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EFFECTIVENESS OF BIOPHYSICAL CRITERIA IN THE HIERARCHICAL CLASSIFICATION OF DRAINAGE BASINS[1]

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ABSTRACT: A subwatershed base map of 84 hydrologic subregions within the Columbia River Basin (approximately 58,361,000 ha) was developed following hierarchical principles of ecological unit mapping. Our primary objectives were to inspect the relations between direct and indirect biophysical variables in the prediction of valley bottom and stream type patterns, and to identify hydrologic subregions (based on these results) that had similar aquatic patterns for which consistent management practices could be applied. Realization of these objectives required: (1) stratified subsampling of valley bottom and stream type composition within selected subwatersheds, (2) identification of direct and indirect biophysical variables that were mappable across the basin and that exerted primary control on the distribution of sampled aquatic patterns, and (3) development of hydrologic subregion maps based on the primary biophysical variables identified. Canonical correspondence analysis indicated that a core set of 15 direct variables (e.g., average watershed slope, drainage density, ten-year peak flow) and 19 indirect variables (i.e., nine subsection groups, four lithology groups, and six potential vegetation settings) accounted for 31 and 30 percent (respectively) of valley bottom/stream type composition variability and 84 and 80 percent (respectively) of valley bottom/stream type environmental variability within subsamples. The 19 indirect biophysical variables identified were used to produce an ecological unit classification of 7,462 subwatersheds within the basin by a hierarchical agglomerative clustering technique (i.e., hydrologic subregions were identified). Discriminant analysis indicated that 13 direct biophysical variables could correctly assign 80 percent of the subwatersheds to their indirect biophysical classification, thus demonstrating the strong relation that exists between indirect biophysical based classifications (ecological units) and the direct biophysical variables that determine finer-level aquatic patterns. Our hydrologic subregion classifications were also effective in explaining observed differences in management hazard ratings across all subwatersheds of the basin. Results of this research indicate that ecological units can be effectively used to produce watershed classifications that integrate the effects of direct biophysical variables on finer-level aquatic patterns, and predict opportunities and limitations for management.

(KEY TERMS: aquatic ecosystems; forest hydrology; hydrogeology; hydrologic regionalization; land use planning; water resources planning; watershed management/wildland hydrology.)

INTRODUCTION

Ecosystem management involves the maintenance of ecosystem integrity (i.e., function, composition, and structure) for future generations while providing immediate goods and services to an increasingly diverse public (Jensen and Everett, 1994). Realization of this objective requires integrated ecological assessments (Lessard *et al.*, 1999; Jensen and Bourgeron; 2001) that use hierarchical characterization of ecosystems (Table 1) to determine relations between ecological patterns and processes at multiple spatial and temporal scales. Ecosystem patterns of importance to management (e.g., vegetation, wildlife species distributions, fishery habitat) are spatially and temporally dynamic; consequently, they can only be understood through identification of the primary factors responsible for their formation (i.e., biophysical environments and ecosystem processes) (Levin 1978; Urban *et al.*, 1987).

Biophysical environments are identified through integrated mapping of ecosystem components that are relatively stable at a given scale of study (e.g., climate zones, landforms, soils) and that establish the primary constraints on the types of finer-level patterns found in an ecosystem (Bailey *et al.*, 1994; Bourgeron

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TABLE 1. Listing of Generalized Scales Used in Ecological Assessment Efforts and the Types of Biophysical Environments Commonly Described at Each Scale (Jensen *et al.* 1996). Approximate relations between USGS hydrologic unit codes and aquatic ecological units are denoted by (HUC) number.

Assessment Scale	Biophysical Environments Typical Polygon Size (km^2)	Terrestrial Ecological Units	Aquatic Ecological Units
Global	>1,000,000	Domain	Aquatic Region (HUC-1)
Continental	100,000-1,000,000	Division	Aquatic Subregion (HUC-2)
Regional	10,000-100,000	Province	River Basin (HUC-3)
Subregional	1,000-10,000 100-1,000	Section Subsection	Subbasin (HUC-4)
Landscape	10-100	Landtype Association	Watershed (HUC-5) Subwatershed (HUC-6)
Land Unit	1-10 0.1-1	Landtype Landtype Phase	Valley Bottoms, Lake Types Stream Reach, Lake Zones
Site	<0.1	Ecological Site	Channel Unit, Lake Sites

and Jensen, 1994; Jensen *et al.*, 1996). Mapping units derived by this process are commonly referred to as "ecological units" in many assessment efforts (Cleland *et al.*, 1997; Lessard *et al.*, 1999). For example, the types of landform, geology, and climatic criteria commonly used in the development of landtype association terrestrial ecological unit maps are those that exert primary control on the soil and potential vegetation patterns identified at the landtype or landtype phase level of mapping (Table 1). In a similar manner, the landtype association composition of watersheds or subwatersheds establish limits to the types of valley bottoms or stream types found in finer-level aquatic ecological units. Biophysical environments also affect ecosystem processes (e.g., fire, sedimentation) that create heterogeneity in landscape patterns (Swanson *et al.*, 1988; Baker, 1989; Turner *et al.*, 1994). Accordingly, characterizing the composition of biophysical variables at different spatial scales facilitates hierarchical classification of drainage basins useful to the management of aquatic resources, such as fishery habitat (Frissell *et al.*, 1986; Gregory *et al.*, 1991; Maxwell *et al.*, 1995; Platts, 1979). Because it is not financially prudent to study every drainage basin individually (Loptspeich, 1980), development of hierarchical watershed classifications (based on biophysical environment criteria) is essential to ongoing watershed assessment efforts (Maxwell *et al.*, 1995; Montgomery *et al.*, 1995).

