ABSTRACT: River Environment Classification (REC) is a new system for classifying river environments that is based on climate, topography, geology, and land cover factors that control spatial patterns in river ecosystems. REC builds on existing principles for environmental regionalization and introduces three specific additions to the “ecoregion” approach. First, the REC assumes that ecological patterns are dependent on a range of factors and associated landscape scale processes, some of which may show significant variation within an ecoregion. REC arranges the controlling factors in a hierarchy with each level defining the cause of ecological variation at a given characteristic scale. Second, REC assumes that ecological characteristics of rivers are responses to fluvial (i.e., hydrological and hydraulic) processes. Thus, REC uses a network of channels and associated watersheds to classify specific sections of river. When mapped, REC has the form of a linear mosaic in which classes change in the downstream direction as the integrated characteristics of the watershed change, producing longitudinal spatial patterns that are typical of river ecosystems. Third, REC assigns individual river sections to a class independently and objectively according to criteria that result in a geographically independent framework in which classes may show wide geographic dispersion rather than the geographically dependent schemes that result from the ecoregion approach. REC has been developed to provide a multiscale spatial framework for river management that employs a similar conceptual basis to other landscape classifications. REC, however, is based on more explicit consideration of the fluvial processes that are the cause of patterns in river ecosystems at a range of spatial scales. The REC approach may improve on the ability of existing landscape classification methods such as ecoregions, to predict patterns in river ecosystems.

Landscape classifications are generally based on environmental factors that are assumed to largely determine (e.g., climate, topography, and geology) or reflect (e.g., land cover) patterns in organization and functioning of the associated ecosystems (Bailey, 1995; Klijn and Udo de Haes, 1994). Thus they codify, in a simple way, understanding of ecosystem processes at large scales that provide for and also constrain management options (Christensen et al., 1996). We distinguish two types of commonly used approaches to landscape classification: controlling factors and ecoregions. Both of these classifications differ from simple typologies in that each class can be geographically located and mapped.

CONTROLLING FACTOR APPROACHES TO LANDSCAPE CLASSIFICATION PROVIDE A GENERALIZED HIERARCHICAL DIFFERENTIATION OF THE LANDSCAPE BASED ON A CONCEPTUAL VIEW OF

INTRODUCTION

Landscape classifications have been developed as a tool for understanding ecosystem processes and resultant patterns at large scales. Such classifications have been specifically promoted as spatial frameworks for environmental management activities such as developing inventories, data interpretation, interpolating information from specific sites to larger areas, strategic development of objectives and standards, design of monitoring strategies, and evaluating the uniqueness of areas (e.g., Bailey, 1995; Klijn, 1994; Griffith et al., 1999). River Environment Classification (REC) is a new approach to classifying and mapping spatial patterns in river ecosystems. REC has been developed as a spatial framework for river management that employs a similar conceptual basis to other landscape classifications. REC, however, is based on more explicit consideration of the fluvial processes that are the cause of patterns in river ecosystems at a range of spatial scales. The REC approach may improve on the ability of existing landscape classification methods such as ecoregions, to predict patterns in river ecosystems.

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how ecosystems are organized. Classes are defined by subdivision of factors into categories that are diagnostic (sensu Zonneveld, 1994) of particular characteristics (e.g., wet mountains and dry hills). In landscape classifications, classes are mapped by the geographic coincidence of factor categories and, therefore, classifications appear as mosaics of spatially independent polygons. Thus, controlling factor classifications are geographically independent, describing similar ecosystem types that may show wide geographic dispersion (Detenbeck et al., 2000).

Controlling factor approaches have been used to develop classifications of river environments. A significant difference between terrestrial and river ecosystems, however, is the recognition of the watershed as a fundamental spatial unit determining processes in rivers. This has led to controlling factor approaches that attempt to discriminate patterns within watersheds (e.g., Lotspeich and Platts, 1982; Frissell et al., 1986). These classifications consider that watersheds are contained within homogeneous land type or region classes based on climatic, topographic, geologic, and vegetation factors. The classes attempt to define patterns within watersheds that are controlled by local-scale factors. Geographically independent classes are delineated using morphological features that are assumed to control processes at a variety of nested spatial scales within the watershed.

The second approach to river classification, commonly called ecoregions (Omernik, 1987), describe patterns among watersheds. Ecoregion classification uses understanding of large-scale ecosystem patterns to develop a mosaic of regions within which watersheds can be considered homogeneous. However, a strict hierarchy of controlling factors is not adhered to in defining ecoregions. Rather, the factors are varied within a classification level to make use of whichever is considered to best distinguish each ecoregion (Bryce et al., 1999). For example, topographic characteristics may be used to define a mountain ecoregion, whereas differences in soils or vegetation may be used to differentiate ecoregions in a valley. This classification procedure is a “gestalt” in which classes and boundaries are selected that appear to be the best determinants of the character of river water quality and biota based on subjective judgments of experts (Bailey, 1995). Ecoregions are geographically dependent classifications where classes form discrete units in geographic space that are not repeated across the classified area (Detenbeck et al., 2000).

Ecoregions have been widely promoted as a framework for water resources management (e.g., Omernik and Griffith, 1991; Griffith et al., 1999). A number of shortcomings of the ecoregion approach, however, can be identified. First, the gestalt classification procedure means that the functional links between the factors and characteristics are not explicit. Second, the mosaic of spatially independent polygons does not represent the configuration of watersheds and connecting channel networks. Thus, ecoregions are unable to represent longitudinal gradients, which are recognized as typical of spatial patterns in river ecosystems such as the river continuum concept (Vannote et al., 1980). This is perhaps a major factor limiting the effectiveness of these classifications in discriminating biotic composition of rivers (see Biggs et al., 1990; Hawkins and Vinson, 2000).

