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Landscape approaches to the analysis of aquatic ecosystems

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SUMMARY

1. In the mid-1970s, Hynes (1975) wrote eloquently about the complex interactions between aquatic and terrestrial systems. Central theories in stream ecology developed thereafter have dealt with the longitudinal flow of energy, materials and organisms in streams, and, with the exception of the flood pulse concept (Junk, Bayley & Sparks, 1989), have largely ignored areas outside the riparian zone. The structure of the upland and activities occurring there play a more important part than previously recognized in regulating community structure and ecosystem processes in streams.
2. These new perspectives are made possible by developments in hierarchy theory, patch dynamics, and the refinement of tools used to quantify spatial and temporal heterogeneity.
3. Geographical information systems (GIS), image processing technology and spatial statistical techniques allow quantitative assessment of lateral, longitudinal and vertical components of the landscape that interact at several spatial and temporal scales to influence streams. When GIS is used in concert with geostatistics, multivariate statistics, or landscape models, complex relationships can be elucidated and predicted.
4. To a certain extent, the tools discussed above have only automated functions that were previously performed manually. This suite of tools has improved the ability of aquatic ecologists to examine relationships and test theories over larger, more heterogeneous regions than were previously possible.
5. At the local, state and federal level, management and regulatory frameworks are currently being re-evaluated to incorporate this new perspective in resource management and policy decision making.
6. We will discuss current and future trends in technologies and tools used for aquatic ecosystem research, and the use of techniques as they are applied in these regional assessments are also discussed.

Introduction

The character of streams and rivers reflects an integration of physical and biological processes occurring in the catchment, yet ecological studies and management of natural resources have traditionally occurred at the scale of a stream reach, forest stand or vegetation plot. This is due, in part, to our inability to handle and analyse large heterogeneous data sets. The scale of disturbances such as acid deposition, climate change, desertification and wetland loss, along with the concomitant recognition that management must occur at larger spatial scales to satisfy the multiple demands on the world's resources, have led to the development of a landscape perspective for addressing environmental issues. This approach to environmental problem-solving occurs in a patchwork of adjoining ecosystems with multiple, sometimes overlapping, political and management jurisdictions. Catchment-based assessments that address hydrological, geological and biological components, are being implemented to address in-stream flow requirements (Petts *et al*., 1995), and numerous non-point source pollution issues (Euphrat & Warkentin, 1994).

In 1975 Hynes stressed the linkage between the stream and its valley; since that time the interaction between a stream and its catchment is often acknowledged. This theme has had a long history in ecological (Huet, 1949; Fisher & Likens, 1973; Likens & Bormann, 1974; Vannote *et al*., 1980; Schlosser & Karr, 1981a,b; Junk, Bayley & Sparks, 1989), geomorphic (Horton, 1945; Leopold, Wolman & Miller, 1964; Schumm & Lichty, 1965) and hydrological (Hewlett & Nutter, 1970; Hewlett & Troendle, 1975) studies of river systems. However, specific relationships permitting predictions of biotic community structure and in-stream processes are still poorly understood. When Hynes made his remarks during the Edgardo Baldi lecture of the International Society of Limnology (SIL) conference in 1975, appropriate tools for quantifying the nature of catchments and analysing large, heterogeneous data sets were not available. Along with technology development, the availability of spatial data and cartographic data handling tools have recently made regional and landscape-scale studies more feasible, and have led to catchment-based national water quality assessment programmes (National Research Council, 1990; Powell, 1995), and local/regional water quality assessment studies and management (Petts *et al*., 1995; Puckett, 1995).

Geographical information systems (GIS) and image processing technology allow quantitative assessment of lateral, longitudinal and vertical components of landscapes that interact at a variety of spatial and temporal scales to influence streams. When GIS is used in concert with spatial statistics (geostatistics), multivariate statistics, or landscape models, complex relationships can be elucidated and predicted. To a certain extent, these tools have only automated functions that were previously performed manually. What these tools have achieved for the discipline of aquatic ecology is the ability to examine relationships and test theories over much larger regions. The implications have been far-reaching. At the local, state and federal level, management and regulatory frameworks in the U.S.A. (Powell, 1995), New Zealand (Biggs *et al*., 1990), United Kingdom (Petts *et al*., 1995), and elsewhere, are currently being re-evaluated to incorporate this new perspective in resource management. Pijanowski *et al.* (1996) analysed ecological and human impacts on catchment dynamics using a GIS grid-based modelling approach to characterize land use change. GIS technology can produce visual material on landscape characteristics and patterns which provide policy makers with a better visual perspective on the areas for which policies are designed and developed (Jones *et al*., 1996). In this paper, we will discuss current and future trends in technologies and tools used for catchment research and will comment on their use as they are applied for regional assessments.

Analysis tools

The tools that have made catchment assessments feasible include: powerful, compact computers, global positioning devices, image processing/remote sensing software, GIS, multivariate statistics and geostatistics software packages. Previously, only experienced users with access to large computational environments, such as government laboratories and facilities, could consider analysing landscape patterns using high resolution satellite imagery and overlaying these with polygons of other features to test complex hypotheses. Today, this type of analysis is within reach of those with the insight and desire to conduct the analysis. Furthermore, the trend toward 'openness in government', as well as almost universal internet access, has increased the availability of regional databases (Table 1) necessary for conducting catchment-scale assessments.

