

MODELING THE HYDROCLIMATIC DISTURBANCE OF SOIL LANDSCAPES IN THE SOUTHERN CANADIAN PLAINS: THE PROBLEMS OF SCALE AND PLACE

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Abstract. The sensitivity of soil landscapes to climatic variability and hydroclimatic events can be expressed as a landscape change safety factor, the ratio of potential disturbance to resistance to change. The use of a geographic information system (GIS) enables the spatially-explicit modeling of landscape sensitivity, but also raises the risk of violating the characteristic scales of disturbance and resistance, because the GIS technically simplifies the extrapolation of models, and associated concepts, to landscapes and scales not represented by the digital data base. Embedding landscape sensitivity into hierarchy theory, the formal analysis of the hierarchical structure of complex systems, provides a conceptual framework for the transfer of models and variables among landscape scales. In the subhumid southern Canadian plains, major hydroclimatic events (strong winds, intense rain, rapid snow melt) cause much of the physical disturbance of soil landscapes and terrestrial ecosystems. Prolonged dry or wet weather influences the resistance of soil and vegetation to these events. The potential disturbance of soil landscapes therefore can be derived from the probabilities of extreme events and seasonal conditions, as recorded in instrumental and proxy climate records. This time series analysis can be linked to the modeling of landscape sensitivity by establishing the probabilities of hydroclimatic events and climatic conditions which may exceed or lower the resistance of individual soil landscapes.

Keywords: disturbance, geomorphology, GIS, landscape sensitivity, modeling

1. Introduction

The sensitivity of subhumid landscapes to climate change and hydroclimatic events (Bull, 1991), and forecasts of global warming, necessitate the study of the southern Canadian plains for the impacts of climate on biophysical processes (Herrington *et al.*, 1997; Lemmen and Vance, 1999). The Canadian Climate Centre's general circulation model predicts that the largest CO₂-induced rise in mean surface temperature in southern Canada will occur in the Interior Plains (Boer *et al.*, 1992; Laprise *et al.*, 1998). Recent projections forecast net average warming of 4–6 °C by 2050 AD (Government of Canada, 1997). Most models also forecast increased average winter precipitation but with decreased soil and surface water in summer.

Climatic change research challenges earth scientists and ecologists to apply their understanding of biophysical processes measured over small areas (plots, slopes, stands, etc.) to the modeling of processes at a landscape scale (Running



et al., 1989; Sugden *et al.*, 1997; Vitek and Giardino, 1993). Studies of climate impacts can be categorized according to the degree to which place, scale and spatial heterogeneity are recognized:

1. Spatially implicit: forecasting change to biophysical systems without specific reference to location, e.g., impact of climate change on the boreal forest.
2. Spatially discontinuous: evaluating models at points and interpolating among these locations, e.g., climate stations or grid intersections.
3. Spatially continuous: evaluating a model (e.g., soil erosion risk) by map unit.
4. Spatially continuous and explicit: modeling the spatial distributions of specific variables, e.g., the spatial distributions of disturbance and resistance.

The fourth approach is enabled with a geographic information system (GIS), as described here for the mixed grass prairie ecoregion of the southern Canadian plains (Figure 1). Use of a GIS and digital geographic data also raise the potential for misuse of models and data, because a GIS technically facilitates and simplifies the extrapolation of models, and associated concepts, to landscapes and scales not represented by the digital data base. A review of existing models of landscape change leads to the conclusion that virtually all of them are inappropriate for a spatial analysis of the climatic forcing of surface processes in the Canadian plains (Sauchyn, 1997, in press). This region lacks the geomorphic and hydrologic characteristics that most models assume. More important is the lack of a theoretical basis for the modeling of process or disturbance over large areas, in this case 138 600 km². Therefore this article first examines the problems of place and scale, and then applies the concepts of landscape sensitivity and hierarchy theory towards a framework for the regional modeling of climate impacts on natural systems, and in particular the hydroclimatic disturbance of soil landscapes.

