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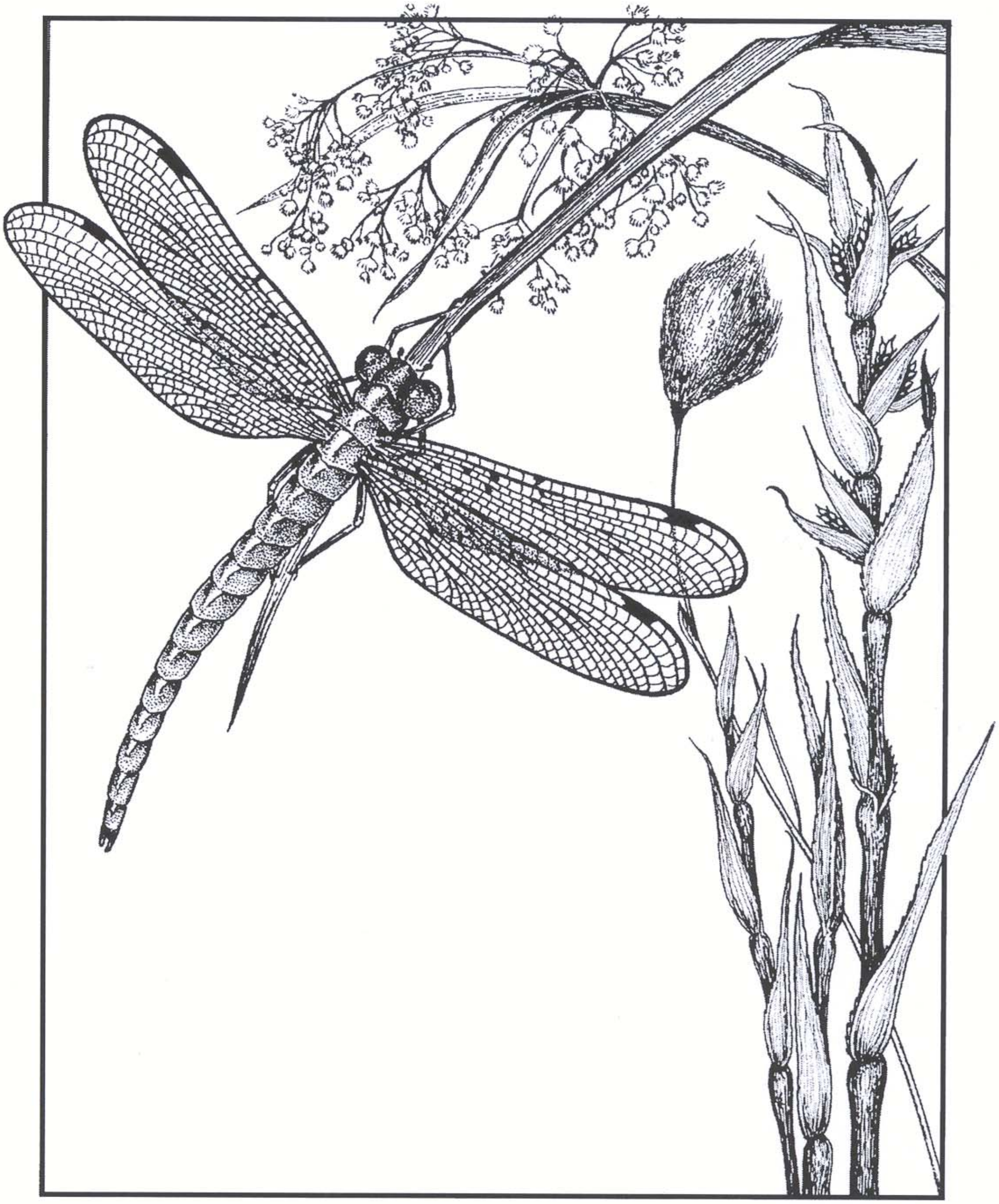
HYDROGEOMORPHIC WETLAND PROFILING: AN APPROACH TO LANDSCAPE AND CUMULATIVE IMPACTS ANALYSIS



Environmental Monitoring and
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HYDROGEOMORPHIC WETLAND PROFILING: AN APPROACH TO LANDSCAPE AND CUMULATIVE IMPACTS ANALYSIS

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EXECUTIVE SUMMARY

Cumulative impacts and their resultant cumulative effects have become an important focus of both environmental regulation and scientific investigation because of their potentially severe consequences. For example, the National Environmental Policy Act (38 CFR Sect. 1500.6) and Section 404(b)(1) of the Clean Water Act (40 CFR 230.11) explicitly require that projects proposing impacts to wetlands consider the cumulative effects of the actions and not solely the direct impacts of the project. Despite the recognized potential for significant, negative consequences, cumulative effects are seldom sufficiently addressed in environmental management because of the lack of effective tools to describe and assess them.

This study developed a synthetic, hierarchical and scalable approach to landscape characterization and cumulative impacts analysis that is based on current scientific thought of how wetlands develop and function within landscapes. Specifically, this study investigated whether a reference-based approach to cumulative impacts analysis could be developed by using a hydrogeomorphically-based version of landscape profiles (Brinson 1993, Bedford 1996, Gwin et al. 1999) in conjunction with the concepts of landscape formation and processes forwarded by Montgomery (1999), Winter (2001), and Omernik and Bailey (1997). This approach, termed Hydrogeomorphic Wetland Profiling (HGM WP), seeks to refine coarse acreage-based approaches by applying a functionally-based framework to provide a landscape-scale characterization of wetland resources that is useful to regulatory, management, mitigation, and conservation programs.

Most basically, HGM WP is a method of summarizing the abundance and diversity of HGM wetland types within a given ecoregion or portion thereof. Three related applications of the HGM WP approach are detailed in this report, landscape characterization, cumulative impacts analysis, and first-order approximation of wetland-related cumulative effects.

Landscape characterization

This research asserts that HGM WP provides a valuable means of characterizing of landscapes with regard to their wetland component and the functions occurring within. Using a functionally-based classification, such as HGM, to summarize the abundance and diversity wetlands provides an estimation of the potential types and magnitude of wetland functions performed in that landscape. For instance, a landscape with a high proportion of slope wetlands would be expected to predominately perform the functions ascribed to slope wetlands, such as groundwater discharge, carbon retention, and maintenance of stream base flow.

Cumulative Impacts Analysis

The main focus of the HGM WP approach is to provide a practically implementable, reference-based approach to wetland cumulative impacts analysis. Specifically, HGM WP quantifies impacts to the abundance and diversity of wetlands resulting from outright wetland destruction or functional conversion (i.e. from one HGM class to another). This analytical focuses stems from the idea that these whole-wetland impacts are the primary driver or “forcing factor” of wetland functioning at the landscape scale.

The key principle underlying HGM WP in a reference-based capacity is that the abundance and diversity of wetlands is dictated by the physical setting of the landscape (Bedford 1996). Consequently, it follows that landscapes possessing similar physical attributes should possess similar patterns of wetland abundance and diversity. That is, physically similar landscapes would be expected to have similar HGM WPs. Conversely, physically disparate landscapes should have distinctly different HGM WPs. If these hypotheses are true, then landscape references appropriate for cumulative wetland impact analyses may be defined through analysis of comparable, minimally-impacted landscapes. This study tested the validity of these hypotheses and tested the viability of the HGM WP approach in cumulative impacts analysis.

First-order Approximation of Cumulative Effects

While some agencies and investigators have chosen to synonymize cumulative impacts and cumulative effects (e.g., CEQ 1997), it is important to differentiate the terms. Following Leibowitz et. al. (1992), cumulative wetland *impacts* are defined as the sum of wetland impacts that have occurred across a given landscape, while cumulative *effects* are the resultant environmental ramifications.

Since wetland profiling utilizes a functionally-based wetland classification system, I suggest that evaluation of the changes in the relative abundance of HGM wetland classes provides an index of the loss of the specific functions associated with the wetlands destroyed. Moreover, since loss of wetland function is the root of wetland-mediated cumulative effects, evaluation of HGM WP alterations provides a picture of the potential types of cumulative effects present in the landscape. The information yielded through HGM WP analyses can then be used to guide more data-intensive, quantitative studies of actual cumulative effects.

This study began by investigating the consistency of HGM WPs within and between ecoregions found in Summit County, Colorado. It then evaluated whether the method could detect differences in HGM WPs between landscapes classified *a priori* as reference standard (minimally-impacted) or impacted. Specifically, in this report :

1. Landscapes in Summit County, Colorado were delineated and classified according to their physical setting and level of land cover alteration.

2. The hypothesis that landscapes have inherent, characteristic HGM WPs resulting from their physical composition of the landscape setting was evaluated.

3. The HGM WPs found in landscapes classified *a priori* as reference standard or impacted were compared to determine whether this approach is sufficiently sensitive to detect cumulative wetland impacts.

4. The use of HGM WP as a means of first-order cumulative effects estimation was discussed along with the method's limitations and its potential for further refinement.

Summit County is located in the heart of the Rocky Mountains in central Colorado. The county is characterized by rugged terrain and strong physical and biological gradients. Much of Summit County is undeveloped, and 76% is under the management of the U.S. Forest Service. The county was partitioned into 95 process domain (*sensu* Montgomery 1999) sample units in which physical and ecological processes were internally homogeneous. Based on cluster analysis, the 95 process domains were aggregated into three ecoregions: 1) low lands, 2) middle-elevation transitional, and 3) high mountains.

Since no data exist on actual wetland impacts that have occurred in Summit County, land use/land cover (LULC) and road density were used to index the likelihood or severity of cumulative wetland impacts. Process domains were classified into one of two, *a priori* impact categories (reference standard or impacted) based on LULC and road density using cluster analysis.

Two primary questions were evaluated during this study: 1) considering only minimally-impacted, reference standard landscapes, are HGM WPs relatively consistent *within* ecoregions and do they differ *between* ecoregions?; and 2) within ecoregions, do HGM WPs statistically differ between impacted and reference standard landscapes as a result of cumulative wetland impacts?

The results of this investigation support both hypotheses within the study area. First, HGM WPs within the study units were found to be more similar within than between ecoregions. Between ecoregions, profiles differed in overall shape or in the relative abundance of two or more wetland classes. This result suggests that ecoregions have characteristic and discernable HGM WPs. This is a key finding since there had not been an empirical evaluation of how tightly the abundance and diversity of wetlands is tied to the physical setting. Because of the demonstrated linkage between physical setting and HGM WP, this approach provides a plausible means of reference-based cumulative impacts analysis.

Comparison of reference standard and impacted landscape units (process domains) within ecoregions showed that profile alterations could be statistically detected. Profile differences were manifested as an overall change in profile shape or in an alteration in the ratio between two or more wetland classes. Changes to HGM WPs in impacted landscapes could be readily tied to current and historical land use patterns.

These findings show that HGM WP is a promising method with which to characterize cumulative wetland impacts. Further, as a result of its design, HGM WP results can be combined with data derived through smaller-scale approaches to yield multi-scale analyses of wetland resources. The method also seems a useful means of addressing additional facets of landscape analysis of wetlands, including wetland-based landscape classification, threshold detection, and synoptic analyses.

The report is presented in four major sections. The first is this executive summary which outlines the project's approach and major findings. The second provides an introduction to the concepts underlying hydrogeomorphic wetland profiling including background on the regulatory and scientific context of the method. In the third section, a generalized approach to HGM WP is described, implemented, and tested in Summit County, Colorado. Lastly, a tool for remotely classifying wetlands is provided as an appendix.

INTRODUCTION

Cumulative impacts and their resultant cumulative effects have become an important focus of both environmental regulation and scientific investigation because of their potentially severe consequences. For example, the National Environmental Policy Act (38 CFR Sect. 1500.6) and Section 404(b)(1) of the Clean Water Act (40 CFR 230.11) explicitly require that projects proposing impacts to wetlands consider the cumulative effects of the actions and not solely the direct project impacts. Despite the recognized potential for significant negative consequences, cumulative effects are seldom adequately addressed in environmental management because of the lack of effective tools to describe and assess them. The purpose of the research documented in this report was to explore how recent, innovative concepts in wetland ecology could be integrated to create a practical and powerful approach to wetland cumulative impacts analysis.

Specifically, this study investigated whether a reference-based approach to cumulative impacts analysis could be developed by using a hydrogeomorphically-based version of landscape profiles (Brinson 1993, Bedford 1996, Gwin et al. 1999) in conjunction with the concepts of landscape formation and processes forwarded by Montgomery (1999), Winter (2001), and Omernik and Bailey (1997). This approach, termed Hydrogeomorphic Wetland Profiling (HGM WP), seeks to refine coarse acreage-based approaches by applying a functionally-based framework that provides the landscape-scale view of wetland resources needed by regulatory, management, mitigation, and conservation programs.

Theoretical Basis for Approach

Scientific investigations have shown that wetlands unquestionably perform important environmental functions (National Research Council [NRC] 1995, Mitsch and Gosselink 2000) and that different types of wetlands perform different functions or the same functions to various degrees (e.g., Brinson 1993, NRC 1995). Thus, with loss and degradation of wetlands comes a concomitant loss of functions generally associated with wetlands and the particular environmental functions attributed to specific wetland types. The functional losses result in both direct and indirect negative effects on environmental quality such as impairment of water quality, reduction of flood flow attenuation, and loss of wildlife habitat (Hemond and Benoit 1988, Croonquist and Brooks 1991, Council on Environmental Quality [CEQ] 1997, Bedford

1999, McAllister et al. 2000, NRC 2001). When taken singly, any particular wetland impact may have little effect on overall environmental quality. But considering whole watersheds and basins, the cumulative sum of wetland impacts may have significant additive effects, or wetland impacts can act synergistically to produce disproportionately severe cumulative effects (Hemond and Benoit 1988, Nestler and Long 1997).

While some agencies and investigators have chosen to synonymize cumulative impacts with cumulative effects (e.g., CEQ 1997), it is important to differentiate the terms. Following Leibowitz et. al. (1992), cumulative wetland *impacts* are defined as the sum of extant and historical wetland impacts that have occurred across a given landscape, while cumulative *effects* are the resultant environmental consequences. Cumulative wetland impacts can take the form of outright destruction of wetland habitat, of functional conversion (e.g., converting riparian wetlands to depressions), or of a decline in wetland functioning through mechanisms such as sedimentation, hydrologic alteration, or logging. Alternatively, the cumulative effects of wetland loss are manifested as a degradation of environmental quality. One way of contrasting cumulative wetlands impacts with cumulative effects, is that cumulative wetland impacts always occur within wetlands across a landscape, while cumulative effects are commonly manifested outside of wetland ecosystems, in receiving waters.

Analysis of wetland acreage trends is the most basic method of characterizing cumulative wetland impacts. Such analyses provide data on wetland losses (or gains) and thereby provide an indication of the general types of ecosystem functions that have been lost within the study region. While an important means of tracking broad environmental trends, such an approach suffers from its inherent generality and insensitivity to differential wetland functioning, and it does not provide the level of detail necessary for smaller-scale regional studies. These short-comings are especially significant in light of the non-random distribution of wetland impacts (Bedford 1999), which make accurate predictions about wetland-related functional losses and cumulative effects unlikely.

The information rendered through trend analyses can be greatly increased by stratifying surveyed wetlands into discrete categories. Wetland classifications can be structured around any group of parameters, but recent studies suggest that hydrogeomorphic (HGM) classification (Brinson 1993) is particularly powerful because of its physical basis and its direct ties to wetland

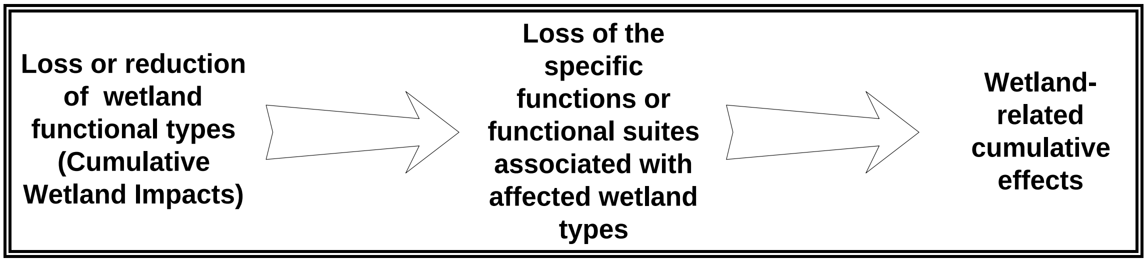

Figure 1. Flow diagram showing the relationship between cumulative wetland impacts and related cumulative effects. Hydrogeomorphic class (slope, riverine, etc.) is one way to define functional types of wetlands.

functioning. It stands to reason that evaluation of the changes in the relative abundance of HGM categories provides an index of the loss of the specific functions associated with the wetlands destroyed, and that such functional losses are the causative factors behind wetland-mediated cumulative effects (Fig. 1). Thus, evaluation of wetland trends in terms of HGM categories seems a promising way of tracking cumulative impacts and indexing wetland-related cumulative effects. Hydrogeomorphic wetland profiling provides a functionally-based method for improving trend analyses and investigating cumulative impacts and their resultant effects.

Background on HGM WP Development

Bedford (1996) argued that surveys of the abundance and diversity of wetland "developmental templates" is an important means of quantifying the wetland diversity of landscapes. She suggested that tallies of wetland templates in a landscape could be displayed as simple diagrams which she termed "landscape profiles"[1], and that these profiles could be a valuable means of summarizing wetland diversity and tracking cumulative impacts. Bedford did not provide specifics about how templates should be parameterized and classified, however.

Gwin et al. (1999) empirically applied the concept of wetland profiling to the evaluation of the effects and effectiveness of wetland mitigation resulting from Clean Water Act permit requirements. In developing their approach, Gwin et al. (1999) took advantage of the conceptual

[1] Although Bedford applied the term "landscape profiling", I will instead use the term "hydrogeomorphic wetland profiling" throughout this report, since it makes the focus of the technique more explicit.

similarities between Bedford's templates and Brinson's HGM classification framework, using HGM classes in place of Bedford's templates. They then compared a profile of natural wetlands to that of mitigation wetlands. In this specific case, the natural HGM WP was taken as the reference with which to compare the HGM WP of mitigation wetlands. The departure between these two profiles was used as the measure of cumulative impacts due to mitigation actions. Using this approach Gwin et al. (1999) characterized cumulative wetland impacts within a portion of the Willamette River watershed, but more generally they showed that HGM WP was useful and applicable in a management setting.

Extension of HGM WP to the Generalized Case of Cumulative Impacts Analysis

The key principle supporting the idea of HGM WP in a reference-based capacity is that the abundance and diversity of wetland types is dictated by the physical setting of the landscape (Bedford and Preston 1988, Winter and Woo 1990, Winter 1992, Bedford 1996, Halsey et al. 1997, Winter 2001). According to these studies the physical attributes most relevant to wetland formation are local and regional climate, and basin hydrology, geomorphology, and hydrogeology. Similar findings have been presented in regard to aquatic systems as well (Frisell et al. 1986, Richards et al. 1996, Johnson and Gage 1997, Kratz et al. 1997, Wiley et al. 1997, Montgomery 1999). Thus, it follows that landscapes possessing similar physical attributes should consequently possess similar patterns of wetland abundance and diversity, when diversity is summarized in terms of physical makeup. That is, physically similar landscapes would be expected to have similar HGM WPs. Conversely, physically disparate landscapes should have distinctly different HGM WPs. If these assertions are true, then landscape references appropriate for cumulative wetland impact analyses may be defined through characterization of comparable, minimally-impacted landscapes.

The ideas described above form the basis for the work presented in this report. This study began by investigating the consistency of HGM WPs within and between physically-based ecoregions. It then evaluated whether the method could detect differences in HGM WPs between landscapes classified *a priori* as reference standard or impacted. Specifically, in this report :

1. Landscapes in Summit County, Colorado are delineated according to their physical setting and impact level;

2. The hypothesis that landscapes have inherent, characteristic HGM WPs that result from the physical composition of the landscape setting is evaluated;

3. The HGM WPs found in landscapes classified *a priori* as reference standard or impacted are compared to determine whether this approach is sufficiently sensitive to detect cumulative wetland impacts;

4. And finally, the ways in which the HGM WP can be used as a index of cumulative effects, and the limitations and potential further extensions of the approach are discussed.

METHODS

Description of Study Area

The study area for this investigation was Summit County, Colorado. Summit County covers approximately 1,600 km^2 of the Rocky Mountains in central Colorado (Fig. 2). Following the Continental Divide in the southwest, the county boundary corresponds to that of the Blue River watershed, although a small portion continues beyond the northern tip of the county. The watershed is dissected by three major alluvial valleys formed by the Blue River, Snake River and Ten-mile Creek. Rimming these valleys and nearly surrounding the county are high mountains of the Gore, Ten-mile, and Mosquito Ranges and the William's Fork Mountains. Peaks in these ranges reach elevations over 4,250 m.

The county is characterized by rugged terrain and strong physical and biological gradients. The high mountains are comprised mainly of granites, granodiorite dikes and sills, and Precambrian metamorphic rocks, that have been carved by Pleistocene glaciers. Only a few, small active glaciers exist today. On the shoulders of the mountains, depositional features dominate the landscape mainly in the form of moraines and outwash plains. The major valleys are dominated by alluvial landforms, and contain the topographically flattest areas.

Strong patterns in climate, vegetation, and land use follow the physiographical gradients that are present. Long-term climate data are not available for the high mountain areas, but at 2,920 m average annual precipitation is 48.7 cm (Breckenridge Station), while at 2,359 m it is 38.8 cm (Green Mountain Dam Station). Vegetational zones present in the county range from montane in the lower Blue River Valley, to the high alpine in the surrounding mountains (Marr 1961). As is typical in mountain environs, vegetational zonation is pronounced and tightly controlled by topography, elevation, and the associated climatic changes. Low in the alluvial valleys and plateau areas, montane vegetation is dominated by grasslands and sagebrush shrublands. In the upper montane zone, open conifer woodlands and mixed aspen-conifer forests cover most of the landscape. The subalpine zone is typical of that found across most of the Colorado, being strongly dominated by spruce-fir (*Picea engelmannii-Abies lasiocarpa*) forest (Peet 1981). Above tree-line (~3,490 m) in the alpine zone, vegetation consists of a mix of meadows, krumholtz and low-shrub woodlands.

