**SPACE AND TIME IN RIVER BANK EROSION RESEARCH: A REVIEW.**

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**Abstract.**

The intention of this article is to identify the ways in which ideas about space and time are manifest in river bank erosion research, thus linking abstract theoretical discussion with the ‘practice’ of geomorphological research. Bank erosion research to date has involved a range of space- and time-scales, different perspectives resulting from these views. Scale linkage via mathematical translation has been attempted in some cases, but studies are often contextualised through loosely hierarchical ideas. The application of hierarchy theory and notions of space-time are considered, concluding with the identification of questions that might usefully be considered in future research.

**Key words:** River bank erosion, scale, space, time, space-time, hierarchy.

Space and time lie at the heart of geomorphology. Landforms and the way they change in space and time form the fundamental core of the discipline. ‘Scale’ – of space, time and substance (Lane, 2001) or attribute (Reitsma, undated) – thus represents one of the major issues within geomorphology (e.g. Penning-Rowsell & Townshend, 1978; Rhoads & Thorn, 1996; Phillips, 1997; Lane 2001), as it does in geography (e.g. Bendix 1994; Massey, 1999), environmental science (Curran *et al.*, 1997), and other sub-disciplines of them such as hydrology (Seyfried & Wilcox 1995). The purpose of this paper is to explore ideas relating to space- and time-scales within the context of research in a particular area of fluvial geomorphology, namely river bank erosion. At various times geomorphology has been criticised for a lack of awareness of theoretical and philosophical issues (e.g. Chorley, 1978; Thorn, 1988; Spedding, 1997). Publications which do address theoretical issues often (necessarily) do so in an abstract way (e.g. Baker, 1996; Rhoads & Thorn, 1996; Spedding, 1997) which may seem distanced from the “pragmatic business of research“ (Spedding, 1997, 262), and so this article also represents an attempt to ‘bridge the gap’ between the two. Essentially then, this is a review article, aiming to identify approaches to time and space that have been used in bank erosion research to date (whether explicitly or implicitly), with the hope that this may point the way towards fresh insights. No claim is made to address *every* notion of space and time that may be applied in, or applicable to, geomorphology. Rather, the content of the article is led by the bank erosion research literature, concentrating on the commonly emerging ideas. As the title suggests, the focus is on space- and time-scales, neglecting scale of substance/attribute, although clearly these are not entirely separate. Similarly, ‘scale problems’ are both conceptual and practical (e.g. sampling) problems (Thorn, 1988), and whilst acknowledging the two are inter-related, emphasis is here given to conceptual issues.

Curran *et al.* (1997) and Kavvas (1999) usefully identify that multiple definitions of the word ‘scale’ exist, and according to Zhang *et al.* (2004) there are over 30. Of these, Zhang *et al* present five: cartographic scale; geographic scale; operational (or characteristic) scale; measurement scale and modelling scale (Table I). Again, expediency requires some delimitation of focus and the primary interest of this article thus lies in measurement scales, although other forms of scale will be included where necessary. Note also that the term measurement scale is used in the broadest sense of the definition provided by Zhang *et al.*; essentially, the time- and space-scales at which bank erosion is conceptualised. This definition allows some overlap with ‘modelling scale’.

Perhaps the most commonly recognised ‘scale problem’ in geography is that things look different at different scales: observations, results and theories are all dependent upon the scale of investigation (e.g. Kennedy 1977; De Boer 1992; Bendix, 1994; Peuquet, 1994; Poesen *et al.,* 1994; Kirkby *et al*., 1996; Moussa, 2003), such that ideas derived at one scale may not apply at another (Lam & Quattrochi, 1992; Kirkby *et al.,* 1996; Rhoads & Thorn 1996; Curren *et al.,* 1997). If our understanding of landforms and processes is dependent upon the scale at which we study them, decisions regarding management (Lane, 2001) and the sustainability of management practices (Thomas & Adams, 1997) are also dependent on the scale of enquiry. An alternative view to this ‘scale-dependence’ can also be found though. Scale invariance (either self-similarity or self-affinity) has been identified in form (for example in braided rivers, Sapozhnikov & Foufoula-Georgiou 1996), and in changes in form over time (Sapozhnikov & Foufoula-Georgiou, 1997; 1999; Foufoula-Georgiou & Sapozhnikov, 1998), with Butler *et al.* (2001), suggesting that scale-invariance within river-bed gravels can be identified over particular scale ranges, which may be characteristic of different processes. The ‘scale problem’ thus pervades geomorphology and any applications of it, and a considerable challenge lies in reconciling the different views of the landscape afforded by different scales of study (e.g. Lane & Richards, 1997), and perhaps in reconciling scale-dependence with scale-independence. This paper primarily focuses on scale-dependent perspectives, as these appear most commonly in the bank erosion literature.