2. The Problem of Place

Place is an important consideration because most any large area has a unique combination of biophysical characteristics that often prevent the legitimate use of models derived elsewhere, and because with increasing space and geographic diversity, prediction and verification become less feasible (Church, 1996; Haff, 1996). Use of analogues, a common approach to climate impact assessment, is problematic without complete understanding of the physical geography and geologic histories of the comparative regions. For example, the present climate of the southern Great Plains is a tempting analogue for the future climate of the northern Great Plains. Despite the appeal to substituting the regional climatic gradient for climatic change over time, the northern Great Plains lie within the limit of late-Pleistocene glaciation and therefore have distinct regional morphology, hydrography, soils and biogeography. Similarly, intervals of Holocene aridity (e.g.,

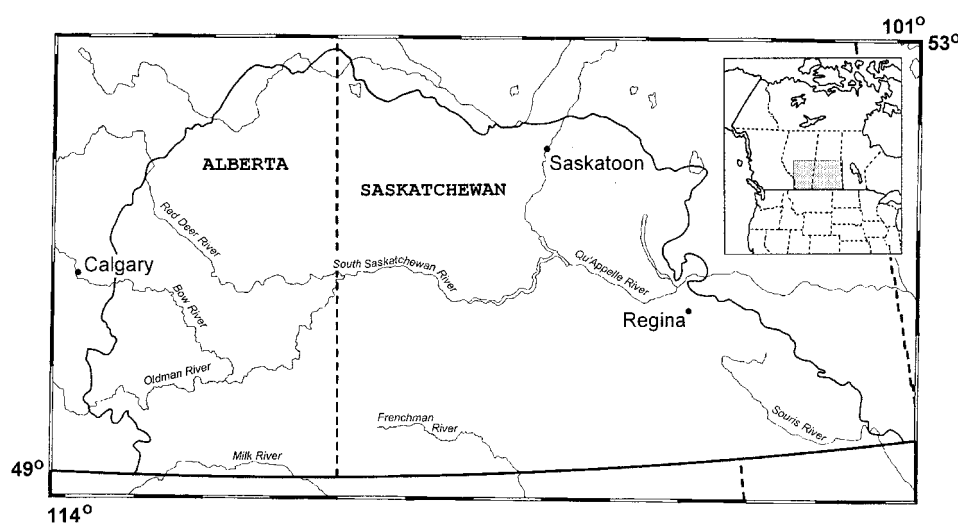


Figure 1. A map of the southern Canadian plains. The solid bold line is the boundary of the subhumid mixed grass prairie ecoregion and brown soil zone.

the hypsithermal and medieval warm periods) could be poor analogues for global warming, if the current human impacts on the atmosphere cause the global climate system to shift to a brand new state (Broecker, 1994).

For the purpose of the spatial modeling of climate impacts, a digital geographic database was constructed for the mixed grass prairie ecoregion of the southern Canadian plains (Figure 1; Sauchyn, 1997), the region commonly known as Palliser's Triangle. Following his expedition of 1857–1860, Captain John Palliser concluded that this region was 'by no means a desirable district for settlement', and that a large area 'will for ever be comparatively useless' (Palliser, 1859: 9). Nevertheless, EuroCanadians settled Palliser's Triangle and converted it to agricultural land use, but not without major and continuous adaptations to climatic variability, especially seasonal shortages of water. In this subhumid to semi-arid region, major hydroclimatic events (strong winds, intense rain, rapid snow melt) and prolonged drought have a profound impact on soils and vegetation. Much of the change in ecosystems and soil landscapes is driven by the surface and shallow subsurface water balances (Lemmen and Vance, 1999).