Both direct and indirect biophysical variables are commonly used in ecosystem characterization efforts (Austin *et al.*, 1984, 1991). Maps of direct biophysical variables display primary landscape features or processes that are presumed to constrain finer-level patterns of interest. For example, variables such as watershed drainage density, 24-hour storm intensity, and slope are determinants of peak flows which in turn influence bankfull channel width/depth ratios and streambed particle size distribution, and thus stream type distributions within watersheds (Leopold *et al.*, 1964). Mapping such direct biophysical variables is both difficult and costly; consequently, indirect biophysical environment maps are more commonly used in most ecosystem characterization efforts (Jensen and Bourgeron, 2001).

Indirect biophysical variables are assumed to integrate the effects of direct biophysical variables on finer-level ecosystem patterns (Cleland *et al.*, 1997; Frissell *et al.*, 1986; Lessard *et al.*, 1999). Examples of ecological unit maps commonly used to depict indirect biophysical environments include: geoclimatic (McNab and Avers, 1994), potential vegetation (Daubenmire, 1968), and lithologic group settings (Jensen *et al.*, 1997). These indirect biophysical variables have been found useful to the classification and description of drainage basins for aquatic ecosystem assessment purposes (Frissell *et al.*, 1986, Maxwell *et al.*, 1995).

The Landscape Ecology Group of the Interior Columbia Basin Ecosystem Management Project has produced data sets (Jensen *et al.*, 1997) for the Columbia River Basin (CRB) useful for testing biophysical environment relations at regional, subregional, landscape and land unit assessment scales (Table 1). The primary goals of this study were twofold: (1) to identify which regional scale biophysical variables were the best predictors of valley bottom and stream type composition within subwatersheds, and (2) to contrast the effectiveness of indirect and direct biophysical variables in predicting such finer-level aquatic patterns. Additionally, we present examples of how our hydrologic classification of subbasins (based on indirect variables) is effective in describing potentials and limitations for management across the CRB.

STUDY AREA

The study area included all lands within the United States portion of the Interior Columbia River Basin (CRB), an area of ca. 58,361,400 ha. The study area encompassed lands east of the Cascade Range Crest of Washington and Oregon to the Continental Divide of Montana, the Klamath Basin, and part of the Lahontan Basin. A total of 13 Ecological Reporting Units (ERUs) were previously identified in the basin at a regional assessment scale to facilitate integrated descriptions of biophysical environments, ecological processes, effects of management activities, and landscape management opportunities (Jensen *et al.*, 1997). Delineation of ERUs was accomplished through synthesis of three primary base maps utilizing input from all disciplines of the CRB Science Integration Team. These base maps included: (1) hydrologic regions based on aggregation of similar United States Geologic Survey (USGS) fourth code subbasins using geoclimatic and flow regime criteria, (2) similar terrestrial environments as determined by geoclimatic section and subsection composition, and (3) similar county settings based on socio-economic criteria such as economic resiliency and sense of place (Jensen *et al.*, 1997). These three base maps provided similar stratifications of the CRB and were used in developing initial ERU boundaries (i.e., areas of overlap between the three maps were identified). Final ERU delineations were developed following sixth code subwatershed boundaries (hereafter referred to as subwatersheds) that best approximated initial ERU boundaries. Descriptions of the geoclimatic, potential vegetation, and hydrologic properties of the ERUs within the Columbia River Basin are provided by Jensen *et al.* (1997).

METHODS

Accomplishment of the goals of this study involved the following ecosystem characterization and analysis steps:

1. Stratified subsampling of valley bottom and stream type composition within selected subwatersheds of the CRB.
2. Association of regional scale direct and indirect biophysical variables with each subwatershed of the CRB.
3. Determination of relations between finer-level valley bottom and stream type patterns and regional level biophysical variables.
4. Classification of subwatersheds across the CRB based on similarity of important indirect biophysical variables.
5. Assessment of the correspondence between indirect biophysical variable-based subwatershed classifications and direct biophysical variables.
6. Assessment of the effectiveness of subwatershed classifications in predicting hazards and opportunities for management across the CRB.

Each of these characterizations and analyses steps are briefly described below.

Stratified Subsampling of Valley Bottoms and Stream Types

Valley bottom types (Cupp, 1989; Frissell, 1992) and stream types (Rosgen, 1996) were selected as finer-level patterns to be predicted in this study because of their interpretive importance to management (Jensen *et al.*, 1997). These patterns are also those that are commonly addressed at the land unit scale of aquatic ecological unit mapping (Table 1) and represent appropriate patterns to be predicted at the landscape and possibly the subregional scale of ecological assessment (Maxwell *et al.*, 1995). The criteria used in distinguishing valley bottoms and stream types in this study are presented in Table 2 and are more fully described by Jensen *et al.* (1997).