# Scale in river bank erosion

The first step in examining scale issues as they are manifest in river bank erosion research must be to identify the scales at which river banks are studied, and the different perspectives of bank erosion afforded by these views. A distinction must be made here between geographic scale and measurement scale. Geographic scale relating to river bank erosion is the size of drainage basin and/or channel, and studies of catchments ranging from less than 1km2 (Duijsings, 1987) to 75,000km2 (Dietrich *et al.,* 1999) have been reported. Of more direct relevance here is measurement scale, i.e. the spatial and temporal scales that define the focus of enquiry in bank erosion studies. Spatially, research may range from a single ‘bank’ or site (such as the bank stability analysis of Osman & Thorne, 1988), through river reaches of varying lengths (e.g. Pizzutto, 1984a; Odgaard, 1987; Gurnell, 1997) to the whole drainage network (Brierley & Murn, 1997; Abernethey & Rutherfurd, 1998; Lawler *et al.*, 1999). Similarly, the temporal scale of interest may range from the ‘ahistorical’ properties of a bank which determine its erodibility (e.g. Osman & Thorne, 1988) – viewed here as the smallest timescale as it is essentially a “slice-through-time” (Massey 1999, 264) – through timescales of months (e.g. Laubel *et al.* 2000) and years (e.g. Stott, 1997) up to centuries. At the upper end of the scale, La Marche (1966) assessed channel change over 800 years, although Lawler (1993) suggests that sedimentary analysis has the potential to yield data on channel change at a temporal scale of up to 20,000 years. Table II illustrates the combinations of space- and time-scales used by a number of researchers. It should be noted that the divisions of time into ‘ahistorical, short, intermediate and long’ (based on Lawler, 1993), and of space into ‘site, reach and catchment’ are arbitrary, but the analysis provides some insight into bank erosion research nonetheless. While some variation is evident in the combinations used, two generalisations can be made: Firstly, that there is a broad positive relationship between the time- and space-scales used, such that shorter temporal scales tend to be studied in combination with smaller spatial scales. This will be considered again later. Secondly, a predominance of temporally short studies at the ‘reach’ spatial scale is evident. While it could be the case that this reflects a bias in the selection of articles for inclusion, it certainly seems that studies of erosion processes and mechanisms (as opposed to simply rates of retreat) do tend to be conducted (or reported) at this scale.

Turning to the perspectives of bank erosion afforded by these varying scales of study, at the ‘large (space- and time-) scale’, river bank erosion is seen as a part of long-term channel change, meander migration and floodplain development and destruction. This may result from local degradation (La Marche, 1966) or large-scale human settlement of the catchment (Brierley & Murn, 1997), for example. The emphasis is thus on the role of bank erosion in landscape development, rather than on the processes of erosion themselves. Studies which view erosion over river networks or ‘long reaches’ (e.g. Odgaard, 1987, studied two reaches, one of 65.3 and the other 230 km) may result in erosion rates being seen as a function of variables such as catchment area, width:depth ratio (Hooke, 1980), channel width or radius of bend curvature (Odgaard, 1987), for example. These characteristics vary at the spatial scale of study. Moving towards the ‘smaller scale’ studies, spatial variation of erosion rates within river reaches is recognised, as is temporal variation on a seasonal, monthly, weekly, or even quasi-continuous basis (e.g. Lawler, 1994). Examples of factors that may influence this spatio-temporal variability include velocity distributions and secondary currents within the channel (Hey & Thorne, 1975), freeze-thaw and desiccation (Lawler, 1994; Green *et al.* 1999: Couper & Maddock, 2001), tension crack development (Darby & Thorne, 1994), bank geometry (e.g. Osman & Thorne, 1988), and basal sediment removal (Thorne, 1982). At the very ‘smallest’ scale (ahistorical study of a site), the erodibility of a bank is determined by the mechanical and electrochemical properties of the bank material, pore water and eroding fluids (e.g. Thorne & Osman, 1988). In summary, perceptions of river bank erosion are clearly influenced by the scale of study, as variability identified at any one scale is usually explained through factors which vary *at the same scale*. This raises the issue of ‘closure’.

# Closure

Any attempt to understand complex phenomena necessitates some kind of delimitation of enquiry (Bauer, 1996), and it is this that Lane (2001) and Massey (2001) refer to as closure. Massey (2001, 260) identifies two types of closure: i) the “delimitation of a field/object of study in the sense of placing temporal and spatial (for instance) bounds around it”; and ii) the adoption of a particular approach “*to* that object of study.” In the context of this article the former type of closure is the most significant and so is given priority, but the latter cannot be ignored entirely.

*Delimitation of the field/object of study.*

The scales of river bank erosion enquiry outlined earlier are examples of the segmentation of time and space (Peuquet, 1994) involved in closure. These scales are defined, either consciously or unconsciously, by the researcher (e.g. Turner *et al.,* 1989).

Spatial closure, which Lane (2001, 249) defines as “bounding a region which should otherwise be bounded by operating processes rather than space”, firstly involves selection of the river(s), reach(es), or site(s) to be studied. This will be determined by the aims of the study, as in the case of Lawler *et al.* (1999) monitoring sites that had appeared to be actively eroding during reconnaissance surveys, on the basis that focusing on such sites facilitates study of the processes of erosion. However it may also be influenced by accessibility (e.g. Couper & Maddock, 2001). Once the location has been selected, spatial closure/delimitation continues to occur. Whereas Lawler (1991) and Couper and Maddock (2001), for example, limit study to the bank face, Wood *et al.* (2001) include the zone of basal sediment scour and Darby *et al.* (2002a) look beyond this to the sediment dynamics and migration of the channel.

