

Assessment of Stream Ecosystem Function and Sensitivity in the Bighorn National Forest, Wyoming

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Abstract This paper presents a hierarchical analysis of stream ecosystem distribution and sensitivity to natural and anthropogenic disturbances for the Bighorn National Forest, Wyoming. We designated stream gradient, flow regime, and lithology as environmental parameters that would result in the most robust, readily applied, and parsimonious description of physical and chemical characteristics of individual stream segments. We used these parameters to map the spatial distribution and relative abundance of stream habitats in the study area. We then used the proportion of each sixth-level hydrologic unit boundary comprised by each category of stream gradient, flow regime, and lithology as input to an agglomerative cluster analysis, which identified six clusters for the 74 watersheds intersecting or within the national forest

boundary. Five of the six clusters have predominantly high gradient streams and runoff dominated by snowmelt or mixed snowmelt and rainfall. Most watersheds on the Bighorn National Forest are sensitive to alterations in water supply because of the relatively small size of streams. Although watersheds are generally less sensitive to changed sediment supply, low-gradient stream segments create sensitive sites within individual watersheds. Field verification studies indicate that this approach reasonably characterizes physical channel properties and biological associations for the study area.

Keywords Hierarchical analysis · Stream ecosystems · Sensitivity to disturbance · Channel classification · Bighorn National Forest

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Introduction

Landscape modification and subsequent changes in hydrology, channel morphology, and physicochemical properties in the western United States have resulted in a dramatic decrease in biological diversity in riparian and aquatic ecosystems (Ricciardi and Rasmussen, 1990). This trend appears to be increasing as human populations continue to grow in many western states (Graham, 2001; Riessame and others, 1997). Decreasing biological diversity and increasing population growth drive a proportionate increase in the complexity of issues and decisions concerning proper management of public lands. Land management agencies are subject to increased public and political pressures to implement strategies that allow for the use of natural resources while simultaneously maintaining ecological integrity. The Rocky Mountain Region of the U.S. Forest Service (Region 2) has recognized the need to

improve implementation of the National Forest Management Act of 1976 (NFMA) and other laws in part to maintain biological diversity and ecological sustainability.

A thorough understanding of the natural ecological processes and human influences that determine the structure of biological communities is necessary to accomplish the objectives in the NFMA regulations (Jensen and others, 2001). Consequently, the USDA Forest Service has attempted to understand landscape influences on aquatic ecosystems throughout many parts of the country (Graham, 2001; Maxwell and others, 1995; Van Sickle, 2001.), but these efforts have experienced varying success over time.

Interdisciplinary, multiple-scale analyses provide the spatial and temporal information necessary to understand ecological form and function and provide tools necessary for land managers to develop ecological assessment procedures. The analyses also facilitate sound resource management decisions (Petts, 1994). These ecological assessments need to include descriptions of the biological and physical characteristics of each ecosystem as well as the principal ecological processes that influence ecosystem structure and composition in the analysis area. Such descriptions should include the distribution, intensity, and frequency of natural disturbances during the current climatic regime, particularly insofar as the disturbances regulate ecological processes important to ecosystem sustainability.

Aquatic and riparian ecosystem function is influenced by geomorphic and ecological processes operating at multiple spatial and temporal scales (Benda and others, 2004; Friend, 1993; Frissel and others, 1986; Imhof and others, 1996; Montgomery and Buffington, 1997; Petts, 1994; Poff, 1997; Poole, 2002). The inherent complexity in the relationship between form and function and trans-scale linkages of matter and energy complicates simple classifications of riparian and aquatic ecosystems at a fine spatial scale (Snelder and Biggs, 2002; Snelder and others, 2004, 2005). Multiscaled environmental processes are typically characterized in a hierarchical fashion that emphasizes top-down constraint of large-scale processes on small-scale processes and pattern. Watershed hydrologic regime, for example, dictates local rates of habitat disturbance.