Late-Pleistocene glaciation of an interior sedimentary basin created a landscape in the Canadian plains which differs significantly from the boundary conditions assumed by most models of the climatic forcing of geomorphic processes (c.f., Kirkby, 1993; Willgoose *et al.*, 1992). With a short geomorphic history and dry climate, the landscape is poorly integrated and the sediment budgets of slopes and channels are mostly unrelated or 'decoupled' (Phillips, 1995). Water erosion mostly redistributes soil locally, especially in the extensive areas of hummocky and rolling moraine (Pennock and de Jong, 1995). There are few permanent streams.

TABLE I

Geographic characteristics of the mixed grass prairie ecoregion of the southern Canadian plains

General	
• 138 600 km ²	• >50% of Canada's agricultural land
Ecoclimate	
• subhumid to semiarid	• mixed grass prairie
• high inter-annual climatic variability	• extreme temperature seasonality
Hydrography	
• major rivers are throughflowing	• significant snow melt runoff
• mostly intermittent streams	• large area of internal drainage
Geomorphology	
• poorly integrated drainage network	• underfit streams in glacial meltwater valleys
• glaciated sedimentary basin	• weakly linked slopes and channels

Large areas are internally drained by intermittent stream flow into shallow saline lakes. Lacking are the order and characteristic structure of a landscape dissected by an integrated stream network (Lemmen *et al.*, 1998), except over small areas which have evolved rapidly since deglaciation. At a regional scale, these small areas are segments of larger landscapes. For example, badlands are scattered throughout the valley networks. Among the geographic characteristics of the mixed grass prairie ecoregion (Table I), its area (138 600 km²) necessitates modeling of climate impacts at a coarse-scale.

A suitable spatial data structure for modeling geomorphic systems at coarse scales is largely a practical consideration (Running *et al.*, 1989; Sauchyn, 1997), because the sources of geo-referenced data covering large areas are digital satellite data and existing small scale maps. The geographic expressions of geomorphic processes, landforms, are not mapped systematically over large areas. The mapping of Quaternary or surficial geology, at least in Canada, tends to be at relatively small map scales given the size of the country. Also classification schemes can vary among mapping agencies. For the small proportion of Canada which is arable land, soil surveys are generally available at relatively large map scales and with a consistent legend (Expert Committee on Soil Survey, 1987). Most soil maps capture landforms, because topography is a primary control on soil formation and geography at larger map scales. Given the relevance and scale of these soil surveys, the soil landscape and soil landscape map unit are the most useful concept and construct, respectively, for the modeling of the sensitivity of geomorphic systems

to climate. Soil landscape is a key concept in the field of soil geography (Buol *et al.*, 1980; Hole, 1978). In a textbook devoted to 'the study of the soil landscape from a geographic perspective (p. xv)', Hole and Campbell (1985) concluded from a literature review 'that soil landscape, and the abbreviation soilscape, are of value as general introductory terms, but perhaps not as specific ones' (p. 12). Accordingly, they used a broad definition: 'the total mass of unconsolidated geologic and pedologic material'. Applying this concept to soil survey, however, requires an operational definition: 'The full array of attributes that describe a distinct type of soil and its associated characteristics, such as landform, slope, water table, permafrost and lakes, is called a soil landscape' (Shields *et al.*, 1991: 5).

3. The Problem of Scale

"It has thus been generally agreed (although not always observed in practice) that different processes become significant to our understanding of spatial patterns at different scales. For the most part, however, we have no measure of the scale at which a particular process has most to contribute to the formation of a spatial pattern and our notions regarding the scale problem remain intuitively rather than empirically based" (Harvey, 1968: 71–72).