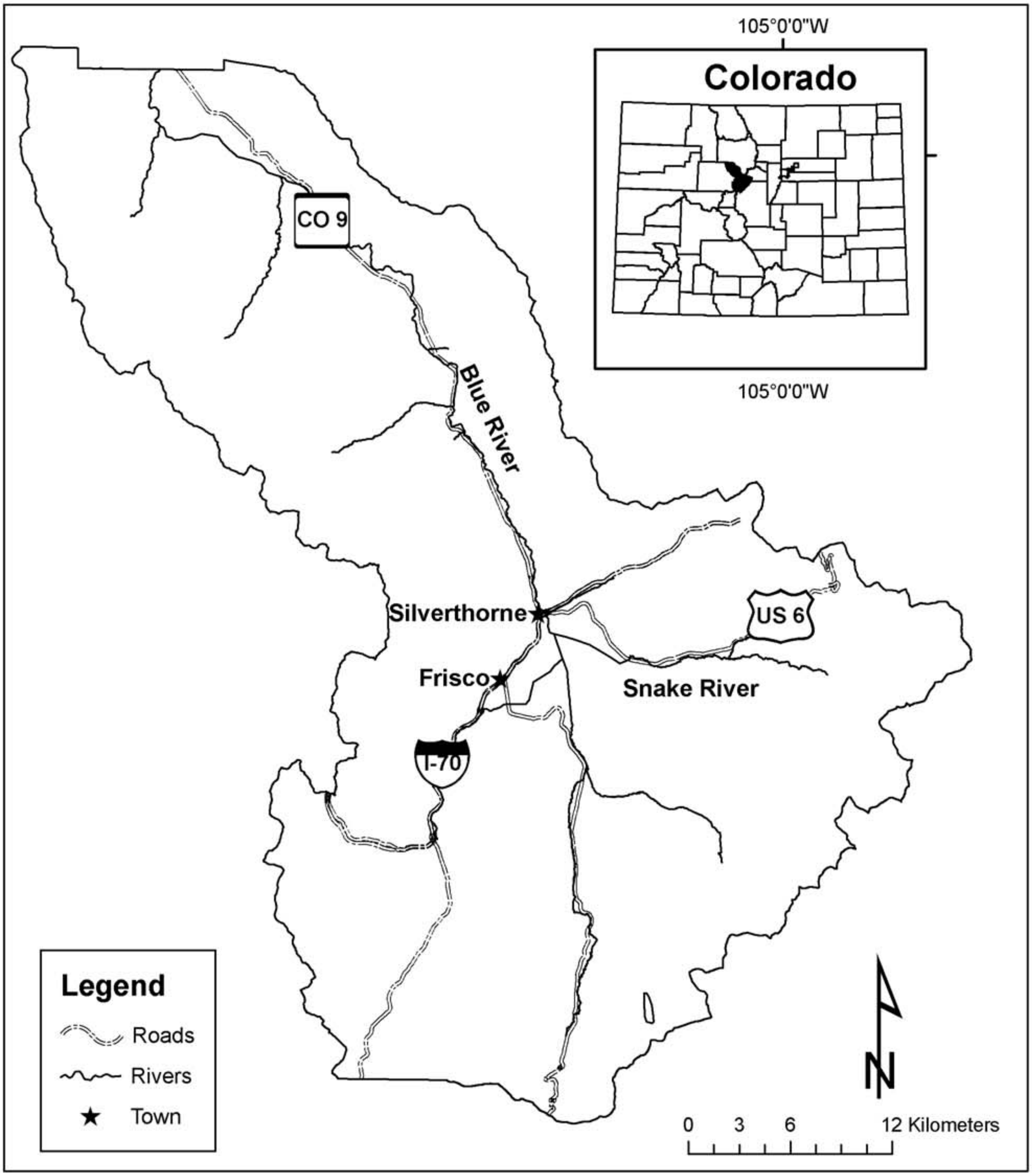

Figure 2. Map showing Colorado (inset) and the Summit County study area.

Much of Summit County is undeveloped, and 76% is under the management of the U.S. Forest Service. Only twenty-two percent of the land is privately owned, with these properties being strongly concentrated in the open and relatively flat valley bottoms, at the Climax molybdenum mine in the southwest, and in the immediate vicinity of the four major ski resorts scattered across the southern half of the county.

Development of the Geographic Information System

A geographic information system (GIS) was constructed using ArcView version 8.2 software (ESRI 2002) and incorporating data from numerous sources (Table 1). All GIS data were projected into the Universal Transverse Mercator system using the North American Datum of 1927.

Wetland polygons were derived from a compilation of three aerial photograph surveys of Summit County (Table 1). Identified wetlands were placed the one of the HGM classes: riverine, slope, depressional or lacustrine fringe (henceforth "fringe"). A fifth class of "wetlands" was included in the analyses – "irrigated meadows". Broad interpretation of these areas is problematic. Irrigated meadows are commonly associated with natural wetlands wherein irrigation waters greatly expand the extent of naturally occurring hydric conditions. Commonly interspersed within the this mix of natural and irrigation-supported wetland are expanses of upland meadow not practicably discernable on aerial photographs. The ecological role of irrigated meadows is also difficult to interpret since irrigated meadows are indicative of land use alteration and impact, but such areas commonly perform many beneficial wetland functions. Owing to practical limitations these sites were aggregated into an artificial category.

Wetland polygons mapped by the Whitehorse and Ward aerial photograph surveys (Table 1) were placed into HGM classes by the Science Applications International Corporation (SAIC) using aerial photograph interpretation, GIS, and field surveys (SAIC 2000). I classified wetlands identified by the U.S. Forest Service aerial photograph survey into HGM classes using a dichotomous keying algorithm based on GIS-interpreted physical attributes (Appendix 1). In a randomly chosen set of test wetlands, a 95% concurrence was found between these two methods. Based on this comparison, the results obtained through either approach were deemed practically equivalent and the data sets were combined.

Table 1. Description and sources of geographic data included in the study's GIS.

Data layer	Description	Citation or Source
USGS 7.5' Digital raster graphics (DRGs)	Topographical maps	http://www.lighthouse.nrcs.usda.gov/gateway/gatewayhome.html
1:250,000 scale geologic maps	Denver and Leadville Quadrangles	http://greenwood.cr.usgs.gov/pub/mf-maps/mf-2347 and http://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-99-0427, respectively.
Soil survey geographic data (SSURGO)	Partial coverage, large-scale soils data	http://www.ftw.nrcs.usda.gov/ssurgo/metadata/co690.html
State soil geographic database (STATSGO)	1:250,000 scale soils data	http://www.ftw.nrcs.usda.gov/stat_data.html.
Hydrography	US EPA-BASINS Streams and waterbodies	http://www.epa.gov/OST/BASINS/
Roads	All roads within Summit County as surveyed by the county	Summit County Government
Land use and land cover	US EPA-BASINS Anderson Level II land cover classes	http://www.epa.gov/OST/BASINS/
Digital elevation model (DEM)	10 m resolution	Summit County Government
Sub-watershed boundaries	Draft Hydrologic Unit Code (HUC)12 shapefiles	US Natural Resource Conservation Service (not yet generally released)
White River National Forest aerial photograph survey	Wetland polygons on USFS land classified by vegetation	USFS White River National Forest Field Office, Silverthorne, CO
Summit County private land aerial photograph survey	Wetland polygons on private lands classified by vegetation coverage	Whitehorse survey. Data obtained through Summit County Government
Town of Silverthorne aerial photograph survey	Wetland polygon in and around the Town of Silverthorne, classified by vegetation coverage.	Ward survey. Data obtained through Summit County Government

Topographic slope, total basin relief, and mean elevation were calculated using a 10 m digital elevation model. Stream order was determined by Strahler's (1957) method using 1:100,000 digital line graphics (DLGs) and was completed by Summit County Government (H. McLaughlin, *personal communication*).

Designation of Process Domains

Summit County is composed of a complex mosaic of landscape types. To effect a analytical comparison of HGM WPs, the county had to be divided into ecologically relevant and relatively homogeneous sample units. Summit County is entirely included within a single hydrologic unit code (HUC) 8 watershed that is divided into 62 HUC 12 sub-watersheds (henceforth HUC 12s). These HUC 12s were used to produce a preliminary division of the county into objectively defined sampling units. The HUC 12 layer was laid over shade relief and geologic data layers in ArcScene to provide a 3-dimensional geologic/geomorphic view of the region. Geologic units were grouped into functional groups reflective of their effects on hydrogeology and geomorphology (Table 2).

Table 2. Summary description of geologic functional groups.

Group Name	Sandstones and shales	Sandstones, carbonates, and siltstones	Unconsolidated	Volcanic	Granite and metamorphic
Lithological types Included	• clastic sandstones • various sandstones • shales	• Various sandstones • carbonates • conglomerates • siltstones	• Glacial deposits • Landslides features • Colluvium • Alluvium	• Trachytic lava • Extruded lava	• Granites • Precambrian metamorphic • Grandodiorite dikes and sills
Total % coverage	20	7	23	0.4	49

In spite of their relatively modest areal extent, in Summit County HUC 12 sub-watersheds commonly encompass significant physical heterogeneity which can confound attempts to link ecological, physical, and land use patterns (Montgomery 1999). To facilitate ecologically meaningful analyses, sub-watersheds were used in conjunction with ecologically defined boundaries (Omernik and Bailey 1997). Often sub-watersheds were adequately homogenous to consider as a whole, but when HUC 12s included marked physical heterogeneity, they were subdivided into relatively homogeneous process domains (*sensu* Montgomery 1999). These units could also validly be termed fundamental hydrologic landscape units following Winter (2001), although process domain terminology is preferred here since it conveys the dynamic nature of wetland formation and maintenance.

When the requirement of homogeneity was not met, HUC 12s were subdivided into preliminary process domains by partitioning the sub-watersheds at marked breaks in geology and geomorphology. Not surprisingly, geomorphic breaks followed shifts in geology in almost every case. Principle Components Analysis was used to evaluate these preliminary process domain boundaries based on maximum stream order, percent coverage of geologic functional units, total basin relief, mean elevation, and mean slope in each domain. This analysis was used to identify outliers and sub-optimal process domain boundaries. When necessary, process domain boundaries were reevaluated and revised based on this analysis. SPSS (2003) version 12 software was used to carry out all statistical analyses.

Identification of Ecoregions

The purpose of delineating process domains was to divide the study region into units within which the degree of topographic, geologic, hydrologic and climatic heterogeneity were relatively even. By its nature, such a delineation presupposes that physical and ecological differences exist among the various process domains. Cursory examination of the diversity among process domains bore out this supposition. Thus, all of the individual process domains formed the inclusive study population, which itself could be stratified into categories based on predominant physical and ecological characteristics.

Process domain categories were defined using agglomerative, hierarchical clustering utilizing Euclidian distance and group centroids (McKune and Grace 2002). The variables employed during the analysis were the same ones used during the delineation of process domains. Because the process domain categories were delineated such that each possessed similar climate, landforms, soils, potential natural vegetation, and hydrology, I call these categories ecoregions following Bailey (1995), Omernik (1995) and others. Discriminant analysis (DA) was used to test the robustness of this quantitative, but ultimately subjective, ecoregion categorization. Ecoregions formed the basis of comparison and statistical analysis, with each ecoregion being represented by several replicate process domains.

Classification of Impact Categories

No data exist on actual wetland impacts that have occurred in Summit County. In lieu of such data, land use/land cover (LULC) and road density were used to index the likelihood or severity of cumulative wetland impacts. Land use/land cover was the preferred index because certain types of land cover are known to affect wetlands and water quality (NRC 2001, Johnson et al. 1997). Land use/land cover was characterized using Anderson Level II resolution data and classes (Anderson et al. 1976). Areal extents of LULC classes were converted to relative proportions. Land use/land cover classes were placed into two groups, those LULCs which commonly result in wetland loss (“impacting”) and those which are essentially “natural” management regimes (“reference standard”) (Table 3). Road density was calculated from the GIS, as meters of road per hectare.

Process domains were classified into *a priori* impact categories based on LULC and road density using the cluster analysis procedures described above. Process domains were categorized as “reference standard” if minimal alterations and development had occurred, and “impacted” when significant land cover conversions were present. This simple, two-category classification was found to provide the clearest, most readily interpretable results during preliminary analyses. Discriminant analysis was used to test the robustness of this grouping.

Generation of HGM WPs and Detection of Cumulative Impacts

Recall that an HGM WP summarizes the relative abundance of HGM (functional) wetland types in a unit of the landscape. The first step in generating the HGM WP was to tally the areal coverage of HGM classes within each process domain using native ArcView geoprocessing routines. Data on areal coverage by HGM class were then compiled in a

Microsoft Excel™ spreadsheet and grouped by ecoregion. HGM WPs were generated for each ecoregion and then assigned an impact status as determined by the LULC analyses.

Table 3. Grouping of Anderson Level II land cover class into reference standard or impacted land use categories.

Management Class	Anderson Level II LULC classes
"Natural" land cover types	Bare exposed rock Bare ground Deciduous forest land Evergreen forest land Forested wetland Herb rangeland Herb tundra Lakes Mixed forest land Mixed rangeland Mixed tundra Mixed urban or built-up Non-forested wetland Shrub rangeland Shrub tundra
Altered land cover types	Commercial and services Industrial Other urban or built-up Reservoirs Residential Strip mines Transportation, communications, utilities Other agricultural land Cropland and pasture

Multivariate general linear modeling (MGLM) was used to compare mean, proportional coverage of HGM classes, i.e., to compare HGM WPs. Two types of comparisons were made:

1) comparison of reference standard HGM WPs *between* ecoregions; and 2) comparison of HGM WPs between impact classes *within* ecoregions. The first comparison was used to test the hypothesis that HGM WPs are relatively consistent within ecoregions. The second comparison tested the hypothesis that within ecoregions HGM WPs differ between reference standard landscapes and those subjected to environmentally disruptive land uses. Statistical results were considered significant at the $p \leq 0.05$ level. When multiple statistical comparisons were made, significance values were Bonferroni corrected.

Methodological Assumptions

Hydrogeomorphic wetland profiling is designed to provide a functionally-based, scale-appropriate characterization of cumulative wetland impacts. Specifically, HGM WP quantifies impacts to the abundance and diversity of wetlands resulting from outright wetland destruction or functional conversion (i.e. from one HGM class to another). This analytical focus stems from the idea that these whole-wetland impacts are the primary driver or "forcing factor" of wetland functioning at the landscape scale.

In developing the HGM WP approach it was necessary to make a number of assumptions based on first principles and logical constructs. These assumptions listed below, have not been explicitly tested in this study.

1). Cumulative impacts to wetlands cause degradations of environmental quality and ecological integrity which are termed cumulative effects.

2). The particular manifestation and types of cumulative effects incurred depend on the specific functional wetland types that are impacted.

3). Alteration of land cover and land use stemming from civil development, conversion to agriculture and natural resource utilization results in loss and functional conversion of wetlands.

4). Cumulative impacts have accumulated over time since settlement by Europeans, however, the rate and spatial distribution of impacts has been uneven and episodic.

5). The temporal distribution of wetland impacts does not change affect the manifestation or severity of cumulative effects. For example, given an equivalent loss of wetland acreage, it is insignificant in terms of cumulative effects whether those impacts accumulated over 100 years or 10 years.

RESULTS

Identification of Ecoregions

Based on cluster analyses, the ninety-five process domains were grouped into three ecoregions: 1) low lands, 2) middle-elevation transitional, and 3) high mountains (Fig. 3). In the dendrogram presented here, the clusters of the middle-elevational transition and high mountain ecoregions are coarsely interspersed. Non-adjacent clusters were included within the same ecoregion based on the results of preliminary cluster analyses that used different distance measures and which generally grouped the separated clusters together, and also on subjective evaluation of process domain characteristics. The groupings as reported here were found to be the most statistically parsimonious and provide the clearest, most interpretable results. For comparison, Fig. 4 presents a shade-relief map of raw HUC 12 sub-watersheds laid over regional geology, contrasted with a map of process domains grouped into the three ecoregions. Table 4 provides the mean values of physical variables measured in each ecoregion.

Discriminant analysis (DA) validated the final ecoregion groupings. Using proportional coverage of geologic units, total basin relief, mean elevation, and mean slope – the same parameters used in the cluster analysis – process domains were assigned to the *a priori* ecoregions with 100% accuracy. Table 5 provides a correlation matrix of the discriminant variables with the first two standardized discriminant functions. Mean process domain slope and elevation are most strongly, positively correlated with function 1, whereas geologic parameters were most highly correlated with function 2. Exposure was also highly correlated with discriminant functions but it was not included within these analyses owing to its strong intercorrelation with other parameters such as slope and basin relief. Note that vegetational composition was not explicitly included within this classification framework, although there is a strong correspondence between ecoregions and vegetational zones.

Each of the physical parameters included within ecoregion analyses have fundamental effects on landscape hydrogeology, geomorphology, and disturbance processes, which in turn constrain the ecological character of those areas. Each ecoregion is briefly characterized below.

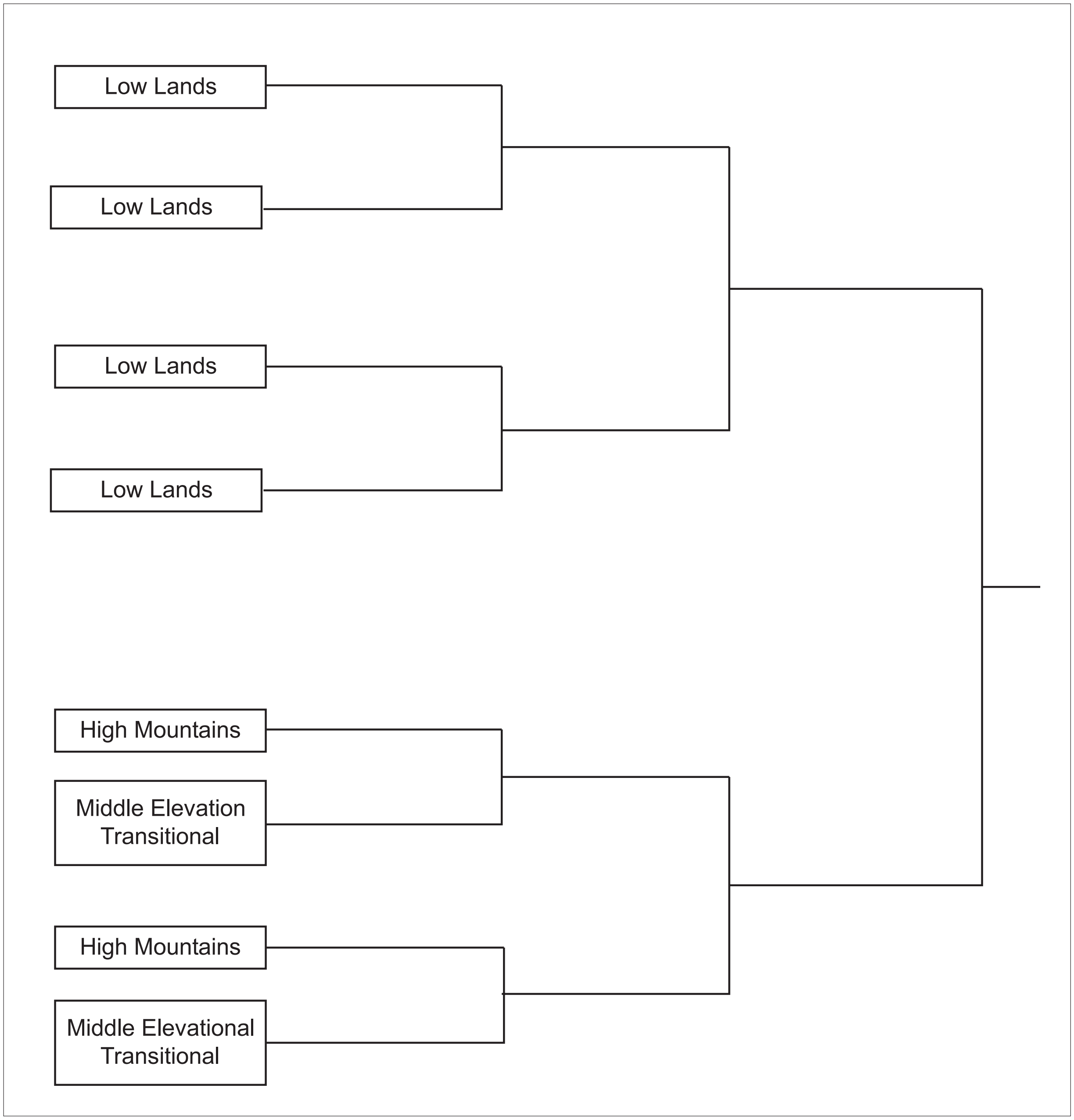

Figure 3. Dendrogram of a hierarchical, aglomerative cluster analysis, grouping process domains into ecoregions based on mean elevation, mean slope, basin relief, and geology.

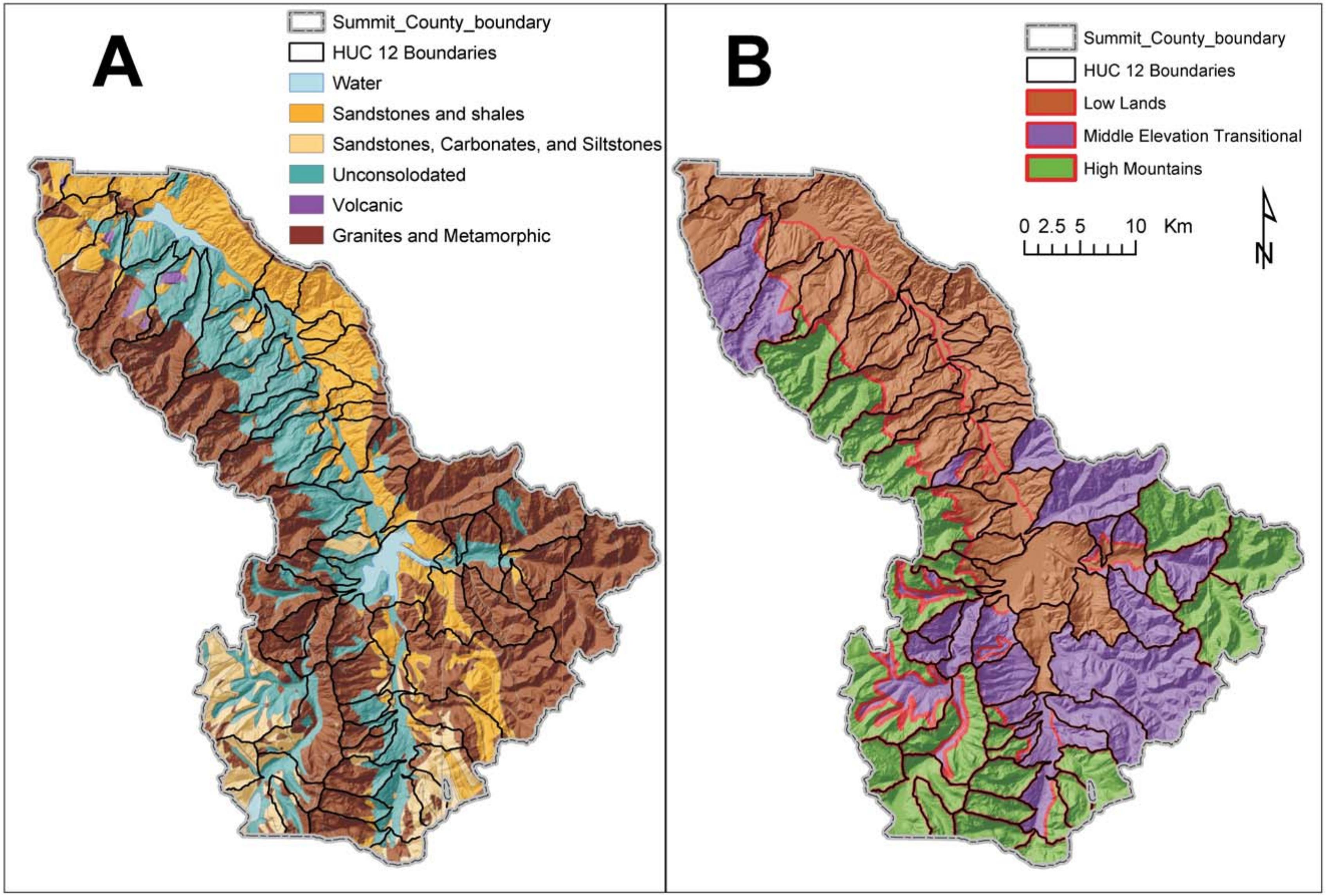

Figure 4. Geology and HUC 12 boundaries (A) in comparison to process domains and ecoregions (B) in Summit County, CO. See the Methods section for additional explanation of boundary designation.