Similarly temporal bounding, the selection of the timescale of study, will be a conscious decision on the part of the researcher in defining the aims of research, but may also (in part) be determined by other constraints such as data availability. The obvious example is that of the intermediate- to long-term studies (using the categories of Lawler, 1993) dependent on historic maps (e.g. McEwen, 1989), aerial photographs (e.g. Springer *et al.,* 1985; Kondolf & Curry, 1986), dendrochronological (La Marche, 1966) or sedimentological evidence (e.g. Taylor & Lewin, 1996). The temporal limit of such studies is determined by the data sources available.

Massey (2001) suggests that such closure does not necessarily deny conceptualisation of that which falls ‘outside’ the limits of study, and this can be seen within bank erosion research. Some authors comment on events extraneous to the space and time of focus (e.g. Twidale, 1964), and/or recognise a broader context (spatial and/or temporal) within which their study lies. Thus Thorne and Abt (1993) present the computer application of a limit equilibrium bank stability equation which takes a ‘slice-through-time’ approach, but they start by qualitatively placing this within channel sediment transport processes. Indeed, Thorne (1981) comments on the limited value of studying bank processes at a small scale without an awareness of the context of up- and down-stream influences on the location in question.

The restrictions imposed by closure can have far-reaching consequences, as:

“…proper handling of the bank retreat problem depends on correct identification of the actual cause of bank erosion, which may be associated with local scour, general scour, lateral instability or system-wide degradation.”

(Thorne & Abt, 1993, 836). The spatial and temporal limits imposed on a study may preclude consideration of each of these, and thus influence the resulting perception of erosion significantly (echoing the comments of Lane, 2001, regarding management decisions). The implications of this will depend on the aims of the individual enquiry, but the importance of an awareness of closure is highlighted.

*Approach adopted to the object of study.*

Closure in terms of the approach adopted will also influence the findings of research, and whilst less specifically related to ‘scale’ issues, this is also worthy of consideration. Perhaps at its simplest, this type of closure involves the choice of variables to be included in a study, and Bradbury *et al.* (1995) recognise the difficulty of isolating a single variable for consideration within a complex natural system. To exemplify, an empirical study of bank erosion processes based on short-term, reach-scale, field observation may include any or all of a number of variables (such as erosion rate, ground or air temperature, precipitation, stage, discharge, velocity and secondary currents within the flow, bank geometry and tension cracking, and a variety of soil properties including cohesion, friction, cation exchange capacity, and pore water pressure) and the results of the research will thus reflect the decisions made.

The technical capacities of the methods used also represent a form of closure. After observing spatial and temporal variability in bank erosion rates beyond the detection capabilities of ‘traditional’ erosion pins, Lawler (1991) developed a photo-electronic alternative, allowing monitoring in real-time. Similarly Prosser *et al.* (2000) designed an ‘electronic groundprofiler’ to obtain greater spatial coverage of the bank than erosion pin methods. These three methods (erosion pins, photo-electronic erosion pins, and electronic groundprofiler) will each involve a different level of spatial and/or temporal aggregation, which could conceivably lead to different patterns in erosional activity being identified, and explained in different ways. Lawler (1993) provides a comprehensive review of the application, and limitations, of river bank erosion measurement methods.

Decisions taken in data analysis will also be significant. Lawler *et al.* (1999) demonstrate that the use of mean bank erosion rates masks spatial and temporal variability, which can “reveal much of the process dynamics” (1999: 984). In this case the occurrence of spatial variability in erosion across the bank face, with the greatest rates occurring in the upper and middle portions of the bank, is identified as indicative of freeze-thaw action. Clearly use of an aggregate mean erosion rate for the whole bank would preclude this insight. Couper *et al.* (2002) suggest that the way particular aspects of the data – specifically negative erosion pin readings – are included in (or excluded from) data analysis can have further influence. They demonstrate that not just erosion rates, but also the direction of change in the temporal sequence of erosion rates, can be altered. Again, this holds consequences for subsequent interpretation.

In the development and/or application of models of bank erosion, the inclusion or exclusion of particular variables within the models is important. Darby *et* al (2000) provide a nice example, describing the bank stability model of Thorne and Tovey (1981) being developed by Osman and Thorne (1988) to account for the presence of tension cracks, further work then involving the inclusion of a more realistic bank geometry (Darby and Thorne, 1996), and consideration of pore water pressure and hydrostatic confining pressure (Rinaldi and Casagli, 1999; Simon *et al.,* 1999). Each model has limitations – such as application of the Darby and Thorne (1996) model being limited to straight rivers (Nicholas *et al.,* 1999; Darby *et al.,* 2002a). The approach taken to modelling is also important, Mosselman (1995) distinguishing between kinematic and dynamical models, and Abam (1997) discussing deterministic and probabilistic approaches.