Two tools in particular have made it possible to quantify spatial patterns of landscapes: GIS and image processing/remote sensing technology. Until the early to mid 1980s most landscape characterization studies relied on interpretation of aerial photographs. The product of this effort, a paper map, was static; therefore analysis of different thematic data for the same region (e.g. soils, topography, land use) was difficult to use due to differences in map projections and scale. Furthermore, updating such information was

Table 1 Landscape factors that can be used to describe catchment characteristics, and potential sources of spatial data available for most regions of the U.S.A. Additional data may be available from state agencies and non-governmental organizations

Catchment characteristic	Data source, program name
Bedrock geology	Individual states
Climate	National Climate Data Center, US Geological Survey, others
Elevation	US Geological Survey—Digital Elevation Model
Hydrography	US Geological Survey—Digital Line Graph
Land use/land cover	US Geological Survey—LUDA; individual states
Quaternary Geology	Individual states
Soils	U.S. Department of Agriculture—STATSGO; individual states
Transportation Network	U.S. Geological Survey—Digital Line Graph
Wetlands	U.S. Department of Interior, Fish and Wildlife Service—National Wetland Inventory

laborious and time consuming. GIS has become a fundamental tool for natural resource managers and ecologists concerned with analysis of spatially referenced data (Johnson, 1990). GIS capabilities range from performing simple map measurements (length, distance, area) and creating map composites, to quantifying spatial pattern, position and spatial relationships (e.g. shape, diversity, proximity, connectivity and juxtaposition). The ability to create buffers (polygons surrounding points, lines, or other polygons at a fixed distance) has permitted researchers to describe and analyse edge effects, core areas and to define ecotones (cf., Johnson, 1990). GIS technology has contributed to the analysis of change detection, at temporal scales ranging from hours to centuries. Newer methods for encoding attributes of linear features now permit more flexibility in the depiction of rivers, riparian zones, roads and other linear features of landscapes (e.g. Dynamic Segmentation in ARC/INFO software, Environmental Systems Research Institute, Redlands, CA). The ability to integrate spatial data with models has further expanded the utility of GIS for analysing and predicting environmental phenomena. Entire conferences are now dedicated to the integration of GIS and environmental modelling (Goodchild *et al.*, 1996). Some examples of GIS applications relevant to catchment assessment are found in Table 2.

Table 2 Some potential applications of GIS technology for catchment assessments

Application	Examples
Produce secondary data from primary data	Slope and aspect from elevation points; contour maps from point data
Quantify associations between spatial features	Land use, geology, soils, topography, hydrography, population density, species distributions
Quantify landscape patterns and spatial relationships	Shape, connectivity, juxtaposition, or diversity of landscape patches
Quantify temporal patterns	Greenness, ice/snow cover, wetland area
Quantify temporal change	Land use conversion
Link spatial data with models	Hydrological, ecosystem, climate change

Remote sensing and image processing technologies have been available for analysis of regional patterns and phenomena for at least three decades. This technology is based on the premise that absorption and reflection properties of objects can be used to identify and classify objects remotely on the ground. Airborne sensors detect thermal and spectral signatures in specific band intervals. Bands are used singly and in combination to classify targets on the ground. Spatial resolutions of commonly used sensors range from 10×10 m pixels to 1×1 km pixels (Table 3). Individual sensors have distinct spectral and spatial resolutions, making them suitable for different objectives (Table 4). Return intervals of sensors over a single location range from multiple passes in a single day (weather satellites) to once every 16 days or more (Thematic Mapper, SPOT; see Johnson and Covich, *this issue*). A newly deployed sensor, RADARSAT (RADARSAT Inc., Vancouver, BC), uses side-borne radar, which penetrates darkness and cloud cover to detect surface texture. This sensor has flexible resolutions ranging from 10 to 100 m and multiple images sizes ranging from 50×50 km to 500×500 km. RADARSAT imagery was recently used to monitor flood extent (Paterson *et al.*, 1996) and may prove to be very useful for catchment and other landscape-scale studies. Characteristics of remote sensing systems and their application to study of rivers are reviewed by Müller, Décamps & Dobson (1993) and summarized in Table 5.

Table 3 Description of satellite imagery and aerial photography commonly used for constructing spatial databases

Sensor	Pixel size/ resolution	Image size (swath width)	Data channels	Temporal repeatability	Source	Notes/applications
Advanced Very High Resolution Radiometry (AVHRR)	1×1 km	2399 km	4–5	12–24 h	EROS Data Center	monitor vegetation conditions and trends; quantify seasonal vegetation growth; map temperature, turbidity, and chlorophyll a concentrations
Thematic Mapper (TM)	30×30 m	185 km	7	16 days	EOSAT (products < 10 yrs old) EROS Data Center (> 10 yrs old)	map land use/cover; map vegetation types; detect macrophyte distribution patterns and senescence
Multi Spectral Scanner (MSS)	80×80 m	185 km	4–5	16 days	EROS Data Center	same as TM
RADARSAT	100×100 m to 10×10 m	35–500 km	1	6–24 days	Canadian Centre for Remote Sensing	Synthetic aperture radar imaging; used for mapping texture (e.g. topography) and viewing areas with cloud or smoke cover
SPOT	20×20 m or 10×10 m	60 km	3 1	3–26 days 3–26 days	SPOT Corporation	Same as TM
National High Altitude Photography (NAPP, NHAP)	1 : 14 000 to 1 : 80 000	Variable	Colour IR or black/white	Variable	EROS Data Center	Unrectified aerial photograph, film resolution 2 m
Shuttle Photography	Variable	Variable	Variable	Variable	NASA	Unrectified aerial photograph, color
Digital Orthophotographs	Variable	Variable	1	Variable	USGS, state government	Georeferenced aerial photograph, monochrome
Farm Services Agency, Aerial Compliance Slides	Variable	1 mile^2	Black/white	Annual	FSA	Crop reporting , land use classification (agricultural regions only)

Table 4 Digital data available for catchment assessments at various spatial (and temporal scales). (See Table 3 for explanations of sensor abbreviations)

Region/large catchment	Hierarchical scale			
	River segment	Reach	Pool/riffle	Habitat
AVHRR	TM/MSS	Aerial photographs (helicopter—low altitude)	Aerial photographs (helicopter—low altitude, balloon, tower)	Photographs (balloon, tripod)
TM/ MSS	Radiometer	Video (low altitude, helicopter)	Video (tower)	Video (tripod)
RADARSAT	Spectrometer		Radiometer	
SPOT	Digital orthophotographs		Spectrometer	
ERS1	Videography (airborne)			
Shuttle photography	Aerial photographs (fixed wing–medium altitude)			
Digital elevation model	Digital line graph (transportation, hydrography, hypsography) TIGER (Census Bureau)			
Aerial photographs (fixed wing–high altitude)				