The stream ecosystem assessments described in this paper utilize the concept of ecological drivers as a means of classifying watershed units into broad groupings that we expect to have similar responses to natural and anthropogenic disturbances. Ecological drivers are defined as environmental factors that exert a major influence on the fitness of individual organisms and their populations (e.g., Poff and Ward, 1990; Townsend and Hildrew, 1994). In the context of this paper, environmental factors include hydrology, sediment dynamics, channel morphology, nutrient availability and flux, and water chemistry and temperature.

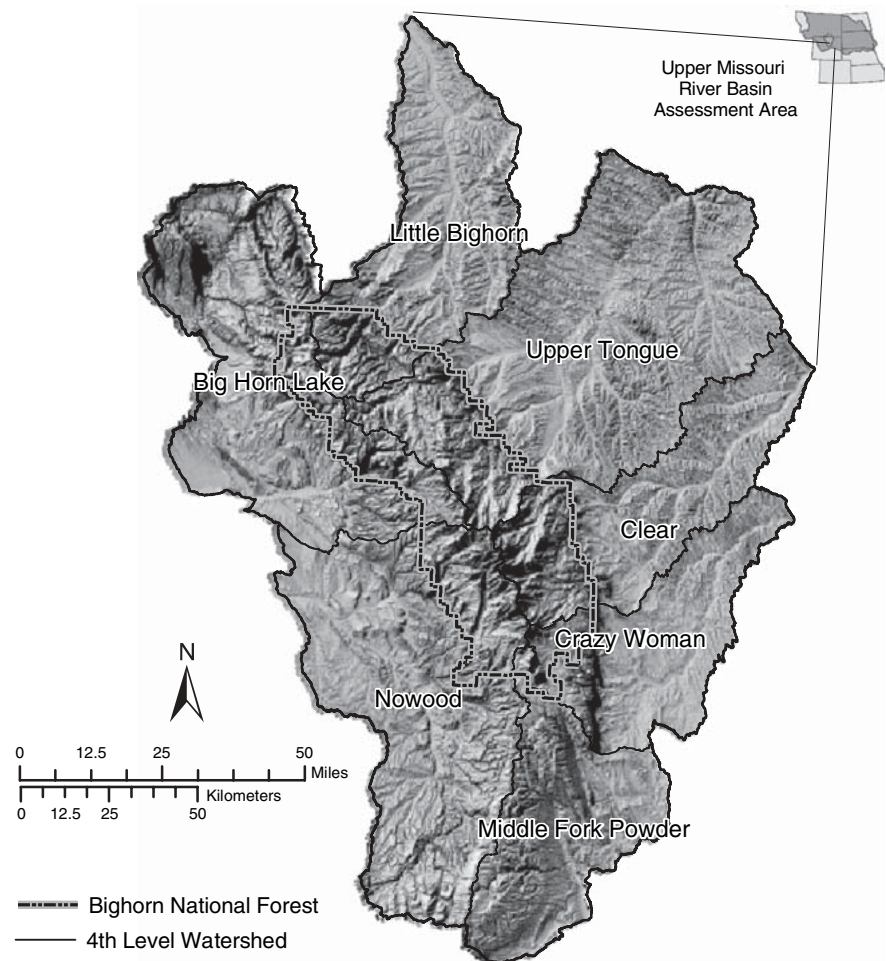
Here, we review the stream ecosystem driver analysis component of the Aquatic, Riparian, and Wetland Assessment (ARWA) process on the Bighorn National Forest in Wyoming (Winters and others, 2004) (Fig. 1). We had three primary objectives in this assessment process: (1) to select environmental parameters that would result in the most robust, readily applied, and parsimonious description of physical and chemical characteristics of individual stream segments, (2) to use these parameters to map the spatial distribution and relative abundance of stream habitats in the study area, and (3) to assess the relative sensitivity of watersheds to natural disturbance and land use. We describe the rationale behind ecological driver selection and present the cluster analysis methods used to group watersheds that have similar driver combinations, and then present the findings of validation studies. Our findings indicate that multiple-scale assessments are an invaluable tool for the purpose of developing a proactive, long-term approach to aquatic and riparian species and ecosystem management. Furthermore, this approach may be used to aid national forest and national grassland managers in identifying potential restoration and protection areas for important aquatic and riparian ecological conditions and species.