A specific benefit of controlling factor approaches is the ability to vary the grain (sensu O'Neill et al., 1987; Wiens, 1989) of classifications by altering the level that is used to define and map classes at different spatial scales. Both controlling factor and ecoregion approaches to river classification, however, have limitations on changing the grain size. This causes difficulties when attempting to apply such classifications to water management because watersheds of large rivers generally comprise a heterogeneous mix of factors (Griffith et al., 1999) whose spatial distribution can be independent of watershed boundaries (Bryce et al., 1999). For example, there are often large variations in climate, topography, and geology within watersheds (Biggs et al., 1990). This means that ecoregions are only effective for classifying parts of the channel network whose watersheds are endogenous to the classifying ecoregion, effectively streams between first and third order (Griffith et al., 1999). Parts of the channel network whose watersheds are exogenous to the immediate ecoregion are not correctly classified. On the other hand, controlling factor classifications that differentiate the channel network within a watershed using morphological features can only assume comparability of classes when watersheds are wholly contained within identical land type or region. These existing approaches to river classification are, therefore, restricted in their ability to move between grain sizes while retaining their coherence.

In this article we present a new approach to the classification of river environments. The River Environment Classification (REC) is based on a controlling factors approach and uses understanding of fluvial processes to classify river environments and delineate classes. The aim of the REC is to discriminate patterns of instream physical components of river ecosystems (e.g., hydrological variables, temperature regimes, geomorphologic features, physical habitat, water chemistry) at a range of scales and allow for the integration of landscape and local-scale process in the definition of classes. These physically defined classes are expected to discriminate specific ecosystem properties (e.g., biological communities and water quality). We start by outlining a conceptual framework for
applying controlling factor principles to classification of river environments and then describe an example of how the methodology has been applied to New Zealand rivers.

CONCEPTUAL FRAMEWORK FOR REC

Controlling Factor Classification

Controlling factor classifications are developed using a priori or top-down approaches. Top-down classifications assume that the classification is more useful if classes are defined according to a model of the causes of ecosystem organization and function rather than by direct observation of biological patterns (Bailey, 1995). The guiding principles (sensu Zonneveld, 1994) for controlling factor classification starts with the development of a simplified hierarchical model of the assumed causes of ecosystem pattern. This model is a pragmatic simplification of reality that allows us to “approach the truth by a series of approximations” (Bailey, 1995). Bailey’s (1995) model for classification of terrestrial ecosystems is based on an assumption that soil and biota are a function of climate, land surface shape, and geological substrate. This relationship expresses two important assumptions. First, climate, land surface shape, and geological substrate are treated as independent physical components of the landscape. These independent components are assumed to control physical regimes (e.g., hydrological, thermal, and chemical) at subordinate scales. The second idea is that the organization and functioning of biotic communities is largely a direct response to the organization and functioning of the physical environment. Thus, the problem of delineating ecosystem pattern is reduced to understanding the processes that determine the organization and functioning of the physical environment.

The model manages complexity further by viewing ecosystems as hierarchies. The hierarchy refers first to “dominance in spatial scale” (Klijn, 1994). The approach delineates patterns on the earth’s surface that are homogeneous with respect to physical and biotic characteristics (Bailey, 1995). This homogeneity is not absolute but depends on the scale of observation (O’Neill et al., 1987; Wiens, 1989). Thus a hierarchy in space delineates patterns that are spatially nested with the internal variability of large-scale patterns being shown by patterns at smaller scales (see Table 1).

The problem becomes one of delineating patterns in the relevant physical regimes at various spatial scales. The complexity of the processes that cause patterns in these regimes is reduced by restricting the details of the independent components to only those that are needed to explain the most important or significant patterns at specific scales (O’Neill et al., 1987). Thus, the model characterizes specific processes at a series of system levels. Each system level is defined by controlling factors, which are landscape components observed at specific spatial scales that are the cause of patterns at that scale. The system levels are linked by the hierarchical organization of the classification so that system components and processes at a particular level are constrained by the behavior of the level above. Thus, patterns develop within the constraints set by larger-scale regimes.

<table>
<thead>
<tr>
<th>General Scale</th>
<th>Indicative Size of Delineated Regions (km²)</th>
<th>Controlling Factors</th>
<th>Name of Classification Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro</td>
<td>$10^5$</td>
<td>Macroclimate</td>
<td>Ecozone*</td>
</tr>
<tr>
<td></td>
<td>$10^4$</td>
<td>Land surface shape and Geological Substrate</td>
<td>Ecoprovince*</td>
</tr>
<tr>
<td>Meso</td>
<td>100-1000</td>
<td>Land Surface Shape and Geological Substrate</td>
<td>Ecoregion*</td>
</tr>
<tr>
<td></td>
<td>10-100</td>
<td>Land Surface Shape and Geological Substrate</td>
<td>Ecodistrict*</td>
</tr>
<tr>
<td>Micro</td>
<td>1-10</td>
<td>Land Surface Shape and Lithology</td>
<td>Eosection*</td>
</tr>
</tbody>
</table>

representing a hierarchy in “dominance of process” (Klijn and Udo de Haes, 1994).

We take the view that a controlling factor classification will be most useful to management because it is based on a conceptual view of how river ecosystems are organized in space (Frissell et al., 1986). The idea that river ecosystems can be understood in terms of a set of hierarchically related physical processes has been conceptualized by Minshall (1988) and as the multiscale filtering framework by Poff (1997) or the river scaling concept by Habersack (2000). Thus our classification codifies these conceptualizations of the processes controlling river ecosystems at various scales.