Harvey's discussion of the 'scale problem' was published at the very early stage of a technical revolution in the geographical sciences: satellite remote sensing and geographic information systems have enabled the empirical analysis of geographic patterns at regional to global scales. At the same time, the rigorous observation and measurement of processes has focused much geomorphic and ecological research on human scales of time and space where natural phenomena are most accessible (Hoekstra *et al.*, 1991; Saab, 1999; Vitek and Giardino, 1993). Typical sampling frames include the stand and plot in ecology; slopes, channels, and small catchments in hydrology and geomorphology; and catenas in soil science. A 'scaling down' of climate and a 'scaling up' of process is required to link the modeling of climate at coarse scales to biophysical processes at finer scales (Bass, *et al.*, 1996; Hostetler, 1994; Kirkby *et al.*, 1996; Sugden *et al.*, 1997). Schumm (1991: 38) suggested that "earth scientists operate at the wrong scale for the problems that they are required to solve ... records are too short as our scientific lives. Perhaps the present is too short to be a key to the past or future". The study of geomorphic and ecological processes also has tended to be at the wrong spatial scale to address regional and global problems.

While coarse observations of large areas cannot explain the climate forcing of most biophysical processes, decades of detailed observation and experiments have led ecologists and earth scientists to recognize that this methodology can produce poor judgements about larger areas and times spans (Spedding, 1997). Most process simulation models fail to work when scaled up because of the greater complexity of larger systems and non-linearity caused by feedback among system

variables, and the emergence of characteristic patterns and processes at coarser scales (Haff, 1996). The most serious violations of scale involve the application of empirical plot-scale models to remote locations and/or regional scales. Agricultural soil loss commonly is predicted by extrapolating empirical equations, notably versions of the Universal Soil Loss Equation (Wischmeier and Smith 1978), sometimes over large areas (e.g., Logan *et al.*, 1982; Snell 1985). This requires judicious interpretation of the soil loss predictions, because parameter values averaged over heterogeneous map units represent a misuse of these empirical field-scale models (Wischmeier, 1976; Roels, 1985; Sauchyn, 1993).

Another violation of scale involves the evaluation of process models at high resolution and then aggregation of the results over large areas with low resolution. This patching together of simple small-area models to account for the behaviour of complex systems is inappropriate because the relevant and dominant variables change with scale (Klemes, 1983; Schumm, 1991). Thus, for example, the understanding of ecosystems is not based on the individual behaviour of organisms (Saab, 1999; Valentine, and May, 1996). While stream slope is correlated with the size of bed materials over short distances and with discharge (climate) over longer reaches. Local vegetation and soil reflect topography and drainage, the controls with the strongest local gradients. The regional distributions of soil and vegetation reflect mostly synoptic-scale climate and historical biogeography.

The geographical tradition of mapping regional climate from vegetation associations and zonal soils assumes a stable climate, whereas 'the earth climate system has proven beyond any doubt that it is capable of jumping abruptly from one state of operation to another' (Broecker, 1997: 1). Long system relaxation times following perturbations and persistence of the effects of major disturbances cause lack of agreement between contemporary patterns and boundary conditions. Scaling up in time and space gives historical and geographic context to local observations. The streams of the southern Canadian plains, for example, mostly flow in large valleys which were created at the margins of an ice sheet or from the draining of glacial lakes, and commonly do not conform the regional topographic gradient. The geometry of the stream channels tend to conform to the time-independent principles of stream hydraulics. This is another example of how explanation of form changes with scale, in this case as past processes become evident at a coarser scale.

A scientific community previously preoccupied with the detailed observation of small areas is now emphatic about the significance of scale:

"it is, I will argue, the fundamental conceptual problem in ecology, if not in all of science. Theoretical ecology, and theoretical science more generally, relates processes that occur on different scales of time, space and organizational complexity. Understanding patterns in terms of the processes that produce them is the essence of science, and is the key to the development of principles for management" (Levin, 1992: 1944).

“Because science hopes to enhance understanding, necessarily in human terms, it may not be bad that ecology is scaled in human terms. Rather than fight human nature, ecologists are well advised to be explicit about the scales they use, so that they can anticipate the consequences of decisions that were formerly made subconsciously. By modeling with appropriately scaled concepts, ecologists can hope to advance with fewer delusions of objectivity, but more consensus” (Hoekstra, *et al.*, 1991: 154).