Approximately 7,462 subwatersheds were delineated within the 164 existing USGS subbasins of the study area based on topographic and drainage basin size criteria (Jensen *et al.*, 1997). These subwatersheds typically ranged from 12,000 to 32,000 ha in size and were used extensively in subsampling within the CRB, development of ecological reporting units, and in the delineation of hydrologic subregions. A total of 500 subwatersheds (approximately 7 percent

TABLE 2. Description of Valley Bottoms and Stream Types Identified in Subwatershed Samples. These valley bottoms and stream types follow classification criteria previously described by Frissell (1986) and Rosgen (1996), respectively.

Variable Code	Description
	Valley Bottom Types
VB1	Highly confined (< 16 m), steep slope (> 6 percent)
VB2	Moderately confined (16-64 m), steep slope
VB4	Highly confined, moderate slope (2-6 percent)
VB5	Moderately confined, moderate slope
VB6	Unconfined (> 64 m), moderate slope
VB8	Moderately confined, gentle slope (< 2 percent)
VB9	Unconfined, gentle slope
	Stream Types
A	Steep, entrenched, low sinuosity channels
B	Moderate gradient, entrenchment, and moderate sinuosity channels
C	Low gradient, meandering, alluvial channels
D	Low gradient, braided, unstable channels
E	Low gradient, high sinuosity, stable channels
F	Low gradient, entrenched, stable channels
G	Entrenched, unstable channels
L	Lakes
W	Wetlands

of the CRB) were selected for finer-level characterization of valley bottom and stream type composition based on a stratified random sampling design (Jensen *et al.*, 1997).

Association of Direct and Indirect Biophysical Variables to Subwatersheds

A total of 55 biophysical variables considered to directly influence the distribution of valley bottoms and stream types across the basin were attributed to each subwatershed of the CRB through various ecological process models and Geographic Information System (GIS) map overlay procedures (Jensen *et al.*, 1997). These variables included 15 watershed morphometric parameters, ten-year peak flow estimates, three map-based estimates of climate, and 36 raster-based climatic attributes. Morphometric parameters were calculated for each watershed using a 90 m digital elevation model, 1:100,000 scale stream network maps, and 1:100,000 scale watershed maps with ARCINFO GIS software. These morphometric parameters included watershed perimeter; total, perennial, and intermittent stream lengths; drainage density; sediment transport efficiency; average slope; composition of 0-10, 10-30, 30-50, and 50+ percent slope classes; relief; and mean, minimum, and maximum elevations.

Ten-year peak flow estimates were derived for each subwatershed following regionalized regression relations developed for the CRB by the USGS (Jensen *et al.*, 1997). Vector maps of climatic attributes included two-year, 24-hour storm intensity, 20-year average annual precipitation, and 30-minute storm kenetic energy maps (U.S. EPA, 1980). A total of 36 raster-based climatic attributes were summarized for each subwatershed based on interpolation of measured daily temperature and precipitation data from various weather stations throughout the CRB using a modification of the mountain climate model (MTCLIM) (Hungerford *et al.*, 1989). These climatic attributes were attributed to a 2 km raster base across the CRB and included temperature, precipitation and solar loading values for year-long, seasonal, growing season, January, July, and August time periods.

Composition of 1:500,000 scale lithology, geoclimatic subsection, and regional potential vegetation ecological unit maps were attributed to each of the 7,462 subwatersheds within the CRB to facilitate development of hydrologic subregion watershed classifications. A total of 92 indirect biophysical environments were identified from these maps in this analysis. These environments included 41 lithologic groups, 39 subsection groups, and 12 potential vegetation settings (Jensen *et al.*, 1997).

A variety of spatial projections were used in this analysis to describe various biophysical environment variables. Raster-based scales ranged from 90m for topography (because a 30m base was not consistently available) to 2 km for climate attributes. In a similar manner, vector projections ranged from 1:100,000 for hydrography to 1:500,000 for both state lithology and subsection group maps. We acknowledge that these discrepancies in spatial data may contribute to diminished performance in subsequent modeling; however, these were the only data sets available for our analysis. Ideally a variety of spatial scales would have been assessed in determining the ultimate predictiveness of each biophysical variable. Unfortunately, this was not possible given financial and time constraints.

Determination of Relations Between Finer-Level Aquatic Patterns and Biophysical Variables

Biophysical variables assumed to influence valley bottom/stream type distribution across the CRB either directly (e.g., drainage density, watershed slope) or indirectly (e.g., climate zones, landforms, lithology) were tested by multivariate ordination procedures using Canonical Correspondence Analysis (CCA) (terBraak, 1992). CCA was used to determine the minimal set of biophysical variables that best explained the observed variance in valley bottom/stream type composition of subsamples. Ordination analysis was performed using default options of CANOCO statistical software (terBraak, 1992), and important biophysical variables were identified through multivariate forward selection procedures. Separate CCAs were performed for direct and indirect biophysical variables in this analysis.

A total of four ordination axes (linear combinations of valley bottom/stream types and biophysical variables) were derived to explain relations between valley bottom/stream type and biophysical variables for both the direct and indirect variable data sets. Monte Carlo permutation tests were performed on both the first canonical ordination axis and all ordination axes (collectively) to determine their significance in explaining valley bottom/stream type variance. Interset correlation of biophysical variables with valley bottom/stream type scores along the first canonical ordination axes of each CCA were also calculated to facilitate description of the environmental relations present in the subsample data set.