REC Controlling Factor Hierarchy

The classification procedure (sensu Zonneveld, 1994) comprises three major steps: defining the system levels in a simplified hierarchical model, characterizing the variation at each system level with categories, and finally mapping the classes.

The REC model assumes that physical regimes in rivers are controlled by four independent landscape components: climate, topography (land surface shape), geological substrate, and land cover. We include land cover, which superficially deviates from the controlling factor approach to landscape classification in which vegetation is a dependent variable. For rivers, however, watershed vegetation is a significant independent landscape component that controls instream processes. Vegetation is also generally highly modified by human activities and is therefore not necessarily closely linked to natural physical factors. Watershed vegetation has, accordingly, been identified as a classification variable in many river classification schemes (e.g., Lotspeich and Platts, 1982; Omernik and Bailey, 1997).

Physical regimes at all system levels are the result of interactions between all four of the independent components of the landscape (climate, topography, geology, and land cover). However, the relative importance of each component differs with scale. The simplified model uses the most important, or dominant, component at each scale and declares this to be the controlling factor at that system level. Our simplified hierarchical model also assumes that physical patterns in river environments are essentially responses to fluvial processes, including hydrological, morphodynamic and hydrochemical. These are driven by the downstream flux of water and constituents derived from watershed sources (Hynes, 1975). It is the configuration of the independent landscape components (climate, topography, geological substrate, and land cover) within the watershed that controls physical patterns within the river network. For example, climate and topography broadly control flood flow regimes as well as erosion and sediment transport processes. Another fundamental aspect of our model is recognition that patterns in physical regimes such as flow, sediment supply, and water chemistry occur downstream in the channel network, remote from the geographic location of the watershed. An example is the pattern of unstable braiding in the lower reaches of rivers draining mountainous watersheds. These channels may be located in flat areas with low rainfall, well away from the mountains that generate the flood flows and sediment supply regimes that are responsible for the braiding.

The REC classification hierarchy comprises six main system levels, the names of which reflect the nominated controlling factors: climate, source of flow, geology, land cover, network position, and valley landform (Figure 1). Each system level represents a set of processes that are observable as patterns in physical and/or biotic components of rivers at a specific spatial scale. Patterns at each system level are assumed to be the result of variation in each controlling factor. Thus each controlling factor is subdivided into categories by differentiating differences in each factor at one of three general scales: macro, meso, and micro. We adopt the same ranges for each of these general spatial scales that is used by other landscape classification (e.g., Bailey, 1995) for consistency (see Table 1). Thus in our classification, topography is a factor at meso scales, differentiating watersheds into mountain, hill, and low elevation classes; or at micro scales, differentiating individual sections of the channel network according to the landform of the valley the section traverses.

The first four levels of the model hierarchy characterize watershed processes that supply and route water, sediment, and other constituents of flow through and off a landscape (Montgomery, 1999). REC recognizes that the factors controlling these processes may be heterogeneous within watersheds. Thus, class membership for the first four system levels is based on the integrated effect of controlling factors within the watershed. This is evaluated at points along the network, and therefore, classes generally change in the downstream direction as the product of this integration changes. The fifth and sixth system levels characterize local processes (sensu Montgomery, 1999), which are understood as the outcome of watershed processes (e.g., hydrology and sediment supply) interacting with topographic factors operating at the scale of the local channel network.

Characterizing the watershed processes described by the first four classification levels has two complications. First, the controlling factors at these classification levels are rarely homogeneous for large
watersheds. Therefore, a decision must be made as to what category to assign to that watershed based on the intensity of effect of each factor category on instream processes being described. Second, category membership cannot always be determined on the basis of spatial predominance because certain factor categories have a disproportionate effect on instream environmental or biotic characteristics. For example, certain rock types can have a disproportionate effect on nutrient supply in watersheds (Close and Davies-Colley, 1990; Biggs, 1995). Another example is pastoral land use, which has been shown to have a disproportionate influence on suspended solids and nutrient concentrations (Quinn et al., 1997).

Our solution is to apply criteria for watershed processes in the form of rules. Rules consider the disproportionate effect of some factors on fluvial processes and assign categories accordingly. For example, a rule may recognize the disproportionate effect of soft sedimentary geological categories, and membership of that category may be prescribed when this rock type exceeds 25 percent of the watershed. Rules may need to be changed depending on the specific processes and patterns a classification aims to characterize. For example, the differentiation of soft and hard sedimentary rock classes might use different thresholds if the classification was to optimize discrimination of either hydrological or hydrochemical processes. While the rules contain another set of pragmatic decisions that enable reality to be simplified, they are based on knowledge of the ecosystem effects of differences in the given factors, which are then objectively applied to determine class membership.

**Climate.** The highest REC system level describes climatic processes that drive the hydrological cycle and river water temperature regimes. Variation in macroclimate differentiates variation in precipitation and potential evapotranspiration, which drive patterns in hydrological cycles including frequency of flooding and low flow periods. Variation in macroclimate also differentiates temperature, which modifies the watershed response to precipitation and, in tandem with solar radiation, sets the potential thermal regime of rivers.

In cool regions precipitation as snow is stored in winter and is released as snowmelt in spring and summer (Bailey, 1995). In warm regions snowmelt is
negligible and runoff regimes follow the temporal distribution of precipitation. Thus, classes at this level discriminate large-scale patterns in hydroclimatology including seasonal thermal regimes and patterns in high and low flow, but without the influence of lower system levels (see Poff and Ward, 1989).

Macroclimatic variation can be discerned at a number of scales. Bailey (1995) suggests very large-scale macroclimatic categories are differentiated by latitudinal variation at scales of 10^5 km^2 and further differentiation associated with continental position and large topographic features at scales of 10^4 to 10^3 km^2. Importantly, however, macroclimate may vary within watersheds. Climate categories must be assessed at each point in a river network by spatial integration of macroclimate across the watershed.