These statements reflect a new or renewed interest in scale among ecologists. Geomorphologists, with their geographic roots, periodically remind themselves of the fundamental significance of scale:

“it is possible to argue that, to date, geomorphologists have considered that the difficulties associated with widely varying scales of enquiry constitute a strait jacket for the subject: in reality, however, these problems may point to the fundamental skeleton of the discipline. If we understood the nature of that skeleton more clearly then we might also understand the rules linking events and forms on different temporal and spatial scales” (Kennedy, 1977: 156).

“Spatial analysis should assume a greater role in geomorphology and hydrology, in at least two ways: determination of the scale of spatial patterns, and identification of scale-related breaks or discontinuities in relationships” (Phillips, 1988: 311).

“we arrive at the possibility to ground theories of landscape (and, I would claim, of all else) in some concept of order at various distinct scales. This is what humans seek” (Church, 1996: 168).

The shared histories of the ‘composite’ natural sciences (Drury and Nisbet, 1971; Osterkamp and Huff, 1996) have evolved to a mutual use of scale to reconcile equilibrium (time-independent) and developmental (time-dependent) philosophies (Church, 1996), but they have yet to produce a theoretical basis for the transfer of observations and models among scales. The hierarchical classification of soil and ecological map units (Hole and Campbell, 1985; Wiken, 1986), and the spatial resolutions of earth observation satellites (Running, *et al.*, 1989), are pragmatic solutions to the problem of recording and mapping the spatial expressions of biophysical processes operating over various time scales. Sediment budgets and biogeochemical cycles are a dynamic basis for scaling in geomorphology and ecology, but lack the universality and continuity of atmospheric and oceanic circulation and the hydrological cycle that are the basis for physically-based scaling of climate and hydrologic systems (Bass, *et al.*, 1996; Hostetler and Giorgi, 1993; Klemes, 1983). The scaling of biophysical systems requires a conceptual framework which preserves the ‘spatiotemporal integrity and characteristic scale’ (Valentine and May, 1996: 23) of system variables, and accounts for the change in relevant and dominant controls and responses with spatial and temporal scale.

4. Landscape sensitivity and hierarchy theory

A methodology for identifying combinations of surficial material, landform and land cover that may respond to climatic variability and change (Sauchyn, 1997, in press) was built initially on the concept of landscape sensitivity, 'the likelihood that a given change in the controls of a system will produce a sensible, recognizable and persistent response' (Brunsden and Thornes, 1979: 476). The probability of a geomorphic response can be modeled and mapped as a landscape change safety factor: 'the ratio of the magnitude of barriers to change [resistance] to the magnitude of the disturbing forces' (Brunsden and Thornes 1979: 476). A continuum of landscape sensitivity can be derived from the relative spatial distributions of disturbance and resistance variables, such as the probabilities of hydroclimatic events, clusters of events, and seasonal and annual climatic conditions. Resistance to major hydroclimatic events can depend very much on the recent history of a biophysical system (Brunsden, 1992), including the effects of prolonged dry or wet weather (Wolfe *et al.*, in press). If adequate data were available, the time series analysis of climate could be linked to the spatial modeling of landscape sensitivity by relating the probabilities of hydroclimatic events to the properties of biophysical systems and soil landscapes that control resistance or amplify disturbance. A serious limitation of this approach, however, is the point distribution and low spatial resolution of climate records in contrast to the spatially continuous surveys of land cover, geology, topography and soil.

Geomorphic and ecological responses to a change in controls (landscape sensitivity) and the ratio of resistance to disturbance (the landscape change safety factor) exist at all scales, although landscape implies a regional scale. Spatial scale 'is a vital element of landscape sensitivity' (Brunsden 1993: 11) and 'permeates' hierarchy theory (de Boer, 1992), the formal study of the hierarchical structure of complex systems (Allen and Starr, 1982). Ecologists have embraced the concept of hierarchy, and elevated it to the status of theory (O'Neill *et al.*, 1986; Salthe, 1985). Some aspects of hierarchy theory, as applied to ecosystems, do not apply to geophysical systems because they are exclusively aggregative, that is, they are collectives of basic units (e.g., landforms) that physically exist independent of the system (Valentine and May, 1992). Conversely, cells do not exist independent of organisms, which in turn will perish outside a community. Slopes, on the other hand, exist whether or not they contribute sediment and runoff to the drainage basin in which they are located.