Table 5 Applications of remote sensing to aquatic systems

Applications	References
Detecting physical properties, e.g. temperature, moisture content, 'greenness', organic and inorganic composition, turbidity, surface texture, drainage patterns; circulation patterns	Finley & Baumgardner, 1980; Argialas, Lyon & Mintzer, 1988
Vegetation mapping, land use/land cover mapping	Dottavio & Dottavio, 1984; Jensen *et al.*, 1986; Ackleson *et al.*, 1985
Mapping macrophyte distribution	Gross & Klemas, 1986; Ackleson & Klemas, 1987
Mapping chlorophyll *a* distribution and primary production	Hardisky *et al.*, 1984; Harding, Itsweire & Esaias, 1995; Ruiz- Azuara, 1995; Rundquist *et al.*, 1996.
Mapping turbidity and temperature	Aranuvachapun & Walling, 1988; Brakel 1984; Goodin, *et al.*, 1993; Bolgrien, Granin & Levin 1995; Liedtke, Roberts & Luternauer 1995
Detecting temporal change, e.g. land use, temperature, macrophyte distribution	Christensen, *et al.*, 1988; Jensen *et al.*, 1993; Jensen *et al.*, 1995; Lee & Marsh, 1995
Mapping water depth, e.g. mesoscale river habitat	Gilvear, Waters & Milner, 1995; Lyon & Hutchinson, 1995
Detecting water quality	Lillisand *et al.*, 1983; Khorram & Cheshire, 1985; Ormsby, Gervin & Willey, 1985; Lathrop & Lillisand, 1986, 1989

GIS and image processing tools alone can provide a means of quantifying the character of landscapes. When input into hydrological models or ecosystem simulation models, spatial data derived from these technologies can be used to make specific predictions about stream processes from landscape-scale attributes (Pastor & Johnston, 1992; Goodchild *et al*., 1996).

Future trends in GIS and remote sensing

Data

Regional spatial databases are becoming increasingly available (Table 1), as are second generation databases (e.g. North American Landscape Characterization, http://edcwww.cr.usgs.gov/glis) and compendia of data sets (CIESIN, 1995; Wickham, Wu & Bradford, 1995). As more users become dependent upon GIS and remote sensing technology to accomplish their research and management goals, the gaps in the availability of accurate and timely spatial data are becoming apparent. Owing to the expanding number of applications that employ mapping technologies there is increased demand for data of both larger and smaller grains (spatial resolution) and extents (boundaries defined by study; defined by the underlying phenomena and their controlling mechanisms), as well as for greater resolution in the mapped features. For example, vegetation cover maps that include understory species and distinguish riparian types are increasingly in demand for biodiversity assessments in forested landscapes (Minnesota Forest Resources Council, Riparian Assessment Task Force, personal communication). Current trends in public policy are driving governments and agencies towards increasing accessibility to data developed with public funds. This trend has resulted in easier access, lower prices and data standardization between agencies (e.g. implementation of the Spatial Data Transfer Standard; U.S.G.S., 1990). The World Wide Web and other network resources now permit users to peruse lists of available data, access metadata (data about databases, such as data source, resolution, extent, acquisition methods), and ultimately to download data directly to their systems. Software manufacturers are now enticing new customers by bundling data sets with software. Data clearinghouses that provide personalized services such as data conversion also are being established, thereby increasing data accessibility. Funding constraints, however, are compelling agencies towards cost recovery scenarios that may substantially increase the price of new data in the future. The ramification of this will be felt when new data sensors such as LANDSAT 7 are deployed.

Hardware

Access to computing technology has provided to researchers the ability to consider quantifying ecological patterns at larger scales and at multiple levels of interaction. New advances in image processing and digital mapping software and competition between companies are driving significant advances in spatial processing technology. The personal computer has played a varying role in the analysis of landscape processes. Although image processing and GIS have been available on personal computing systems since the mid-1980s (e.g. Arc/Info, ERDAS), time required to process and analyse digital map information was significant. During the 1990s, a transition by some ecologists to more advanced computational hardware (multi-user workstations, e.g. Sun Microsystems) and multi-user operating systems (e.g. Unix) to overcome the limitations of personal computers brought significant advantages, including increased access to processing power, increased storage, access to mainframe software and multi-user access. Although these higher-end systems provided several advantages, costs of software acquisition, maintenance costs of hardware and software and the need to employ a manager to keep the systems functional, restricted lower budget research programmes from performing analysis of landscape patterns and processes. Upcoming releases of popular GIS software on powerful personal computers using the Windows NT operating system may further reduce hardware costs for users of spatial analysis technologies.

Table 6 Approximate costs of GIS and image processing software systems for multi-user (single seed) and personal computing environments. Prices are comparative only and should not be used for budget purposes

Computing platform	GIS product	Cost for system (US$)*
Unix (multi-user)	Arc/Info	18 000.00
Personal computer	Arc/Info	3000.00
Unix (multi-user)	Arcview 2.1	1995.00
Personal computer	Arcview 2.1	995.00
Unix (multi-user)	Erdas Imagine	12 000.00
Personal computer	Erdas Imagine	6000.00
Unix (multi-user)	ER Mapper	14 000.00
Personal computer	ER Mapper	2900.00
Unix (multi-user)	Intergraf	NA
Personal computer	Intergraf	15 000.00
Unix (multi-user)	IDRISI	NA
Personal computer	IDRISI	990.00

*Approximate list price subject to change. Call organization for special pricing for academic and government institutions.

Software

One of the greatest impediments to complex spatial analyses was the steep learning curve associated with pre-1990s GIS and image processing software, and the expense associated with training and data acquisition.