**Source of Flow.** The next system level, source of flow, further describes watershed processes of hydrology as well as broadly describing sediment supply and transport processes. Source of flow is defined by the factor “watershed topography” and is differentiated in spatial units of approximately 100 to 1,000 km^2. At these scales, watershed topography is the dominant control of climatic variation and therefore hydrological processes, and it also controls erosion and sediment transport.

Climatic variation at meso scales is a result of the interaction of broader macroclimate with meso-scale topographic features (Lotspeich and Platts, 1982; Bailey, 1995). Elevation differences result in variation in climate due to its effect on precipitation and temperature. Variation in watershed elevation is, therefore, the cause of patterns in hydrological regimes within a climate class including variation in flood frequency and the seasonality of flow regimes. We distinguish three main watershed topography categories: mountain, hill, and low elevation, which are used to define patterns in river environments within the higher level climate classes.

Mountain source of flow categories are characterized by greater precipitation and lower temperatures, relative to the climate class mean. These watersheds will therefore store a greater proportion of their total precipitation as snow or ice and have significant areas of permanent snow. Seasonal peak flows occur when solar radiation is highest in spring and mid-summer. Low flows typically occur in winter (Duncan, 1992). Hill source of flow classes are characterized by some snowpack storage, which increases in the colder climate classes. Snowpack, however, is limited and is usually melted entirely by mid-spring to late spring. Thus, rivers whose source of flow category is “hill” are characterized by two low flow periods – summer and winter (Duncan, 1992). Flood frequency in hill categories is typically high compared to the climate class mean because of orographic effects of the topography. Precipitation and flood frequency in “low elevation” classes tend to be low compared to the climate class mean. Temperature is higher and runoff processes are not influenced by storage of precipitation as snow. Thus, low-elevation source of flow categories are characterized by flow regimes that follow precipitation and evapotranspiration regimes (Duncan, 1992).

Topography at this system level is also the dominant controller of processes that attenuate watershed responses to rainfall as well as controlling surficial erosion and sediment transport. Runoff, erosion, and sediment transport processes are intense in steeper mountain source of flow categories meaning that flood frequency and potential sediment supply are high. Runoff response is typically more attenuated and erosion less intense in less steep watersheds. Sediment supply and flood frequency are typically lower in hill and low-elevation source of flow categories where watershed slope is generally lower.

Other meso-scale topographic features – lakes, wetlands, springs, and constructed impoundments – can be added to the possible source of flow categories. The presence of these landscape features in the watershed attenuates runoff response and reduces sediment transport.

The hydrological and sediment supply regimes that are characterized by source of flow categories interact to produce geomorphological process governing channel characteristics. These processes also govern instream disturbance regimes that are due to flow variability and substrate stability. Thus source of flow is expected to broadly discriminate patterns of specific habitat attributes that influence biotic communities at finer spatial scales (Biggs and Close, 1989; Poff and Ward, 1989).

Watersheds by their very nature comprise heterogeneous topography. Classes at the source of flow level, therefore, must be assessed at each point in a river network by integrating the topographic variation across the watershed and basing a watershed topography category on the dominant topography of the watershed.

**Geology.** The next classification level describes watershed processes and assumes that the factor “watershed geology” is the next dominant cause of variation in hydrological, sediment supply, and hydrochemical processes. Thus, the REC model assumes that where rivers are homogeneous with respect to the higher-level classes, patterns in hydrology, sediment supply, and hydrochemical regimes are dominated by watershed geology. The REC defines this system level using rock type in broad groups, differentiating spatial units of approximately 10 to 100 km^2.
Watershed geology controls ground water storage capacity and transmissivity and thus is likely to be the dominant influence on base flow at this scale. Watershed geology is also the dominant controller of hydrochemical processes, particularly at base flow. Watershed geology strongly influences erosion rates, and therefore, classes at this level provide increased discrimination of sediment supply. Watershed geology categories are also expected to discriminate patterns in the architecture of material forming channel substrates (e.g., platy versus rounded) and sediment particle size.

Watersheds often comprise heterogeneous geology. REC accounts for this at each point in a river network by integrating the geologic variation across the watershed and basing a category on the dominant geology of the watershed.

**Land Cover.** The final system level dealing with watershed processes is defined by the factor “watershed land cover.” The REC defines this system level using micro-scale differentiation of vegetation types into broad groups in spatial units of approximately 1 to 10 km².

Watershed land cover controls surface interception of rainfall as well as potential evapotranspiration. This classification level therefore discriminates variation in hydrological patterns such as low flow regimes (Rowe et al., 1997). At this level, watershed land cover is also the dominant control on hydrochemical processes. Land cover classes therefore further discriminate water chemistry (Close and Davies-Colley, 1990). Watershed land cover also influences local variations in erosion rates and the type of sediment reaching stream channels. Land cover classes therefore provide increased discrimination of sediment supply and the type of material forming channel substrates.

Watersheds generally comprise heterogeneous land cover, which REC assesses at each point in a river network by integrating land cover variation across the watershed and basing a category on the dominant land cover of the watershed.

**Network Position.** The fifth classification level, “network position,” provides greater discrimination of ecosystem patterns that are caused by local processes occurring in sections of the river network. This system level describes the flux of water, sediment, and other constituents of the flow. The characteristics of these fluxes change along the network due to increasing catchment area. Network position also characterizes changes in river environments that are caused by attenuation of flood flows, homogenization of flow constituents, and changes in the relative contribution of flow from ground water storage. Network position therefore discriminates patterns in aspects of flow including the intensity of flood flows, fluxes of sediment and fluxes of chemicals including nutrients.