Classification of Subwatersheds. Subregional assessment scale classifications of subwatersheds were developed for each of the 13 ecological reporting units identified for the CRB using the indirect biophysical variables that best explained the observed variance in valley bottoms and stream types across the CRB. A model-based clustering algorithm (Banfield and Raftery, 1993) was used in identifying the optimum number of hydrologic subregion classifications for each ERU with the MCLUST program of S-PLUS (Statistical Sciences, Inc., 1993). Results of this analysis were used to stipulate the maximum number of classifications (clusters) to be developed within each ERU. Assignment of subwatersheds to hydrologic subregion classifications by ERU was accomplished using the Ward's (1963) hierarchical agglomerative clustering method of MCLUST.

Assessment of the Correspondence Between Indirect and Direct Biophysical Variables

Discriminant analysis (Wilkinson, 1989) was used to test the assumption that direct biophysical variables were related to indirect biophysical variable classifications (i.e., ecological units). Specifically, discriminant functions were developed by ecological reporting unit in this analysis to test the ability of direct biophysical variables to place subwatersheds into their correct hydrologic subregion classification (as determined by indirect biophysical variable criteria). Correlations between direct biophysical variables and the hydrologic subregion membership of each subwatershed were also calculated by ecological reporting unit using the DISCRIM program of SYSTAT. This analysis was performed to determine which direct biophysical variables best explained differences in indirect biophysical variable based hydrologic subregion classifications across the CRB.

Assessment of the Effectiveness of Subwatershed Classifications

Various watershed and stream hazard ratings were developed for each subwatershed of the CRB following U.S. EPA (1980) and other procedural guidelines (Jensen *et al.*, 1997). To determine the appropriateness of hydrologic subregion classifications for management use, an analysis of variance and Fisher's Least Significant Difference Method were used to determine if hydrologic subregions significantly minimized the observed variance in watershed hazard and stream hazard ratings across all subwatersheds of the CRB. To facilitate direct comparison of hazard ratings between subwatersheds of the CRB in this analysis, the absolute value of each unit was normalized to reflect the percentage of other subwatersheds in the CRB that possessed an equal or smaller value (i.e., absolute values were converted to a cumulative frequency distribution value that ranged between 0 and 100).

RESULTS

Identification of Appropriate Direct and Indirect Biophysical Variables for Watershed Classification

Based on CCA, the 54 direct biophysical environment variables studied explained 43 percent of the variance in the valley bottom/stream type composition of subsamples. However, a reduced list of only 15 direct variables (each having greater than 80 percent confidence) accounted for 31 percent of the valley bottom/stream type composition variance (Table 3).

The total percent variance of valley bottom/stream type composition explained by all indirect biophysical environment variables in CCA was 25, 29, and 14 percent for 41 lithologic groups, 39 subsection groups, and 12 potential vegetation settings, respectively. A reduced set of the optimum four lithologic groups, nine subsection groups, and six potential vegetation settings (as determined at an 80 percent confidence level) were combined in a separate CCA run to determine the relative importance of each variable in explaining valley bottom/stream type composition. Forward selection of these 19 variables indicated that 30 percent of the valley bottom/stream type composition variance was explained by this reduced list of variables (Table 4). This result suggests that the combination of such factors as lithology, geoclimatic subsections, and potential vegetation in the construction of integrated ecological unit maps produces a product that is superior to their individual components in the prediction of finer-level aquatic features. Only variables with significance greater than or equal to an 80 percent confidence level (as determined by a Monte Carlo permutation test) are displayed in Tables 3 and 4. An 80 percent confidence level was chosen because this level is commonly used by land managers in ecological assessments and it facilitated inclusion of biophysical variables in classification analysis that were considered important to the prediction of finer-level aquatic patterns.

To investigate the relations between valley bottom/stream types and both direct and indirect biophysical variables, a total of four canonical ordination axes were constructed for each of the direct and indirect biophysical environment variable lists displayed in Tables 3 and 4. The four axes derived using direct variables accounted for 47, 69, 77 and 84 percent, respectively, of the cumulative variance in valley bottom/stream type-environmental relations. In comparison, axes derived using indirect variables

TABLE 3. Description of the 15 Direct Biophysical Environment Variables Most Useful in Explaining Valley Bottom/Stream Type Composition Variability Within Subwatershed Samples.

Variable Code	Description	Cumulative Variance Explained
SLOPE	Percent slope, calculated from a 90m digital elevation model	14
24HR	Two-Year maximum 24-hour storm intensity (cm)	19
DDENSITY	Drainage density (total stream length/watershed area)	21
JULYTAVG	Average daily air temperature (Celcius) for July	23
WNSRAD	Average daily solar radiation loading (langleys) for winter months (December, January, February)	24
MINZ	Minimum elevation (m)	25
AUGTAVG	Average daily air temperature for August	26
TDEW	Average annual daily dew point temperature	27
STE	Sediment transport efficiency (DDENSITY x SLOPE)	28
WNTMAX	Average daily maximum air temperature for winter months	29
FLOOD10	Estimated pore point, 10-year peak flow level (cfs)	29
PRECIP	20-year average annual precipitation (cm)	30
RELIEF	Relief ratio (MAXZ-MINZ/Watershed Area)	30
MAXZ	Maximum elevation	31
SUPRCP	Average daily precipitation for summer months (June, July, August)	31

TABLE 4. Description of the 19 Indirect Biophysical Environment Variables Most Useful in Explaining Valley Bottom/Stream Type Composition Variability Within Subwatershed Samples.