Software and data costs as well as learning curves have since sharply declined (Table 6). Current trends show that GIS and image processing software are moving towards a greater reliance on Windows 95 or Windows NT (32-bit operating systems) and away from UNIX-based systems (Anonymous, GIS World, 1995). Systems targeting specific applications are resulting in 'desktop GIS', with lower prices and reduced learning curves. Additional capabilities are being provided through 'macro' and scripting languages embedded in the software. Standards for data transfer and data encoding have increased data exchange capabilities between software packages and hardware platforms. Future software will have increased intercompatability with word processing, desktop publishing and CAD systems, as well as statistical, spreadsheet and data visualization packages (Hargrove, 1996; Wilson, 1996). The greatest advances will evolve from systems with data structures that accommodate all data formats interchangeably so that satellite imagery, CAD drawings and vector data can be displayed and analysed simultaneously. This will increase the efficiency of image rectification (process to remove distortion) and identification of mapped features. Data acquisition technologies are becoming streamlined through the use of global positioning technology and video imaging, and data visualization techniques are rapidly bringing spatial data to the end-user in a form that enhances communication and exchange of ideas.

Describing landscapes

Hierarchy theory (Allen & Starr, 1982; O'Neill, Johnson & King, 1989) and patch dynamics (Picket & White, 1985) have set the stage for the interpretation of phenomena occurring at temporal and spatial scales ranging over several orders of magnitude (e.g. Pringle *et al.*, 1988). Hierarchy theory is a framework for ordering nature into nested levels whereby lower levels are constrained by higher levels. Thus, patterns observed at one level of organization may appear as noise from a higher scale and as a set of emergent properties characterized by regular patterns from a smaller scale. The appropriate focal level or scale of observation is defined by the boundaries of the system under study, where scale represents either a temporal or spatial dimension. The grain (the smallest resolvable area) and extent (area influenced by the phenomenon under study) are properties of landscape phenomena and influence the manner in which spatial phenomena are sampled, analysed and interpreted (cf. Forman & Godron, 1986; Turner & Gardner, 1991; Wiley, Kohler & Seelbach, this issue). Hierarchical relationships, for example, have been invoked to explain 'top down' and 'bottom up' control of food webs, where process rates operate at different temporal and spatial scales (Carpenter & Kitchell, 1993).

Landscape properties that contribute most directly to the structure and function of aquatic systems include prevailing climate, catchment and riparian land use/cover patterns, channel slope and aspect, Quaternary and bedrock geology, and hydrography (see Allan, Erickson & Fay, this issue; Johnson *et al.* this issue; Richards *et al.* this issue; Townsend *et al.* this issue; Wiley *et al.* this issue). In the United States, these data can be summarized in digital form directly or can be derived from national databases (Table 1). Johnson and colleagues (this issue) summarized land use, Quaternary geology, catchment slope and the standard deviation of catchment elevation to describe water chemistry trends in a large catchment in Michigan, USA. Greater than 65% of the variance in summer nitrate–nitrite concentrations in these Midwestern agricultural streams was explained by the percentage of rowcrop agriculture within a catchment; however, all landscape factors combined explained only 31% of the total phosphorus concentrations. During autumn, geological factors were important explanatory variables. Similar studies were performed for rivers in New Zealand (Close & Davies-Colley, 1990) and Illinois (Hunsaker & Levine, 1995). Other studies have used a similar approach (with varying degrees of success) to explain variation in stream habitat structure and biotic communities (Quinn & Hickey, 1990; Richards, Johnson & Host, 1996; Wiley *et al.* this issue). While Quaternary geology largely explains the distribution of cold-water fish in Michigan streams (Wiley *et al.* this issue), and landscape factors, in general, accurately predicted brown trout *v* rainbow trout habitat in New Zealand (Jowett, 1990), these approaches did not successfully predict the effects of perturbations on periphyton and invertebrate communities in New Zealand streams (Quinn & Hickey, 1990; Biggs, 1990). None of these approaches have taken into account the configuration or spatial position of landscape elements within the catchment, which may account for much of the variation that is unexplained. Furthermore, these approaches have been correlative and thus do little to explain the underlying mechanisms regulating the phenomena.

The studies described above used spatial databases to derive independent variables to explain variation of some component of aquatic ecosystems. Another use for these databases is to derive secondary data synthesizing knowledge about the landscape over multiple spatial scales. These hierarchically nested classification systems are useful for predicting ecological risk, ecosystem productivity, biotic communities and potential responses to management practices. Several systems that classify landscapes into homogeneous units have been created by combining spatial data such as physiography, climate, geology, soils, vegetation and/or land use (e.g. Bailey, 1976; Wilken & Ironside, 1977; Omernik & Gallant, 1986). Attempts to classify aquatic ecological land units in North America are underway (Maxwell *et al*., 1995). Prior to the widespread use of spatial analysis technologies such as image processing and GIS, classification of ecological properties of regions was accomplished by synthesizing field data and delineating trends based on a collection of rules (Bailey, 1983). At the largest spatial scales these systems have not relied upon GIS and remote sensing for delineation of individual units. As units are subdivided, developers of these systems have increasingly depended upon these technologies to produce sound classifications (Bailey, 1995; Host *et al*., 1996). Omernik's (1995) ecoregions have gained wider acceptance by aquatic scientists, while Bailey's system, which is largely founded on potential natural vegetation, is more widely used by terrestrial scientists and managers. Individual states in the U.S.A. have developed indices of biotic integrity for streams and rivers based on ecoregions and subregions (Ohio EPA, 1987), reflecting the perception that fundamental ecosystem properties tend to vary across regions and thus influence the potential species assemblages that can occur at any location. Fish, macroinvertebrates, water quality and physical habitat have been shown to respond to regional patterns delineated by ecoregions (Whittier, Hughes & Larsen, 1988; Lyons, 1989). Ecoregions also have been used to establish reference sites (Hughes, Larsen & Omernik, 1986) and to set stream recovery criteria (Hughes *et al*., 1990).