Variation in the factor network position may be delineated using categories based on stream order (Strahler, 1964). Alternatively, other categorizations may be useful for subdivision at this level, such as the average elevation of network section or distance from the river mouth.

**Valley Landform.** Physical patterns at micro scales and smaller are generally attributed to morphodynamic processes of local sediment transport, channel erosion, and sediment deposition (e.g., Habersack, 2000). The landform characteristics of the valley the channel occupies, including its shape and geological features, are generally assumed to control these morphodynamic processes at a variety of scales (Frissell et al., 1986; Naiman et al., 1992; Habersack, 2000). This sixth REC system level is defined by micro scale (1 to 10 km) differentiation of the landform of the valley the channel occupies. Patterns that are discernable at the valley landform level include patterns in lateral (floodplain) and vertical (hyporheic) connections, hydraulic geometry and bankfull discharge (and therefore habitat volume), local flood power, sediment size range, and the influence of riparian conditions (Poff, 1997).

A variety of local geological and geomorphic characteristics of the valley may be useful for categorizing variation at the valley landform level, including valley slope, side slope gradient, and valley bottom width (Naiman et al., 1992).

**Mapping the Classification.** The conceptual framework for the REC is operationalized by representing rivers as networks of channels and associated watersheds. A network consists of adjoining sections, which are the fundamental classification unit. REC classifications for large areas are developed in a Geographic Information System (GIS) environment, which enables automation of the process described below. In our experience, existing spatial data sets are available over large areas at sufficient resolution to classify and map classes down to the valley landform level of the classification.

A channel network and associated watersheds for the geographic area being classified are required. We derive the channel networks from a 30 m Digital Elevation Model (DEM) after post-processing the data by techniques described in Nikora et al. (1996) and using the tools available within the GRID module of Arc/Info. The network comprises individual sections that link each network junction. A uniquely identified
‘node’ terminates each section. The minimum watershed area to define a section is 0.02 km². This produces a network that is commensurate with 1:50,000 scale topographic maps, with sections having an average length of approximately 700 m. The network is stored as a set of GIS polylines. Each section is associated with its own watershed, which is derived from the DEM. All network nodes are linked, allowing the node watershed to be defined by accumulating all upstream section watersheds.

Landscape classification does not always explicitly separate the process of classification, that is, the characterization and labeling of classes, from the process of mapping. Assignment is the process of choosing or recognizing the class to which a new object should be allotted (Cormack, 1971; Gordon, 1981). In ecosystem classification, the process of mapping involves assignment and is distinct from the process of classification (Kljin, 1994). REC uses mapping characteristics (sensu Kljin and Udo de Haes, 1994) for recognition and mapping of the factor categories for each classification level. Choice of mapping characteristics includes subjective judgments and will also be constrained by spatial data that are available as GIS coverages. Either continuous or categorical data can be used to produce mapping characteristics, provided spatial resolution is commensurate with the factors being represented.

The network approach used by the REC means that recognition and mapping of classes at each classification level is not as simple as defining polygons within which mapping characteristics comply with certain criteria such as in landscape classifications. For the REC, mapping characteristics are evaluated for each node in the network individually, and criteria are then applied to determine category membership. Factors dominating watershed processes characterized at the first four classification levels are generally heterogeneous within watersheds. The mapping characteristic is therefore evaluated from maps of categories (e.g., geological maps) or surfaces of a continuous variable (e.g., DEMs) that describe the spatial variation of each factor in the watershed. These maps or surfaces are spatially integrated for the watershed of each node. The product of this integration is the mapping characteristic, and category membership is determined by applying criteria to this. Category membership for the network position and valley landform classification levels are determined from mapping characteristics that are evaluated for each individual section.

Mapping characteristics are evaluated for each node, and the data are organized into a database with rows pertaining to nodes and columns pertaining to the various mapping characteristics. For mapping characteristics that are derived from continuous variable surfaces, a single mapping characteristic - the average value of the surface for the watershed - may be calculated by spatial integration. However, the integration process for categorical maps results in a set of mapping characteristics that describe the proportion of each of the map categories in the watershed. Depending on how a continuous variable is to be evaluated, a similar set of mapping characteristics could also be generated for the classification (e.g., areas of each watershed in various elevation bands).

The mapping procedure applies criteria to the database of mapping characteristics. This produces a simpler database in which each node is assigned a category for each level of the classification. The class at any level of the REC hierarchy is simply the concatenation of categories for each level in the classification hierarchy. The classification for each node is attached, as a set of attributes, to the polyline that represents the upstream network section, and the entire network and classification is saved as a GIS map layer. Classes are mapped by displaying sections by class at any hierarchical level required.

EXAMPLE APPLICATION: CLASSIFICATION OF NEW ZEALAND RIVERS

We present an example of the application of the REC method and discuss the mapping characteristics and criteria used to classify New Zealand rivers. We do not attempt to detail or justify all the criteria but discuss them in broad terms to illustrate how the methodology may be applied. We also discuss a pragmatic variation to the conceptual framework in our application of the REC method at the climate and source of flow levels where classes are mapped using actual climatic data.

Choice of Categories and Mapping Characteristics

New Zealand is a maritime country, with hills and mountains generally oriented transverse to the prevailing westerly winds. Thus, precipitation is strongly related to elevation, with maximum precipitation in the Southern Alps occurring at 1,200 to 1,700 meters (Tomlinson, 1992). Precipitation extremes generally reflect the pattern of annual precipitation – the heaviest and most intense falls tend to occur where annual totals are highest and dry periods and droughts where annual totals are least (Mosley and Pearson, 1997). However, rain-shadow areas occur on the eastern side of the mountains. Because these rain-shadow...
areas are also subject to warm Föhn winds, the relationship between topography and “effective annual precipitation” (i.e., precipitation minus potential evapotranspiration) that produces stream flow is not simple (Tomlinson, 1992). Because of this partial independence of climate and topography, we use direct measures of precipitation minus potential evapotranspiration, and temperature, as mapping characteristics to determine categories at the climate level of our classification.