Variable Code	Description	Cumulative Variance Explained
M242-01	Glaciated, igneous and sedimentary mountains with medium textured soils	5
SHD	Shrublands – hot, dry	8
M332-02	Granitic foothills with medium textured soils	10
Litho-23	Mafic pyroclastics	13
342-02	Basalt plateaus with coarse textured soils	15
Litho-17	Lake sediments and playas	17
Litho-25	Mafic volcanic flows	18
FCW	Forestlands – cold, wet	19
M242-02	Ash mantled, basalt plains with fine textured soils	20
M331-06	Sedimentary/volcanic mountains with fine textured soils	21
Litho-19	Loess	22
FCD	Forestlands – cold, dry	23
HHW	Herbaceous lands – hot, wet	24
342-05	Volcanic tuff foothills with medium textured soils	25
FHW	Forestlands – hot, wet	26
FHD	Forestlands – Hot, dry	27
M242-04	Alluvium intermontane basins with fine textured soils	28
342-04	Lacustrine plateaus with fine textured soils	29
M333-03	Glaciated mountains with medium textured soils	30

explained 39, 58, 69, and 80 percent, respectively, of the valley bottom/stream type environmental variance. A Monte Carlo permutation test of significance was performed on the first canonical axis of each ordination. Axis 1 was found to be highly significant (P = .01) for both the direct and indirect biophysical environment ordinations. A test of combined axes significance also indicated highly significant relations (P = .01) were achieved in both ordinations.

Interset correlations of biophysical variables with valley bottom/stream type scores along the first canonical ordination axes of CCA indicated that valley bottoms and stream types displayed significant relations to the biophysical variables studied. For example, in the direct variable ordination, environments with steep, moderately to highly confined valley bottom types (i.e., VB1, VB2) and high energy stream types (i.e., A) were correlated with higher average watershed slopes (SLOPE, r = .68), sediment transport efficiencies (STE, r = .67), relief ratios (RELIEF, r = .58), average annual precipitation (PRECIP, r = .41), 24-hour storm intensities (24HR, r = .39) and maximum elevation (MAXZ, r = .38). Conversely, environments with more gentle valley bottom slopes and lower confinement (e.g., VB 5, VB 8, VB 9) and lower energy stream types (e.g., D, E, F, G) were associated with watersheds that had higher July (JULYTAVG, r = -.42) and August (AUGTAVG, r = -.40) air temperatures, higher maximum winter air temperatures (WNTMAX, r = -.38), and high winter solar radiation loadings (WNSRAD, r = -.23). These relations are consistent with observed distribution patterns of these valley bottoms and stream types across the CRB (Jensen *et al.,* 1997).

Indirect biophysical environment ordination results suggest that lower gradient, less confined valley bottom types (e.g., VB 8, VB 9) and lower energy stream types (e.g., D, E, F, G) tend to occur in ecological unit settings that contain: hot, dry shrublands (SHD, r = .30), basalt plateaus with coarse textured soils (342-02, r = .29), lake sediments and playas (Litho-17, r = .21), alluvium intermontane basins with medium textured soils (342-04, r = .20), and mafic volcanic flows (Litho-25, r = .20). Steeper valley bottom types (e.g., VB 1, VB 2, VB 6) and high energy stream types (i.e., A) were associated with: glaciated, igneous and sedimentary mountains with medium textured soils (M242-01, r = -.33), cold-wet and cold-dry forestlands (FCW, r = -.32; FCD = -.26), and sedimentary/volcanic mountains with fine textured soils (M331-06, r = -.10).

These relations are also consistent with observed valley bottom/stream type patterns across the CRB (Jensen *et al.,* 1997).

Development of Hydrologic Subregion Classifications. The 19 indirect biophysical environment variables listed in Table 4 were used to develop hydrologic subregion classifications of subwatersheds by ERU (Figure 1). Based on model-based clustering of indirect biophysical environment data, we suggest that 84 hydrologic subregions provide optimum separation of subwatersheds across the CRB. The number of hydrologic subregions identified within each ERU by this analysis ranged from four to ten.

Indirect biophysical environment maps (Ecological Units) are commonly assumed to integrate the affects that direct biophysical variables (e.g., climate, watershed slope) have on finer-level patterns (e.g., stream types) of ecological relevance (Austin *et al.,* 1984; Austin and Heyligers, 1991). Discriminant analysis was used to test this assumption which indicated that collectively, 80 percent of the 7,462 subwatersheds within the CRB were correctly assigned to their corresponding hydrologic subregion classification based on 13 of the 15 direct biophysical variables listed in Table 3. Variables JULYTAVG (average daily July air temperature) and STE (sediment transport efficiency) were omitted from discriminant function calculations because they displayed high covariance with other direct variables and did not significantly improve discriminant function predictions. Success of discriminant predictions by ERU ranged from 74 to 95 percent (Table 5). These results indicate that our classifications of subwatersheds based on indirect biophysical criteria provides a reasonable synthesis of the direct biophysical variables that influence the distribution of finer-level valley bottom and stream type patterns across the CRB. The use of ecological units in watershed classification (Maxwell *et al.,* 1995) is strongly supported by these findings.