The nested hierarchical structure of landscapes and drainage networks is implicit in the study of landforms and hydrologic systems and underlies some of the classic works in geomorphology (Strahler, 1952; Schumm and Lichty, 1965). Earth scientists, however, generally have not adopted the notions and terminology of hierarchy theory. This may reflect a preference for empirical research, and especially field work (Baker and Twidale, 1991). This author is aware of only two papers (de Boer, 1992; Haigh, 1987) that specifically address the application of hierarchies to

TABLE II
Scales of geomorphic systems: The triadic hierarchy

Level	Function	Spatiotemporal characteristics
Physiographic divisions	Boundary conditions	Cyclic; substitution of space for time
Soil landscapes and small watersheds	Focal level for environmental problems	Graded; scaling up from slopes and channels
Slopes and channels	Process mechanics	Steady (time independence); integration of events over small areas and short time spans

geomorphology. Furthermore, these papers consider only the heuristic value, while here I attempt to consider the practical applications of an hierarchical perspective to the spatially-explicit modeling of potential geomorphic responses to climate change and variability.

The concepts of a 'triad' of adjacent levels and the 'focal' (central) level of greatest interest (Valentine and May, 1996) are applied to geomorphology in Table II. This arbitrary classification of time and space is an attempt to deal conceptually with the transfer of models of geomorphic systems among scales. Although hierarchical level is defined in terms of geographic features and spatial scale, there is an inherent increase in time spanned at progressively higher levels. In Table II, time is scaled according to Schumm and Lichty (1965). Relative to the focal level, the next coarser scale provides context, that is, the initial or boundary conditions for processes which operate at the focal level, but are measured and modeled at the higher resolution of the next lower level.

Resistance and disturbance have different meaning across levels of the hierarchy, as variables emerge at levels below which they are irrelevant or simply do not exist. These emergent variables typically represent the interaction of processes and integration of responses, for example (Table III), inter-annual to decadal climatic variability (the synthesis of climatic observations over time) and the relative order or degree of coupling of landscape elements. Controls and responses must be synthesized for modeling and mapping at higher levels, as the cumulative outcome of processes operating locally is expressed over larger areas. Local variability cannot be resolved at a higher level at which patterns correlate with emergent variables, although the smaller units and local variation remained stored at their original scale in the GIS, as the (relational) data base is in itself a nested hierarchy. When complex models are applied without explicit reference to scale, the 'spatiotemporal integrity

TABLE III

A triadic hierarchy of landscape sensitivity: Some sources and controls of disturbance and resistance

Level	Disturbance	Resistance
Physiographic divisions	<ul style="list-style-type: none"> • Climatic change: frequency and magnitude of hydroclimatic events • Tectonism • Intrinsic geomorphic thresholds in large systems 	<ul style="list-style-type: none"> • Climatic change: surface and sub-surface water balances • Ecoclimate and surficial geology • Geomorphic history
Soil landscapes and small watersheds	<ul style="list-style-type: none"> • Climatic variability • Major hydroclimatic events • Coupling of systems 	<ul style="list-style-type: none"> • Landscape disorder • Land cover • Shear strength of surficial materials
Slopes and channels	<ul style="list-style-type: none"> • Hydroclimatic events • Soil hydraulic conductivity • Local relief and slope 	<ul style="list-style-type: none"> • Channel roughness • Slope morphology • Plant cover

and characteristic scale' (Valentine and May, 1996: 23–33) of the variables tend to get obscured or lost. Reference to scale includes an explicit spatial data structure and spatial models of specific variables, as opposed to mapping the output of a model that incorporates many variables. Similarly, synthetic landscapes, constructed from variables and relationships measured at finer scales, are a more rigorous approach to scale linkage than statistical smoothing, whereby dominant or significant features can be lost, replaced or masked by averaged results (Thorn, 1988: 85).