Surfaces of annual mean precipitation, annual mean evapotranspiration, and annual mean air temperature were estimated for points on a 1 km grid across New Zealand from thin plate splines (Hutchinson and Gessler, 1994) fitted to meteorological station data. The mapping characteristics for the climate level of the classification are evaluated by integrating the climate surfaces to determine the watershed average annual effective precipitation and temperature for each node. Criteria are applied to determine membership of six climate classes: warm extremely wet, warm wet, warm dry, cool extremely wet, cool wet, and cool dry (see Table 2).

Source of flow categories are assigned primarily from rainfall weighted watershed elevation derived from the mean annual precipitation surface and the DEM. For each node, the mapping characteristics are a set of data that tabulates the total annual precipitation volume evaluated in 100 m elevation bands. Because source of flow characterizes variation in flood frequency, potential evapotranspiration is not subtracted from the annual rainfall surface, in order to

<table>
<thead>
<tr>
<th>Classification Level</th>
<th>Classes</th>
<th>Notation</th>
<th>Mapping Characteristics</th>
<th>Category Assignment Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Climate</td>
<td>Warm Extremely Wet</td>
<td>WX</td>
<td>Mean annual precipitation, mean annual potential evapotranspiration, and mean annual temperature.</td>
<td>Warm: Mean annual temperature ≥ 12°C. Cold: Mean annual temperature &lt; 12°C. Extremely Wet: Mean annual effective precipitation ≥ 1,500 mm. Wet: 500 &gt; mean annual effective precipitation ≥ 1,500 mm. Dry: Mean annual effective precipitation &lt; 500 mm.</td>
</tr>
<tr>
<td></td>
<td>Warm Wet</td>
<td>WW</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Warm Dry</td>
<td>WD</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cool Extremely Wet</td>
<td>CX</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cool Wet</td>
<td>CW</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cool Dry</td>
<td>CD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Source of Flow</td>
<td>Mountain</td>
<td>M</td>
<td>Catchment rainfall volume in elevation categories, lake influence index</td>
<td>M: &gt; 50 percent annual rainfall volume above 1,000 m ASL. H: 50 percent rainfall volume between 400 and 100 m ASL. L: 50 percent rainfall below 400 m ASL. Lk: Lake influence index &gt; 0.033.</td>
</tr>
<tr>
<td></td>
<td>Hill</td>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low Elevation</td>
<td>L</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lake</td>
<td>Lk</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Geology</td>
<td>Alluvium</td>
<td>AI</td>
<td>Proportions of each geological category in section catchment</td>
<td>Class = The spatially dominant geology category unless combined soft sedimentary geological categories exceed 25 percent of catchment area, in which case class = SS.</td>
</tr>
<tr>
<td></td>
<td>Hard Sedimentary</td>
<td>HS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soft Sedimentary</td>
<td>SS</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Volcanic Basic</td>
<td>Vb</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Volcanic Acidic</td>
<td>Va</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Plutonic</td>
<td>PI</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Land Cover</td>
<td>Bare</td>
<td>B</td>
<td>Proportions of each land cover category in section catchment</td>
<td>Class = The spatially dominant land cover category unless P exceeds 25 percent of catchment area, in which case class = P, or unless U exceed 15 percent of catchment area, in which case class = U.</td>
</tr>
<tr>
<td></td>
<td>Indigenous Forest</td>
<td>IF</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pasture</td>
<td>P</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Tussock</td>
<td>T</td>
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<td></td>
<td>Scrub</td>
<td>S</td>
<td></td>
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<tr>
<td></td>
<td>Exotic Forest</td>
<td>EF</td>
<td></td>
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<tr>
<td></td>
<td>Wetland</td>
<td>W</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Urban</td>
<td>B</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Middle Order</td>
<td>MO</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High Order</td>
<td>HO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Valley Landform</td>
<td>High Gradient</td>
<td>HG</td>
<td>Valley slope of section based on Euclidian length</td>
<td>Valley slope &gt; 0.04. 0.02 ≥ Valley slope ≤ 0.04. Valley slope &lt; 0.02.</td>
</tr>
<tr>
<td></td>
<td>Medium Gradient</td>
<td>MG</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low Gradient</td>
<td>LG</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
maximize discrimination of patterns in flood frequency. New Zealand is a narrow country, and watershed slope is therefore highly correlated with watershed elevation. We therefore consider that it is unnecessary to include measures of watershed slope as a specific mapping characteristic.

Rules assign the four major source of flow categories (mountain, hill, low elevation, and lake) at each node (Table 2). The mountain class is defined by watershed nodes that receive more than 50 percent of their total annual rainfall above a nominated elevation threshold of 1,000 m. Nodes receiving greater than 50 percent of their total annual rainfall below the mountain threshold but above a nominal elevation of 400 m are categorized as hill. Watersheds that receive greater than 50 percent of their annual average rainfall below the lower hill threshold of 400 m are categorized as low elevation.