Correlations between direct biophysical variables and the hydrologic subregion membership of each subwatershed suggest that the types of direct biophysical environments indicated by hydrologic

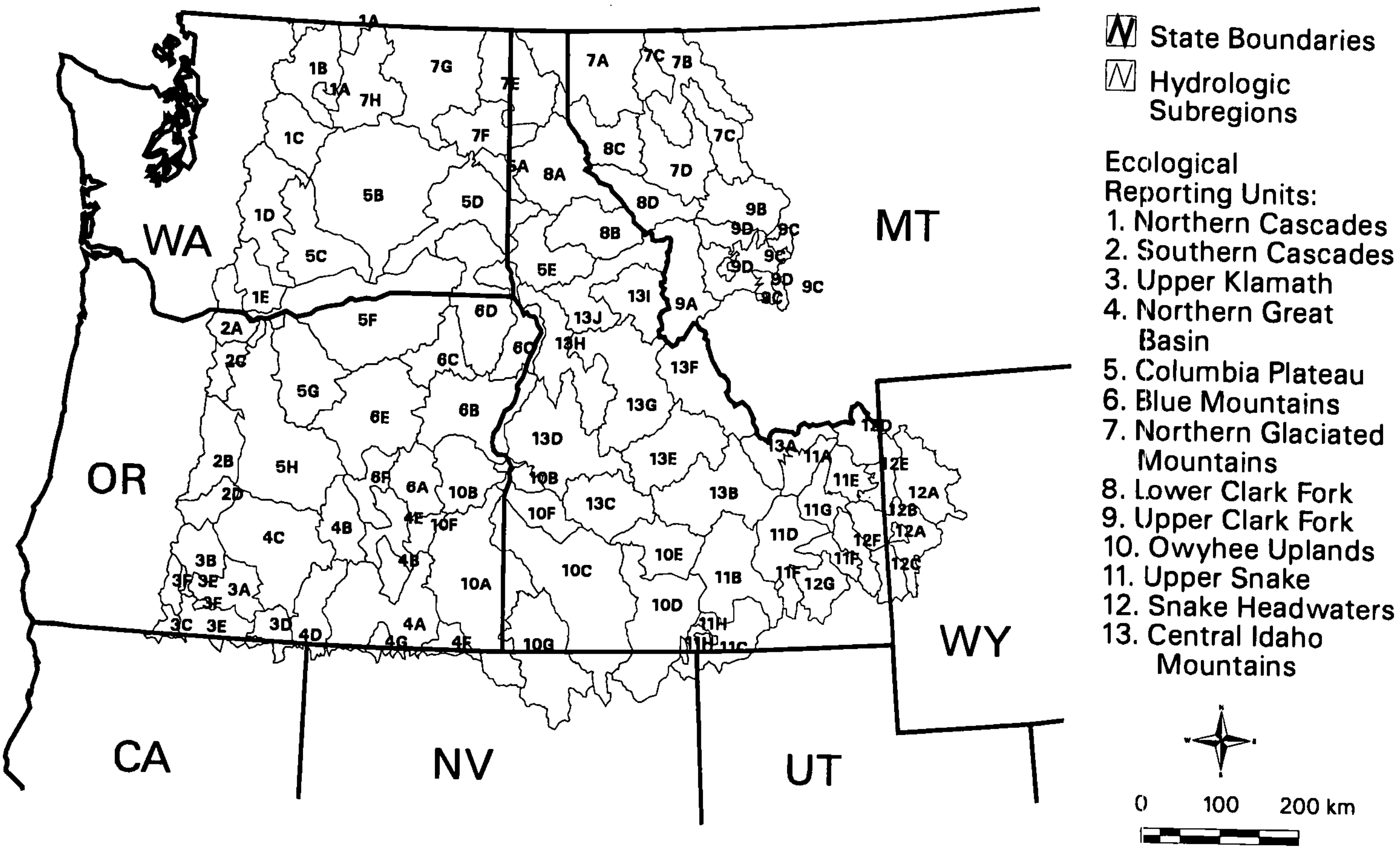

Figure 1. Map of Hydrologic Subregions (A to J) by Ecological Reporting Unit (1 to 13) Within the Columbia River Basin Aquatic Assessment Area.

TABLE 5. Percent of Subwatersheds Within an Ecological Reporting Unit Correctly Assigned to Their Indirect Biophysical Hydrologic Subregion Classification Based on Discriminant Analysis of Direct Biophysical Variables.