The Bighorn National Forest Study Area

The Bighorn National Forest in northern Wyoming includes approximately 445,000 ha. The Forest is located in the Big Horn Mountains of the upper Missouri River Basin, with about 99% of the Forest exceeding 1600 m in elevation. The Big Horn Mountains have a core of Precambrian-age igneous and metamorphic rocks. The northern mountains have a granitic core, whereas the southern mountains have a core of gneiss. The flanks of the mountains are composed of Paleozoic- and Mesozoic-age sedimentary rocks, which dip steeply away from the center of the mountain mass toward the adjacent basins (Crowley and others, 2002). The mountains presently have the form of a doubly plunging anticline, with steeper topography on the eastern side.

Much of the land at higher elevations is a dissected plateau surmounted by glacial-sculpted peaks. Pleistocene glaciation in the Forest was concentrated around the Cloud Peak area, with moraine deposits extending down to approximately 1980 m (Darton, 1906). Glaciation produced broad, u-shaped valleys that now hold fens, marshes, and low-gradient stream segments. Terrestrial ecosystems in the Forest range from alpine tundra and rocky lands at the highest elevations to mixed conifer and aspen forests interspersed with mountain meadows. Most of the aquatic ecosystems in the Forest are coldwater systems.

Fig. 1 Location map of Bighorn National Forest, showing fourth-level hydrologic unit boundaries



The high-elevation lands of the Forest include sensitive aquatic, riparian, and wetland resources that are not commonly found throughout the upper Missouri River basin.

Precipitation in the Big Horn Mountains results primarily from winter snowfall or summer convective storms. The majority of precipitation falls during April to July. The mountains have a strong orographic gradient, with mean annual precipitation of 860 mm at 2850 m, dropping to less than 250 mm below 1520 m (Takacs and others, 1995). The eastern side of the range is slightly wetter, with mean annual precipitation levels of 250 to 380 mm to the north and northeast of the mountains.

The Upper Missouri River ecoregion in which the Bighorn National Forest is situated is characterized by low fish species richness and few endemic species relative to the other aquatic ecoregions of North America (Abell and others, 2000). The proportion of fish species considered imperiled is low in the Upper Missouri ecoregion because most fish species are generally widespread and occur in other ecoregions.

Eleven fish taxa occur within the boundary of the Bighorn National Forest. Members of the family Salmon-

idae dominate the fish fauna. The only other types of fish present are one species of sucker (family Catostomidae) and one species of minnow (family Cyprinidae). Only 2 of the 11 fish taxa are native to the Bighorn National Forest, the mountain sucker (*Catostomus platyrhynchus*) and the Yellowstone cutthroat trout (*Oncorhynchus clarki bouvieri*), both of which are of conservation concern. Most of the remaining taxa were introduced for sport fishing and have subsequently established self-reproducing populations. Lower elevation portions of catchments that originate on the Bighorn National Forest contain a more diverse assemblage of fish species than is found within higher elevation catchments in the Forest.

Archeological records of people in the region go back at least 8300 years before present, when hunter-gatherers occupied the Bighorn Basin (Chase and Montgomery, 1996). Native Americans of the Shoshone, Sioux, Crow, Arapaho, and Cheyenne tribes occupied the region by AD 1500. The first Europeans known to have reached the Big Horn Mountains are French fur trappers who crossed the mountains near Sheridan in 1743. Fur trapping became more extensive in the region starting in the 1820s, but

