experiment is designed such that an interpretable outcome arises:

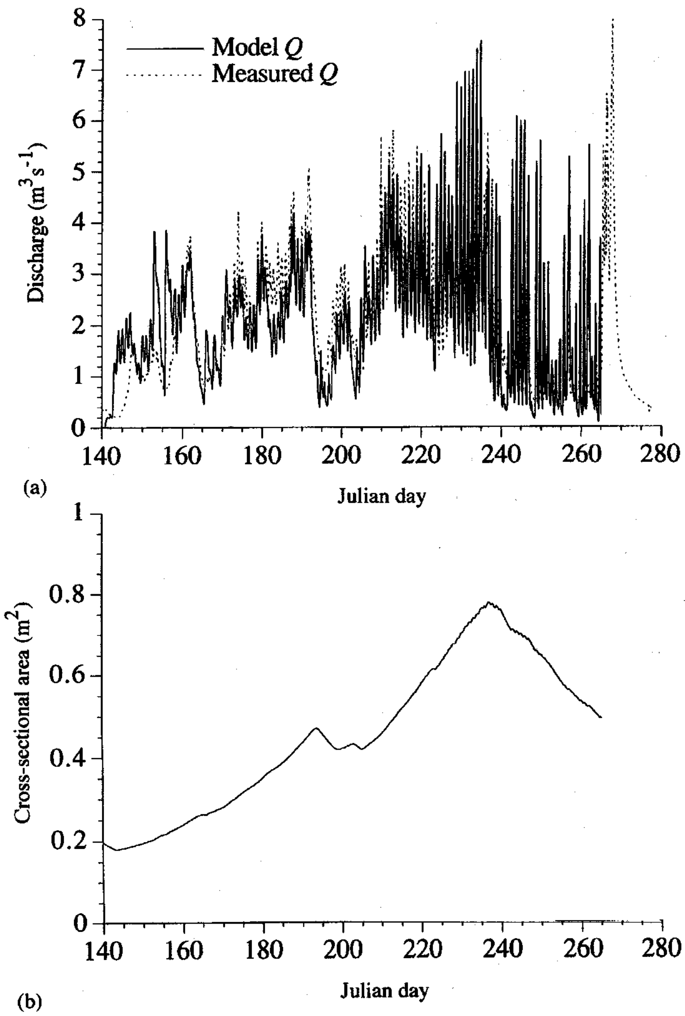


**Figure 7.3** (a) Observed and simulated seasonal runoff (Q) patterns from the Haut Glacier d'Arolla, Valais, Switzerland. Simulated patterns are based on an energy-balance melt model, a drainage network structure reconstructed from the map of cumulated drainage area over the subglacial hydraulic potential surface, and connecting the mapped moulin locations to the melt-stream portal, and a hydraulic sewer-flow routing model; (b) the simulated evolution of the width of the main subglacial conduit at about 1000 m upstream from the portal, based on the calculated balance of wall melting and closure by the ice overburden pressure

in field science where the experiment is conducted in the 'naughty world' (Kennedy 1979), the outcome is only interpretable if the experimental conditions are fully understood. This suggests that the manner in which a field location is chosen, and the characteristics of that location, need to be given much more detailed attention than is commonly the case. It does not suffice to provide a bland statement of the broad climatic and geological characteristics of the field location; what is important is identification of the properties of the site that have led to its selection in order that the mechanisms under investigation might be expected to produce observable events consistent with the hypotheses being evaluated. For example, the hypothesis that bed degradation occurs in a glacial meltwater stream on the rising limb of the diurnal hydrograph may not be supportable if the upstream boundary conditions are affected by changes in sediment supply (Lane et al. 1996).

Furthermore, debates in the literature may be more productive if it is recognised that process interpretations based on research in one location may be appropriate for that site, but not for a different one. Thus, different degrees of emphasis on back-to-back secondary circulation cells (Ashmore et al. 1992) and shear layers (Biron et al. 1993) as key aspects of turbulent motion and bed scour at tributary junctions may reflect not the fundamentals of the processes, but rather the different ways in which they are manifested in different environments. There is no reason to suppose that hydrodynamic processes and associated sediment transport will necessarily be comparable for a case where shallow, rapid flows of high Froude number combine over a rough gravel-bed boundary with equal depths in the two tributaries, and a case where deeper flows of low Froude number combine over a sand bed of low relative roughness and unequal depths. However, the flows in both types of confluence obey the same fundamental physical laws, and the same constraints of conservation of mass and momentum.