Ecological Reporting Unit ID/Name	Total Number of Sixth Code Watersheds	Total Number of Hydrologic Subregions Identified	Percent of Watersheds Correctly Assigned to Hydrologic Subregion
1. Northern Cascades	338	5	79
2. Southern Cascades	140	4	95
3. Upper Klamath	163	6	88
4. Northern Great Basin	491	7	74
5. Columbia Plateau	1089	8	80
6. Blue Mountains	695	6	83
7. Northern Glaciated Mountains	949	8	77
8. Lower Clark Fork	415	4	92
9. Upper Clark Fork	306	4	91
10. Owyhee Uplands	956	7	74
11. Upper Snake	301	8	77
12. Snake Headwaters	387	7	82
13. Central Idaho Mountains	1232	10	77

TABLE 6. Squared Multiple Correlation Coefficients (R2) Between Hydrologic Subregion Membership of Each Subwatershed Within an Ecological Reporting Unit (ERU) and Direct Biophysical Variables. Variance in direct variables not significantly reduced by hydrologic subregion stratification (as determined by an ANOVA interpreted at the P = .01 level) is indicated by an asterisk (*). Variables are defined in Table 3.

Variable	ERU1	ERU2	ERU3	ERU4	ERU5	ERU6	ERU7	ERU8	ERU9	ERU10	ERU11	ERU12	ERU13
SLOPE	.36	.26	.38	.06	.26	.16	.31	.08	.16	.03	.31	.32	.27
24HR	.08	.13	.64	.26	.43	.09	.48	.33	.28	.18	.12	.10	.33
MAXZ	.20	.09	.29	.13	.34	.14	.51	.29	.37	.17	.30	.42	.51
WNSRAD	.26	.82	.57	.62	.79	.58	.38	.47	.05	.23	.40	.56	.76
WNTMAX	.21	.06*	.28	.17	.25	.26	.57	.14	.14	.42	.52	.38	.27
SUPRCP	.35	.18	.30	.39	.68	.35	.84	.43	.36	.44	.46	.56	.50
RELIEF	.21	.17	.23	.08	.25	.14	.15	.14	.15	.05	.32	.21	.23
DDENSITY	.04	.38	.37	.08	.09	.03	.10	.09	.18	.16	.32	.32	.10
TDEW	.20	.82	.71	.40	.56	.27	.80	.48	.10	.37	.71	.73	.35
PRECIP	.01*	.10	.66	.13	.42	.07	.45	.16	.27	.03	.15	.49	.44
MINZ	.08	.64	.49	.10	.36	.36	.67	.07	.23	.39	.28	.57	.48
AUGTAVG	.20	.07*	.36	.15	.28	.16	.43	.24	.40	.21	.24	.63	.29
FLOOD10	.16	.40	.16	.14	.16	.17	.04	.28	.06	.22	.19	.02*	.28

subregions changes by ERU across the CRB (Table 6). For example, in the Southern Cascades (ERU 2) winter solar radiation loading (WNSRAD, r^2 = .82), average annual dew point temperature (TDEW, r^2 = .82), and minimum watershed elevation (MINZ, r^2 = .64) display the strongest relation to differences in hydrologic subregions. A contrast to this situation is observed in the Upper Clark Fork (ERU 9), where average daily August air temperature (AUGTAVG, r^2 = .40), maximum watershed elevation (MAXZ, r^2 = .37) and average summer precipitation (SUPRCP, r^2 = .36) display the strongest relation with subwatershed hydrologic subregion membership. Variance in each direct biophysical environment variable was significantly reduced by hydrologic subregion stratifications in most ERUs as determined by an ANOVA test interpreted at the P = .01 level (Table 6).

Evaluation of Hydrologic Subregion Map Performance. The primary objective of any ecologic unit map is to delineate areas that possess similar potentials for the intended use of the map (Bailey *et al.*, 1994; Jensen *et al.*, 1996). The effectiveness of our hydrologic subregion map (Figure 1) in meeting this objective was assessed by determining its ability to minimize the observed variance in watershed and stream type management hazard ratings across all subwatersheds of the CRB. Results of this assessment are provided in the following discussion.

An ANOVA was performed to determine if hydrologic subregions (Figure 1) were effective in explaining management hazard rating variability across subwatersheds of the CRB. Results of this analysis indicated that hydrologic subregions were highly effective (P = .01) in explaining the watershed and stream management hazard variability of subwatersheds across all ERUs (Table 7).

We further tested the effectiveness of our hydrologic subregions in explaining differences in mean watershed hazard ratings within each ERU through use of Fisher's Least Significant Difference Method with a significance level of P = .01. Results of this analysis indicated that an average 65 percent of the hydrologic subregions displayed significantly different mean values for erosion, 46 percent for mass wasting, and 50 percent for sediment based on all possible comparisons of subregions within an ERU (Figure 1). Greatest differences in mean hazard ratings between hydrologic subregions were observed in the Northern Cascades (erosion equals 80 percent, mass wasting equals 50 percent, sediment equals 80 percent) and the Northern Glaciated Mountains (erosion equals 86 percent, mass wasting equals 89 percent, sediment equals 68 percent). Fewest differences in mean hazard ratings were found in the Northern Great Basin (erosion equals 36 percent, mass wasting equals 23 percent, sediment equals 18 percent) and the Owyhee Uplands (erosion equals 38 percent, mass wasting equals 38 percent, sediment equals 29 percent). These results suggest that our hydrologic subregions do a better job of partitioning differences in management hazard ratings within higher elevation, mountainous settings than in lower elevation, relative flat rangeland environments.