European Americans did not settle the area until the 1860s and 1870s. Nearly every watercourse in the region had diversions into irrigation ditches by 1880 (Mead, 1899), and the irrigation network continued to grow rapidly during the 1890s (Moulton, 1995). More than a thousand holders of water rights used diverted water for irrigation, placer mining, cattle ranching, and flour mills in the region by 1899 (Mead, 1899). Ties for transcontinental and regional railroads were cut in the mountains and transported along flumes and stream channels (“tie drives”) during the 1890s and early 1900s. Although the Big Horn Mountains and surrounding lowlands have had and continue to have low population densities relative to other regions of the country, stream processes in many parts of the mountains have been substantially impacted by cattle ranching, crop irrigation, flow regulation and diversion, and timber harvest.

Ecological Drivers

Identifying Drivers and Driver Categories for the Bighorn National Forest

The approach described in this paper is designed specifically for mountain streams, which we define as having average reach-scale gradients of 0.2% or greater (Wohl, 2000). Mountain streams are commonly characterized by longitudinal profiles that are segmented as a result of glacial history, tectonism, spatial variation in lithology or geologic structure, or the activity of beavers (Wohl, 2000). Aquatic and riparian habitat and ecosystem function can also vary abruptly downstream because abrupt downstream changes in gradient along mountain streams are associated with changes in channel geometry, substrate type, grain-size distribution, and hydraulics (Montgomery and Buffington, 1997).

We began our characterization of ecological drivers in mountain streams at the scale of a reach, defined as a length of channel at least several times the bankfull channel width and having consistent gradient and morphology (Wohl, 2000). Most of our analyses, however, were conducted at the scale of a watershed defined by a sixth-level hydrologic unit boundary. The system of hydrologic unit boundaries (HUBs) is used to designate watersheds within the National Hydrography Dataset of the U.S. Geological Survey. Each HUB is a watershed designated using topographic drainage divides. Delineated watersheds in the National Hydrography Dataset decrease in size from larger first-level HUBs to the smaller sixth-level HUBs of our analyses that cover areas less than approximately 1000 km².

Our delineation of ecological drivers was based on physical variables most likely to parsimoniously reflect channel geometry, hydraulics, and natural disturbance

Table 1 Drivers, categories, and symbols used for ecological driver analyses of the Bighorn National Forest

Driver	Category	Symbol
Lithology	Calcareous geology	<i>Ca</i>
	Noncalcareous geology	<i>Cn</i>
Flow regime	Snowmelt-generated runoff	<i>Ps</i>
	Mixed snowmelt- and rainfall-generated runoff	<i>Prs</i>
	Rainfall-generated runoff	<i>Pr</i>
Stream gradient	High gradient	<i>h</i>
	Medium gradient	<i>m</i>
	Low gradient	<i>l</i>

regime. We chose stream gradient, flow regime, and lithology as the three physical variables of most importance (Table 1).

Gradient strongly correlates with channel morphology, grain-size distribution, lateral confinement and sensitivity to disturbance in mountain streams. Wohl and Merritt (2005) found that a three-variable discriminant function of gradient, channel width, and grain size, for example, correctly predicted channel morphologic type in the Montgomery and Buffington (1997) classification system for 76% of the channel reaches in a dataset containing 335 mountain stream reaches from around the world. In this analysis, gradient acted as the strongest discriminant variable. Montgomery and Buffington’s (1997) classification of mountain streams into cascade, step-pool, plane-bed, pool-riffle, and dune-ripple channel types recognizes that (i) a characteristic morphology tends to occur under a specific combination of gradient, sediment supply, and transport capacity, and (ii) each channel morphology has a differing sensitivity to disturbance in the form of changed water or sediment supply. Thus, we reasoned in the Bighorn analysis that gradient could serve as a surrogate indicator for several aspects of channel morphology and stability. We chose gradient as an indicator because it can be adequately assessed on topographic maps or digital elevation models. Delineation of gradient categories then facilitates rapid and relatively simple assessment of channel types throughout a study area.