Biomes, ecoregions and other landscape classification systems integrate physical and/or biological data with the objective of identifying a homogeneous unit based on a set of rules. These units do not quantify interrelationships between landscape elements. Landscape ecologists have developed a number of metrics that describe properties of landscapes in terms of the shape, diversity and position of patches within a landscape. A patch is a homogeneous unit defined on the basis of land cover, geology, topography, substrate, habitat type or any other parameter of interest. Landscape metrics commonly used to quantify landscape pattern are summarized in Table 7. These metrics reflect landscape properties as a whole, properties of individual patch types, or individual patches. For a more complete discussion of these metrics consult Turner & Gardner (1991), Baker & Cai (1992) and Hunsaker *et al.* (1994). Few studies have assessed the relationship of these metrics to structure or function in aquatic systems (see Hunsaker & Levine, 1995; Johnson *et al.* this issue).

Analytical methods

The greatest challenge in the study of landscapes is to devise tests of hypotheses through the use of experimental manipulation at appropriate spatial scales, something that is expensive and difficult to implement (Carpenter *et al*., 1989). Thus, the objective of many catchment studies to date has been to develop empirical models of ecosystem processes. These objectives are best achieved using extensive sampling designs (cf. Hall, Murphy, & Aho, 1978) and analysed using gradient analysis, regression or other multivariate techniques that predict species composition (or other response variables such as physical or chemical attributes) from gradients in environmental conditions. For example, components of habitat structure can be predicted from reach- and landscape-scale factors such as riparian condition, topography, surficial geology and land use (e.g. Richards *et al*., 1996), while water chemistry can be predicted from similar reach- and landscape-scale factors (see Osborne & Wiley, 1988; Hunsacker & Levine, 1995; Johnson *et al.* this issue). The greatest shortcoming of such approaches is that underlying mechanisms are unclear.

Some of the statistical challenges facing investigators performing catchment assessments include: skewed data sets, lack of true replication, the inherent multivariate nature of the research problems, and the highly collinear and autocorrelated nature of landscape data. For example, surficial geology and elevation gradients

Table 7 Metrics developed to quantify landscape structure and pattern. (From Baker & Cai, 1992; Forman & Godron, 1986). Patch type refers to classes of patches, e.g. land use or cover type categories; patch refers to an individual polygon. FRAGSTATS (McGarigal & Marks, 1995), and R.le (Baker & Cai (1992) are available as share-ware, and can be used to calculate many of these indices

Metric	Modifier	Rationale
Total area	landscape	defines 'extent' of landscape unit of study
Patch size	patch type, patch	mean of a patch type or landscape
Patch number	landscape, patch type	total number of patches or total per patchtype
Patch density	landscape, patch type	patch number per unit area
Composition		
Proportion	landscape	proportion of each patch type
Richness	landscape	quantity of each patch type
Evenness	landscape	numeric of each patch type
Diversity	landscape	measures relative distribution of patch types
Dominance	landscape	measures relative distribution of patch types
Configuration		
Nearest neighbour	patch type, patch	distance to edge of similar patch type
Proximity	landscape, patch type	measures degree of isolation and degree of fragmentation of the landscape
Core area	landscape, patch type, patch	patch interior area; mean patch core area or total core area
Edge length	landscape, patch type	patch or landscape perimeter length
Shape	landscape, patch type	patch or landscape shape; various metrics used
Interspersion/juxtaposition	landscape, patch type	measures extent of interspersion of patch types
Contagion	landscape	configuration of patch types; measures extent of clumping and spatial arrangement of patch types

limit potential land uses; thus these data can be highly intercorrelated. Eigenanalysis techniques such as principal components analysis (PCA), can be used to reduce the total number of variables, resulting in a series of orthogonal (uncorrelated) axes that successively account for the variation in the multivariate data set. These axes can then be interpreted in terms of known variation in the data set and treated as independent variables in ANOVA or regression analyses, or interpreted along gradients of the observed variation to discern patterns among sample sites (see below).

Landscape and other spatially distributed data frequently are spatially or temporally autocorrelated (meaning that an observation can be predicted from surrounding observations), and thus lack the independence required for many tests of association (Davis, 1993; Legendre, 1993; Thompson *et al*., 1996). When observations are not independent, the degrees of freedom become inflated, thus increasing the probability of committing a Type I error. There are several approaches for addressing this problem, including modelling the spatial autocorrelation to determine the level of independence between sample points (Clifford, Richardson & Hemón, 1989; Legendre, 1993), and then removing samples to achieve spatial/temporal independence or using trend surface analysis to filter out the spatial structure. Alternatively, one can account for autocorrelation using statistical techniques described by Legendre (1993).

Lack of replication in an experimental setting can be addressed using before–after–control–impact analysis (Stewart-Oaten, Bence & Osenberg, 1992) or randomized intervention analysis (Carpenter *et al*., 1989). Some statistical techniques that can be used for catchment assessments are listed in Table 8. The discussion below is not intended to be a comprehensive review of statistical techniques used in catchment studies, but rather is meant to briefly cover methods that have potential applications for regional assessments.

Gradient analysis

Gradient analysis is rooted in community ecology, where it was used to study the distribution of species along environmental gradients, such as depth of a lake, elevation or moisture (e.g. Whittaker, 1967, 1978). Gradient analysis is based on the assumption that species (or similar end-points such as water quality variables) respond to changes along an

Table 8 Univariate and multivariate statistical techniques applicable to watershed assessments