These issues imply that meticulous description of local boundary conditions is now as critical to successful experimentation and interpretation as the development of fundamental theory, and that increased attention must be focused on innovative means of describing and measuring these boundary conditions. Two brief examples illustrate this point. The first concerns the application of computational fluid dynamics (CFD) to the examination of two- and three-dimensional spatial patterns of flow velocity in braided river reaches (Lane et al. 1994). Engineering applications of CFD often involve regular, uniform channels, and of major concern is the turbulence model used in the closure of the shallow-water equations employed in numerical simulation. In fluvial geomorphological studies of natural channels with complex three-dimensional bed topographies, DEMS must be used to represent the boundary condition for flow modelling (Richards et al. 1995). This requires efficient data acquisition, and terrestrial analytical photogrammetry and stereo-matching procedures offer great potential (Lane et al. 1993). Geomorphological studies of flows over such complex, irregular surfaces (Figure 7.4) may be more concerned with description of this (external) boundary condition, rather than with the choice of (internal) turbulence model. The second example of innovative definition of boundary conditions is in the simulation of flow in soils with macro-pores. The physics of soil water movement, whether as Darcian flow or pipe-flow, are generally understood. However, description of the boundary conditions is extremely difficult because of the destructive nature of most methods for describing the internal structure of soils. Magnetic resonance imaging (MRI) does provide a non-destructive means of resolving the macro-pore structure (Figure 7.5), and therefore a basis for defining the geometry of the irregular conduits within which the flow must be modelled as a turbulent rather than a laminar process (Amin et al. 1993).

These two examples of attempts to represent the boundary characteristics for complex natural flows involve detailed case studies. In terms of Table 7.2, they might be considered 'realist' case studies - their focus is on the precise characteristics of a particular 'place'