5. Discussion

The spatial modeling of the hydroclimatic disturbance of soil landscapes involves the coupling of a digital geographic data base and models that are appropriate in terms of scale and place. Literature on the role of scale in ecology and geomorphology (Allen and Starr, 1982; Church, 1996; de Boer, 1992; Harvey, 1968; Haig, 1987; Hostetler, 1994; Kennedy, 1977; Kirkby *et al.*, 1996; Klemes, 1983; Leven, 1992; O'Neill *et al.*, 1986; Phillips, 1988; Saab, 1999; Willgoose *et al.*, 1992) and a conceptual framework based on landscape sensitivity and hierarchy theory suggest

the following implications of scale for the modeling of geomorphic response to climate.

1. Because disturbance and resistance have spatiotemporal dimensions and characteristic scale, their relative magnitudes, or the landscape change safety factor, is hierarchical. Controls and responses, and therefore landscape sensitivity, also occur at various scales. Sensitivity can exist over large areas and at coarse scales, for example, in dune fields where resistance to wind tends to uniformly low, or in densely dissected terrain, where potential disturbance is uniformly high. Scarps, valley heads and long or windward slopes, on the other hand, can represent islands of sensitivity which are located in otherwise insensitive landscapes and thus detectable only at fine scales. This local instability can be expressed at coarser scales as basin sediment yield and the growth of channel networks.
2. The spatial aggregation of details cannot reproduce structures and dynamics that emerge only at coarse scales. The regional evaluation of landscape sensitivity therefore requires both the synthesis of local spatiotemporal variability and the modeling of emergent controls and responses. Whereas processes at adjacent levels may differ significantly in rate, they are not independent (Phillips, 1988). Local, quasi-continuous activity can predispose landscapes to events of higher magnitude and lower frequency operating at a coarse scale. They can also produce resistant sediments (e.g., lag deposits) and stable (graded) landforms. Processes which operate at a coarse spatiotemporal scale (e.g., tectonic events; major floods and landslides) establish new boundary conditions which cause geomorphic systems to react with accelerated activity at finer temporal and spatial scales.
3. Geomorphic history and physical geography observable above the focal level set the context and constraints on regional landscape sensitivity. Every landscape has elements that resist change (i.e., are unresponsive to changes in controls) by virtue of geomorphic history and surficial geology. Unless a landscape is 'saturated' by a dominant process (Haigh, 1987: 190), scaling up involves moving up the hierarchy from responsive (time-independent) slopes and channels to encompass (time-dependent) landscapes that correspond to past processes and resist change. Because stream channels act as conduits of geomorphic activity, largely inactive drainage networks inherited from a wetter paleoclimate, can be a locus of future geomorphic activity. In the southern Canadian plains, geomorphic activity is concentrated in the vicinity of large meltwater channels and incised tributary valleys. The intervening landscapes, mostly late-Pleistocene till and lake plains are largely inactive. However, the response of these glacial landforms and soils to cultivation in this century (Martz and de Jong, 1991; Mermut *et al.*, 1983; Pennock *et al.*, 1995) demonstrates their sensitivity to disturbance, which is potentially accelerated by climate variability and change.

4. Models based on present conditions and processes become a less relevant and accurate basis for forecasting the future and explaining the past. The fine scale also fails to capture regional interactions among systems and the spatiotemporal context of contemporary processes and systems. Coarse-scale models should include historical variables. At a coarse scale, the immediate hydroclimatic controls on geomorphic processes are not measurable. Rather, the relevant variables are regional climate, surface geology, land cover and relative relief. The impacts of climate change are expressed as changes in regional sediment yields and changing productivity of soil landscapes.

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