We chose three gradient categories for the Bighorn National Forest study area: high ($\geq 4\%$), medium (2%–3.9%), and low ($\leq 1.9\%$). All three of these categories are well above the lower limit for reach-scale gradient of mountain streams defined previously. High-gradient streams generally correspond to steep, narrow valley segments with a high connectivity between hillslope and valley bottom, where debris flows and landslides can introduce coarse sediment directly to the channel. These streams have boulder-sized coarse sediment and step-pool

morphology. Medium-gradient streams have wider valley bottoms in which some of the sediment transported from valley side slopes can be stored before reaching the active channel. These streams can be transitional between step-pool and plane-bed or pool-riffle morphology, and are likely to have cobble- to boulder-size coarse sediment. Low-gradient streams have wider valley bottoms and greater lateral mobility compared to streams in other gradient categories. Low-gradient streams are generally pool-riffle channels with cobble- or gravel-sized coarse sediment.

Flow regime in this analysis was categorized according to the primary runoff-generating mechanism. Different types of precipitation are associated with distinct differences in the magnitude, frequency, duration, and rate of rise and fall in stream discharge. Snowmelt discharges in the portion of the western United States included within Region 2 of the Forest Service, for example, are of lower magnitude, longer duration, and slower rise and fall than floods caused by rainfall from convective storms (Jarrett, 1990). Snowmelt streams also tend to have less interannual variability than streams dominated by rainfall runoff. Although factors such as infiltration rate and valley geometry—which in turn reflect rock type, weathering regime, vegetation cover, hillslope stability, and so forth—also influence runoff generation and stream flow, we used the simplifying assumption that runoff-generating mechanism could serve as a surrogate indicator for all of the factors that influence reach-scale differences in stream flow within the study area. Flow regime is ecologically important because it partially controls sediment transport and channel stability, as well as available habitat and characteristics such as water temperature and chemistry that drive life cycles of aquatic and riparian organisms (Poff and others, 1997). Flow regime in the mountains of the western United States can be adequately assessed using a few simple indicators such as elevation, aspect, and drainage area. Catchments at the highest elevations tend to be dominated by snowmelt, whereas those at intermediate and lower elevations can also have rainfall-generated runoff. The relative importance of these runoff-generating mechanisms varies with drainage area. Very small high-elevation catchments, for example, may be snowmelt-dominated but ephemeral, whereas larger snowmelt-dominated catchments at the same elevations are perennial.

We chose three flow regime categories for the Bighorn National Forest study area. *Ps* refers to streams dominated by snowmelt runoff, which in the Bighorns are present at elevations of 2370 to 4005 m. *Pr* indicates streams dominated by rainfall runoff at 2370- to 1520-m elevation. Streams designated *Pr* do not have tributary streams or upstream segments above 2370 m and, thus, do not have substantial snowmelt runoff. *Prs* designates streams with a

spring-early summer snowmelt flow peak and secondary peaks associated with rainfall. These stream segments occur at elevations below 2370 m but have upstream segments or tributary streams at elevations above 2370 m that contribute snowmelt runoff.

Lithology in this analysis is divided into categories that reflect clastic sediment and solutes supplied to streams. The volume, grain-size distribution, and processes of clastic sediment introduction (e.g., hillslope mass movements that episodically introduce large volumes of sediment to a limited length of stream versus gradual soil creep throughout the drainage) strongly influence channel morphology and stability. Yield of sand-size and finer sediment to streams is particularly important in controlling habitat and disturbance regime for aquatic organisms (Waters, 1995). Consequently, we begin by subdividing lithologies in the study area into those that produce minimal amounts of fine sediment and those that produce greater amounts of fine sediment. Stream chemistry can also be an important ecological driver, as it can regulate organismal physiology and ecosystem productivity (Allan, 1995). Consequently, a second set of categories was developed for lithology that distinguishes rock types which produce biologically reactive solutes (e.g., carbonate rocks, rocks rich in salts or nutrients, or metal-bearing rocks) from rocks that produce few solutes. Because the drainage area of even a relatively small stream may not be underlain by a single lithology, we categorize catchments by the percent of rock units that weather to fine sediments or produce high solute loads. If rock units with either of these characteristics occupy more than a third of the catchment, this influence is likely to be substantial enough to warrant classifying that catchment as dominantly underlain by the rock type that weathers to fines or solutes.