Every study of river bank erosion thus involves a number of forms of closure delimiting its boundaries (including this one - no implication that all relevant forms of closure, or all relevant spatial and temporal issues, have been covered here is intended). Although these closures may be seen as limitations in that they ‘restrict the view’ of the researcher(s), as Lewin (1980, 7) points out, *“it is…quite impractical for an aimless concern for all and any timescale to be maintained.”* Closure thus remains a necessary part of research. Arguably though, the variety of closure involved in ‘collective’ bank erosion research represents a strength, as it does in geomorphology as a whole; each study adds to the ‘patchwork’ of understanding, with each ‘filling gaps’ left by others. Thus Lane (2001) argues against prioritising any particular type of closure (Massey, 2001), while emphasising that these issues should be recognised in research.

**Scale linkage**

If we have a ‘patchwork’ knowledge of river bank erosion then, with each patch delimited by the closure involved in the research, the challenge remains to ‘sew the patches together’ and gain a coherent view of the whole. Regarding space- and time-scales, this leads to the challenge of scale linkage. Such is the significance of this task in geomorphology that Rhoads & Thorn (1996, 145) describe it as the discipline’s “Holy Grail”. Phillips (1997, 98) defines scale linkage as “the problem of establishing and elucidating the relationships between processes operating over different spatial and temporal scales,” but clearly this definition refers to ‘characteristic scales’ of processes. Linkage of measurement scales (or perhaps of measurement scales with characteristic scales) is equally important, and this is essentially an attempt to overcome closure. We place temporal and spatial bounds around our enquiry, but then want to understand how our findings translate beyond these bounds.

An awareness of the ‘broader context’ within which the focus of research lies (such as is demonstrated by Thorne & Abt, 1993) is scale linkage at a basic level. Commonly in bank erosion research this involves short time-scale / small (site or reach) space-scale study of processes with acknowledgement that these are part of the longer time-scale / larger space-scale processes of the river system (e.g. Twidale 1964; Kesel & Baumann, 1981; Bradbury *et al.*, 1995; Meentemeyer *et al.*, 1998; Rowntree & Dollar, 1999; Couper & Maddock, 2001). Some authors go a step further, attempting to explicitly include two time- or space-scales in their research. For example Hill (1973) examines variability in erosion both within reaches and between reaches of two different streams. Hooke (1980) combines 21/2 years of field monitoring with 135 years of historic map data in a study of Devon rivers. Similarly, Pizzuto & Meckelnburg (1989) attempt to evaluate a linear bank erosion equation at timescales of three years and 43 years, using a combination of field observation, aerial photographs and modelling. Comparable timescales (three years and 30 years) are considered by Nicholas *et al.* (1999) in studying the response of river bank erosion to dam construction and gravel extraction. These latter three studies thus all make some attempt at temporal scale linkage.

Focusing on spatial scale, Lawler (1992) introduced the concept of downstream changes in bank erosion process dominance. He suggests that, due largely to increasing channel size and discharge in a downstream direction, subaerial processes account for the most retreat in the headwater regions of a drainage basin, fluvial entrainment dominates the middle reaches, and mass failures, the lower reaches (for further detail see Lawler 1992; 1995). This idea been supported by field evidence from Abernethy & Rutherfurd (1998) and Lawler *et al.* (1999), and thus reach-observed processes are placed in the context of the whole river network, and a scale-dependence in river bank erosion processes defined.

Thorne (1999) and Hooke and Redmond (1989; 1992) consider both space- and time-scales. Thorne (1999) cites the addition by Darby & Thorne (1996) of a probabilistic element to a site-based, deterministic (ahistoric time-scale) bank stability analysis in order to account for local variability in bank material strength. He then considers this within the context of reach-scale sedimentary processes over a time-period of 11 years. Hooke and Redmond (1992) tackle larger scales, considering meander and river development at the reach, basin and national scales. They thus emphasise the importance of an awareness of longer-term, basin-wide river change in understanding meander development and channel change at the reach or bend scale.

To summarise, researchers studying river bank erosion demonstrate an awareness of the need for scale linkage, and attempt to provide some scale linkage in a number of ways. However, the majority of these attempts lack explicit reference to any particular theoretical basis. Cammeraat (2002) suggests that scale linkage can be approached via extrapolation, scaling (similar media) theory, or hierarchy. Extrapolation and scaling can be grouped together as mathematical devices for translating across scales (Phillips, 1999a) and of these extrapolation appears to be the most important for measurement scale linkage in bank erosion research. Thus these two forms of scale linkage, mathematical translation and hierarchy, will be considered in turn.

## Mathematical translation across scales.

As a brief divergence from measurement scales, geographic scale linkage has been attempted in river bank erosion research. Hooke (1980, 154) identified a relationship between erosion rate and drainage basin area, thus stating that “erosion rates are similar for all sizes of basins if scaled as channel widths per year” (taking channel width as a surrogate for catchment area). Odgaard (1987) similarly acknowledges such a relationship. Downstream changes in bank erosion process dominance (Lawler, 1992) can also be seen as a form of geographic scale linkage. The dominant bank erosion process in each part of the drainage basin is largely determined by the size of the channel and associated discharge, although other factors such as stream power also play a role. Thus ‘scaling’ (either mathematically or conceptually) has been used as a form of geographic scale linkage with some success.