Table 4. Summary description of physical properties of the three ecoregions.

Ecoregion	Low lands	Middle-elevation transitional	High mountains
n	41	25	29
Average process domain size (km^2)	143	191	184
Sandstones and shales (%)	43	12	2
Sandstones, carbonates, and	2	2	18
Unconsolidated (%)	42	18	6
Volcanic (%)	0	1	0
Granite and metamorphic (%)	12	67	73
Area (ha)	58,687	47,813	53,465
Total basin relief (m)	1,484	1,739	1,632
Mean elevation (m)	2,818	3,247	3,514
Mean Slope (%)	33	42	49

Table 5. Discriminant analysis of process domain physical characteristics showing the pooled within-groups correlations between discriminating variables and standardized canonical discriminant functions.

		Discriminant Function	
		1	2
Geomorphic Parameters	Mean elevation	0.879	-0.123
	Mean slope	0.332	0.158
	Basin relief	0.145	-0.133
	Stream order	-0.076	0.034
Geologic Units	Sandstones and shales	-0.207	0.604
	Sandstones, carbonates, and siltstones	0.116	0.581
	Unconsolidated	0.307	-0.384
	Volcanic	-0.161	-0.343
	Granite and metamorphic	-0.036	-0.163

Low Lands Ecoregion

The Low Lands Ecoregion typically includes low elevation areas with relatively shallow topographical gradients. Although mean process domain elevation can reach to over 3000 m in the northeastern areas, high elevation portions of these domains have more affinity to lower elevations owing their southwest exposure (Geiger 1965). Process domains grouped in this class are typically sited on sandstone deposits, glacial terrain, or alluvium. Although all regional vegetational zones are represented to varying degrees in this ecoregion, it is primarily associated with the montane zone.

Middle-elevation Transitional Ecoregion

The Middle-elevation Transitional Ecoregion is spatially and characteristically intermediate between the low lands and high mountains, but it is more allied to the high mountain systems. Process domains in this ecoregion are located in heavily glaciated, middle-elevation, mountainous landscapes. Commonly, this ecoregion includes high, intermountain valley systems. Middle-elevation transitional areas are geologically heterogeneous. Granites and Precambrian formations dominate the geology, but glacial and sandstone deposits are also common. Portions of process domains classified within this ecoregion may reach the alpine zone, but the ecoregion is most strongly associated with the subalpine zone.

High Mountains Ecoregion

The High Mountains Ecoregion is found in the highest, most rugged settings in the upper subalpine to alpine zones. Its geology is dominated by resistive Precambrian granites and metamorphic rocks that have been subjected to extensive Pleistocene glaciation. The high mountain areas possess the greatest basin relief and highest mean slope of the three ecoregions.

Classification of Impact Categories

The highest level division in the land use cluster analysis was used to assign process domains into reference standard or impacted categories. Process domains classified as reference standard have less than 10% cover of intensive land uses, such as urban and residential development, and they generally have road densities below 20 m/ha (Fig. 5). Many of the reference standard process domains are entirely undeveloped and essentially roadless, notably those in the Eagle's Nest Wilderness Area along the western edge of the county. The remainder of process domains were classified as impacted. The validity of this classification was cross-checked using discriminant analysis and only five of 95 samples were misclassified (94.7% accuracy). The five "misclassified" process domains were examined and kept in their original category as assigned by cluster analysis, although these were truly borderline cases. As expected, impacted process domains are mainly those in or adjacent to the Blue River Valley, which contains the most readily developable land (Fig. 6).

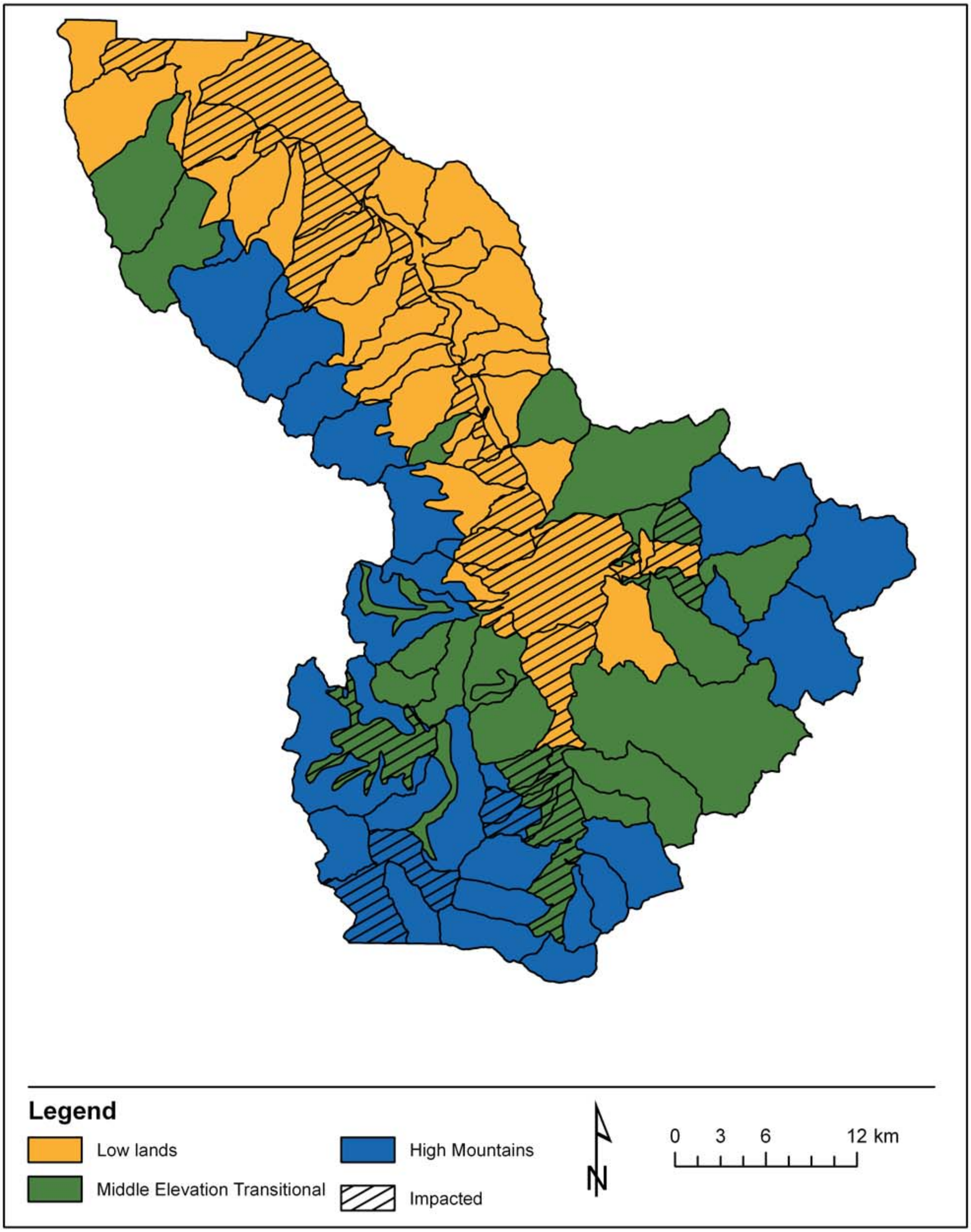

Figure 5. Map of Summit County, CO showing the distribution ecoregions. Hatching indicates those ecoregions that were classified as impacted. All others are reference standard.

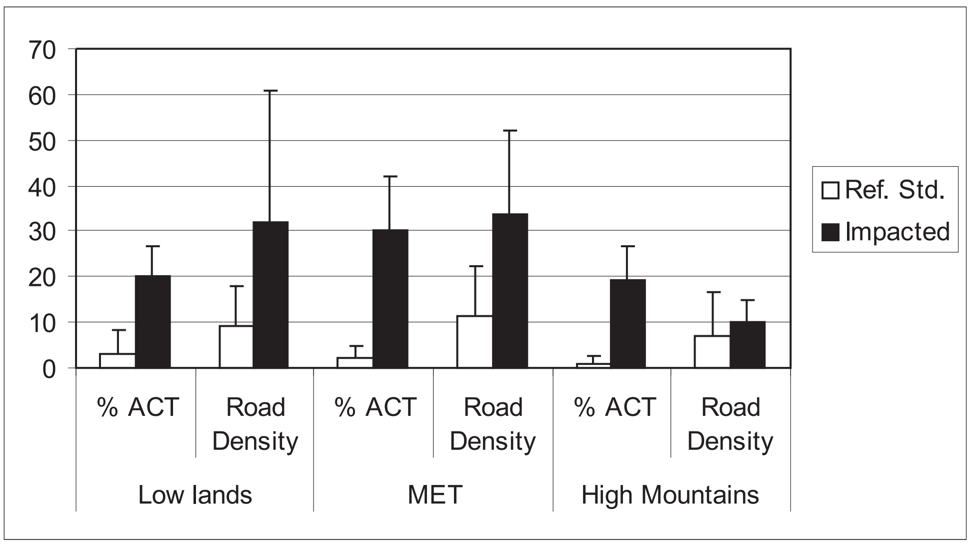

Figure 6. A comparison of mean percent coverage of altered land cover types (%ACT) and road density in reference standard and impacted process domains. Refer to Table 3 for Anderson level II land use classes included within the ACT category. T-bars show one standard deviation.

Use of HGM WPs to Detect Cumulative Impacts

The detection of cumulative impacts was done in two steps that evaluated the hypotheses posed in the Methods Section. First, reference standard HGM WPs were compared between ecoregions to determine whether HGM WPs were more consistent within than between ecoregions. Once this had been confirmed, then I determined whether cumulative impacts could be detected by comparing HGM WPs from reference standard and impacted landscapes within an ecoregion.

Evaluation of Consistency of HGM WPs Within Ecoregions

Multivariate general linear modeling (MGLM) shows that reference standard HGM WPs differ significantly between ecoregions (Table 6). Examination of between-subject effects indicates that coverage of fringe wetlands was the only parameter that did not differ significantly between the three ecoregions (Table 7). This pattern can be seen in Figure 7 which compares the reference standard HGM WPs developed for each of the three ecoregions.

Summit County landscapes are heavily biased towards riverine and/or slope wetlands, with other classes being almost incidental to the profiles. Clear patterns in the occurrence of HGM types within the ecoregions, particularly in the coverage of these two classes, are evident in Fig. 7. To evaluate the significance of coverage patterns, Bonferroni corrected, multiple pair-wise comparisons of wetland functional class coverages were made between ecoregions (Table 8). Coverage of riverine wetlands varied significantly between the Middle-elevation Transitional and High Mountain Ecoregions. Although there is an apparent decline in mean riverine coverage between low lands and middle-elevation transitional ecoregions, this difference is not statistically significant (Table 8). The inverse trend is seen in slope wetlands, with such wetlands becoming increasingly common in the higher elevation ecoregions. All differences in slope wetland coverage between ecoregions were significant.

Examination of between-subject effects indicates that coverage of fringe wetlands was the only parameter that did not differ significantly between the three ecoregions (Table 7).

Table 6. Results of a MGLM analysis comparing the reference standard HGM WPs between ecoregions. The Wilk's Lambda F statistic is included here, but other multivariate statistics yielded identical significance values.

Effect	Value	F	Hypothesis df	Error df	Sig.
Intercept	0.022	753.404	4.000	67.000	0.000
Ecoregion	0.255	16.391	8.000	134.000	0.000

Table 7. Results of a MGLM analysis of effects between HGM classes. Analysis is based on proportional coverage of HGM classes.

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Ecoregion	Riverine	18581.941	2	9290.970	26.768	0.000
	Slope	45244.010	2	22622.005	72.859	0.000
	Depressional	132.187	2	66.094	3.843	0.026
	Fringe	10.220	2	5.110	1.038	0.360
	Irrigated meadow	6965.248	2	3482.624	17.193	0.000
Intercept	Riverine	101391.366	1	101391.366	292.122	0.000
	Slope	200935.979	1	200935.979	647.161	0.000
	Depressional	171.211	1	171.211	9.955	0.002
	Fringe	36.113	1	36.113	7.335	0.008
	Irrigated meadow	3213.334	1	3213.334	15.864	0.000
Error	Riverine	24296.025	70	347.086		
	Slope	21734.199	70	310.489		
	Depressional	1203.916	70	17.199		
	Fringe	344.640	70	4.923		
	Irrigated meadow	14179.071	70	202.558		

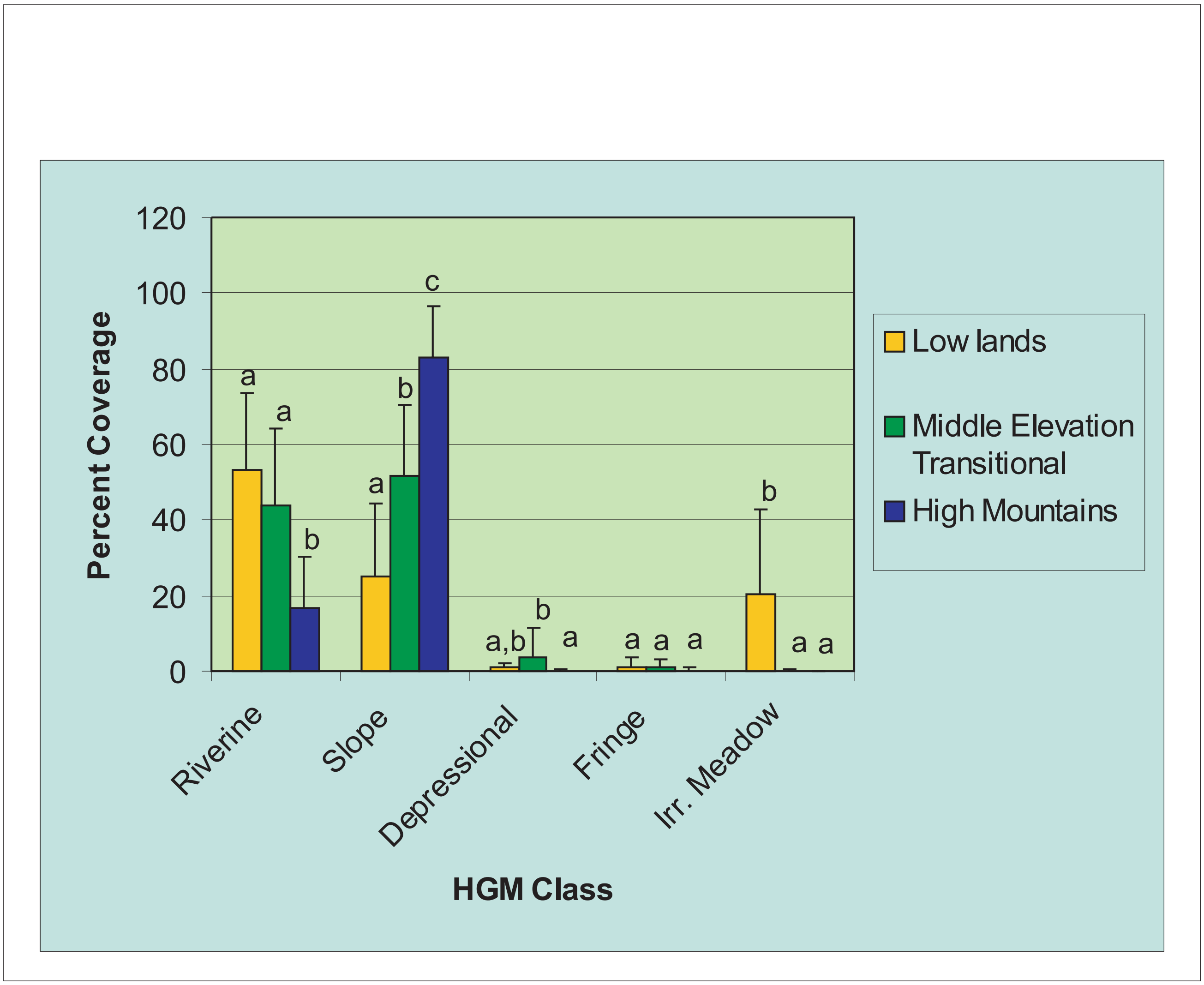

Figure 7. HGM wetland profiles from reference standard process domains grouped by ecoregion. HGM classes are arrayed along the x-axis. Within individual HGM class clusters, columns with shared letters are not significantly different. T-bars are one standard deviation.

Table 8. Results of multiple pair-wise comparisons of the proportional coverage of each wetland class within ecoregions. Middle-elevation Transitional Ecoregion has been abbreviated as MET. All results have been Bonferroni corrected.

Dependent Variable (proportional coverage)	Ecoregion	Ecoregion	Mean Difference	Std. Error	Sig.
Riverine	Low lands	MET	9.3	5.5	0.290
		High mountains	36.1	5.0	0.000
	MET	Low lands	-9.3	5.5	0.290
		High mountains	26.8	5.6	0.000
	High Mountains	Low lands	-36.1	5.0	0.000
		MET	-26.8	5.6	0.000
Slope	Low lands	MET	-26.8	5.2	0.000
		High mountains	-57.9	4.7	0.000
	MET	Low lands	26.8	5.2	0.000
		High mountains	-31.0	5.3	0.000
	High Mountains	Low lands	57.9	4.7	0.000
		MET	31.0	5.3	0.000
Depressional	Low lands	MET	-2.6	1.2	0.121
		High mountains	0.8	1.1	1.000
	MET	Low lands	2.6	1.2	0.121
		High mountains	3.4	1.2	0.026
	High Mountains	Low lands	-0.8	1.1	1.000
		MET	-3.4	1.2	0.026
Fringe	Low lands	MET	0.1	0.6	1.000
		High mountains	0.8	0.6	0.559
	MET	Low lands	-0.1	0.7	1.000
		High mountains	0.7	0.7	0.819
	High Mountains	Low lands	-0.8	0.6	0.559
		MET	-0.7	0.7	0.819
Irrigated meadow	Low lands	MET	20.0	4.2	0.000
		High mountains	20.1	3.9	0.000
	MET	Low lands	-20.0	4.2	0.000
		High mountains	0.1	4.3	1.000
	High Mountains	Low lands	-20.1	3.9	0.000
		MET	-0.1	4.3	1.000

These patterns are readily interpretable considering the hydrogeologic setting of each ecoregion. For example, high in the mountains, hydrologic pathways are short, bedrock fractures reside near the surface, and slope breaks which commonly result in the day-lighting of groundwater are common. These conditions are highly favorable to the formation of slope wetlands, and these wetlands form the headwaters of a multitude of small stream systems, which in turn support riverine wetlands. Lower in elevation, the shift to predominantly riverine wetlands continues as large, high-order river systems form through the coalescence of the small streams. Sites conducive to the formation of slope wetlands become less common, as the terrain flattens and surficial geology becomes more complex.

Relatively few depressional wetlands exist in the study region (Fig. 7). In reference standard areas, depressional wetlands are usually associated with small pator noster lakes and kettle ponds. The low lands and middle-elevation transitional areas do not differ in coverage of this wetland class, apparently since the low lands include the large outwash plains where most kettle ponds are located, and middle-elevation transitional areas have both kettle ponds and pator nostor lakes. The coverage of depressional wetlands was significantly higher in middle-elevation transitional areas as compared to high mountain areas, and very few depressional systems are found high in these mountains. None of the ecoregions differed in their coverage of lacustrine fringe wetlands. In all cases, naturally occurring fringe wetlands are rare in this mountainous landscape.

These results corroborate the hypothesis that landscapes that are similar with respect to hydrogeology, geomorphology, and climatic conditions possess inherent and consistent HGM WPs and that profiles differ between disparate landscapes. These conclusions support the use of HGM WP in reference-based evaluation of cumulative wetland impacts. They also provide empirical support for theoretical assertions arguing that physical landscape attributes dictate the abundance and diversity of wetlands on the landscape.

Detection of Cumulative Impacts

As demonstrated above, reference standard portions of ecoregions have characteristic HGM WPs. It follows that cumulative impacts manifested as wetland loss or functional-type conversion modify these characteristic HGM WPs, but it was uncertain whether such alterations would be statistically detectable owing to naturally occurring variation.

To determine the ability of this approach to detect cumulative wetland impacts, I evaluated the hypothesis that HGM WPs differ between reference standard and impacted process domains *within* ecoregions. For analysis, process domains were first grouped by ecoregion and then by impact class (i.e., reference standard or impacted). Figure 8 provides a comparison of these data. Using multivariate GLM, HGM WPs from impacted and reference standard ecoregions were found to differ statistically in the Low Lands and High Mountains Ecoregions, but not in the Middle-elevation Transitional areas (Table 9).

Examination of patterns of individual HGM class coverages (between-subjects effects) show that in the Low Lands, the coverage of riverine, fringe and irrigated meadows differed between impact classes. In the Middle-elevation Transitional ecoregion, riverine and slope wetland coverages were statistically different, while in the High Mountains Ecoregion, riverine, depressional and fringe wetlands differed (Fig. 8).

Examination of these data suggests two main mechanisms working to alter profiles. The first is direct loss of wetlands through conversion to upland. Such losses are not directly tabulated in these analyses, but are evident through changes in proportional distributions of wetland classes. One way to evaluate changes in relative data is through ratio analysis. In the heavily riverine and slope wetland-biased region of Summit County, those wetland classes are the obvious choices for ratio comparisons. In all ecoregions, the ratio of riverine to slope wetlands differed between reference standard and impacted areas ($p \leq 0.10$), showing that ratio alteration is one of the manifestations of cumulative wetland impacts. A caution is necessary in the interpretation of ratio analyses, however – if two or more classes of wetland are impacted to the same degree, no difference in ratio will be detected. In the case of Summit County, this situation seems improbable, though, owing to land use patterns, and elsewhere the selective nature of wetland impacts have been noted (Bedford 1999). Still this potentiality should be considered in the interpretation of results.