Statistic	Major objective	Dominant uses	Variations of test
ANOVA (Sokal & Rohlf, 1995)	hypothesis testing	test differences among sample means using one (ANOVA) or more (MANOVA) dependent variables	MANOVA (Pielou, 1984; Barker & Barker, 1984), ANCOVA (Barlow *et al*., 1972)
Regression (ter Braak & Looman, 1995)	prediction	estimate parameter of interest, quantify explained variance in response variable, predict species response from environmental variable	multiple regression (Sokal & Rohlf, 1995); logistic regression; Trexler & Travis, 1993); locally weighted regression scatterplot smoothing (LOWESS; Trexler & Travis, 1993); ANCOVA (Barlow *et al*., 1972)
Principal Components Analysis (ter Braak, 1995)	pattern searching; hypothesis generation	reduce the number of variables, resulting in a series of uncorrelated (orthogonal) axes that explain the majority of the variation in the data; linear model	partial principal components analysis (ter Braak, 1995)
Correspondence Analysis (Digby & Kempton, 1987; ter Braak, 1995)	prediction; hypothesis generation	predict environmental conditions from species composition data; unimodal response model	reciprocal averaging (Digby & Kempton, 1987); weighted averaging (ter Braak & Looman, 1995); canonical correspondence analysis (CCA; ter Braak, 1995); detrended correspondence analysis (DCA; Hill, 1979b)
Multidimensional Scaling (ter Braak, 1995); Non-Metric Ordination (Digby & Kempton, 1987)	pattern searching; hypothesis generation	detect patterns of variation between sample sites, based on ranked similarity or dissimilarity in species compositions (or other response variables)	principal coordinate analysis (Digby & Kempton, 1987)
Canonical Correspondence Analysis (Digby & Kempton, 1987; ter Braak, 1995)	pattern searching; hypothesis generation; prediction	detect patterns of variation in species (or other response variable) best explained by environmental data; response model is unimodal	correspondence analysis (ter Braak, 1995); detrended correspondence analysis (Hill, 1979b)
Redundancy Analysis (ter Braak, 1995)	pattern searching; hypothesis generation; prediction	detect patterns of variation in species (or other response variable) best exaplained by environmental data; response model is linear	principal components analysis (ter Braak, 1995); regression analysis (ter Braak & Looman, 1995)
RLQ Analysis (Dolédec *et al*., 1996)	pattern searching; hypothesis generation; prediction	ordination method to detect patterns of variation among three data sets (e.g. environmental data, species, species traits)	correspondence analysis (ter Braak, 1995)
Cluster Analysis (van Tongeren, 1995)	pattern searching; hypothesis generation	classify species, response variables or sites into groups based on underlying structure of the data	see Gauch (1982)
Discriminant Function Analysis (Morrison, 1976)	pattern searching, prediction	detect patterns of variation in species (or other response variable) best exaplained by environmental data; species are first clustered using classification techniques, MDFA is then used to discriminate between groups of species based on environmental (or other predictor) variables	multiple discriminant function analysis (MDFA; Morrison, 1976)

Table 8 *continued*

Statistic	Major objective	Dominant uses	Variations of test
Randomized Intervention Analysis (Carpenter *et al.*, 1989)	hypothesis testing	detect whether nonrandom changes have occurred in a disturbed or manipulated ecosystem relative to an undisturbed ecosystem; does not imply causation	BACI: before–after–control–impacts analysis (Stewart-Oaten, Murdoch & Parker, 1986)
Before-After-Control-Impact-Pairs (Stewart-Oaten, Murdoch & Parker, 1986; Stewart-Oaten, Bence & Osenberg, 1992)	estimate effects size, estimate precision of estimates	determine the effects of unreplicated perturbations	Welch t test (Snedecor & Cochran, 1980)
Path Analysis (Bollen, 1989)	prediction	combine correlation and multiple regression techniques to establish relationships between dependent (criterion) and independent (predictor) variables through the development of a causal network model	tmultiple regression (Sokal & Rohlf, 1995)
Structural Equation Modeling (Hayduk, 1987)	prediction	model causal relations between variables by independently estimating dependence relationships among multiple variables; also known as linear equation modelling or covariance analysis	multiple regression (Sokal & Rohlf, 1995); factor analysis (Morrison, 1976); path analysis (Bollen, 1989)
Kriging (Rossi *et al.*, 1992)	prediction, mapping	interpolate values with a known variance and then generate contour maps of the interpolated data	interpolation (Haining, 1990); cokriging (Goovaerts, 1994)

environmental gradient. Gradient analysis can be divided into 'direct' and 'indirect' methods. In addition to reducing the total number of predictor variables, indirect gradient analysis techniques (e.g. PCA, Correspondence Analysis) are used to infer patterns of variations within a data set. Sites exhibiting similar patterns along environmental gradients tend to be clustered together in an ordination diagram when the major axes of variation are plotted against one another (axis 1 *v* axis 2, etc.). The patterns exhibited by the response variables are then inferred from environmental conditions, which are not measured directly (see Townsend *et al.* this issue). In contrast, the methods of direct gradient analysis (e.g. redundancy analysis, canonical correspondence analysis) combines PCA and regression analysis to predict patterns of variation from explicitly measured environmental conditions. In these tests, the ordination of the response variables is constrained by environmental variables; thus patterns of species composition, and physical or chemical attributes can be directly attributed to predictor variables. For example, species composition can be explained by variation in reach- or landscape-scale factors such as habitat structure, riparian condition, topography, surficial geology or land use pattern (cf. Richards *et al.*, 1996). These techniques are discussed in detail in ter Braak & Prentice (1988) and Jongman, ter Braak & van Tongeren (1995). The joint response among three sets of data can be investigated using a recently developed statistical technique called RLQ analysis (Dolédec *et al.*, 1996). This technique was used to examine the response of bird species and species traits to environmental variables. Statistical techniques based on PCA (e.g. canonical correspondence analysis, redundancy analysis) permit variance to be partitioned to separate effects of covariates such as land use and geology, and the *shared* effects of land use plus geology. These techniques are particularly important for explaining interactions between landscapes and stream structure/function (cf. Richards *et al.*, 1996; Johnson *et al.* this issue). Excellent discussions on partitioning variance can be found in Borcard, Legendre & Drapeau (1992) and ter Braak (1995). Analysis of covariance (ANCOVA) also can be used to separate effects of covariates (see Johnson & Covich, this issue).