The degree to which upstream lakes control flow and sediment regimes at any node is a function of the runoff volume within each lake’s watershed, its storage-discharge relationship, and the contribution of runoff to that node from any “non-lake” watershed. Because storage-discharge relationships are unavailable for most lakes, we use an index as a mapping characteristic. The lake index (LI) includes: \( V_{LW} \), the volume of annual rainfall in the watershed of each lake; \( A_L \), the area of each lake; \( A_{LW} \), the area of each lake’s watershed; and \( V_W \), the volume of annual rainfall in the node watershed, as has the form:

\[
LI = \frac{\sum V_{LW} \cdot \sum A_L}{V_W}
\]

A rule assigns a lake class to all nodes where the value of LI exceeds a specified value (see Table 2). Our classification also recognizes wetlands, springs, and regulated rivers (downstream of controlled impoundments) as source of flow categories because of the dominant effect of these topographic features on fluvial processes. Because these infrequently occurring categories cannot be mapped from available topographic data, they are classified by hand.

For the geology level of REC, we use the New Zealand Land Resources Inventory (LRI), which classifies geology into 55 categories at a scale of 1:50,000. This resolution of rock type is higher than necessary to differentiate the processes being considered at this scale. The rock types defined by the LRI are therefore aggregated into six summary categories that occur in characteristic spatial units of 10 to 100 km² (Table 2). For example, metamorphic rocks (e.g., argillite, schist, and greywacke) are merged into a category termed “hard sedimentary rocks.”

Even with the aggregation of geological categories, watershed geology is rarely homogeneous when stream order exceeds approximately 3. Rules are applied to data listing the summarized rock type by proportion of node watershed area in order to assign a geological category for each node. Rules recognize the nonproportional effect of different geologies on sedimentary and hydrochemical processes. For example, our rules assign a “soft sedimentary” geology category if the area of soft sedimentary rock types in the node watershed exceeds 25 percent. This recognizes the proportionally greater contribution of this geology to sediment (Hicks et al., 1996) and nutrient supply (Biggs, 1995; Biggs and Gerbeaux, 1993).

We use a national Land Cover Database (LCDB) to evaluate the proportion of watershed in various vegetation categories at each node of the network. The LCDB defines 17 land cover categories, derived from digitizing satellite images, at a mapping scale of 1:50,000. We group the LCDB categories to nine broad categories that occur in characteristic spatial units of 1 to 10 km² (Table 2).

Land cover is rarely homogeneous in watersheds of stream order exceeding 2. Our rules, once again, recognize the nonproportional contribution of different land cover to water chemistry and sediment supply. For example, if the area of pasture is greater than 25 percent, land cover is classified as “pasture” recognizing the proportionally greater contribution of nutrients associated with pastoral runoff (e.g., Biggs, 1995) and effects of this on higher trophic levels (e.g., Quinn and Hickey, 1990).

Network position categories (see Table 2) are assigned from the stream order (Strahler, 1964), which is evaluated for each network section during the development of the river network. Valley landform categories (see Table 2) are assigned using a single characteristic, the slope of the valley that the section occupies. This is determined from the DEM using the Euclidian distance and elevation difference between downstream and upstream ends of each network section.

Results

A full classification follows the form climate/source of flow/geology/land cover/network position/valley landform, with potential classes at each classification level and shortened notation being summarized on Table 2. Figure 2 shows an abbreviated classification diagram for the first four levels of the classification. This “tree” diagram illustrates the formation of lower level classes by subdivision of the preceding level and the hierarchical nature of the classification. The
number of potential classes at any level in the classification is dependent on the number of categories defined at that level, multiplied by the number of classes at the subsequent level. The number of potential classes therefore rapidly increases moving down the classification. For example, the geology level of our classification has $6 \times 4 \times 6 = 144$ potential classes. However, not all will occur in any given region of New Zealand. In the Southland region (Figure 3), which covers an area of 30,000 km$^2$, 61 of these potential classes occur, of which 22 classes make up 90 percent of the total network length.

Figure 3 shows classes mapped for the climate level of the classification for the South Island of New Zealand and additionally, source of flow, geology, and valley landform levels within the Southland region. Indicative mapping scales for landscape classifications, such as those suggested by Klijn (1994), are inappropriate due to the dendritic nature of the channel network. Larger scales than those used for landscape classification are thus preferred to map REC classes across equivalent geographic areas.

The mapped classes appear as linear mosaics. Classes at the first three system levels are generally homogeneous over large areas of the network (Figure 3). This occurs because qualitative change in the factors causing patterns at large spatial scales occur relatively infrequently within watersheds. Main stems in the channel network tend to appear as linear features, which are formed by network sections that share the same classification. These linear features may pass through areas where influent tributaries have different classifications. For example, Figure 3 shows hill source of flow rivers traversing alluvial out-wash plains where local streams are classified as low elevation. The mapped classifications show, however, that changes in high level classes often occur within different parts of the network in large watersheds. For example, Figure 3 shows that source of flow may be categorized “mountain” high in the watershed but may eventually change to “hill” as the lower elevation parts of the watershed are integrated and become the dominant watershed topography. Changes in class often occur at discontinuities where large tributaries meet main stems that have significantly different controlling factors. This reflects the observation that tributary junctions can result in discontinuities in morphology (Knighton, 1982), water quality (Vannote et al., 1980), and biological communities (Bruns et al., 1984). This means the criteria used to define classes may not be critical to the patterns that are delineated. This is because change in classes tends to be associated with the addition of tributaries where major changes in characteristics occur relative to the criteria that determine class membership.

The size of classes (i.e., total length of channel in each class) is easily retrieved from the GIS database, as section length is an attribute that is derived in developing the network, allowing the relative frequency of occurrence of each class to be calculated. The classification of each section at every level, plus the flexibility of GIS for handling the classification as a multiple attribute GIS layer, allows the classification to be mapped at any level. The classification is therefore not a single map or series of maps such as

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**Figure 2.** An Abbreviated Classification Diagram Showing the Formation of Selected Classes to the Land Cover Level of the REC Classification. The large font is the factor category and the small font is the full class at each level (see Table 2 for the notation key).
DISCUSSION

The REC codifies knowledge of the factors controlling river ecosystems to enable patterns to be delineated and help elucidate the causative processes. A major advantage of the REC is the ability to treat rivers as networks and through this the increased ability to change the "grain" of the classification. The ability to detect patterns is a function of both the extent and the grain of the investigation (Wiens, 1989). The REC may be carried out over any spatial extent; however, the range in grain size that is achievable is much greater than classifications such as ecoregions. REC can assist in pattern detection in many characteristics of river ecosystems provided the graining of the dependent ecosystem variables (e.g., ecoregions. Classifications can be made to suit individual applications and show patterns of processes and properties of interest.