To link measurement scales, extrapolation is probably the most common form of mathematical translation attempted in bank erosion research. Spatially, this involves using erosion rates measured at specific sites or reaches and identifying some criteria by which they can be extended across the whole river network. Thus Stott (1997) uses erosion rates measured on stream reaches in forest and moorland areas of the Balquhidder catchments, then extrapolates these rates according to the estimated proportions of eroding banks in each type of land use within the catchments. Similarly, Green *et al.* (1999) multiply measured erosion rates by the proportion of banks on the Warrah Creek estimated to be erosionally active. In both cases the aim is to consider amounts of sediment being delivered to the channel by bank erosion across the catchment(s), and the authors involved recognise that the methods entail some degree of generalisation. Laubel *et al.* (2000) discuss optimal monitoring strategies when such spatial extrapolation of data is required, thus highlighting the need to consider scale linkage in research design if it is part of the aim of a project. Temporal extrapolation is attempted by Prosser *et al.* (2000); bank erosion rates measured at a number of points on a site are projected over a ten-year period in order to explore potential future bank morphology. Again, the results are viewed with caution but are considered to yield some insight into future trends.

Problems with extrapolation have been highlighted particularly where researchers have compared measured erosion rates derived from a short time-scale study to longer-term evidence. Wolman (1959), Twidale (1964) and Hooke (1980), using field observation periods of between two and five years, all found measured rates to be in excess of those suggested by sources of historic data. This is eloquently illustrated by Wolman (1959, 216):

“*It is certain that if the observed rate of erosion of 1.5 to 2.0 feet per year were the rule in this region, numerous bridge abutments and gaging stations would long since have fallen prey to the rivers on which they are built.”*

Part of the problem here may lie in closure. Firstly, temporal and spatial bounding of a study involves sampling bank erosion across a particular space and time-period (Hooke, 1980) and the spatial or temporal ‘location’ chosen may not be representative of a larger space or time-period. This is exemplified by Twidale (1964), who recognises that conditions specific to his ‘temporal sample’ may have caused the seemingly excessive erosion rates, in that three ‘large floods’ occurred within the field-monitoring period described. Extrapolation assumes a degree of stability in the phenomena being extrapolated (i.e. river bank erosion rates) and/or the variables underlying it (Driver & Chapman, 1996), and this assumption may be untenable. Secondly, the nature of variability of a process may depend on the scale at which the process is defined and/or observed, and so observation at two scales may not be directly comparable. Clearly related to this is the (lack of) comparability of data obtained by differing methods: at historic timescales data on river channel change may be obtained from historic maps and aerial photographs, whereas at shorter timescales field measurements are more likely to be used. Hooke (1980), Hooke & Kain (1982), McEwen (1982), Lawler (1993) and Hooke & Redmond (1989) provide further discussion of such issues in relation to bank erosion, while Schumm (1991) considers problems of extrapolation in geomorphology in some detail.

*A hierarchy of scales.*

In hierarchy theory, a system is considered to be structured in hierarchical levels. A hierarchy may be nested or non-nested, and it is nested hierarchies, where each level contains (and is composed of) the levels below it (O’Neill *et al.*, 1986), that are of the most interest here. The entities, or ‘holons’ (Koestler, 1967), within each level of a nested hierarchy are themselves subsystems at a lower level of the hierarchy. A holon thus consists of, and contains, holons at the next lower level of the hierarchy. A hierarchy may be structured according to any criteria: Koestler (1967) predominantly discusses social hierarchies, whereas O’Neill *et al.* (1986) consider hierarchies based on form (or ‘tangible components’) and space (size), and propose that a hierarchy of process rates is the most useful to ecologists. However the levels of a hierarchy are defined, each level acts as a constraint on the behaviour of the holons within the next lower level. In essence, a higher level defines the environmental conditions of its lower level constituent holons (Bendix, 1994). Relations between the levels are thus asymmetrical (O’Neill *et al.,* 1986), as a higher level is considered to be independent of a lower level, whereas a lower level is dependent on the higher level (Koestler, 1967; O’Neill *et al.,* 1986; De Boer, 1992). In contrast ‘horizontal’ relationships, those between holons, are symmetrical as the holons can interact with each other (O’Neill *et al.,*1986).