Classification and clustering

Another set of multivariate statistical techniques commonly used by aquatic scientists includes the use of classification and clustering techniques. The objective of classification techniques is to develop groupings based on degree of similarity, using either non-hierarchical or hierarchical methods. Non-hierarchical methods produce groupings that are most similar, but the relationships within the group may be difficult to interpret (Norris & Georges, 1993). Hierarchical methods produce hierarchically structured subgroups based on two distinct approaches: agglomerative and divisive. Agglomerative methods consider each element to be a separate group, and combine elements to form smaller numbers of units, until a single group is formed or the appropriate criterion for group membership has been achieved. Divisive techniques begin with a single group and subdivide the groups until all the units are separate or the stopping rule is implemented (Digby & Kempton, 1987). Ordination diagrams and dendrograms are two methods used to visually assess the success of the classification process. In addition to visual displays, Procrustes Rotation (Digby & Kempton, 1987), bootstrapping and other resampling techniques may now be applied to test the success of clustering techniques (Crowley, 1992). Norris & Georges (1993) provide an excellent discussion of clustering methods for benthic macroinvertebrate surveys.

Two-way indicator species analysis (TWINSPAN; Hill, 1979a) and detrended correspondence analysis (DECORANA; Hill, 1979b) have been used to cluster macroinvertebrate species data. Group membership in a cluster can then be predicted on the basis of environmental variables using multiple discriminant analysis (cf. Marchant, Mitchell & Norris, 1984; Armitage *et al*., 1987). This method provides another technique, analogous to direct gradient analysis, to quantify associations between species and environmental gradients. Ordination methods, as well as data standardization techniques, may influence the interpretation of results, and therefore must be carefully chosen (Jackson, 1993; Norris & Georges, 1993).

Path analysis

Path analysis uses correlation and multiple regression techniques to establish relationships between dependent (criterion) and independent (predictor) variables through the development of a causal network model (Bollen, 1989). This technique is used most commonly in cases where experiments are not possible and in which variables cannot be randomized (Mitchell, 1993), a common situation in the analysis of landscape data. A path diagram summarizes the direct and indirect effects into a causal model. Path coefficients are determined using least-squares regression techniques; however, path analysis can accommodate only unidirectional causation models so no feedback is assumed. Path analysis is used primarily for testing theory and is discussed in some detail in Sokal & Rohlf (1995) and Mitchell (1993). Agreement between the path diagram (predicted correlations) and the correlations between data and prediction are assessed using goodness of fit techniques in structural equation modelling (see below; Loehlin, 1987; Hayduk, 1987; Johnson, Huggins & deNoyelles, 1991; Mitchell, 1993).

Structural equation modelling

Structural equation modelling (SEM; Hayduk, 1987), also known as linear equation modelling or covariance analysis, models causal relations between variables. This technique has its roots in multiple regression, factor analysis and path analysis. SEM independently estimates dependence relationships among multiple variables (as opposed to multiple regression, which depends on the order in which variables are tested). Variables are separated into two types: concept and indicator variables. Concept variables, such as 'ecosystem health', cannot be measured directly. Rather, indicator variables such as species richness, biotic indices, or suites of water quality measures are used as surrogates of the concept variable (Johnson *et al*., 1991). Unlike path analysis, SEM allows concept and indicator variables to be modelled separately, and to test how well indicators predict concept variables. It involves an iterative process of building and testing/confirming models for a system containing multiple variables. Path coefficients are established using maximum likelihood estimation techniques; models incorporate measurement errors and permit feedback mechanisms to account for reciprocal causation.

Geostatistics

Both temporal and spatial scales are issues of concern for basin studies, demanding trade-offs in the number, frequency and duration of sampling efforts. Funding cycles limit the duration of most projects, while economic considerations are most often the limiting factor in the number and type of samples that can be collected. 'Found' data, from previous or parallel studies, can be used to expand the number of sample points. These data frequently are collected using different methods, posing analytical problems. Two pathways exist for dealing with the problem of sparse data: (i) use existing or novel methods to increase the utility of 'found' data, or (ii) use statistical techniques to derive reliable estimates in unsampled areas to 'densify' sample points. Fuzzy logic has been used to synthesize data derived from multiple sources including databases with diverse structures (Chevenet, Dolédec & Chessel, 1994). Geostatistics or spatial statistics can be used to generate estimates with known variance in unsampled areas.

Spatial statistics or geostatistics represent a transition between mapping technologies and statistics. These statistical techniques are based on the rather simple notion that entities that are closely separated are more similar than those that are further apart. Thus, spatial dependence rather than independence is assumed. Geostatistics can provide a means to interpolate values with a known variance and then generate contour maps of the interpolated data. This technique cannot be used to compensate for sparse data sets, but rather is a tool for 'densifying' data across an area with existing data. The product of the analysis, known as a semivariogram or variogram, is a graph of the average similarity between two successive data points as a function of their separation distance (Rossi *et al.*, 1992). The variogram describes the general form, magnitude and spatial scale of the variation between points. Exploratory data analysis, including bivariate plots to reveal directional biases, is an important component of geostatistical analysis. Relationships that are biased in a particular direction, due to factors such as latitude or position on a ridge or in a river, can be detected by a variogram (Fig. 1). The variogram, then, can be used to quantify relationships as a function of distance between sites (known as the lag distance), or both distance and direction between sites. Scale effects can be detected by varying the lag distance; directional bias can be detected by computing variograms for specific directions. As variograms are highly influenced by small-scale changes in local mean and variance differences, variograms are best used in conjunction with covariance measures to detect and quantify patterns over the study area (Rossi *et al.*, 1992; Burrough, 1995). A rule of thumb is that a minimum of thirty to fifty pairs of points must be used for each lag interval (Rosse *et al.*, 1992). This constraint may be the largest impediment to the use of geostatistics in catchment assessments.