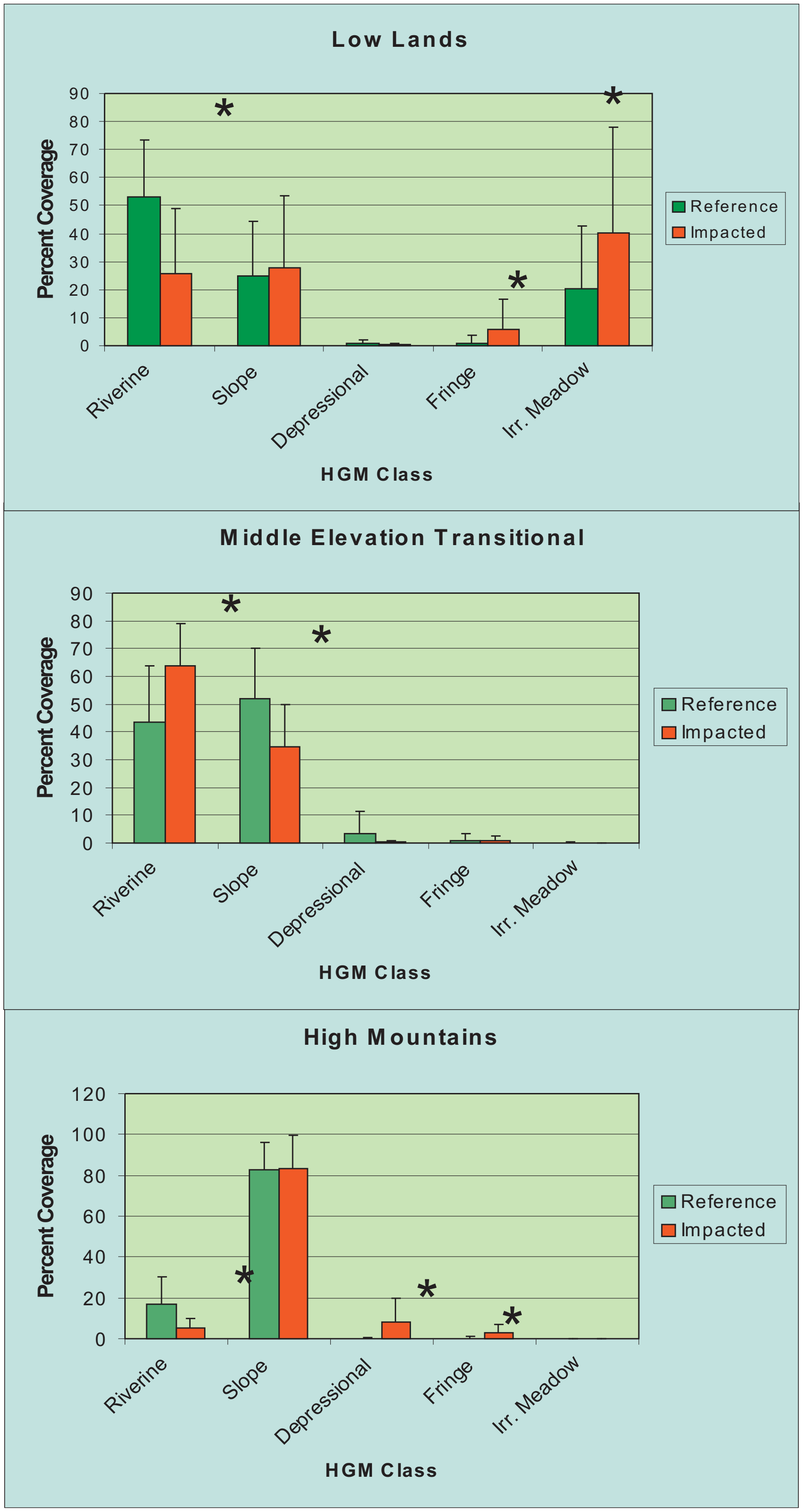

Figure 8. Comparison of HGM wetland profiles in reference standard and impacted process domains within each of the three ecoregioins. A * indicates a significant difference in mean HGM class coverage between reference standard and impacted process domains. T-bars are one standard deviation.

Table 9. Results from a multivariate general linear modeling analyses comparing HGM WPs in reference standard and impacted process domains grouped by ecoregion. The Wilk's Lambda F statistic is included here, but other multivariate statistics yielded identical significance values.

Effect	Value	F	Hypothesis df	Error df	Sig.
		Low Lands			
Intercept	0.139	55.651	4.000	36.000	0.000
Impact Level	0.620	5.528	4.000	36.000	0.001
		Middle-elevation Transitional			
Intercept	0.000	1315050.838	4.000	20.000	0.000
Impact Level	0.744	1.723	4.000	20.000	0.184
		High Mountains			
Intercept	0.000	67852.817	3.000	25.000	0.000
Impact Level	0.664	4.207	3.000	25.000	0.015

A second type of cumulative wetland impact is conversion of wetlands from one functional class to another. The best examples of this are seen in the Low Lands Ecoregion. In reference standard process domains, fringe wetlands are quite uncommon, but in impacted process domains the coverage of fringe wetlands is elevated five-fold (Fig. 8). Irrigated meadows show this same general trend. Based on the proportional reduction in riverine wetlands, the data suggest that riverine wetlands have been converted to these two atypical or artificial wetland types. Examination of land use patterns corroborates this assertion. Reservoir construction and gravel mining activities have been significant in these areas and irrigated meadows are also commonly found associated with streams, which facilitate water transport and delivery to the cultivated lands.

Similar conclusions are made with regard to wetland functional conversion in the High Mountains Ecoregion. In those areas, coverage of depressional and fringe wetlands have been inflated, again, apparently at the cost of riverine wetlands. In the Middle-elevation Transitional Ecoregion, impacts seem to have been focused on slope wetlands. In reference standard areas, there is nearly an even ratio between riverine and slope wetlands, whereas in impacted process domains, the relative coverage of riverine wetlands is inflated relative to that of slope wetlands. Once again, this pattern can be explained in light of land use patterns. All of the impacted process domains contain major ski resorts. As opposed to most mountain land development which occurs in relatively flat river valleys, ski resort development expressly occurs away from such flat lands, on high elevation mountain sides where slope wetlands are most frequently located. Impacts to slope wetlands through ski resort development are a commonly noted and disturbing side-effect of the industry (US Army Corps of Engineers Omaha and Sacramento Districts CWA, §404 permit records).

In Fig. 8 (Middle-elevation Transitional), the profile further indicates an *increase* in the percentage of riverine wetlands. This should not be interpreted as an actual increase in the number or coverage of riverine wetlands but rather an increase in the *relative* percentage of riverine wetlands. Namely, since the percentage of all wetland coverage must sum to 100%, a decrease in the relative coverage of one class must be balanced by an increase in another.

DISCUSSION

Despite the existence of generic frameworks and host of specific methods (e.g., Preston and Bedford 1988, Brooks et al. 1989, Leibowitz et al. 1992, Stein and Ambrose 2001, Hauer et al. 2001), the scientific and regulatory communities still wrestle with how to most effectively evaluate cumulative wetland impacts and their resultant effects. Hydrogeomorphic wetland profiling is forwarded as an means of improving cumulative wetland impacts analyses by linking them to current concepts of wetland development and functioning. This approach provides a means of wetland-based landscape characterization and cumulative impacts analysis that also affords a first approximation of potential wetland-mediated cumulative effects.

By partitioning Summit County Colorado into three physio-ecologically based ecoregions, it was determined that reference standard examples of each ecoregion had a characteristic and statistically discernable HGM WP. This is a key finding since there had not been an empirical evaluation of how tightly the abundance and diversity of wetlands is tied to the physical setting (Bedford 1996, Winter 2001). Nor had there been an indication of whether theoretical patterns in wetland occurrence could be quantitatively discerned owing to natural variation in landscapes. This finding also underscores the necessity of using ecologically-based units such as process domains, fundamental hydrologic landscape units or ecoregions in the design of management strategies, assessment tools, and ecological studies alike. Just as in the case of socio-political boundaries, *ad hoc* use of watershed boundaries to answer ecologically-based questions, such as those of wetland diversity and function, aquatic life use characteristics, habitat abundance can provide a muddled or even misleading picture of large-scale trends. This is not to suggest that watershed-based analyses are inappropriate for addressing many other types of management and research problems, however.

Because reference standard HGM WPs were found to be consistent within ecoregions, I suggest that reference standard landscapes can validly be contrasted with physically comparable, impacted landscapes to determine the extent of cumulative impacts in the central Rocky Mountains. This finding would have little value, however, if HGM WP differences between reference standard and impacted landscapes were not detectable owing to natural systemic variation. In direct comparisons within ecoregions, HGM WPs from reference standard landscapes were found to be significantly different from profiles derived from impacted landscapes. Thus it is concluded that the approach also is sensitive enough to detect cumulative impacts.

Reference-based Cumulative Impacts Analysis

The concept of reference bears some additional consideration since it is so fundamental to the HGM WP approach. To account for historical wetland losses and circumvent the lack of historical data, HGM WP follows current thinking in landscape and wetland assessment by adopting a reference-based approach. In particular, it compares ecologically similar landscapes in an manner akin to the time-for-space substitutions common to investigations of vegetation succession (White and Walker 1997, Pickett 1989). Comparative approaches such as this have been extremely productive in such diverse pursuits as watershed analyses (McCulloch and Robinson 1993), wetland evaluations (Brinson 1993, US EPA 1998, Gernes and Helgen 2002, SAIC 2000), stream assessments (Karr et al. 1986, Karr and Chu 1997, Hughes et al. 1986), and studies of forest succession (Pickett 1989).

Here, profiles from a target landscapes are contrasted with ecologically similar, minimally-impacted (reference standard) landscapes. The main conceptual difference between the HGM WP reference approach and that of successional studies is that the relationship between time and accumulation of impacts cannot be described by a simple deterministic model. For instance, severe impacts could have accumulated in an area over a long period of time, or they could have been brought about quickly during a period of intense urban growth and development. This technique does not differentiate between these two scenarios, and therefore explicitly assumes that the resultant environmental effects are similar whether cumulative impact accumulation was slow, rapid, historical or recent.

Comparative approaches such as this do possess inherent limitations, however (MacDonald 2000, White and Walker 1997). Considering paired-watershed studies of cumulative impacts, MacDonald (2000) challenged that “The implicit assumption is that the [contrasted] systems are part of the same population and therefore directly comparable. The corollary is that any differences are presumed to result from past disturbance.” In particular, for a referenced-based approach to be useful, the parameter of interest must be relatively invariant within categories, while at the same time being detectably different among categories. This is echoed in Rheinhardt et al.’s (1997) discussion of critical assumptions of the HGM functional assessment method in which they stated that “Ecological processes [must be] so similar in form and magnitude within any narrowly defined regional subclass that they shape biotic and abiotic components in ways characteristic for the subclass.”

Thus, in order for HGM WP to be used in a referenced-based manner it must be demonstrated that landscapes are validly comparable and that within comparable landscapes HGM WPs are relatively consistent, being more similar to one another than they are to profiles from physically dissimilar landscapes. Theoretical constructs support the idea of HGM WP constancy within physically similar landscapes, since climate, hydrology, geomorphology and hydrogeology drive the abundance and diversity of wetlands. This study provides corroborating empirical support for this hypothesis.

In this study, landscape comparability was achieved through division of the study region into physically similar ecoregions. Comparability was validated by calculating the HGM WP variance within reference standard ecoregions. Unacceptably high variance within reference standard ecoregions would have indicated that either HGM WPs are not related to hydrogeomorphic conditions (unlikely), or that ecoregions were inappropriately designated – that is, they consisted of a mixed landscape types or “populations”. Neither was true in this case, therefore, the uniqueness of the individual ecoregions was established.

An important offshoot of this conclusion is that, as suggested by Bailey and Omernik (1997), predictions with a calculable error rate can be made about the relative abundance and diversity of wetland functional types in landscapes for which no detailed wetland survey information exists. Significantly such predictions can be derived solely through the analysis of geographic data, most of which are readily available as digital files on the World Wide Web and elsewhere.

Landscape Characterization and Indexing of Cumulative Effects

Ecological functions have been usefully attributed to individual wetlands, and it would seem that analogous benefits could be derived from evaluating the wetland functioning of whole landscapes. An obvious approach to evaluating the wetland functioning of a landscape would be to use a functional assessment methodology such as HGM to evaluate all or a statistical population of wetlands in a prescribed area, and subsequently model the total landscape capacity for each wetland function. This approach would be a simple extrapolation of the methods described in Smith et al. (1995). But such large-scale evaluations of wetland functioning would not generally be tractable to owing issues including labor intensiveness and cost, and they would only be feasible when circumstances dictated a highly detailed approach.

Because wetland profiling utilizes HGM categories (here functional classes), the method can be used to broadly characterize the wetland functions associated with various landscape types. For instance, High Mountain areas in Summit County are dominated by slope wetlands with relatively fewer riverine wetlands. Therefore, one can infer that such areas primarily perform those wetland functions associated with slope wetlands such as groundwater discharge, maintenance of stream base flow, and carbon retention (Johnson 2000). Utilization of HGM subclasses, rather than classes, would increase the analytical resolution of such a characterization.

Characterization of landscapes in terms of wetland functioning seems a useful endeavor of itself, but this concept can also be extended to the realm of cumulative *effects* analysis. Per the definitions used in this report, HGM WP is not a cumulative effects assessment method, but it can provide an index of probable wetland-related cumulative effects and it can help focus monitoring, restoration and analysis efforts on variables most likely to be impaired owing to wetland losses. For example, if a HGM WP analysis were to show that the proportion of depressional and fringe wetlands has been increased at the expense of riverine wetlands, one could thereby infer that at the landscape-scale, the composite functional capacity of riverine wetlands had been reduced. That is, such landscapes would be less able to perform functions attributed to riverine wetlands including sediment export or provision of critical wildlife travel corridors (Hauer et al. 2002, Brinson et al. 1995). At the same time, such landscapes would have an increase in the functions provided by depressional and fringe wetlands, most notably surface water storage (Hauer et al. 2000).

It is important to note that, like functional approaches to wetland evaluation, valuation of landscape alterations is not considered by HGM WP. For instance, in spite of detectable cumulative impacts and their presumed cumulative effects, such a situation may be deemed acceptable or even desirable in a given socioeconomic setting. In the Summit County, this is well illustrated in the case of reservoir construction, which creates fringe wetlands at the expense of slope and riverine wetlands (Fig. 8).

Utility and Limitations of HGM WP

Hydrogeomorphic wetland profiling provides a means of characterizing the population of wetlands found in landscapes based on their potential functioning. Moreover, HGM WP analyses provide a coarse-scale view of wetland functioning and cumulative impacts within landscapes. In particular, the method can be seen as *evaluating cumulative impacts to the abundance and diversity of wetland functional types.* This scale of analyses is insensitive to fine-scale patterns, such as the condition of any single wetland. In effect the method filters such information. This is a beneficial characteristic since fine-scale data can clutter large-scale analyses and hinder recognition of large-scale patterns (Holling 1992).

An important ramification of this tactic is that HGM WP only provides an index of *potential* landscape-scale wetland functioning; the actual functioning or condition of individual wetlands is left implicit. While at first seeming a limitation, this strategy is intentional. It was adopted to maintain fidelity to the method's primary focus and aim while explicitly acknowledging the multi-scale complexities of landscape analyses.

As it has commonly been noted, the most efficient way to evaluate a complex system is to focus analyses on the primary driver(s) acting at the desired scale (Warren 1979, Frissell et al. 1986, Brinson 1993, Bedford 1996, Montgomery 1999). In general, a particular process or characteristic is only of preeminent importance at a single scale of observation. For instance, basin geomorphology is a primary driver of wetland functioning (Brinson 1993). When one considers the mechanisms *creating* wetland functions, however, geomorphology falls to the background forming a contextual factor which generally only indirectly affects specific mechanisms such as biotic interactions or nutrient cycling. The existence, diversity, and relative abundance of wetland functional types is seen here as the primary control of wetland functioning at the landscape scale. That is, if a wetland has been eliminated from a landscape, it can perform no beneficial ecological functions; all other forms of impacts are subordinate to this single fact.

This is *not* to say that within-wetland impacts are unimportant. Rather, such impacts are of a secondary importance at the landscape scale.

Thus, HGM WP adheres to analysis of cumulative wetland impacts at a single organizational scale, while at the same time recognizing that cumulative impacts or effects can be evaluated at multiple scales and using a variety of approaches. Such a strategy has important practical ramifications. In leaving fine-scale characteristics implicit, the methodology remains open-ended and able to incorporate fine-scale data, facilitating multi-scaled analysis. Data obtained through a variety of means such as regional inventories, or assessment surveys using any one of the multitude of approaches available such as HGM, indices of biologic integrity, the Wetland Evaluation Technique, or the Habitat Evaluation Procedure can be directly incorporated into HGM WP diagrams. The only requirement for inclusion of such data is that surveyed wetlands be classified into HGM categories. This is a simple and straightforward task even after surveys have been completed (Appendix 1). A hypothetical example of multi-scale profile construction is shown in Fig. 9.

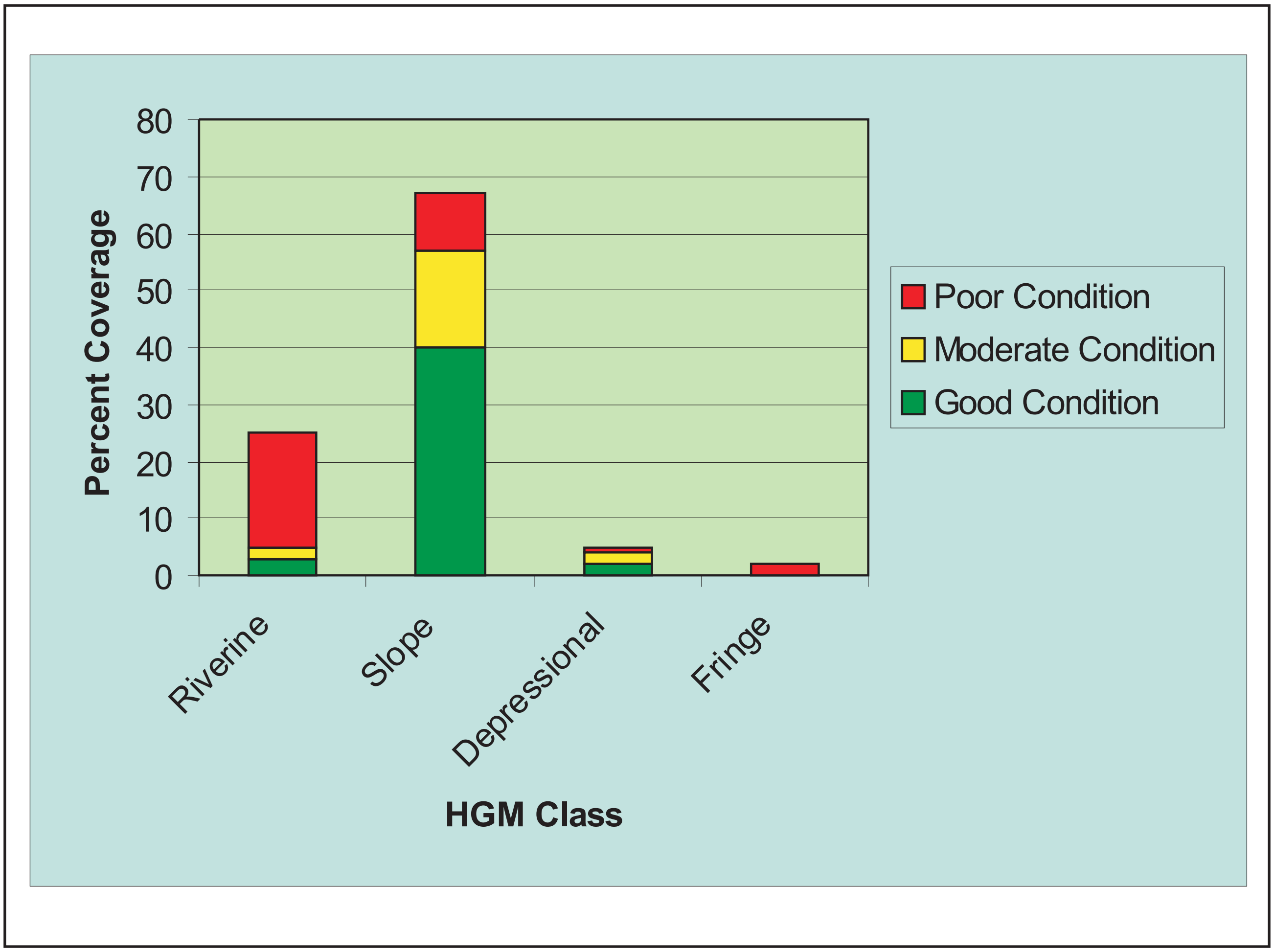

Figure 9. A hypothetical example of how fine-scaled data could be incorporated into an HGM WP analysis. In this example, the condition of wetlands is determined through any number of site-based approaches such as HGM or indices of biological integrity. Wetlands must be classified into HGM categories (here classes) before they can be integrated into the analysis. Within each HGM class, the relative proportion of wetlands within each conditional category are color-coded to indicate the aggregate condition of wetlands. In this example, the majority of riverine wetlands are in poor condition. Multi-scale profiles from target landscapes such as this one could also be compared to reference profiles.

Critical Evaluation of the Method

Hydrogeomorphic wetland profiling has been shown in this study to be a powerful tool for the wetland-based characterization of landscapes, assessment of cumulative wetland impacts, and indexing of cumulative effects. There are certain aspects of the method which could be improved upon with further development or which need to addressed before widespread utilization of the method is possible.

Insensitivity to Within-Wetland Impacts

As discussed above, HGM WP only measures changes in the relative abundance and diversity of wetland types. As a stand-alone method it is wholly insensitive to impacts occurring within wetlands. Thus when used to evaluate cumulative wetland impacts it is susceptible to Type II errors, when the null hypothesis is "no cumulative impacts in the target landscape". To illustrate, given that a HGM WP does not vary statistically from its reference standard, two situations could exist: 1) the landscape could be intact insofar as wetland functioning is concerned; or 2) wetlands have not been outright lost or functionally converted, but there have been within-wetland impacts that have reduced the capacity of individual wetlands to function at their potential.

This form of Type II susceptibility is an unavoidable consequence of the method's single scale focus, but it can be addressed through the inclusion of small-scale data as explained above. I further speculate that such insensitivity is not a widely significant issue since it would seem likely that landscapes possessing unaltered profiles also possess functionally intact wetlands. The converse of this situation seems equally likely, as well.