Explicit discussion of hierarchies can be found within geomorphological literature. The application of hierarchy theory is considered in some depth by De Boer (1992) who makes a series of propositions for a geomorphological hierarchy based predominantly on spatial (geographic) scale. Brunsden (1990; 1996; 2001) discusses a temporal hierarchy of process events, and Bauer (1996, 407) suggests that the notion of a hierarchy of scale, each level with its own distinct characteristics (emergent phenomena), has “found partial support in contemporary geomorphological practice.” However it could also be argued that, within fluvial geomorphology at least, the *implication* of hierarchy is not new. Arguably, any consideration of temporal and spatial scales in fluvial geomorphology would be incomplete without acknowledging the contribution of Schumm & Lichty (1965). They defined a series of cyclic (long), graded (intermediate) and steady (short) timescales, identifying whether given variables within a drainage basin can be considered to be dependent, independent or irrelevant when the basin is viewed at each timescale. Phillips (1999b) lends support to this view of causal independence at different scales, and this idea appears to be inherently hierarchical. The influence of Schumm and Lichty (1965) can be seen throughout fluvial geomorphology, an example being provided by the work of Werrity & Ferguson (1980) on the River Feshie. Recently the idea of a hierarchy has been used more explicitly in studies of river habitat and ecology. Newson & Newson (2000) propose a spatial scale hierarchy for river habitat survey and modelling, building on the work of Frissell *et al.* (1986) and Maddock & Bird (1996). Similarly, Thoms and Parsons (2002) advocate a hierarchical ‘eco-geomorphology’ approach to river research and Parsons *et al.* (2003) depict fluvial systems as hierarchical.

Within river bank erosion research a hierarchy is often implied rather than discussed or defined explicitly. It has already been noted that some studies involve measurement of bank erosion rates over two (or more) timescales (e.g. Wolman, 1959; Twidale, 1964; Hooke, 1980; Pizzuto & Meckelnburg, 1989; Harmel *et al.,* 1999; Nicholas *et al.,* 1999). There are many examples of qualitative recognition of the broader context of short time-scale / small space-scale studies of erosion processes (Twidale 1964; Kesel & Baumann, 1981; Bradbury *et al.*, 1995; Meentemeyer *et al.*, 1998; Rowntree & Dollar, 1999; Couper & Maddock, 2001), and some quantitative attempts to identify the contribution of bank erosion to river sediment budgets (e.g. Duijsings, 1987; Stott, 1997). A hierarchy based on spatial and/or temporal scale is thus frequently implied. It is perhaps when bank erosion forms only part of the focus of study that a fluvial hierarchy becomes more apparent. Mosselman (1995, 668) discusses a model for planform change on the Brahmaputra-Jamuna River consisting of integrated ‘sub-models’. In asserting that;

“[t*]he underlying mechanisms in* [the sub-models] *are not the fundamental laws of physics for small volumes of water and sediment, but fluvial mechanisms on a higher level of aggregation, such as width adjustment, channel migration, island formation, channel creation and channel abandonment”*

he is identifying emergent phenomena at the scale of the sub-model, a feature of hierarchies (e.g. O’Neill *et al.,* 1986). The sub-models form holons at a given level of the hierarchy. Thorne *et al.* (1993, 268) are more explicit in their description of the Brahmaputra River:

“*The pattern that emerges is of a hierarchical series of process-form linkages in both time and space. Island and nodal reaches scale on the first order channel, are measured in tens of kilometres and evolve over decades and centuries.”…”Braid bars scale on the major left- and right-bank anabranches, are several kilometres long and change measurably during each annual hydrograph.”…”Dune bedforms migrate freely through the anabranches and sub-channels at all discharges.”*

The application of hierarchy theory within geomorphology needs careful thought though. The view of causal independence of form and process at different scales is challenged by Lane & Richards (1997) who, in reference to work undertaken on the Arolla River, identify a feedback between processes operating at small time-/space-scales and those operating at larger scales. Thus the lower hierarchical level does influence the next higher level, in what Roy and Lane (2003) term ‘coupling across scales’, and the notion of asymmetrical vertical relationships within the hierarchy is questioned. Koestler (1967), in his lengthy account of hierarchy theory, does recognise a process of feedback but this is described as ‘within-holon’ feedback, a self-regulatory feedback reminiscent of stable or steady state equilibrium, operating only within individual entities. Such criticism should not be taken to imply that hierarchy theory is of no value to geomorphology, simply that a ‘tailored’ version of it may be appropriate. Interestingly, in discussing hierarchy theory in an ecological context Grace *et al.* (1997, 11) specifically state that “in hierarchical systems, information is passed upscale and downscale”, and Kirkby *et al.* (1996) describe a feedback process between levels in their hierarchical approach to studying soil erosion. The adjustments necessary for geomorphological application of the theory in accordance with recent ideas regarding (independence and) dependence have thus perhaps already been made in some instances, and these should be considered alongside the work of De Boer (1992). A more explicitly (or intentionally!) hierarchical study of river bank erosion processes may yield interesting insights, but would necessitate careful thought as to the basis for definition of hierarchical levels. Process rates, as suggested by O’Neill *et al.* (1986) in ecology, may be one option.