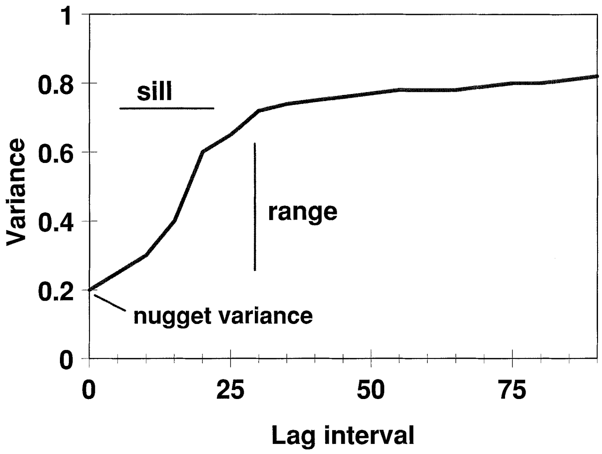

Fig. 1 Example of a variogram. *Nugget* variance represents all spatial variability that is unaccounted-for at the smallest sampling distance. The *sill* is the variogram, covariance or correlogram value at which the plot levels off. This value represents the maximum covariance observed in the data set. The *range* is the lag distance at which the variogram levels off. This distance represents the average distance within which samples continue to remain spatially autocorrelated (= range of influence). Beyond this lag distance samples are considered independent.

Spatial statistics were developed by the mining industry and only recently have been applied to ecological studies. Kriging techniques use the variograms described above to provide sample estimates with known variance in unsampled areas. Most large-scale ecological studies, however, are fundamentally multivariate in nature. Co-kriging uses spatial autocorrelations in conjunction with covarying environmental data (Goovaerts, 1994). For example, elevation was used to help predict the acid neutralizing capacity of soils in acid rain studies (Jager, Sale & Schmoyer, 1990).

Fuzzy logic

Fuzzy set theory attempts to grade objects with respect to their membership in a set; the grade of 1 represents full membership, while grade 0 represents no member-

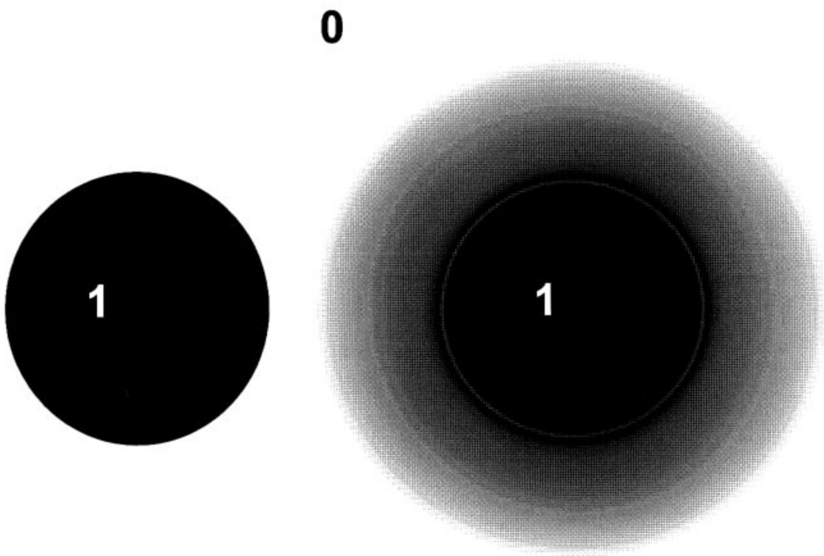

Fig. 2 A representation of fuzzy logic. In non-fuzzy systems objects or classes are categorized as full members (1) or null members (0). In fuzzy systems, gradations in membership are possible, represented by the variation in grey tones.

ship (Fig. 2; Zadeh, 1965). The magnitude of the grade (between 0 and 1) represents the extent to which the object can be regarded as belonging to a particular set. Fuzzy logic is potentially most useful in disciplines where classes lack sharp boundaries (e.g. where ambiguity, vagueness and ambivalence are common) (Burrough, 1989). Fuzzy logic has been used in soil classification and surveying (Burrough, 1989), vegetation mapping (Roberts, 1989) and other data encoding (Wang, 1990; Chevenet, Dolédec & Chessel, 1994). In traditional set theory, a set has precisely defined boundaries and class definitions, thus a pixel in a land use map is classified by one land use type or cover type despite the fact that the area covered by that pixel may contain portions of three distinct cover classes or land use classes. Fuzzy theory provides a mechanism for encoding the mixture of classes in an individual pixel. Species traits exhibit wide variation within a species; therefore, fuzzy coding can be used to assign degree of affinity of particular traits (Chevenet, Dolédec & Chessel, 1994). This technique allowed the authors to synthesize data from multiple sources to examine relationships between habitat variability and species traits by correspondence analysis.

Conclusions

New perspectives in the analysis of aquatic ecosystems at regional scales are made possible by developments in hierarchy theory, patch dynamics and the refinement of tools for quantifying spatial and temporal heterogeneity. GIS and image processing technology have allowed quantitative assessment of lateral, longitudinal and vertical components of landscapes that interact at a variety of spatial and temporal scales to influence streams. These technologies are essential for developing primary spatial databases, consisting of objects such as points, lines and polygons linked to a database management system, that can potentially be used to quantify relationships between spatially (and temporally) distributed objects. However, these tools are most powerful when they are used to calculate derived variables (e.g. slope, interpolation of spatial or temporal phenomena). When GIS is used in concert with geostatistics, multivariate statistics, or landscape models, complex relationships can be elucidated and predicted. New software tools that integrate spatial and visual technologies provide a new perspective on the analysis of landscape features. These tools will enhance the understanding of complex spatial processes for support of management and policy decisions.

The toolbox of statistical techniques available for personal computing platforms has expanded, along with the tools for creating and visualizing spatial databases. Techniques that may see expanded use in aquatic ecology include path analysis, structural equation modelling, along with univariate and multivariate kriging. While the use of multivariate statistics is becoming more common, the potential for misuse will increase as well. Judicious use of exploratory data analysis and robust techniques for correcting correlations for patchy data (Thompson *et al.*, 1996) may prevent misinterpreting patterns in landscape-scale data as applied to aquatic ecosystems.

To a certain extent, the tools discussed above have only automated functions that were previously performed manually. This suite of tools has improved the ability of aquatic ecologists to examine relationships and test theories over larger, more heterogeneous regions than were previously possible.

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