Lack of Appropriate Reference Standard Landscapes

Summit County was in many ways an ideal area to develop and test this approach since it encompasses a wide range of physical settings and it possesses many minimally-impacted landscapes. Clearly these characteristics are not commonplace in many areas, particularly in urbanized regions such as the east coast of the US. Probably the most significant impediment to widespread application of this approach is the lack of minimally-impacted (reference standard) landscapes. This is not a problem unique to this methodology, but to every reference-based analytical technique. There is no easy solution to this problem, although various solutions may be on the horizon.

A promising means of determining reference standard conditions could be modeling expected HGM WPs based on analysis of hydrogeological and/or hydrogeomorphic conditions. McLaughlin (1999) for instance, developed a model to predict the occurrence of wetlands in the Ridge and Valley province of Pennsylvania. If such techniques can successfully be developed, models of expected profiles could be compared to the observed profiles on the landscape.

Of course, another way around this issue is to develop a contemporary HGM WP for a given landscape and monitor it into the future, thereby avoiding the need for space-for-time references. In this case, the reference standard condition is the extant landscape condition. While valuable for monitoring programs this approach would not address the issue of historical impacts.

Categorization of Impact Level

MacDonald's (2000) corollary statement that any differences are presumed to result from past disturbance remains an explicit assumption in this approach. No long-term data exist as to actual wetland impacts in Summit County. Even information in the form of Clean Water Act §404 permit applications were found to be of little worth in describing recent wetland impacts since they were so often incomplete or contained erroneous information (H. McLaughlin, Summit County, Colorado Government – Mapping Department, *personal communication*). This was particularly true of project applications approved early in the program's existence. To address this data gap, LULC data were used as an index of wetland impacts. Although there is significant precedent for such an approach (e.g., Allan et al. 1997, Bolstad and Swank 1997, Herlihy et al. 1998, Lenat and Crawford 1994), the actual relationship between land cover alteration and wetland impacts was not explicitly formulated. Forming a tighter link between land cover alteration and wetland impacts might significantly improve the accuracy of this method and utilization of other indicators of wetland impacts, such as normalized difference vegetation indices (NDVIs) may prove advantageous in this regard (Griffith et al. 2002).

Along these same lines, process domains were herein simply classified as "impacted" or "reference standard". Obviously, impact level is not a simple binary function, but rather it occurs as a gradient. In this study, binary classification was adequate and produced clear results; however, with additional investigation, more refined categories could be delineated which could improve the method's resolution and accuracy.

Problematic Wetlands

Lastly, in Summit County the prevalence of irrigated meadows created pragmatic difficulties. Such systems are to varying degrees artificial. But in the Rocky Mountains, these sites are usually associated with natural wetland systems, and because of the effects of irrigation, large portions of these meadows may be artificial wetlands, performing many of the same functions of natural wetlands (Johnson 2000). Given the practical constraints of this project, I did not find a wholly satisfying way to deal with these areas. Similar classification difficulties would likely occur should the method be applied in other regions.

Future Applications of HGM Wetland Profiling

Hydrogeomorphic wetland profiling seems a promising means of tackling many facets of landscape-scale wetlands analyses. With further development, the method seems particularly suited to address three additional management needs — landscape classification, synoptic analyses (*sensu* Leibowitz et al. 1992), and threshold detection.

Hydrogeomorphic wetland profiling provides a succinct means of characterizing the abundance and diversity of wetland types within landscapes. Because of the utilization of HGM categories, it also provides an index of landscape-scale wetland functioning. Given these characteristics, the approach provides a natural basis from which to construct wetland-based landscape classification frameworks. For instance, in terms of this study, Summit County landscapes could be qualitatively classified as slope-dominated, riverine-dominated, or slope-riverine co-dominated. Given the quantitative nature of the approach, categories could also be explicitly parameterized.

Next, the synoptic approach developed by EPA researchers is intended to prioritize restoration, protection, and permitting efforts in light of almost universal resource shortages (Leibowitz et al. 1992, Abbruzzese and Leibowitz 1997, McAllister et al. 2000). The approach consists of a generic methodology that can incorporate data from a number of different sources depending on availability. After being initially proposed and tested, the methodology has been refined and implemented (McAllister et al. 2000). Being essentially an approach framework, the method requires the inclusion of indices of wetland function, value, functional loss and replacement potential. The exact form of these indices is not specified and can vary from application to application. Hydrogeomorphic wetland profiling results would seem to be particularly appropriate for synoptic analyses, since they can index both wetland functioning and functional loss within landscapes.

Even removed from external approaches such as the synoptic, HGM WP analyses would seem beneficial to wetland regulatory and management programs. Consider a hypothetical situation in which HGM WP analyses indicate that slope wetlands have been significantly reduced in a landscape relative to appropriate references, and further that fringe wetland coverage has been artificially increased. In such a situation, limited agency resources could be allocated such that permit applications proposing impacts to slope wetlands would receive priority status, whereas applications for fringe wetlands could receive lesser scrutiny. A similar usage could be envisioned for conservation or restoration activities, as well.

Finally, identification of thresholds of wetland impacts at which cumulative effects become significant has been a longstanding goal of scientists and managers (Preston and Bedford 1988), yet there has been little success in this endeavor. Utilizing HGM WPs in conjunction with detailed approaches that quantitatively evaluate environmental variables such as water quality, it seems feasible that the thresholds of profile alteration could be identified at which measured variables exhibit a detectable, negative response.

Conclusions

Ecoregions within the mountains of central Colorado were found to possess inherent, characteristic and discernable HGM WPs based on analysis of reference standard landscapes. Because of this consistency, it was suggested that HGM WP may be usable in a reference-based manner to evaluate cumulative wetland impacts occurring within developed landscapes. Within ecoregions, profile differences between reference standard and impacted landscapes were significant, being manifested as an alteration to the overall shape of the HGM WP, or as differences in the relative abundance of particular functional classes.

Hydrogeomorphic wetland profiling is a promising approach to cumulative wetlands impact analysis. The method targets a single analytical scale, while acknowledging that impacts can be evaluated at multiple scales. As a result of this strategy and its clear format, HGM WP results can be combined with data derived through smaller-scale approaches to yield multi-scale analyses of wetland resources. The method also seems a useful means to address additional facets of landscape analysis of wetlands, including wetland-based landscape classification, threshold detection, and synoptic analyses.

REFERENCES CITED

Abbruzzese, B. and S. Leibowitz. 1997. A synoptic approach for assessing cumulative impacts to wetlands. Environmental Management **21**:457-475.

Ainslie, W.B., R. Smith, B. Pruitt, T. Roberts, E. Sparks, L. West, L. Godshalk, and M. Miller. 1999. A Regional Guidebook for Assessing the Functions of Low Gradient, Riverine Wetlands in Western Kentucky. Technical Report WRP-DE-17, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Allan, J., D. Erickson and J. Fay. 1997. The influence of catchment land use on stream integrity across multiple spatial scales. Freshwater Biology **37**:149-162.

Anderson, J. R., E. Ernest, J. Roach and R. Witmer. 1976. A Land Use And Land Cover Classification System For Use With Remote Sensor Data. Geological Survey Professional Paper 964. U.S. Government Printing Office, Washington, D.C.

Bailey, R. 1995. Ecosystem Geography. Springer-Verlag, New York.

Bedford, B. 1999. Cumulative effects on wetland landscapes: links to wetland restoration in the United States and Southern Canada. Wetlands **19**:775-788.

Bedford, B. 1996. The need to define hydrologic equivalence at the landscape scale for freshwater wetland mitigation. Ecological Applications **6**:57-68.

Bedford, B. L. and E. Preston. 1988. Developing the scientific basis for assessing cumulative effects of wetland loss and degradation on landscape functions: status, perspectives and prospects. Environmental Management **12**:751-771.

Bolstad, P. and W. Swank. 1997. Cumulative impacts of land use on water quality in a southern Appalachian watershed. Journal of the American Water Resources Association **33**:519-553.

Brinson, M. M. 1993. A hydrogeomorphic classification for wetlands. Technical report WRP-DE-4, U.S. Army engineer waterways experiment station, Vicksburg, MS .

Brinson, M. M. and R. Rheinhardt. 1996. The role of reference wetlands in functional assessment and mitigation. Ecological Applications **6**:69-76.

Brinson, M. M., F. Hauer, L. Lee, W. Nutter, R. Rheinhardt, D. Smith, and D. Whigham. 1995. A guidebook for application of hydrogeomorphic assessments to riverine wetlands. Technical Report WRP-DE-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Brooks, R., E. Bellis, C. Keener, M. Croonquist, and D. Arnold. 1989. A methodology for biological monitoring of cumulative impacts on wetland, stream and riparian components of watersheds. Pp. 387-398 *in* Proceedings of the international symposium: wetlands and river corridor management, Charleston, SC. Association of State Wetland Managers, Berne, NY.

Council on Environmental Quality (CEQ). 1997. Considering Cumulative Effects Under the National Environmental Policy Act. Council on Environmental Quality, Washington D.C.

Croonquist, M., and R. Brooks. 1991. Use of avian and mammalian guilds as indicators of cumulative impacts in riparian wetland areas. Environmental Management **15**:701-714.

ESRI. 2002. ArcView GIS version 8.2. ESRI, Inc. Redlands, CA.

Frissell, C., W. Liss, C. Warren and M. Hurley. 1986. A hierarchical framework for stream habitat classification: viewing streams in a watershed context. Environmental Management **10**:199-214.

Geiger, R. 1965. The climate near the ground. Harvard University Press, Cambridge, MA.

Gernes, M and J. Helgen. 2002. Indexes of Biological Integrity (IBI) for Large Depressional Wetlands in Minnesota. Minnesota Pollution Control Agency Biological Monitoring Program Environmental Outcomes Division. Final Report to US EPA.

Griffith, J., E. Martinko, J. Whistler and K. Price. 2002. Interrelationships among landscapes, NDVI, and stream water quality in the U.S. central plains. Ecological Applications **12**:1702-1718.

Gwin, S., M.E. Kentula and P. Shaffer. 1999. Evaluating the effects of wetland regulation through hydrogeomorphic classification and landscape profiles. Wetlands **19**:477-489.

Halsey, L., D. Vitt and S. Zoltai. 1997. Climatic and physiographic controls on wetland type and distribution in Manitoba, Canada. Wetlands **17**:243-262.

Hauer, F., B. Cook, M. Gilbert, E. Clarain and R. Smith. 2000. A Regional Guidebook for Assessing the Functions of Intermontane Prairie Pothole Wetlands in the Northern Rocky Mountains. ERDC/EL TR-02-7, U.S. Army Engineer Research and Development Center, Vicksburg, MS. .

Hauer, F., B. Cook, M. Miller, C. Noble, and T. Gonser, T. 2001. Upper Yellowstone River Hydrogeomorphic Functional Assessment for Temporal and Synoptic Cumulative Impact Analyses. WRAP Technical Notes Collection (ERDCTN-WRAP-01-03), U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Hauer, F., B. Cook, M. Gilbert, E. Clarain, and R. Smith. 2002. A regional guidebook for applying the hydrogeomorphic approach to assessing wetland functions of riverine floodplains in the Northern Rocky Mountains. ERDC/EL TR-02-21, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Hauer, F. R., B. Cook, M. Miller, C. Noble, and T. Gonser. 2001. Upper Yellowstone River Hydrogeomorphic Functional Assessment for Temporal and Synoptic Cumulative Impact Analyses. ERDC TN-WRAP-01-03, U.S. Army Research and Development Center, Vicksburg, MS.

Hemond, H. and J. Benoit. 1988. Cumulative impacts on water quality functions of wetlands. Environmental Management **12**:639-653.

Herlihy, A., J. Stoddard, and C. Johnson. 1998. The relationship between stream chemistry and watershed land cover. Water, Air, and Soil Pollution **105**:377-386.

Hey, D.L. 1995. Flood reduction through wetland restoration – the upper Mississippi River basin as a case history. Restoration Ecology **3**:4-17.

Holling, C. S. 1992. Cross-scale morphology, geometry, and dynamics of ecosystems. Ecological Monographs, **62**:447-502 .

Hughes, R., D. Larsen, and J. Omernik. 1986. Regional reference sites: a method for assessing stream potentials. Environmental Management **10**:629 - 635**.**

Johnson, J. B. 2000. Documentation of reference conditions in the slope wetlands of the southern Rocky Mountains: reference database, site descriptions, and revised functional models. Report Submitted to U.S. EPA , Region 8 and the Colorado Department of Natural Resources.

Johnson, L., and S. Gage. 1997. Landscape approaches to the analysis of aquatic ecosystems. Freshwater Biology **37**:113-132.

Johnson, L., C. Richards, G. Host, and J. Arthur. 1997. Landscape influences on water chemistry in Midwestern stream ecosystems. Freshwater Biology **37**:193-208.

Karr, J., K. Fausch, P. Angermeier, P. Yant, and I. Schlosser. 1986. Assessing biological integrity in running waters: A method and its rationale. Champaign, IL, Illinois Natural History Survey.

Karr, J. and E. Chu. 1997. Biological monitoring and assessment: Using multimetric indexes effectively. EPA 235-R97-001. University of Washington, Seattle, WA.

Kratz, T., K. Webster, C. Bowser, J. Magnusun and B. Benson. 1997. The influence of landscape position of lakes in northern Wisconsin. Freshwater Biology **37**:209-217.

Leibowitz, S., B. Abbruzzese, P. Adamus, L. Hughes, and J. Irish. 1992. A synoptic approach to cumulative impact assessment: a proposed methodology. EPA/600/R-92/167. U.S. EPA, Environmental Research Laboratory, Corvallis, OR. 129 pp. .

Lenat, D. and J. Crawford. 1994. Effects of land use on water quality and aquatic biota of three North Carolina piedmont streams. Hydrobiologica **294**:185-199.

Levin, S. 1992. The problem of pattern and scale in ecology. Ecology **73**:1943-1967.

Loftis, J., L. MacDonald, S. Streett, H. Iyer, and K. Bunte. 2001. Detecting cumulative watershed impacts: the statistical power of pairing. Journal of Hydrology **251**:49-64.

Luecke, D.F. 1993. The Mississippi flood. Environment **35**:2-3.

Mac Donald, L. H. 2000. Evaluating and managing cumulative effects: process and constraint. Environmental Management **26**:299-315.

Marr, J. W. 1961. Ecosystems of the Front Range in Colorado. University of Colorado's Studies in Biology **8**.

Maxwell, J., C. Edwards, M. Jensen, S. Paustain, H. Parrot, and D. Hill. 1995. A hierarchical framework of aquatic ecological units in North America (Nearctic Zone). General Technical Report NC-176, USDA Forest Service, North Central Forest Experiment Station, St. Paul, MN.

McAllister, L., B. Peniston, S. Leibowitz, B. Abbruzzese, and J. Hyman. 2000. A synoptic assessment of prioritizing wetland restoration efforts to optimize flood attenuation. Wetlands **20**:70-83.

McCulloch, J. and M. Robinson. 1993. History of forest hydrology. J. Hydrology **150**:189-216.

McCune, B. and J. Grace. 2002. Analysis of ecological communities. MJM software Design, Gleneden Beach, OR.

McLaughlin K. 1999. Probability of wetland occurrence characterized by geology, slope, and stream link number: Spring Creek, White Deer Creek, and Juniata watersheds, Pennsylvania. Undergraduate Thesis in Geosciences, The Pennsylvania State University, University Park, PA.

Mitsch, W. and J. Gosselink. 2000. Wetlands. Van Nastrand Rienhold Co., New York .

Montgomery, D. R. 1999. Process domains and the river continuum. Journal of the American Water Resources Association **35**:397-410.

National Research Council. 1995. Wetlands: characteristics and boundaries. National Academy Press, Washington, D.C.

National Research Council. 2001. Compensating for wetland losses under the Clean Water Act. National Academy Press, Washington D.C.

Nestler, J., and K. Long. 1997. Development of hydrologic indices to aid cumulative impact analysis of riverine wetlands. Regulated Rivers: Research and Management **13**:317-334.

O'Neill, R., D. DeAngelis, J. Waide and T. Allen. 1986. A hierarchical concept of ecosystems. Princeton University Press, Princeton, N.J.

Omernik, J. 1991. Usefulness of natural regions for lake management: analysis of variation among lakes in northwestern Wisconsin, USA. Environmental Management **15**:281-293.

Omernik, J. 1995. Ecoregions: a spatial framework for environmental management. *In* Davis W. and Simon, T. (eds). Biological assessment and criteria: tools for water resource planning and decision making. Lewis Publishers, Boca Raton, FL.

Omernik, J. and R. Bailey. 1997. Distinguishing between watersheds and ecoregions. J. Amer. Water Res. Assoc. **33**:935 - 949.

Peet, R. K. 1981. Forest vegetation of the Colorado Front Range. Vegetaito **45**:3-75 .

Pickett, S. 1989. Space-for-time substitutions as an alternative to long-term studies. Pp. 110 - 135 *in* G.E. Likens (ed.) Long-term Studies in Ecology: Approaches and Alternatives. Springer-Verlag, New York.

Preston, E. and B. Bedford. 1988. Evaluating cumulative effects on wetlands functions: a conceptual overview and generic framework. Environmental Management **12**:565-583.

Rheinhardt, R., M. Brinson, and P. Farley. 1997. Applying reference data to functional assessment mitigation and restoration. Wetlands **17**:195-215.

Richards, C., L. Johnson, and G. Host. 1996. Landscape-scale influences on stream habitats and biota. Can. J. Fish. Aquat. Sci. **53** (Suppl. 1):295 -311.

Science Applications International Corporation (SAIC). 2000. Summit County wetland functional assessment. Report prepared for the Summit County Community Development Division.

Smith, R. D., A. Ammann, C. Bartoldus and M. Brinson. 1995. An approach for assessing wetland functions using hydrogeomorphic classification, reference wetlands and functional indices. Technical Report WRP-DE-9, U.S. Army Corps of Engineer Waterways Experiment Station, Vicksburg, MS.

SPSS. 2003. SPSS version 12.0. SPSS, Inc. Chicago, IL.

Stein, E. D. and R. Ambrose. 2001. Landscape-scale analysis and management of cumulative impacts to riparian ecosystems: past, present. and future. Journal of the American Water Resources Association **37**:1597-1614.

Strahler, A. N. 1957. Quantitative analysis of watershed geomorphology. AmericanGeophysical Union Transactions **38**:1117-1142.

US Environmental Protection Agency (EPA). 1998. Evaluating performance of wetland restoration activities – Wetland Bioassessment Fact Sheet 8. US EPA Office of Wetlands, Oceans and Watersheds, Report No. EPA843-F-98-001h.

Warren, C. E. 1979. Toward classification and rationale for watershed management and stream protection. EPA-600/3-79-059 .

White, P. and J. Walker. 1997. Approximating nature's variation: selecting and using reference information in restoration ecology. Restoration Ecology **5**:338-349.

Wiley, M., S. Kohler, and P. Seelbach. 1997. Reconciling landscape and local views of aquatic communities: lessons from Michigan trout streams. Freshwater Biology **37:**133-148.

Winter, T. and M. Woo. 1990. Hydrology of lakes and wetlands. *In* Wolman, M. and H. Riggs, (eds). Surface water hydrology. Geological Society of North America, Boulder, CO.

Winter, T. 1992. A physiographic and climatic framework for hydrologic studies of wetlands. *In* Robarts, R. and M. Bothwell (eds.). Aquatic Ecosystems in Semi-Arid Regions: Implications for Resource Management. N.H.R.I. Symposium Series 7, Environment Canada, Saskatoon.

Winter, T.2001. The concept of hydrologic landscapes. Journal of the American Water Resources Association **37**:335-349.

APPENDIX 1

KEY TO SUMMIT COUNTY, COLORADO, WETLAND TYPES

HYDROGEOMORPHIC WETLAND CLASSES AND SUBCLASSES IN SUMMIT COUNTY, COLORADO – DEFINITIONS, TAXONOMIC KEYS, AND USER INFORMATION

OPERATIONAL DRAFT – VERSION 2.1

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PREFACE

The following appendix is a provisional description and classification of the hydrogeomorphic wetland classes and subclasses found in Summit County, Colorado. It represents a modification and refinement of the classification devised by SAIC (2000). At the class level, wetland descriptions and diagnostic criteria are forwarded with a high degree of confidence. The preceding document detailing the hydrogeomorphic wetland profiling (HGM WP) approach utilized this level of HGM classification.

Subclass criteria and definitions are included for general consideration and to serve as a guide for HGM subclass definition in other areas. Subclasses appear generally sound having been delineated using the best available information, applied in mapping Summit County wetlands, and reviewed by wetlands experts. This classification has not been rigorously evaluated, however, and there may be valid reasons for revising aspects of it. Owing to its peripheral relevance to the development of HGM WP, it is beyond the scope of the current project to provide systematic testing and revision of the subclass classification. The classification as it stands is forwarded as a "strawman" framework awaiting future application, testing and refinement.

SUMMARY

Classification of wetlands based on hydrogeomorphic (HGM) characteristics is a powerful technique that can be used for wetland inventory, cumulative impacts analysis and functional assessment. Few existing inventories have categorized wetlands based on HGM characteristics, however. To utilize existing wetland inventory data for studies applying HGM, previously identified wetlands must be reclassified into regionally defined HGM categories.

This document first provides an overview of the HGM approach and the general applicability of this key. It then details an HGM classification for wetlands in Summit County, Colorado. The devised classification includes four wetland classes – slope, riverine, depressional, and lacustrine fringe. Each wetland class contains between 2 and 24 subclasses.

Along with HGM category designation, a major goal of this study was to produce an algorithm to classify previously identified wetlands into HGM categories using geographic data. The algorithm was produced as a dichotomous key. A guide to the application of this key and construction of an appropriate GIS model follow the HGM category descriptions. The final section of the report contains the dichotomous key algorithm for determining wetland class and subclass based on hydrogeomorphic characteristics. Illustrative examples of wetland classification are included as an appendix following the key. The characteristics used in this classification are generally obtainable from topographic maps, geographic information system (GIS) data, or aerial photographs.

This classification and taxonomic key are for use only in Summit County, Colorado. Summit County was chosen as the target area for this study since considerable wetland inventory and classification work had already been accomplished, making development and testing of this system possible. With revision this key could be expanded or adapted to other regions of the Rocky Mountains. The intended use of this document is for the classification of identified wetland areas into HGM categories. It may be used in conjunction with existing wetland delineation, classification, functional assessment, and inventory tools, but the classification framework alone cannot be used to determine the jurisdictional status or boundary of any wetland.

INTRODUCTION

In 1993, Brinson introduced a hydrogeomorphic (HGM) approach to wetland classification. HGM is a hierarchical classification method, wherein wetlands are broadly categorized into seven classes: Slope, Riverine, Depressional, Mineral Soil Flats, Organic Soil Flats, Lacustrine Fringe, and Estuarine Fringe. Classes are defined by broad similarities in hydrology, geomorphology and hydrodynamics. Each class may be further divided into a number of subclasses. Subclasses are defined on an ecoregional level based on intra-regional differences in HGM characteristics. Unlike many other wetland classifications, HGM does not use vegetation as a major classification criterion. Instead, HGM utilizes the assumption that wetlands possessing similar hydrologic, geomorphic and hydrodynamic settings will perform similar wetland functions, and further, that the vegetational composition will be a reflection of these physical attributes.