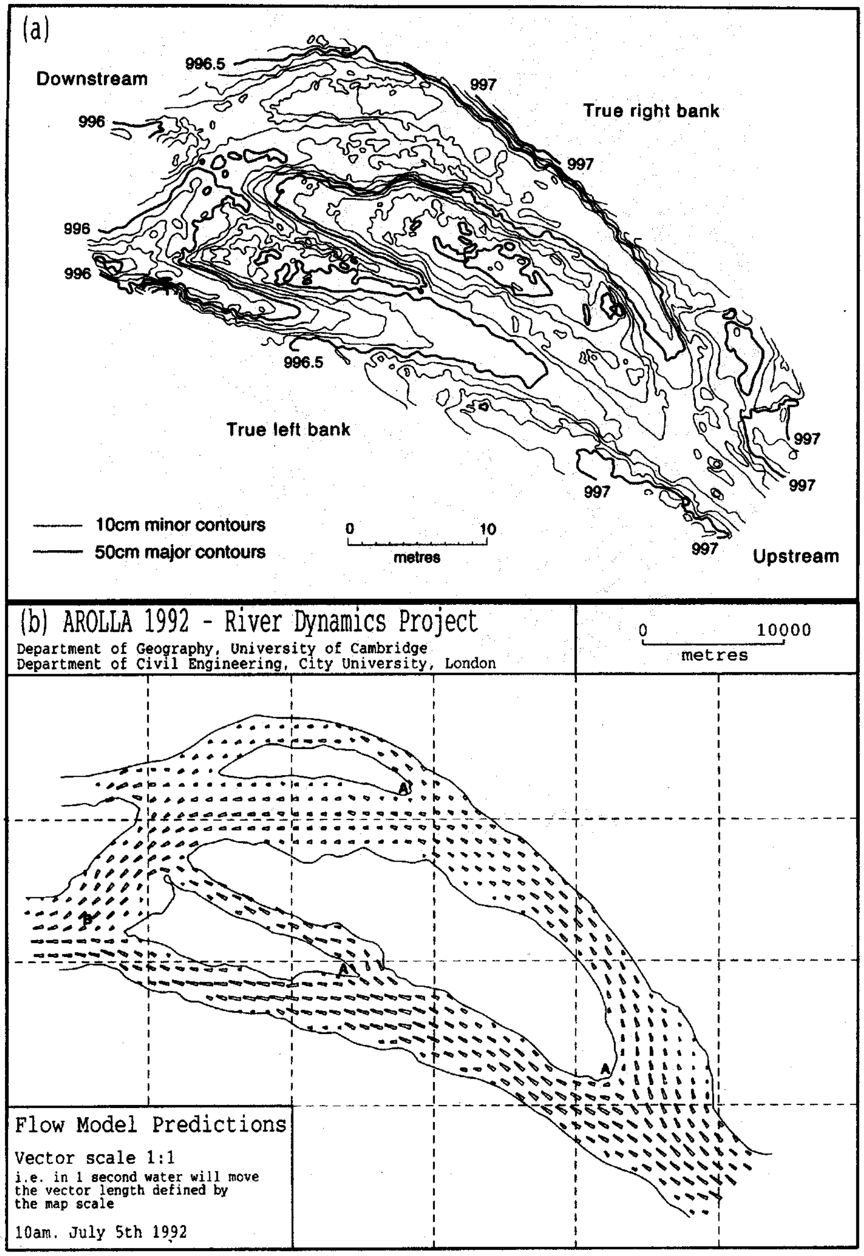


Figure 7.4 (a) A contour map of the terrain model of the bed topography of a study reach on the meltwater stream of the Haut Glacier d'Arolla on the 5 July 1992 at 10 a.m.; (b) the simulated spatial pattern of velocity vectors of flow through this reach at the same time, obtained using a depth-average solution of the Navier-Stokes equations

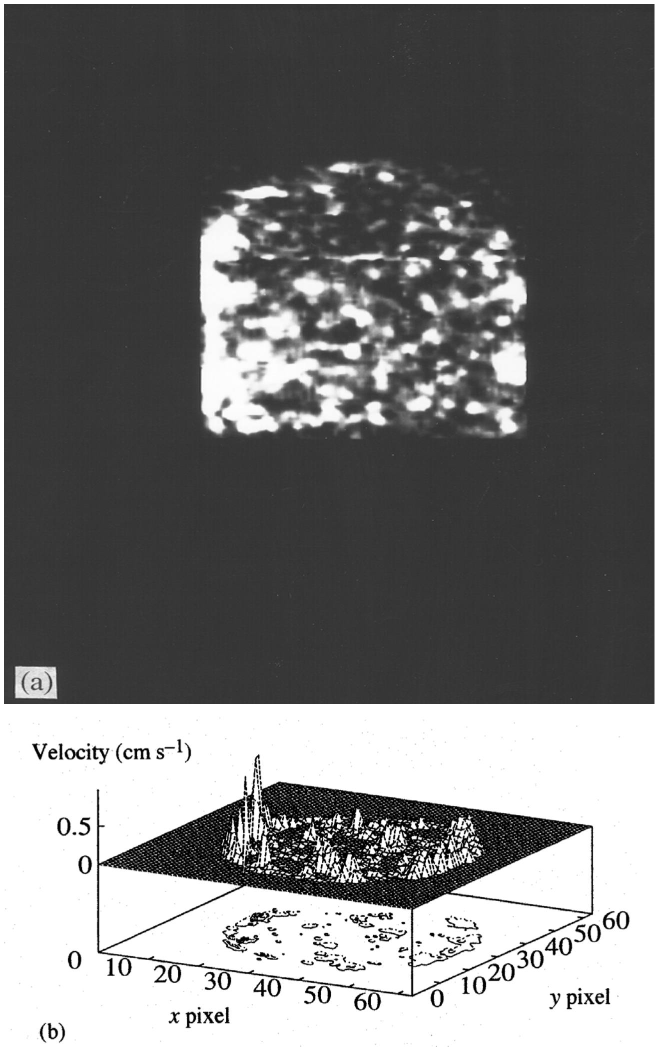


Figure 7.5 (a) A magnetic resonance image of a cylindrical sample of saturated soil, showing the distribution of water held in the larger pores; (b) a velocity distribution for flow through a horizontal surface within a soil sample, again obtained by magnetic resonance imaging