The Bighorn National Forest study area is lithologically relatively simple. At the northern end of the range, the granitic rocks weather to fairly coarse-grained sediment, such as sand, gravel, and cobbles. The gneissic rocks at the southern end of the range are more likely to produce finer, sand- to silt-sized sediment, although the cold, semiarid climate of the mountains limits the intensity of weathering and the amount of fine sediment produced. Interbedded shales among the flanking sedimentary rocks produce minor amounts of clay. Weathering of limestones among the flanking sedimentary rocks releases calcium into solution. For the Bighorn National Forest, we simply differentiated catchments dominantly underlain by calcareous rocks from those dominantly underlain by noncalcareous rocks.

Our intent in designating drivers and driver categories is that these characteristics can be readily quantified across a study area with a minimum amount of field work or on-the-ground verification, and that the driver categories provide sufficient insight on channel pattern, process, and

potential response to disturbance to assist managers in evaluating aquatic habitat distribution and sensitivity. The details of how to subdivide the primary drivers of gradient, flow regime, and lithology differ between mountainous study areas in the western United States. During similar analyses for the San Juan, Gunnison, Uncompahgre, and Grand Mesa national forests in Colorado, for example, it proved necessary to have two subdivisions of lithology; one focused on fine sediments and one on solute chemistry. Application of the methods outlined here to study areas with lower elevation and relief will also need adjustment. Gradient is not likely to be a useful discriminator among channels on national grassland units, for example, and flow regime for these units should include a groundwater component and explicit recognition of ephemeral, intermittent, and perennial channels. The fundamental idea of designating a minimum number of categories of primary drivers, however, should be broadly applicable to study areas that encompass a single mountain range or grassland unit.

Mapping Driver Categories and Analyzing Clusters in the Bighorn National Forest

Topographic data were obtained using elevation values from the 30-m National Elevation Dataset. The stream network for the study area was obtained from the high-resolution (1:24,000) flow lines included in the National Hydrography Dataset. Stream gradient was assigned to individual stream segments. Segment lengths were a product of the digitization process, and do not necessarily reflect morphologic differences in the stream channel. For each stream segment, the FromNode and ToNode were assigned elevation values. Stream gradient was then calculated as the change in elevation between nodes, divided by the length of the individual stream segment. Bedrock geology was obtained from 1:500,000 scale digital maps (U.S. Geological Survey, 1994).

Gradient was mapped at the scale of a stream reach, as defined previously. The drivers of gradient, flow regime, and lithology, when subdivided into categories, produce a total of 18 potential driver combinations. We used data on the proportion of each HUB that was in each stream gradient, flow regime, and lithology category as input to agglomerative cluster analysis. The analysis was performed using the Soreson's similarity matrix and average linkage as the clustering mechanism, using PC Ord (McCune and Mefford, 1999). We identified watershed clusters based on a 25% similarity cut point. This cut point was chosen based on two criteria. First, we wanted to establish six to eight clusters based on the number of driver categories used in the analysis. Second, we chose the cut point where obvious breaks occurred that would separate large numbers of HUBs from each other.

This type of analysis can be conducted at any spatial scale; we chose to conduct analyses at two scales, which we designated as the landscape scale and the management scale. The landscape scale encompassed the seven fourth-level HUBs originating on the Bighorn National Forest that drain into the Big Horn, Tongue, and Powder River systems (Fig. 1). These seven larger HUBs are subdivided into 248 sixth-level HUBs. Because only the headwater portions of the seven fourth-level HUBs lie within the Bighorn National Forest, the landscape scale of analysis emphasizes the uniqueness of watersheds within the Forest relative to the surrounding region. For the management scale analysis, we focused on the 74 sixth-level HUBs that intersect or are wholly contained within the National Forest boundary (Fig. 2) and represent a spatial unit at which the U.S. Forest Service typically designs management actions. This scale of analysis facilitates finer distinctions among streams within the Bighorn National Forest, and the remainder of this paper concentrates on the management scale of analysis.