HGM provides a powerful framework for wetland classification, allowing users to group wetlands into functionally similar guilds. Because of its enormous utility and adaptability, the HGM classification framework has been widely applied by wetland scientists, managers and federal regulatory agencies. Initial applications of the HGM approach have primarily focused on wetland functional assessment. To many, in fact, the HGM method *is* a functional assessment technique. This is not strictly true, however, since fundamentally the HGM approach is simply a classification scheme.

Recently, HGM classification has been used in the inventory of wetlands across watersheds with the goal of investigating the cumulative impacts of wetland mitigation (Gwin et al. 1999). In that study, HGM was strictly used as a classification and inventory tool to compare the hydrogeomorphic characteristics of natural and mitigation wetlands. Such applications of HGM have the advantage of applying the scientifically sound HGM classification in its purest form, without the added complications inherent in the HGM wetland functional assessment method.

A major impediment to applying the HGM approach on a regional basis is that most wetland mapping programs have employed classifications other than HGM; the most notable example of this being the National Wetlands Inventory which applies the Cowardin et al. (1979) classification. In order to apply HGM classification across wide areas, either new surveys must be performed using HGM, or wetlands mapped using other classifications must be re-classified into HGM categories. Due to time and resource limitations, this second approach is the one most commonly applied.

Re-classification of mapped wetlands into HGM classes or subclasses is a somewhat qualitative and, at times, subjective process. To bolster consistency and reduce subjectivity, algorithms, most commonly in the form of dichotomous keys, can be used to re-classify wetlands into HGM categories (e.g. Tiner 2000, Adamus 2001) Development of re-classification algorithms is, of course, predicated on the existence wetland class and subclass definitions within the region of interest.

Regional Development of HGM

At this time, HGM is truly a work in progress rather than a finished product. Wetland classification and functional assessment using HGM is being developed throughout the country, but this development has taken considerably longer than originally envisioned. Since wetland classification is inherent in any application of HGM, designation and description of the HGM classes and subclasses is a necessary first step. As described in the Federal Register (1997, Vol. 62, Number 119), the HGM classes and subclasses present in a region are best defined by an Assessment Team (A-Team) comprised of experts in various aspects of wetland science, and who also specialize in the study of the wetland systems present within an ecological region. Such a classification by committee has not generally proven tenable, however. Rather, regional subclasses are typically defined by small team of scientists who base their classification on the input of local wetland experts, developed reference wetland data sets, existing literature, and professional judgement.

This document provides an HGM classification of wetlands in Summit County Colorado. It identifies two levels of wetland classification – the class and subclass levels. Although intended for use only in Summit County, Colorado this classification could be modified to include other reference domains within the montane, subalpine and alpine zones of the Southern Rocky Mountains.

This document has three primary goals: (1) to designate and describe the HGM classes and subclasses of wetlands existing in Summit County, Colorado; (2) present a dichotomous HGM classification key to these wetland classes and subclasses; and (3) provide a detailed users guide to the classification of wetlands using the developed keys.

General Applicability and Use of this Key

This wetland classification and taxonomic key are for use only in Summit County, Colorado. With revision this key could be expanded or adapted to other regions of the Rocky Mountains. The intended use of this document is for the classification of identified wetland areas into HGM categories. It may be used in conjunction with existing wetland delineation, classification, functional assessment, and inventory tools, but the classification framework alone cannot be used to determine the jurisdictional status or boundary of any wetland.

This key explicitly includes habitats that may not meet the US Army Corps of Engineers (US ACE 1987) criteria for wetlands; this is most commonly the case in riverine areas. Wetlands supported wholly through irrigation or other artificial hydrologic inputs are also not considered jurisdictional wetlands by the Sacramento District of the US ACE, who oversee wetland regulation in Summit County. Other US ACE districts or regions may approach regulation of these wetland types differently. Further, due to recent litigation and policy changes (e.g. The US Supreme Court's SWANCC decision), many areas that meet the strict US ACE definition of wetland are no longer under the jurisdiction of the Corps.

Successful application of this classification key requires the use of various types of geographic and/or remote sensing data. At a minimum, U.S. Geologic Survey 7.5 minute quadrangles with wetland polygons drawn on the map or an affixed to an acetate overlay are needed. Although classification can be accomplished solely using this basic topographic data and best professional judgement, such an approach is limited and may often make proper classification ambiguous.

Optimally, this wetland key should be used in conjunction with Geographic Information System (GIS) software and data. Useful data types are National Wetland Inventory (NWI) maps, Digital Elevation Models (DEMs), soil surveys (digital or hard copy), US EPA Reach File Data, FEMA floodplain maps, geologic maps, and aerial photos. All of these data sources are available on the web and most are free. Digital data types will be discussed in the section, *Application of this Key*.

SUMMIT COUNTY WETLAND TYPES

Four classes of wetland exist in Summit County: Slope, Riverine, Depressional, and Lacustrine Fringe. Within each of these classes, between 2 and 24 possible wetland subclasses have been defined (Table 1). Subclasses definitions are based on existing HGM studies (Noe et al. 1998, Johnson 2000, SAIC 2000, Adamus 2001, Keate 2001), wetland subclass keys (Tiner 2000), consultation with local experts and best professional judgement. Subclass categories may need future revision as additional studies are completed. Justification and definition of HGM subclasses are provided in the following section. Subsequent sections include dichotomous keys for identifying wetland classes and subclasses based on hydrogeomorphic criteria.

Table 1. List of potential HGM wetland classes and subclasses found in Summit County, Co. Wetland types are "potential" since several of the slope subclasses have not yet been identified in the county and may not exist there.

Wetland Class	Wetland Subclass
Slope	Isolated, shallow gradient, mineral/organic soil
	Isolated, moderate gradient, mineral/organic soil
	Isolated, steep gradient mineral/organic soil
	Through-flow, shallow gradient, mineral/organic soil
	Through-flow, moderate gradient, mineral/organic soil
	Through-flow, steep gradient mineral/organic soil
	Inflow, shallow gradient mineral/organic soil
	Inflow, moderate gradient mineral/organic soil
	Inflow, steep gradient mineral/organic soil
	Outflow, shallow gradient mineral/organic soil
	Outflow, moderate gradient mineral/organic soil
	Outflow, steep gradient mineral/organic soil
Riverine	Low-order, steep gradient and/or confined floodplain
	Moderate-order, steep gradient and/or confined floodplain
	High-order, steep gradient and/or confined floodplain

Wetland Class	Wetland Subclass
Riverine	Low-order, unconfined floodplain
	Moderate-order, unconfined floodplain
	High-order, unconfined floodplain
Depression	Kettle Pond Wetlands
	Oxbow and Meander Scar Wetlands
	Other Natural Depressional Wetlands
	Other Man-made Depressional Wetlands
Lacustrine Fringe	Natural Lacustrine Fringe
	Man-made Lacustrine Fringe

Slope Wetlands

Slope wetland subclasses are categorized based on their hydrologic connection to the surrounding landscape, topographical gradient, and soil composition (organic vs. mineral). Slope wetland subclass characteristics are presented in Table 2. The slope wetland subclass categories are taken directly from Johnson (2000). Several of the designated slope wetland subclasses were not identified during Summit County surveys. They are retained in this classification, however, since representatives of these subclasses may be identified with future study. Also, subclasses not identified in the current Summit County surveys may be found in other parts of the southern Rocky Mountains. It is hoped that the retention of these categories in this key increases the adaptability of this classification framework to areas outside of Summit County.

Subclass criteria were chosen based on the results of Johnson's (2000) study, which considered original data, as well as the findings of previous investigations. The chosen criteria are thought to most strongly control the hydrogeomorphic functions performed by Rocky Mountain slope wetlands. Other related sub-classifications of slope wetlands have utilized a variety of hydrogeomorphic, chemical or vegetational characteristics including those used in this classification. For instance, Tiner (2000) subdivided slope wetlands solely based on the hydrologic connection to the surrounding landscape. Keate (2001) divided the slope wetland class on the basis of soil composition, water table depth, and soil pH and salinity. Noe et al. (1998) indirectly categorized slope wetlands based on their hydrology, soil composition and water chemistry. Finally, the Summit County Special Area Management Plan development team developed a slope wetland classification based on soil composition, and topographical gradient (SAIC 2000) .

Although each of the above classifications were developed in response to specific project and management goals, a consistent philosophy exists between the various approaches. The classification criteria chosen for use here are intended to maintain continuity with and refine existing regional classifications for use specifically within the Summit County study area.

Table 2. Table of Summit County slope wetland subclass characteristics, with the name (italics), followed common examples of each (plain text). Shaded cells indicate potential subclasses which probably do not exist in the study area.

	Hydrologic Connection / Slope	**Inlet Present (no surface outlet)**	**Outlet Presence (no surface inlet)**	**Surface Inlet and Outlet Present**	**No surface Inlet or Outlet**
Predominately Organic Soils	0 - 4 %	*Inflow, shallow-gradient, organic soil* Fen or Carr	*Outflow, shallow-gradient, organic soil* Fen or Carr	*Through-flow, shallow-gradient, organic soil* Fen or Carr	*Isolated, shallow-gradient, organic soil* Fen or Carr
	>4 - ~10 %	*Inflow, moderate-gradient, organic soil* Fen or Carr	*Outflow, moderate-gradient, organic soil* Fen or Carr	*Through-flow, moderate-gradient, organic soil* Fen or Carr	*Isolated, moderate-gradient, organic soil* Fen or Carr
	≥10 %		*Outflow, high-gradient, organic soil* Forested Fen (Swamp)	*Through-flow, high-gradient, organic soil* Forested Fen (Swamp)	
Predominately Mineral Soils	0 - 4 %	*Inflow, shallow-gradient, mineral soil* Wet Meadow or Scrub-Shrub	*Outflow, shallow-gradient, mineral soil* Wet Meadow or Scrub-shrub	*Through-flow, shallow-gradient, mineral soil* Wet Meadow or Scrub-Shrub	*Isolated, shallow-gradient, mineral soil* Wet Meadow or Scrub-Shrub
	>4 - ~10 %	*Inflow, moderate-gradient, mineral soil* Wet Meadow or Scrub-Shrub	*Outflow, moderate-gradient, mineral soil* Wet Meadow or Scrub-Shrub	*Through-flow, moderate-gradient, mineral soil* Wet Meadow or Scrub-Shrub	*Isolated, moderate-gradient, mineral soil* Wet Meadow or Scrub-Shrub
	≥10 %		*Outflow, high-gradient, mineral soil* Avalanche chute or Open-canopy Swamp Forest	*Through-flow, high-gradient, mineral soil* Avalanche chute or Open-canopy Swamp Forest	

Riverine Wetlands

The criteria used to define riverine wetland subclasses are quite consistent between various existing HGM classifications. The most commonly used definitional criteria are: stream order, topographical gradient, and character and extent of the floodplain (Hauer and Smith 1998, Noe et al. 1998, Keate 1998, SAIC 2000, Tiner 2000). The classification included herein uses each of these characteristics to differentiate riverine wetland subclasses (Table 3). Here, stream order is used to provide an index of channel and wetland size. Although, at times potentially misleading, such as in the case of trellis networks in which stream order does not increase despite an increase in drainage basin area, in this region stream order seems to generally provide an accurate and practically attainable picture of wetland character.

Definition of additional subclasses could improve the classification in general or for a specific application. To potentially valuable revisions are provided here. First, it could be beneficial to consider flow duration in delineation of low stream order wetland subclasses. Stream duration classes designated by the U.S. Geological Survey, could prove useful in this regard.

Second, subclasses are currently designated solely on criteria pertaining to the physical wetland setting. The influence of biota on wetland functioning is only implied in this classification. Most importantly, in these mountains, beaver can have a profound effects on wetland characteristics and functioning. The structure of this classification assumes that virtually all potential riparian habitat has been historically or is currently utilized by beaver. It could certainly be beneficial to divide subclasses based on the nature or extent of beaver-induced ecosystem changes. Such a goal requires detailed attention, however, since the classification must take into account a complex temporal and spatial mosaic of functional states. The classification presented here acknowledges these complexities, but takes advantage of the sheer ubiquity beaver activity by implying its general existence, and by considering the mosaic of conditions as an intrinsic constituent of mountain riparian systems.

Table 3. Tabular representation of riverine wetland subclasses.

Stream Order	**Steep Gradient and/or Confined Active Floodplain**	**Moderate to Low Gradient with a Unconfined Floodplain**
Low (1^{st} - 3^{rd})	Riverine system bounded by the seasonal high water mark with little or no floodplain. Channels may be artificially entrenched, thereby constraining the active channel within a broader valley.	Channel movement is generally unconstrained but the riparian zone is poorly developed or narrow due to low flow volume. These wetlands often found in association with headwater slope wetland complexes and commonly include beaver-pond complexes.
Moderate (4^{th} - 5^{th})	Riverine system bounded by the seasonal high water mark with little or no floodplain. Narrow, temporary bars and surfaces are common. Channels may be artificially entrenched, thereby constraining the active channel within a broader valley.	Well developed, active floodplains usually present. Floodplains may have a variety of fluvial features such as oxbow ponds and meander scrolls. These riverine wetlands may be created or expanded by beaver activity and are commonly associated with terrace-base slope wetlands. Associated terrace-base wetlands are dominated by groundwater discharge which drains into the flood plain. Such wetlands should be evaluated as slope wetlands.
High (6^{th} - 7^{th})	Riverine system bounded by the seasonal high water mark with little or no floodplain. Temporary bars and surfaces are common. Channels may be artificially entrenched, thereby constraining the active channel within a broader valley.	Well developed, active floodplains usually present. Floodplains may have a variety of fluvial features such as oxbow ponds and meander scrolls. These riverine wetlands are commonly associated with terrace-base slope wetlands. Associated terrace-base wetlands are dominated by groundwater discharge which drains into the flood plain. Such wetlands should be evaluated as slope wetlands.

Depressional Wetlands

Few types of depressional wetlands exist in Summit County. The Summit County Special Area Management Plan (SAMP) technical development group identified three depressional wetland types: kettle ponds including their associated wetlands; oxbow/meander scar ponds including associated wetlands; and other types of natural and man-made wetlands (SAIC 2000). The SAMP subclassification has been generally maintained in this framework, except that the subclass "other types of natural and man-made wetlands" has been divided into two subclasses based on whether the wetland was natural or man-made (Table 4).

The first two depressional wetland subclasses share similar hydrology (groundwater discharge, surface inlet channels and/or surface runoff) and hydrodynamics (vertical water fluctuations), differing primarily in geomorphic position. The third and forth subclasses are artificial, including a variety of either natural or man-made wetlands. Examples of natural depressional wetlands types included within the third subclass are snowmelt-fed depressions above tree line or naturally dammed, landslide-scar wetlands. Man-made depressional wetlands may take many forms and may be wholly dependent on artificial hydrologic inputs for wetland maintenance.

The two artificial subclasses were maintained in this classification since: 1) there is relatively little information available describing these wetlands, 2) these depressional wetlands comprise only a small percentage of the total wetland area in the region, 3) they are often removed from developmental risk, and 4) the types of wetlands included within either of these subclasses probably function similarly on the landscape, with many of the man-made types providing little ecological function.

Table 4. Hydrogeomorphic characteristics of depressional wetland subclasses.

Wetland Subclass	Hydrologic Characteristics	Hydrodynamics	Geomorphic Position
Kettle Pond Wetlands	May be isolated, or may have inflow, outflow, or through-flow channels. Hydrologic inputs may additionally come through groundwater discharge and surface runoff. Hydrology in these wetlands frequently varies seasonally.	Vertical	Found on level or hummocky surfaces of glacial deposits – typically moraines or outwash plain.
Oxbow and Meander Scar Wetlands	Usually lacking perennial, natural surface water inlets and outlets, although high-water inlet or outlet channels may be present. Additional hydrologic inputs may come through groundwater discharge and surface runoff. Hydrology in these wetlands may vary seasonally.	Vertical	Located on a fluvial surface above, or physically isolated from, the active floodplain.
Other Natural Depressional Wetlands	May be isolated, or may have in-flow, out-flow, or through-flow channels. Hydrologic inputs may additionally come through groundwater discharge and surface runoff. Hydrology in these wetlands frequently varies seasonally.	Vertical	Various
Other Man-made Depressional Wetlands	May be isolated, or may have inflow, outflow, or through-flow channels. Additional hydrologic inputs may additionally come through surface runoff or groundwater discharge. Hydrology in these wetlands frequently varies seasonally and may entirely artificially sustained.	Vertical	Various

Lacustrine Fringe

Lacustrine fringe wetlands are broken into two subclasses based on genesis and hydrodynamics: natural lacustrine fringe and man-made lacustrine fringe. These subclasses are consistent with Noe et al. (1998) and SAIC (2000), although Noe et al. (1998) included these wetland types in the Depressional class, and in SAIC (2000) the above subclasses were divided based on the magnitude of water table fluctuations. Table 5 describes the HGM characteristics of the two lacustrine fringe wetland subclasses.

Table 5. Hydrogeomorphic characteristics of Summit County lacustrine fringe wetlands.

Wetland Subclass	**Hydrologic Characteristics**	**Hydrodynamics**	**Geomorphic Position**
Natural Lacustrine Fringe	Surface inlet and outlet.	Vertical. Seasonal water level fluctuations are relatively low.	Valley bottoms and plateaus.
Man-made Lacustrine Fringe	Surface inlet generally with a regulated outlet.	Vertical. Water level fluctuations large and water level may vary sporadically due to water management.	Various

Application, Development and Testing of the Keys to Summit County Wetlands Types

The reader may wish to briefly scan the keys in the following two sections to become generally familiar with the form and approach of the key before reading this section on key usage and application. This section describes the way in which this key was actually implemented during development and testing. This discussion should serve as a user manual for the key during future applications. Much of the discussion below is of a technical nature. To utilize the most current technological approaches, it is assumed that the user already possess experience in geographic information systems (GIS). Users without GIS experience or capacity may skip technical sections and use manual methods as described in the *General Rules to Decision Making* section.

GIS Development

A GIS was developed using ArcView version 8.1 software (ESRI 2001). Data incorporated into the GIS came from a variety of sources. All GIS data was projected into the Universal Transverse Mercator (UTM) system using the North American Datum of 1927 (NAD 27). Digital USGS 7.5 minute quadrangles in GeoTIFF format comprised the base layer. GeoTIFFs are available from the Natural Resources Conservation Service's (NRCS) Geospatial Data Gateway[1] (http://www.lighthouse.nrcs.usda.gov/gateway/gatewayhome.html); although the GeoTIFFs used in this project were obtained from a commercial source.

Wetland polygons were obtained from three aerial photograph surveys of Summit County. Data were provided by Summit County. Each aerial photograph data source is described in SAIC (2002). The original wetland classifications were converted by SAIC (2000 and 2002) to hydrogeomorphic categories based on reinterpretation of aerial photographs, topographical data, and field surveys.

A 10 meter DEM was used to derive 6 m (20 ft.) topographical contours. Wetland topographic gradient was determined by defining an axis within the widest or longest portion of the wetland perpendicular to its topographical gradient. The length or width of the wetland along this axis was then measured using the ArcView "Measure" tool. Finally, the change in elevation across the wetland was determined by counting contour lines and multiplying by the contour interval. When a wetland began or ended between contours, elevation was estimated based on the relative proportion of the contour interval covered by the wetland.

Stream ordering was carried out by hand using Strahler's (1952) method. Ordering was applied to 1:100,000 digital line graphics (DLGs) and was completed by Summit County Government. A field containing stream order data was added to the stream digital line graphic (DLG) attribute table.

Geologic data for the county were obtained from the Denver and Leadville 1 X 2° (1:250,000) Geologic Quadrangles. These data files are available through the USGS web page at http://greenwood.cr.usgs.gov/pub/mf-maps/mf-2347 and http://greenwood.cr.usgs.gov/pub/open-file-reports/ofr-99-0427, respectively.

Soil data were derived from two sources. Soil Survey Geographic Database (SSURGO) data were used were available. These data are the most detailed digital soil data available in the state, but coverage of Summit County is incomplete. SSURGO data are available at: http://www.ftw.nrcs.usda.gov/ssurgo/metadata/co690.html. Where SSURGO data were unavailable, coarser State Soil Geographic Database (STATSGO) data were used. These data, compiled at a scale of 1:250,000, are available at: http://www.ftw.nrcs.usda.gov/stat_data.html.

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[1] Web site addresses (URLs) are current as of time of publishing, but are subject to change.

General Rules to Decision Making

Determination of many hydrogeomorphic traits, such as gradient or stream order, is straight forward using GIS or even simple paper 7.5' topographical quadrangles. Other characteristics such as local soil composition or dominant hydrologic inputs may be more difficult to determine due to lack of site specific data or resolution limitations. What follows are some general guidelines to wetland characterization in cases where description may not be clear cut or where data limitations exist.

Most wetlands have somewhat mixed hydrologies. Of course all wetlands receive meteoric inputs, but most also receive varying degrees of surface and/or groundwater inputs. Brinson (1993), for example, provided a triangular ordination of wetland type based on the relative contribution of precipitation, groundwater and surface water inputs to the total wetland water budget (Fig. 1).

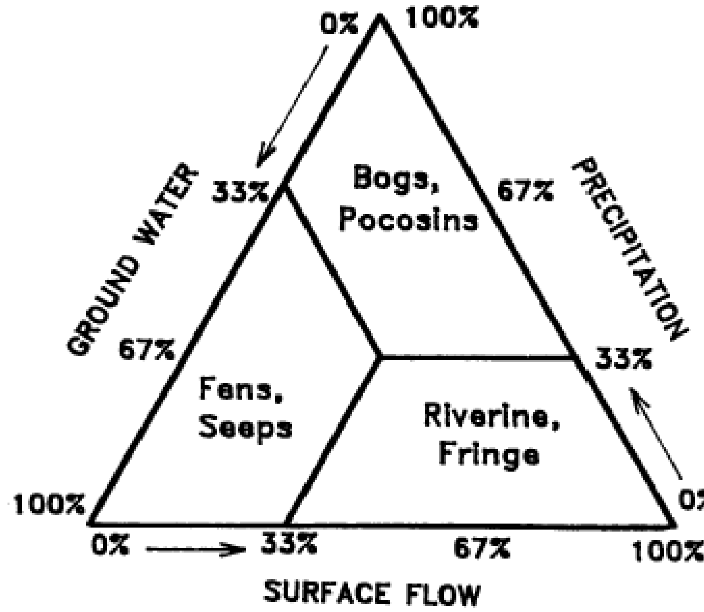


Figure 1. Separation of wetland types based on the relative contribution of hydrologic inputs. From Brinson (1993)

For this HGM classification, in all cases, wetlands should be grouped into classes based on the *dominant* hydrologic source or process. Considering only ground and surface water inputs, riverine wetlands should receive more than 50 % of their hydrologic input from surface water, whereas slope wetlands should derive more than 50% of their hydrologic input from groundwater. As detailed in the description of Summit County wetland subclasses above, water sources of depressional and lacustrine fringe wetlands can vary.