**Space-time**

To this point, space and time have been discussed as separate, though related, variables. Recently within geography there have been calls to reconsider this position, and to view space and time together as the four-dimensional ‘space-time’ that Einstein and Minkowski conceived (Raper & Livingstone, 1995, 2001; Massey 1999; 2001; Lane, 2001; Richards *et al*., in press). The argument is that the occurrence of a phenomenon or entity cannot be separated from either the space or time in which it occurs, that the entity and its space-time are mutually constituted (Massey, 1999). An example of the importance of this approach in fluvial geomorphology is supplied by Lane & Richards (1997), who maintain that a river reach can only really be understood when viewed within the specific spatial and temporal context of the catchment and its development. Spedding (1997), in arguing for a refocusing within geomorphology on the organisational dynamics of landform development, suggests that this view of space-time is compatible with a realist approach to research (as advocated by Richards, 1990; 1994; Richards *et al.,* 1997) or with studying geomorphological systems as complex phenomena. Recognising space-time, according to Massey (1999), also involves recognising that ‘matching pairs’ of space and time are necessary, problems arising when un-matched pairs are used. This is evidenced in the difficulty geomorphologists have found in separating the two, for example De Boer (1992), in an article entitled ‘Hierarchies and spatial scale in process geomorphology: a review’, makes frequent reference to temporal scale. Brunsden (1996) clearly acknowledges this relation of temporal to spatial scales, referring in 2001 to a “hierarchy of process events distributed in time and space” (Brunsden 2001: 109), and it should be noted that the dynamic scaling of braided rivers identified by Sapozhnikov & Foufoula-Georgiou (1997) infers matching spatial and temporal scales.

It could be argued that if we are to adopt this reconceptualisation of space and time in river bank erosion research, the ‘foundations’ have already been laid. Matching pairs of space and time-scale were noted earlier: small spatial-scale processes can be observed during short time-scales but, frequently, catchment-scale studies necessitate data pertaining to longer time-periods. This relation of the two is sometimes made ‘unconsciously’, as appears to be the case in Simon *et al.*’s (1999:124) statement that:

 *“In terms of broader temporal scales, the occurrence of bank failures generally indicates channel instability of an unspecified magnitude and spatial extent and can signify instability of channel pattern.”*

While focusing on temporal scale they clearly cannot separate this from spatial scale. It should be stressed though that the authors recognise this themselves in a later publication (Simon *et al.,* 2000). The notion of downstream changes in bank erosion process dominance (e.g. Lawler, 1992) similarly relates not just to space but to time as well. Couper & Maddock (2001) note that spatial variability in process dominance cannot be separated from temporal variability and the specific time-scale and time-period of study. Recognition that bank erosion processes occurring in the field are determined by local conditions is also not new (e.g. Hooke, 1980), and a number of implications are identified in the research literature. Ashbridge (1995) describes the difficulty posed for predicting the occurrence of erosion at a given site or for particular environmental (temporal) conditions. Brierley & Murn (1997) and Brewer & Lewin (1998) discuss the influence of local conditions in determining the response of the channel/catchment to environmental change and human-induced disturbances. Piégay *et al.* (1997) identify the implications for river management, in that management activities will not result in the channel returning to a former state as changes have occurred within the catchment in the meantime. In effect, the ‘initial conditions’ for operating processes have been altered. More specifically, elements of realism and complexity can be found in some studies. Wood *et al.* (2001) use an intensive study of a single field site to focus on identifying the underlying causal mechanisms that will allow explanation of a process (in this case, the entrainment of failed bank material) rather than prediction via surrogate variables. Fonstad & Marcus (2003) and Hooke (2003) investigate self-organised criticality in bank erosion and river meander behaviour, and both authors note the potential for future research in this area. Ideas relating to space-time can thus already be found in bank erosion research.

Returning to Massey’s argument of the mutual constitution of space-time and entities, this can be demonstrated by considering bank erosion *processes* as the entity of interest (rather than the bank itself). Bank erosion is generally perceived as the movement of an object (bank or floodplain retreat, or lateral channel movement), yet when erosion occurs we recount it in ‘metres per year’ specific to a site or river reach. In effect we are saying “at this location, this much of the process happened in *x* amount of time.” Assuming that the spatial location of river bank erosion is on the face of the bank, as the bank erodes (retreats), the process moves. Saying “at this location, this much of the process happened in *x* amount of time” effectively denies the spatiality of this movement. Either the process moves or it ceases to exist. So the spatio-temporal location of the process moves via the existence of the process itself. Movement requires both space and time, and thus space-time and the process (entity) are inseparable; each defines the other. Turning attention back to ‘form’, this highlights that river bank erosion is not *movement* of the river bank as such, or even movement of the river channel (the same argument from a different perspective), but a redefinition of the two, and a redefinition of the relation between the two. This corresponds to Bergson’s notion of time as the “continuing emergence of novelty” that Massey (1999, 273) describes; time as an ‘open historicity’. As the new bank face emerges, new conditions (in terms of material properties, moisture conditions, temperature conditions, hydraulic conditions) apply. Admittedly they may not be hugely different from the previous conditions, but this does mean that an understanding of river bank erosion, and of a river bank, cannot be separated from its space-time.

**Concluding comments**

Returning to the aims of this paper then, it is useful to consider not just the way time and space have been treated in river bank erosion research to date, but also the implications and potential for future investigations. Three themes have dominated the review; closure, scale linkage and space-time.