Figure 3. A Classification of the South Island of New Zealand Showing Classes at the Climate Level of the REC Classification, and Zooming to Three Scales in the “Southland Region” Showing Source of Flow, Geology, and Valley Landform Levels of the REC Classification (see Table 2 for the notation key). The colors for each panel have been chosen to maximum class discrimination and there is no relationship between class colors in each panel. Line thickness has been scaled by the order of the each network section.
Multiscale River Environment Classification for Water Resources Management

Multiscale River Environment Classification for Water Resources Management

Multiscale River Environment Classification for Water Resources Management

bastic community or water quality characteristics) is commensurate with the level of the classification used to differentiate the area being investigated.

REC classes are geographically independent and characterize similar environments that occur at many locations. The REC classification procedure and use of GIS methods has the advantage that, once determined, classification criteria are consistently applied to map classes. In comparison, gestalt classification procedures such as ecoregions “hide” the reasons for class membership. Ecoregions are geographically dependent and unrelated to each other because classification at any level is not performed according to any model of ecological processes or criteria. Using the REC classification similarities and differences can be investigated between large rivers whose watersheds are heterogeneous with respect to controlling factors, or between different locations on the main stem of a single large river. Thus, the classification provides managers with a more powerful spatial framework for detecting and mapping patterns and stratifying rivers for management purposes.

The longitudinal zonation or position of a site in the hydrographic network has long been recognized as a fundamental predictor of physical and biotic pattern (e.g., Hawkes, 1975). This led Hawkins et al. (2000) to conclude that explicit recognition of the stream continuum may improve the strength of landscape classifications. The REC approach deals with this fundamental problem by explicitly representing the continuum caused by the changing product of integration of watershed factors in the downstream direction. Patterns, however, are not due to this longitudinal change in watershed characteristics alone. The interaction between watershed scale processes such as hydrologic and sediment regimes, with local constraints imposed by more rapidly changing factors at the scale of individual network sections, produces smaller scale patterns in hydraulic and substrate conditions that are major determinants of plant (e.g., Biggs, 1996), invertebrate (e.g., Quinn and Hickey, 1990), and fish (e.g., Jowett and Duncan, 1990) assemblages. In a synthesis of tests of many landscape classifications, Hawkins et al. (2000) concluded that weak explanation of biotic variation was due to an absence of these local habitat features. Classification down to the valley landform level by the REC approach incorporates factors that operate at this scale but emphasizes that these patterns are constrained by larger watershed processes. Lower classification levels such as the reach, pool/riffle, and microhabitat levels of classification suggested by Frissell et al. (1986), would nest coherently below the valley landform level. These classification levels are based on factors that are generally too small to be adequately defined from spatial data that are available for large areas but could be implemented, when necessary, from site data collected in the field.

REC’s classification levels are well justified by the theories of hierarchic control of physical and biotic pattern in rivers (e.g., Poff, 1997). The most subjective aspect of the classification is the division of classes at each level of the classification. Many applications are based on analyses that use information on the relative frequency of occurrence of classes, for example, determination of representativeness of protected areas. Care is therefore needed to ensure that each class discriminates “real” ecological variation at that level of the classification. In addition, discrimination must be balanced against the number of classes that are manageable when using the classification.

The REC method is more technically demanding and involves a more difficult classification procedure than ecoregion approaches. REC, however, is not necessarily more data intensive especially if carried out at lower spatial resolution. Computer based tools, particularly GIS, are necessary for operationalizing the classification in an efficient and consistent manner. Attention to how the large quantity of data is assembled and handled ensures maximum flexibility. Careful database management allows the classification to be “dynamic” enabling the number of classes at any level of the classification to be changed, criteria to be altered, and even other factors to be incorporated at a later date without losing the integrity of the classification. This allows prototypes of the classification to be produced, for example, to examine the effect of changing criteria on the boundaries between classes.

The dynamic form of the REC classification extends its use into other applications such as spatial modeling. For example, the first four levels of the classification stratify rivers into a number of classes that can be expected to exhibit within class similarities (e.g., geology and thus flood flows and sediment input rates controlling morphological patterns). Longitudinal evolution could be expected to vary consistently within a class (e.g., downstream hydraulic geometry). Thus, each high-level class allows certain model parameters to be stabilized and allows a limited set of parameters, related to longitudinal variation (slope, drainage area), to be used as control variables.

The choice of mapping characteristics in our classification of New Zealand’s rivers includes judgments that are not necessarily universally applicable. For example, in continental areas, where elevation and slope are less well correlated than in New Zealand, source of flow may need to incorporate measures of watershed slope to adequately differentiate erosion and sediment transport processes.
Finally, we emphasize that as an a priori classification, the results remain a hypothesis about ecosystem organization and function until tested. Complete testing of such a multiscale classification is unlikely to be performed as a single study. This means the classification must become part of the assumptions and hypotheses underlying policy development that are later tested by monitoring (e.g., Lee, 1993). Comprehensive testing as well as use of the REC for broad scale environmental assessment are now under way in New Zealand with promising results.

ACKNOWLEDGMENTS

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LITERATURE CITED