In practical terms, separating riverine from slope wetlands is commonly quite difficult and, often arbitrary since these two types of systems may be interdependent and spatially intermixed. If fine scale detail is required for a particular application, large contiguous wetlands containing a mix of wetland subclasses can be broken in multiple polygons (Partial Wetland Assessment Areas *sensu* Smith et al. 1996). For larger-scale studies this level of subdivision may not be valuable.

If a data source is lacking or its resolution is insufficient, secondary indicators may provide adequate evidence for decision making and classification. If some wetland characteristics can not be determined, the wetland can be left partially classified. For example a slope wetland could be hydrogeomorphically classified as "isolated, low gradient" even if soil composition is unknown. Examples of common hydrologic, geologic and edaphic indicators are provided below to help resolve common ambiguous situations that could arise while using these keys.

Indicators of Hydrology in Riverine, Slope and Lacustrine Fringe Wetlands

Separating riverine from slope wetlands is the greatest challenge in this method, since the two types are often adjacent to one another, or form portions of a greater wetland complex. Slope wetlands at the base of stream terraces – both large and small – and flow-through slope wetlands are the hardest to distinguish and separate from riverine wetlands. In fact, these wetlands may be so closely associated that their separation is somewhat artificial. Therefore, while a greater number or errors may in classifying these wetlands the consequences of doing so should generally be low. As written before, in classifying a wetland based on hydrology, the *dominant* hydrologic input should be used to determine wetland class. If different water sources dominate distinctly different portions of a wetland, that wetland should be subdivided to reflect the situation. The following characteristics help to distinguish hydrologic types when specific hydrologic data is not available.

- Flow-through slope wetlands can often be identified based on the following characteristics: The stream channel is low order (1^{st} to 3^{rd}) and wetland areas extend up adjacent valley slopes, well above the channel elevation. This characteristic shows that wetlands receive water from sources other than the alluvial system. Presence of a flow-through slope wetland may also be indicated by asymmetry of the wetland with respect to the channel. That is, within a symmetric channel valley, the wetland will be relatively broad and/or wide on the side of the channel possessing the slope wetland. The wetland on the opposite channel, will be more narrow due to the absence of non-alluvial, groundwater input (See Appendix 1).

- Presence of a slope wetland is often indicated by the existence of a wetland on a slope or at a slope break with no other apparent source of water. Ponds may or may not be present. If a pond is present, the wetland may require division into slope and a depressional portions.

- Slope wetlands often occur at the base of riparian terraces, where an abrupt change in slope causes groundwater to emerge. Slope wetlands that occur under these circumstances may often be distinguished from adjacent riverine wetlands in their spatial separation from the channel and origination at the base of terraces. They may also extend up the terrace slope well above the alluvial aquifer, they may be physically separated from other riverine wetlands in the floodplain, and they may develop outlet channels which flow into the main river or stream channel.

- Slope wetlands are often found on or near the shores of reservoirs or natural lakes. In the case of reservoirs, historically expansive slope wetland complexes have frequently been artificially flooded, and remnants of the wetlands exist on the lake fringe. If groundwater inputs, rather than lake water levels, still dominate a wetland's hydrology, the wetland should be classified as slope. An indication of this condition is when the wetland extends well above the elevation of the lake's surface.

Indicators of Soil Composition in Slope Wetlands

- Below 8500' a.m.s.l. it is highly unlikely that a slope wetland would possess organic soils.

- It is uncommon for very steep slope wetlands to possess organic soils.

Indicators of Geologic Composition in Depressional Wetlands

- Large-scale hummocky terrain and/or clustering of small, somewhat-circular depressional wetlands is usually indicative of glacial moraines and outwash. Therefore, depressional wetlands located in such areas should be classified as kettle ponds unless additional contradictory evidence exists.

Testing and Evaluation of the HGM Wetland Key

General Approach

The HGM categories devised in this classification were based on pre-existing literature, consultation with local experts and professional judgement, as explained in the Introduction section of this document. The hierarchical dichotomous key algorithm was produced based distinguishing between the primary attributes defining a wetland category (either class or subclass). Subsequent to testing, this algorithm was revised to increase clarity and usability.

Quality assurance/control (QA/QC) documentation generally considers several procedural attributes including: 1) accuracy; 2) precision; 3) completeness; and 4) representativeness (US EPA, 1995). Other common QA/QC parameters were not applicable to this project since it did not contain laboratory analyses and no comparisons to other data sets were made. Determination of methodological accuracy, completeness and representativeness are described below. A measure of method precision such as relative standard deviation or percent difference could not be used here since all analyses were completed by a single individual and repeated classification of polygons ("repeated measure") would be strongly biased by the classifier's experience.

The wetland data set, assembled by SAIC for Summit County as described in the Introduction section, was used to test the accuracy of the classification key. Wetland classes and subclasses assigned to each wetland polygon in this data set were essentially taken as "true" values. The exception to this was when errors in stream ordering were encountered in the Summit County data set. Stream order calculation, which defines riverine wetland subclass, was performed "on-the-fly" during the Summit County wetland data set construction. For keying, an updated GIS layer containing a Digital Line Graphic showing stream order was used. When inconsistencies arose between the data sets, stream order would be manually re-evaluated. In every case, the GIS DLG of stream order was correct.

One hundred randomly chosen wetland polygons were selected from the Summit County data set. Each randomly selected wetland polygon was first keyed to class and then subclass using this classification algorithm and the GIS resources described in the Introduction section. Upon completion of keying, the wetland category obtained using this algorithm was compared to that contained in the SAIC data set. To assess the accuracy of this key three conditions were defined: 1) correct class and subclass designation; 2) correct class and incorrect subclass designation; 3) incorrect class and subclass designation. The distribution of wetlands in each of these three categories was used to determine the accuracy of the key.

Percent completeness was calculated as: $\%C = (v/T)*100$, where v = the total number of *valid* observations and T = the total number of observations (US EPA 1995). Representativeness was insured by using a random sampling approach and using a sample size large enough such that all wetland classes were sampled. Due to the strong disparities in the commonness of the various wetland types, coupled with the random sampling regime, the sample size of each wetland class differed.

Key Testing Results

The wetland class distribution of the 100 randomly selected wetland polygons is provided in the table below. Of the 100 polygons, 13 could not be used for comparative testing since they were left unclassified in the Summit County data set. Thus sampling completeness was 87%.

HGM Class	**Number represented in sample**
Depression	7
Lacustrine Fringe	2
Riverine	52
Slope	26
Unclassified	13
Total	100

There was a remarkable correspondence between the wetland types as designated in the Summit County data set and the wetlands classified using this keying algorithm; that is, the key was shown to be highly accurate. Eighty-three of 87 wetlands (95%) were classified into the correct wetland class, while 79 of 87 wetlands (91%) were correctly classified to subclass. Only about 5% of wetlands were miss-classified at the class level. Classification errors were of three types: 1) Slope classified as riverine; 2) Slope classified as lacustrine fringe; and 3) Riverine classified as slope.

In the first case, flow-through, slope wetlands were classified as riverine due to their similar appearances and landscape settings. In the second case, slope wetlands were classified as lacustrine fringe when former slope wetland complexes were partially flooded by reservoir waters, and marginal portions of the wetland remained beyond the reservoir shores. Lastly, one riverine wetland was classified as slope. In this case the wetland occurred in the floodplain near a terrace base, which is a common landscape position for slope wetlands. "Decision rules" to help determine wetland type were generated to mitigate errors in cases such as these. These rules are provided above in the *General Rules to Decision Making* section.

KEYS TO SUMMIT COUNTY WETLAND CLASSES AND SUBCLASSES

Following the keys are illustrative examples of wetland types depicted in a GIS

KEY TO WETLAND CLASSES PRESENT IN SUMMIT COUNTY, COLORADO

1a. Wetland is found on the margin of a natural lake or reservoir larger than 0.5 ha with water depth exceeding 2 m, or wetland is located on the margin of an island . . . . LACUSTRINE FRINGE WETLAND

1b. Wetland is not associated with a natural lake or reservoir 2

2a. Wetland surrounds and includes a shallow, open water area. Wetland is **not** located in an active alluvial floodplain, nor is it a beaver pond (these wetlands are classified as Riverine). Wetland is located in an area of closed contour topography and may be hydrologically isolated, have a surface inlet, have a surface outlet, or be a through-flow system (inlet and outlet present). Surface water inflow and outflow may be strongly seasonal . . . . DEPRESSIONAL WETLAND

2b. Wetland possesses open-contour topography, with or without surface water inlets or outlets 3

3a. Wetland is within the 100-year floodplain of a perennial stream or river and **not** located at the base of a fluvial terrace . . . . RIVERINE WETLAND

3b. Wetland is not located within the 100-year floodplain of a perennial stream, **or** if it is within the 100-year floodplain, wetland is located at the base of a fluvial terrace. Groundwater discharge dominates hydrologic inputs. Wetland may be on sloping or relatively flat terrain (1 % gradient). Springs or seeps are usually present . . . . SLOPE WETLAND

KEY TO WETLAND SUBCLASSES PRESENT IN SUMMIT COUNTY, COLORADO

KEY TO LACUSTRINE FRINGE WETLAND SUBCLASSES

1a. Wetland is located on the shore of a natural lake. Wetland hydrology is directly controlled by lake water levels. Water level is relatively stable with small, seasonal variations . . . . **Natural lacustrine fringe wetlands**

1b. Wetland is located on the shore of a man-made lake or reservoir. Wetland hydrology is directly controlled by lake water levels. Lake water level commonly experiences large fluctuations in water level seasonally, or sporadically through active water management . . . . **Man-made lacustrine fringe wetlands**

KEY TO DEPRESSIONAL WETLAND SUBCLASSES

1a. Wetland includes an open-water kettle pond formed during Quaternary glacial retreat. Kettle ponds and associated wetlands are often roughly circular in shape and are associated with glacial till. The kettle pond wetland may include areas of open-water, floating vegetation mats, or solid organic or mineral soils. . . . . **Kettle pond wetland**

1b. Wetland not as above 2

2a. Wetland located in a relic river oxbow or meander scar **and** is located on a geomorphic surface above the active floodplain, **or** wetland has been isolated from the active floodplain through the effects of anthropogenic structures such as dams or dikes. Isolated riverine depressional wetlands may receive hydrologic inputs through precipitation, groundwater inflow and surface runoff . . . . **Isolated riverine depressional wetland**

2b. Wetland is in a geomorphic position not described above. Wetland may be man-made such as a cattle pond, or natural such as a snowmelt-fed wetland above tree line 3

3a. Wetland was formed by natural processes. These wetlands may be located in a variety of hydrogeomorphic situations, such as in snowmelt-fed depressions above tree line or behind dammed landslide scars . . . . **Other natural depressional wetlands**

3b. Wetland is man-made. These wetlands can be found in virtually any hydrogeomorphic position and may be hydrologically maintained solely through artificial means . . . . **Man-made depressional wetlands**

KEY TO RIVERINE WETLAND SUBCLASSES

1a. Wetland and associated stream possess a high gradient (greater than approximately 8 %), **or** wetland and floodplain tightly bounded by geomorphological features such as narrow valley walls or cliff scarps. Due to the steep gradient and/or floodplain confinement, these wetlands will typically be narrow and closely associated with the active channel 2

1b. Wetland and associated stream possess a moderate to low gradient (between 0 and ~ 8%), **and** wetland and floodplain broadly bounded by geomorphological features such as terraces or cliff scarps. Relatively low gradients and broad floodplains allow the development of more expansive riverine wetlands 4

2a. Wetland is located on a stream with an order between 1 and 3 . . . . **Low-order, high-gradient or bounded, riverine wetland**

2b. Wetland is located on a higher order stream 3

3a. Wetland is located on a stream with an order between 4 and 5 . . . . **Mid-order, high-gradient or bounded, riverine wetland**

3b. Wetland is located on a stream with an order between 6 and 7 . . . . **High-order, high-gradient or bounded riverine wetland**

4a. Wetland is located on a stream with an order between 1 and 3 . . . . **Low-order, low-gradient, unbounded riverine wetland**

4b. Wetland is located on a higher order stream 3

5a. Wetland is located on a stream with an order between 4 and 5 . . . . **Mid-order, low-gradient, unbounded, riverine wetland**

5b. Wetland is located on a stream with an order between 6 and 7 . . . . **High-order, low-gradient, unbounded riverine wetland**

KEY TO SLOPE WETLAND SUBCLASSES

1a. No apparent surface inflow from a stream or other water body, **and** no apparent outflow to a stream or water body . . . . **Isolated slope wetlands sub-key**

1b. Wetland possess an inlet channel, an outlet channel, or both 2

2a. Wetland possess both and inlet **and** an outlet channel . . . . **Through-flow slope wetlands sub-key**

2b. Wetland posses only an inlet **or** and outlet channel 3

3a. Wetland only has an inlet channel. Channelized flow become disperse and eventually ceases within the wetland . . . . **Inflow slope wetlands sub-key**

3b. Wetland only has an outlet channel. Wetland forms a stream headwaters . . . . **Outflow slope wetlands sub-key**

Slope Wetland Sub-keys

Isolated Slope Wetland Sub-key

1a. Wetland topographical gradient between 0 - 4 % . . . . *Isolated, shallow gradient, slope wetland*

i. Wetland only having mineral soils . . . . **Isolated, shallow-gradient, mineral soil slope wetland**

ii. Wetland possesses organic soils . . . . **Isolated, shallow-gradient, organic soil slope wetland**

1b. Wetland topographical gradient > 4% 2

2a. Wetland topographical gradient > 4 % to 10 % . . . . *Isolated, moderate-gradient slope wetlands*

i. Wetland only having mineral soils . . . . **Isolated, moderate-gradient, mineral soil slope wetland**

ii. Wetland possesses organic soils . . . . **Isolated, moderate-gradient, organic soil slope wetland**

2b. Wetland topographical gradient > 10% . . . . *Isolated, high gradient slope wetlands*

iii. Wetland only having mineral soils . . . . **Isolated, high-gradient, mineral soil slope wetland**

ii. Wetland possesses organic soils . . . . **Isolated, high-gradient, organic soil slope wetland**

Through-flow Slope Wetland Sub-key

1a. Wetland topographical gradient between 0 - 4 % . . . . *Through-flow, shallow gradient, slope wetland*

i. Wetland only having mineral soils . . . . **Through-flow, shallow-gradient, mineral soil slope wetland**

ii. Wetland possesses organic soils . . . . **Through-flow, shallow-gradient, organic soil slope wetland**

1b. Wetland topographical gradient > 4% 2

2a. Wetland topographical gradient > 4 % to 10 % . . . . *Through-flow, moderate-gradient slope wetlands*

i. Wetland only having mineral soils . . . . **Through-flow, moderate-gradient, mineral soil slope wetland**

ii. Wetland possesses organic soils . . . . **Through-flow, moderate-gradient, organic soil slope wetland**

2b. Wetland topographical gradient > 10% . . . . *Through-flow, high-gradient slope wetlands*

iii. Wetland only having mineral soils . . . . **Through-flow, high-gradient, mineral soil slope wetland**

ii. Wetland possesses organic soils . . . . **Through-flow, high-gradient, organic soil slope wetland**

Inflow Slope Wetland Sub-key

1a. Wetland topographical gradient between 0 - 4 % . . . . *Inflow, shallow gradient, slope wetland*

i. Wetland only having mineral soils . . . . **Inflow, shallow-gradient, mineral soil slope wetland**

ii. Wetland possesses organic soils . . . . **Inflow, shallow-gradient, organic soil slope wetland**

1b. Wetland topographical gradient > 4% 2

2a. Wetland topographical gradient > 4 % to 10 % . . . . *Inflow, moderate-gradient slope wetlands*

i. Wetland only having mineral soils . . . . **Inflow, moderate-gradient, mineral soil slope wetland**

ii. Wetland possesses organic soils . . . . **Inflow, moderate-gradient, organic soil slope wetland**

2b. Wetland topographical gradient > 10% . . . . *Inflow, high gradient slope wetlands*

iii. Wetland only having mineral soils . . . . **Inflow, high-gradient, mineral soil slope wetland**

ii. Wetland possesses organic soils . . . . **Inflow, high-gradient, organic soil slope wetland**

Outflow Slope Wetland Sub-key

1a. Wetland topographical gradient between 0 - 4 % . . . . *Outflow, shallow gradient, slope wetland*

i. Wetland only having mineral soils . . . . **Outflow, shallow-gradient, mineral soil slope wetland**

ii. Wetland possesses organic soils . . . . **Outflow, shallow-gradient, organic soil slope wetland**

1b. Wetland topographical gradient > 4% 2

2a. Wetland topographical gradient > 4 % to 10 % . . . . *Outflow, moderate-gradient slope wetlands*

i. Wetland only having mineral soils . . . . **Outflow, moderate-gradient, mineral soil slope wetland**

ii. Wetland possesses organic soils . . . . **Outflow, moderate-gradient, organic soil slope wetland**

2b. Wetland topographical gradient > 10% . . . . *Outflow, high-gradient slope wetlands*

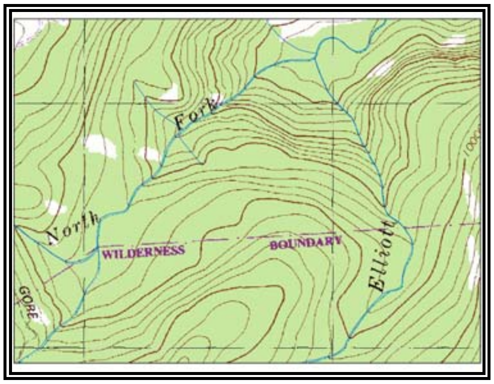
iii. Wetland only having mineral soils . . . .
. . . . **Outflow, high-gradient, mineral soil slope wetland**

ii. Wetland possesses organic soils . . . .
. . . . **Outflow, high-gradient, organic soil slope wetland**

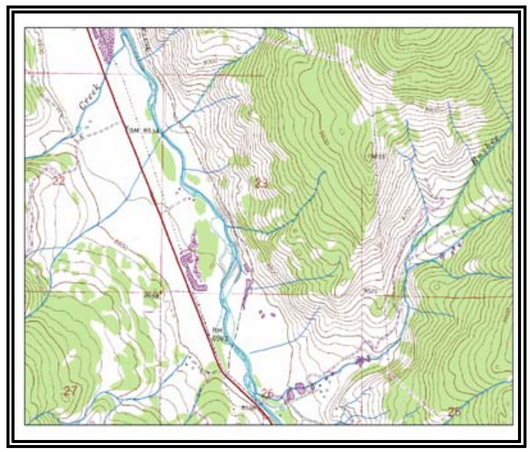
Glossary

Confined (tightly-bounded) or Unconfined (loosely-bounded) Floodplain[3]: The confined floodplain is one in which the hillslopes narrowly constrain the valley floor with little or no floodplain development. An unconfined floodplain is one in which valley hillslopes only broadly constrain channel movement and floodplain development. Unconfined floodplains are often, but not always associated with broad riparian zones. A gauge of confinement is as follows:

Valley floor width < 3 channel widths wide	Strongly to somewhat confined
Valley floor width > 3 channel widths wide	Somewhat confined to unconfined



Confined Reaches


Unconfined Reaches

Depressional Wetland:[4] Depressional wetlands are found within topographic depressions possessing closed elevational contours that allow the accumulation of surface water.

Hydrogeomorphic Approach: An approach to wetland classification which categorizes wetlands based on commonalities in their geomorphology, hydrology and hydrodynamics.

Lacustrine Fringe Wetland:[4] A wetland type found adjacent to lakes where the water elevation of the lake maintains the water table in the wetland. Lacustrine fringe wetlands may also be found on islands within lakes.

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3 Modified from Bisson and Montgomery (1996)

4 Modified from Smith et al. (1995).

Organic soils: Organic soils are those soils which meet the NRCS (1998) definition of a Histosol which is provided below.

Histosols:

Do not have andic soil properties in 60 percent or more of the thickness between the soil surface and either a depth of 60 cm or a densic, lithic, or paralithic contact or duripan
if shallower; *and*
2. Have organic soil materials that meet *one or more* of the following:
a. Overlie cindery, fragmental, or pumiceous materials and/or fill their interstices1 *and* directly below these materials, have a densic, lithic, or paralithic contact;
or
b. When added with the underlying cindery, fragmental, or pumiceous materials, total 40 cm or more between the soil surface and a depth of 50 cm; *or*
c. Constitute two-thirds or more of the total thickness of the soil to a densic, lithic, or paralithic contact *and* have no mineral horizons or have mineral horizons with a total thickness of 10 cm or less; *or*
d. Are saturated with water for 30 days or more per year in normal years (or are artificially drained), have an upper boundary within 40 cm of the soil surface, and have a total thickness of *either*:
(1) 60 cm or more if three-fourths or more of their volume consists of moss fibers or if their bulk density, moist, is less than 0.1 g/cm3; *or*
(2) 40 cm or more if they consist either of sapric or hemic materials, or of fibric materials with less than three-fourths (by volume) moss fibers and a bulk density, moist, of 0.1 g/cm3 or more.

Riverine Wetland:[4] A wetland that occurs within a floodplain or riparian corridor. The dominant water source for this type of wetland is overbank flow from the channel or subsurface hydrologic connection to the alluvial aquifer.

Slope Wetland:[4] A wetland whose hydrology is dominated by groundwater discharge. Slope wetlands lack significant depressional water storage due to their lack of closed contours. Slope wetlands may occur on nearly flat landscapes.

Stream order: A means of classifying streams according to their importance within the drainage basin. The lowest order streams are the most minor tributaries. This study used the Strahler (1952) stream ordering method.

Hydrogeomorphic Wetland Class:[4] The highest level in the hydrogeomorphic (HGM) wetland classification. This document includes four HGM classes: Slope, Riverine, Depression, and Lacustrine Fringe. Class are based on gross difference site hydrology, geomorphology and hydrodynamics.

Hydrogeomorphic Wetland Subclass:[4] Wetlands within a region that are similar based on hydrogeomorphic classification factors. There are multiple subclasses within each wetland class. The actual number of wetland subclasses defined is based on the known diversity of wetlands within a class and particular assessment objectives.

Alluvial: Structures and features produced through river-induced deposition.

Fluvial: Structures, features and characteristics produced through stream action.

Scarp: A steep slope or cliff connecting the surface of a former floodplain to a lower surface.

REFERENCES CITED

Adamus, P. R. 2001. Guidebook for hydrogeomorphic (HGM)-based assessment of Oregon wetland and riparian sites: Statewide classification and profiles. Oregon Division of State Lands, Salem, Or .