that determine the way general processes produce unique patterns. They demonstrate that the primacy accorded to analysis of the physics of a problem has given way to the necessity for sophistication in the description of local characteristics. In general, in geomorphology and hydrology, the fundamental theories relating to mechanisms operating at relevant scales - for example, those of fluid dynamics and sediment transport - are now relatively well understood. Intellectual effort in the future is therefore more likely to have to focus on the means of acquiring suitable data on the specific local environment (in time and space) in which those mechanisms are acting.

## CONCLUSIONS

Geomorphologists - and more broadly, physical geographers and environmental scientists - have often employed experimental methods, although perhaps with a narrower conception of their role than that implied by Table 7. 1. They have particularly employed physical laboratory experiments (Schumm et al. 1987) and statistical experiments (e.g. experimental design; Chorley 1966). Although some physical experiments essentially provide qualitative interpretation of possible natural processes, traditionally a laboratory experiment has embodied elements of both physical and statistical design, as it is necessary to consider the number of 'factors', 'treatments' and 'replicates', in order to assess the significance of the influence of factors and treatments on the variance of a response variable. However, emphasis on these quantitative aspects rarely expands the horizons of the experiment markedly. By contrast, modern field experiments may involve a combination of physical and numerical methods, in which the latter have a mathematical-physical basis rather than a statistical basis, and provide a key bridge between the results of the laboratory experiment and the field environment it seeks to simulate. In addition, these experiments are more likely to develop laterally, through the introduction of new measurements which seek to improve the physical basis for. understanding the role of the control variables.

These new elements of experimentation suggest two important conclusions. Firstly, the classical 'statistical experimental design' structure may render itself redundant as the knowledge it creates undermines the utility of formally structured experimentation. Later experiments can involve unique natural combinations of factors, being case studies in which the results of each (unique) treatment are explained by a variety of ancillary measurements and by physical understanding and associated numerical modelling. Secondly, the answer to a classical empiricist who criticises a study for lacking ‘replication' is that this may be unnecessary if alternative scientific devices exist to allow interpretation, explanation, extrapolation and prediction (of which modelling is perhaps the most important). This conclusion is vitally important for the practice of generalisation from representative experimental catchments, for example, where the expense of replication renders a traditional experimental design impracticable.

Scientific explanation and theoretical understanding may therefore occur particularly through small-N case studies, in which multiple investigations are undertaken simultaneously, guided by 'lateral thinking' which emphasises horizontal connections among related factors. The best experiments are eclectic, and involve 'horizontal' linkage of disparate approaches rather than 'vertical' extension, in terms of increasing N and emphasising replication. However, there are experiments within experiments, and case studies within case studies - comparative studies of river confluences or soil types, for example. Conventional 'extensive' monitoring and experimentation are embedded within 'intensive' case study, as in the glacial hydrology project outlined above, which includes dye-tracing experiments, the monitoring of discharge and solute and suspended sediment concentrations, echo sounding, surveying, meteorological and flow modelling and borehole experiments. Hence the conclusion that the dichotomies in Table 7.2 are more semantic than real.

Case studies, however, may develop at a later stage in a research project than large-N studies, and may be introduced to test ideas about mechanisms. It is necessary to understand mechanisms and processes at a reasonable level of sophistication before a case study can be undertaken. Then, a key issue is description of the local boundary conditions within which those processes operate. This shifts the balance of the science away from developing general laws, towards accounting for the uniqueness of the events produced by their operation in different places. The example of the study of braided stream processes outlined above illustrates this; detailed spatial data on river-bed topography, sedimentology and bed roughness are required as a boundary condition for physically based flow modelling, and this allows analysis of the topographic control of flow direction, and ultimately allows consideration of bedload routing through the study reach, and of spatially distributed patterns of erosion and deposition that allow the dynamic behaviour of the channel to be understood and simulated. Such a specific objective in the case of this case study must surely represent a desirable general goal for geomorphology, providing this framework within which to explore the dynamic, time-dependent behaviour of specific landforms.

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