DISCUSSION

In recent years considerable attention has been focused on understanding the linkages between stream habitats and the broader scale drainage networks and biophysical environments in which they occur (Hynes 1975; Warren 1979; Frissell *et al.*, 1986; Gregory *et al.*, 1991). For example, Platts (1979) established that fish assemblages often are more closely associated with the geomorphic features of drainage catchments than with finer-level channel or instream habitat features. In a similar manner, Allen *et al.* (1997) observed that instream indices of biotic integrity and habitat are more closely correlated with catchment level land use practices than with localized

TABLE 7. Significance of Hydrologic Subregion Classifications in Explaining Observed Management Hazard Rating Variability Across All Subwatersheds of the Columbia River Basin [between and within group degrees of freedom are 83 and 7,373 (respectively) for all F ratio and P value calculations].

Management Hazard Rating	F-Ratio	P-Value
Watershed Hazards		
Erosion (with existing vegetation cover)	66.5	0.01
Erosion (without existing vegetation cover)	177.8	0.01
Sediment (with existing vegetation cover)	79.9	0.01
Sediment (without existing vegetation cover)	154.1	0.01
Sediment Transport	116.5	0.01
Mass Wasting	146.6	0.01
Debris Flow	130.6	0.01
Stream Hazards		
Increased Sediment and Flow Sensitivity	71.0	0.01
Decreased Flow Sensitivity	141.6	0.01
Streambank Sensitivity	97.0	0.01
Riparian Vegetation Sensitivity	81.5	0.01
Recovery Potential	129.6	0.01

riparian features. These studies suggest the importance of recognizing that riverine systems are connected systems (Vannote *et al.,* 1980) and, therefore, can only be understood within a drainage basin context (Loptspeich, 1980; Maxwell *et al.,* 1995). Accordingly, the multi-scale classification of drainage basins based on similarity of biophysical variables (and presumably the ecological processes they influence) is critical to furthering our understanding of aquatic systems and implementation of such insights within watershed planning processes (Montgomery *et al.,* 1995; USDA, 1995).

The primary challenge, therefore, to future watershed planning efforts is to clearly state the rationale for classifying drainage basins (at multiple spatial scales) based on similarity of biophysical variables. Omernik and Bailey (1997) suggest that drainage basins are only appropriately classified within the context of larger ecoregions. In a similar manner, Maxwell *et al.* (1995) suggest that drainage basins can be characterized and assessed on the basis of the broad-level geoclimatic setting (indirect biophysical environment) in which they are nested to provide a contectual basis for analysis. Maxwell *et al.* (1995) further suggest that drainage basins may be further classified or grouped based on similarities of finer resolution ecological unit information. We believe this to be an appropriate method for multi-scale watershed classification. For example, in our study subwatersheds were first stratified by ERUs which approximated section level ecoregion stratifications (Table 1). We then grouped subwatersheds within these strata based on similarities of indirect biophysical variable properties that approximated the subsection and landtype association levels of terrestrial ecological unit mapping (Table 1).

Results of our study suggest that a two-tiered, multi-scale classification of subwatersheds based on indirect environmental variables (ecological units) is effective in predicting the distribution of valley bottoms and stream types that are commonly mapped at much finer spatial resolution (Table 1). Furthermore, our results indicate that indirect biophysical variables can efficiently be used as surrogates for the direct biophysical variables that influence aquatic patterns and that classifications based on indirect biophysical variables are effective in minimizing the variance in management interpretations across watersheds.

Use of ecological unit maps (indirect biophysical variables) in watershed classification is supported by this research and should be considered in other ecosystem characterization efforts (Noss, 1983; Omernik, 1987; FEMAT, 1993; Montgomery *et al.,* 1995; USDA, 1995). We offer the following recommendations to assist such watershed classification efforts:

1. Explicit description of the finer-level aquatic patterns to be predicted by a watershed classification (e.g., stream types, channel unit types) need to be clearly identified to facilitate subsequent testing of classification accuracy and performance.

2. The coarser-level (mappable) biophysical variables considered to influence the finer-level aquatic patterns of interest need to be identified and tested at multiple spatial scales. For example, climate interpolation models (Thornton *et al.,* 1997) can be run at 30 m, 90 m, and 1 km resolution to access the spatial scale at which different climatic attributes influence the patterns of interest.

3. Indirect biophysical variables should be characterized and tested separately at multiple spatial scales before integration of such variables occurs in ecological unit mapping. For example, ecosystem components such as landforms, lithology, potential vegetation, and climate zones can be described individually within appropriate hierarchical structures (Jensen and Bourgeron, 2001) and then attributed to similar scale drainage basin delineations in the development of ecological unit classifications for aquatic systems (as performed in this study).

4. Gradient oriented sampling (Austin *et al.,* 1984; Austin and Heyligers, 1991; Bourgeron *et al.,* 1994) should be utilized in field sampling to facilitate direct testing of assumed coarse level biophysical and finer-level aquatic pattern relations.

5. Hierarchical indices of anthropogenic change (Allen *et al.,* 1997) need to be developed and used in conjunction with biophysical environment criteria in the multi-scale classification of watersheds in future ecological assessment efforts (Lessard *et al.,* 1999).

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