Bisson, P. and D. Montgomery. 1996. Valley segments, stream reaches, and channel units. In: Hauer, F. R. and G. Lamberti (*eds.),* Methods of Stream Ecology. Academic Press, New York.

Brinson, M. M. 1993. A hydrogeomorphic classification for wetlands. Technical Report WRP-DE-4, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS .

Cowardin, L. M. Carter, V. Golet, F. C. and LaRoe, E. T. 1979. Classification of wetlands and deepwater habitats of the United States. U.S. Fish and Wildlife Service, Biological Services Program. Report No. FWS/OBS-79/31 .

Gwin, S. Kentula, M. and Shaffer, P. 1999. Evaluating the effects of wetland regulation through hydrogeomorphic classification and landscape profiles. Wetlands **19**: 477-489.

Hauer, F. R. and Smith, R. D. 1998. The hydrogeomorphic approach to functional assessment of riparian wetlands: evaluating impacts and mitigation on river floodplains in the U.S.A. Freshwater Biology **40**: 517-530.

Johnson, J. B. 2000. Documentation of reference conditions in the slope wetlands of the southern Rocky Mountains: reference database, site descriptions, and revised functional models. Report Submitted to U.S. EPA , Region 8 and the Colorado Department of Natural Resources .

Keate, N. 1998. Utah Riverine Model: low gradient, low elevation, riverine wetlands of the Colorado Plateau and Great Basin of Utah – Draft. Report submitted to U.S. EPA, Region 8.

Keate, N. 2001. Utah montane slope (fens and wet meadows) functional assessment model (draft). Report submitted to U.S. EPA, Region 8 .

Noe, D. Cooper, D. Barry, A. Pavlik, M. Kolm, K. Harper-Arabie, R. Emerick, J. Arp, C. and Chimner, R. 1998. Characterization and functional assessment of reference wetlands in Colorado. Report submitted to Colorado Dept. of Natural Resources and US EPA Region VIII .

SAIC. 2000. Summit County wetland functional assessment. Science Applications International Corporation, Lakewood, CO. Report prepared for the Summit County Community Development Division .

Smith, R. D. Ammann, A. Bartoldus, C. and Brinson, M. M. 1995. An approach for assessing wetland functions using hydrogeomorphic classification, reference wetlands and functional indices. Technical Report WRP-DE-9, U.S. Army Corps of Engineer Waterways Experiment Station, Vicksburg, MS .

Strahler, A. N. 1957. Quantitative analysis of watershed geomorphology. American Geophysical Union Transactions **38**:1117-1142.

Tiner, R. 2000. Keys to waterbody type and hydrogeomorphic-type wetland descriptors for U.S. waters and wetlands (Operational Draft). U.S. Fish and Wildlife Service National Wetlands Inventory Project Report, September 2000.

US EPA. 1995. Generic quality assurance project plan guidance for programs using community level biological assessment in wadable streams and rivers. Office of Water, EPA 841-B-95-004.

APPENDIX 1

EXAMPLES OF KEYING WETLANDS USING TOPOGRAPHIC AND GIS DATA

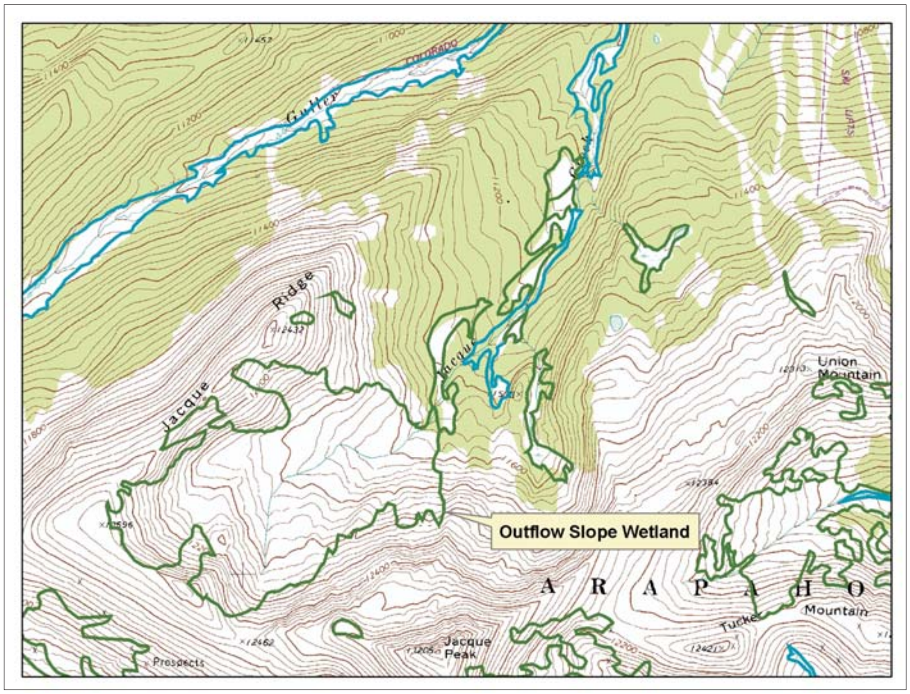

Figure A1. A section of map showing the setting of a large, outflow slope wetland (lower left hand quarter of the map. The wetland, located in a alpine cirque, forms the headwaters of a stream system flowing to the north. A similar, but smaller, wetland can be seen in the lower right hand corner.

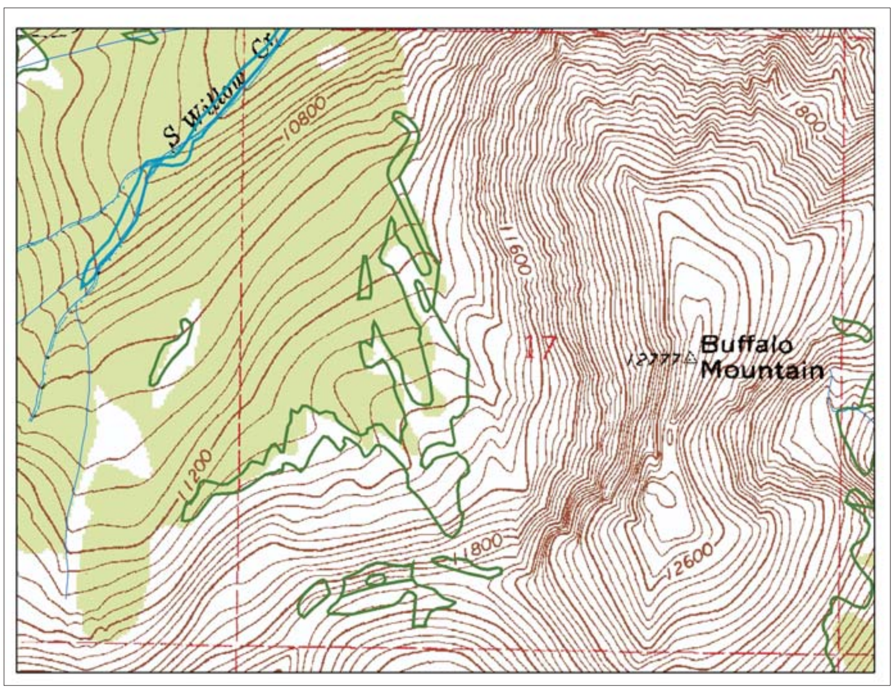

Figure A2. Map showing a isolated slope wetland occurring on the slopes of Buffalo Mountain near tree line. In this case, groundwater that discharges in the alpine zone apparently recharges as it flows onto the more shallowly graded subalpine slopes.

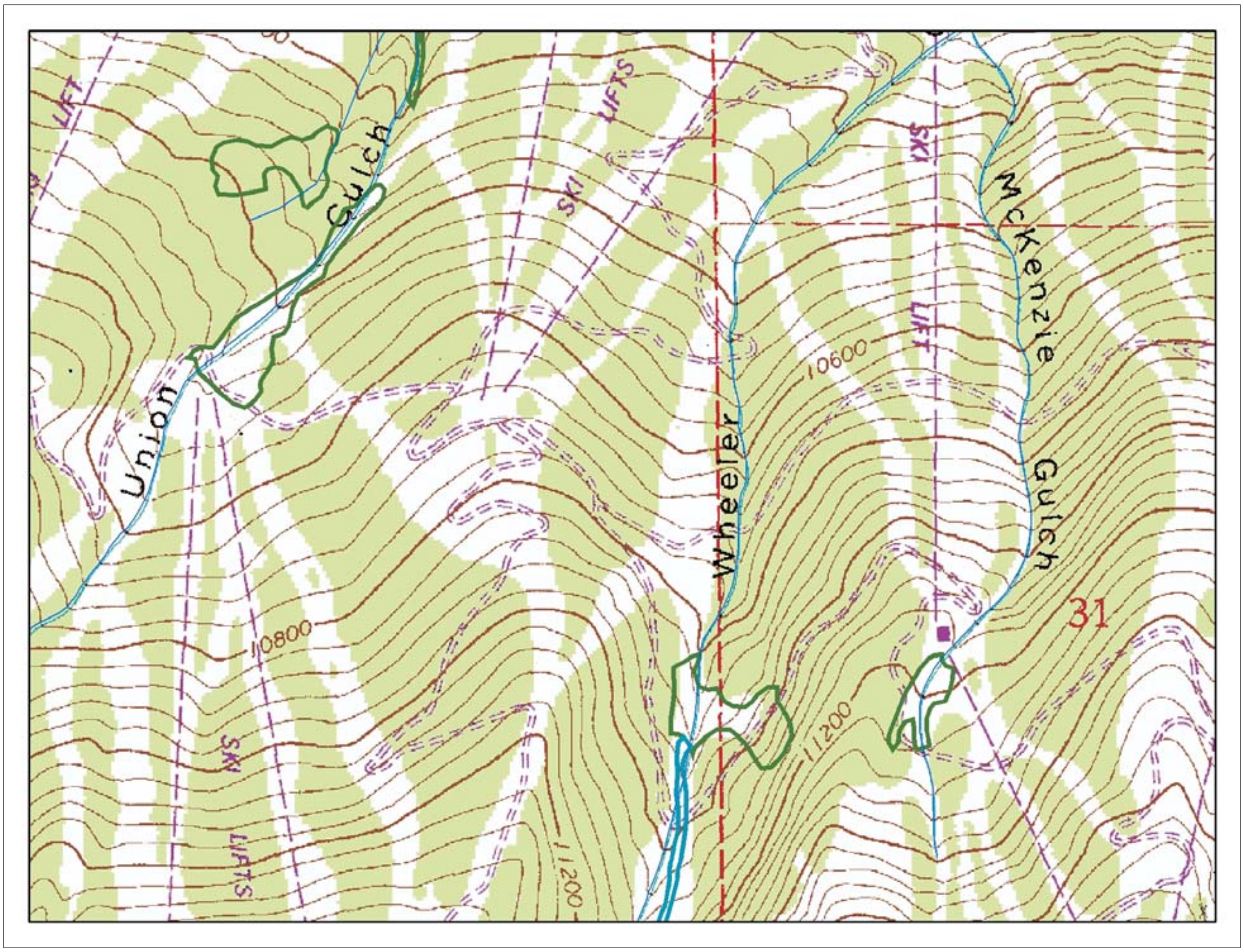

Figure A3. Four examples of through-flow slope wetlands. The asymmetrical shape and extension of the wetland well above the channel helps to identify these sites as slope, rather than, riverine wetlands.

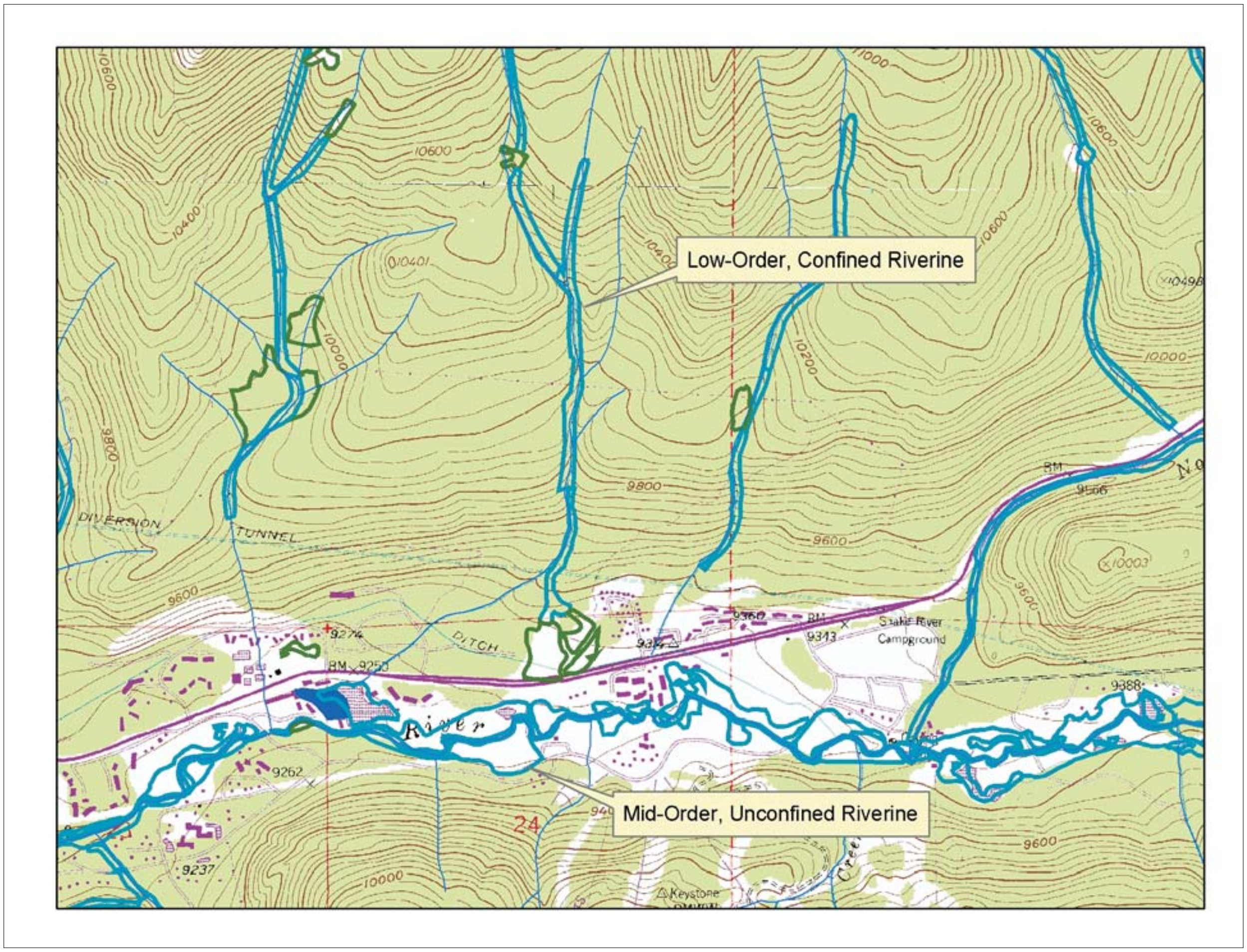

Figure A4. Four low-order, narrow riverine wetlands (confined valley) oriented north-south along the top of the figure. These streams are tributary to a mid-order (5th order) river with a well developed (unconfined) floodplain.

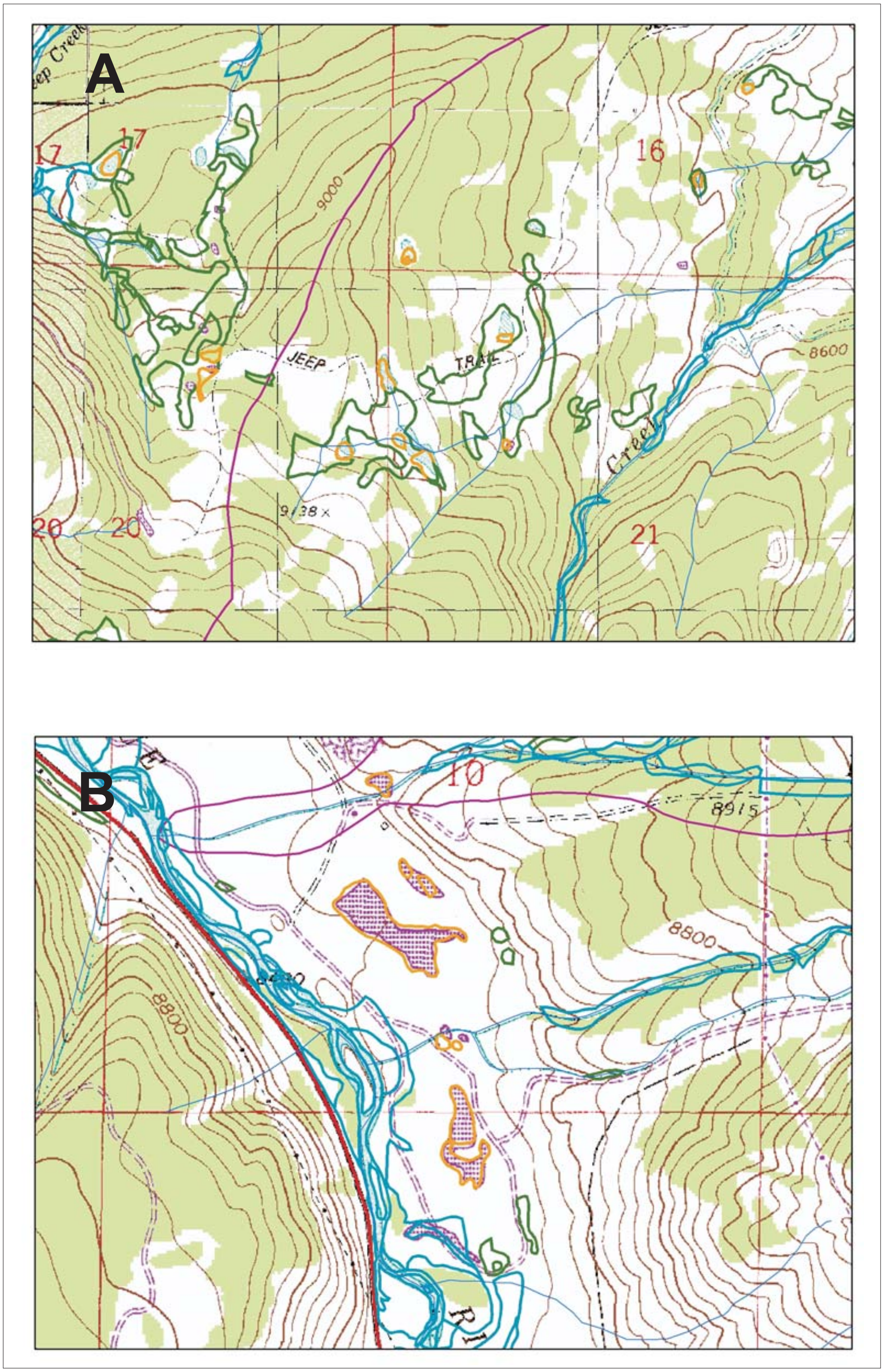

Figure A5 a and b. Outlined in yellow, kettle-pond depressional wetlands can be seen on lobular, glacial terrain (A). Man-made depressional wetlands in the form of gravel mine ponds are evident in Map B.

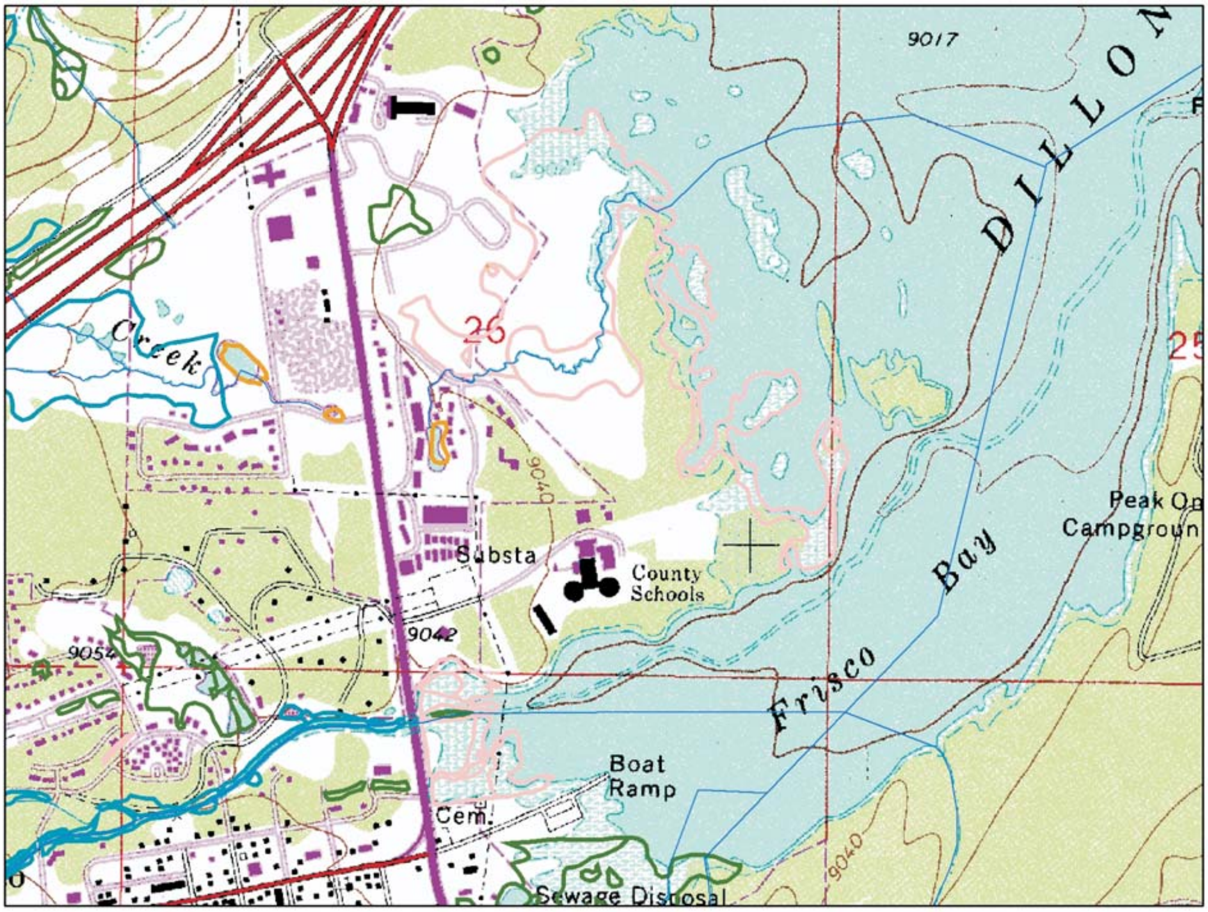

Figure A6. Outlined in pale pink, man-made lacustrine fringe wetlands can be seen on the margins of Dillon Reservoir.