*Closure.*

River bank erosion research to date has involved a variety of closures (spatial, temporal and other) bounding individual studies. In terms of measurement scales of space and time a whole range is used, spatially from site to catchment, and temporally from the ahistorical, ‘slice-through-time’ approach through to centuries. Thus we have some appreciation of how soil properties, meteorological and hydrological variables affect bank erosion mechanisms. We have a developing understanding of the relation between river bank erosion and in-channel sediment processes at the reach scale, and some awareness of bank erosion as a part of the process by which rivers meander and migrate across their floodplains. Often, but not always, research is conducted in apparently ‘matching pairs’ of space and time. It could be argued that more explicit consideration of the closures brought to bear in research would be beneficial though. Key questions to be addressed might be:

* *Is the research to take a geometrically-indexed (absolute space) or object-oriented (relative space-time) (Massey, 1999) approach?*
* *If object-oriented, what are the appropriate space-time bounds?*

For example, Lane (2001) suggests that bounding should be determined by operational processes rather than space. Presumably this requires consideration of the processes/forms that constitute the focus of research, *and* of the processes which influence (or perhaps are influenced by) this, including via feedback. Additionally closure will occur in the relation between the measurements we achieve and the variables we are interested in (or think we are measuring). In other words consideration needs to be given not just to where closure *should* occur, but also to whether or not it occurs where we intend. Clearly it is not just spatial closure that requires such attention. Perception of the ‘optimum’ closure is also likely to change as our understanding evolves and progresses. A nice example of this lies in the riverbank stability analyses of Osman & Thorne (1988), Darby & Thorne (1996), and Simon *et al.* (1999, 2000) being extended to include riparian vegetation (Simon & Collison, 2002) or incorporated into channel migration models (Darby *et al.*, 2002a). Thus there can be no ‘final answer’ to the questions of closure.

*Scale Linkage.*

Bank erosion research activities have often been contextualised through loosely hierarchical ideas. A more explicit, clearly defined, hierarchical study may hold potential – in prompting questions if not providing answers. By way of example, Table III illustrates a tentative suggestion for such a hierarchy. The intention was to focus on processes to define the hierarchical levels, but clearly these cannot be separated from the temporal and spatial scale at which they occur (this is recognised by De Boer, 1992, in his discussion of hierarchy in geomorphology). This aside though, simply taking the initial step of considering what processes might constitute the levels, questions have been raised (see column three of the table) which could be used to prompt further research. It should be stressed that Table III represents a purely exploratory intellectual exercise. A more rigorous application of hierarchy theory would need to address questions such as:

* *On what basis (e.g. form, process?) should levels of a hierarchy be defined/differentiated?*
* *Are there characteristics common to all the levels? For example can non-linearity be identified in all the levels?*
* *In relations between the levels, what are ‘causes’ and what are ‘effects’? In other words can asymmetrical and/or symmetrical relationships be identified?*
* *(How) do relations between the levels vary with space and time? Are they space-time specific?*

It should be noted that a hierarchical approach does not necessarily have to preclude scale-invariance. In discussing dynamic scaling in braided rivers, Sapozhnikov and Foufoula-Georgiou (1999) suggest that the dynamics of large-scale channels are dependent on the dynamics of small-scale channels, which could be taken to imply different levels of a hierarchy. Similarly, the occurrence of scale-invariance over limited scale ranges in river-bed gravels (Butler *et al.*, 2001), one at sub-grain scale and the other at grain scale, could be viewed in terms of a hierarchy.

Hierarchy should not be seen as the only option for scale linkage though – see, for example, Bendix’s (1994) decision to adopt an explicitly non-hierarchical approach to studying riparian vegetation.

*Space-time.*

It should be clear by now that if we are to consider space-time and entities as mutually constituted, this will influence decisions of closure and scale linkage, including the definition of a hierarchy if that were to be pursued. Realist studies, and those exploring complexity and non-linearity, are advancing understanding of bank erosion and offer potential to continue to do so (e.g. Fonstad & Marcus, 2003; Hooke, 2003), the former focusing on how processes are contingent upon local conditions and the latter perhaps to consider “trajectories of landscape develoment” (Spedding, 1997, 264). This may still leave the task of reconciling the two, but Fonstad and Marcus (2003) note that their interpretation of the catchment-wide distribution of bank failures as a self-organised critical system is not necessarily inconsistent with other process explanations, including those at a local scale. Perhaps the key question central to river bank erosion research is:

* *Why do bank erosion ‘events’ occur where and when they do, by the mechanism(s) they do, within the catchment, and how do they relate to each other?*

To date more progress has probably been made in finding answers to the first half of that question than in understanding the catchment context and relation of erosion events to each other.

To conclude, a number of conceptual issues relating to space and time have been explored here. Some of these highlight areas that require careful consideration at the research design stage, such as issues of closure, while others offer the potential for future research. In addition, both within river bank erosion research specifically and geomorphology/geography more generally, it can be said that there is strength in diversity. It is through the diversity of foci, and diversity of treatments of space and time, that river bank erosion research (or geomorphology, or geography) has progressed thus far.

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