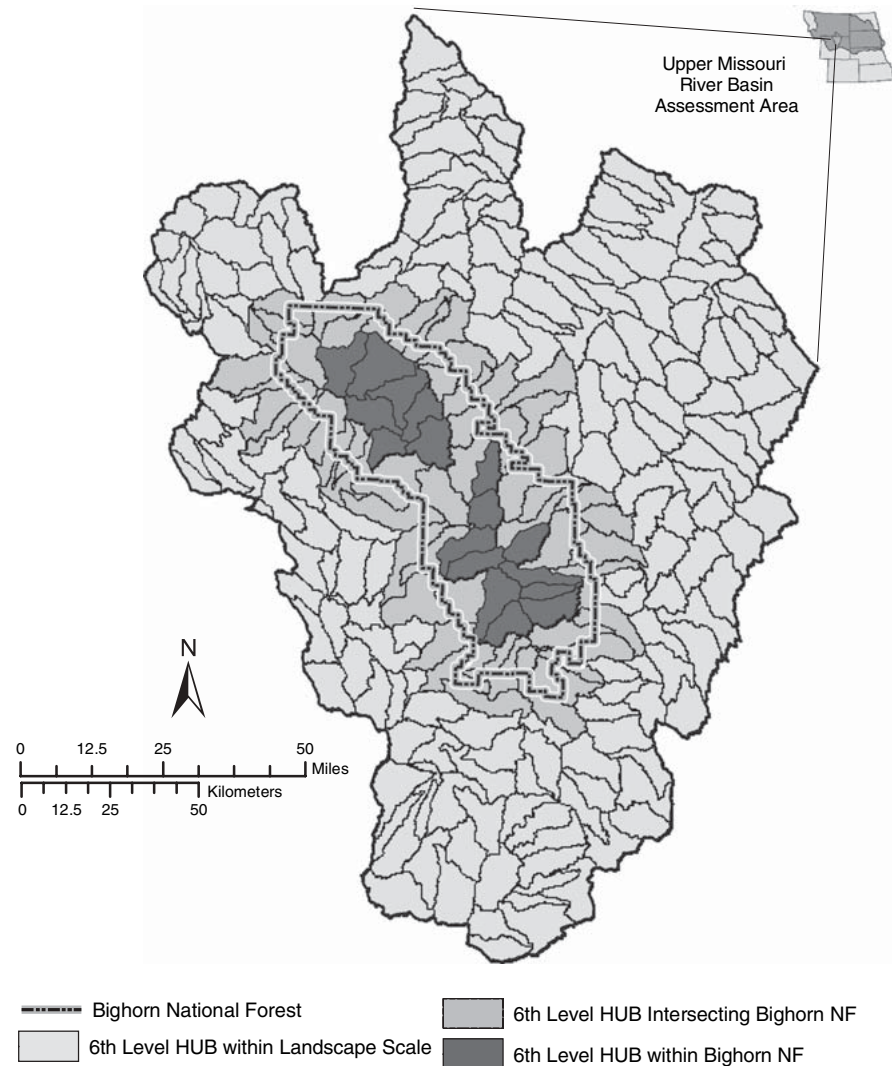
Results

Management-scale cluster analysis identified six clusters for the 74 HUBs intersecting or within the national forest boundary (Fig. 3). Distinct breaks occur between clusters 1–4, located primarily at higher elevations, and clusters 5 and 6, located primarily at lower elevations on the plains (Fig. 4, Table 2). Streams in clusters 1 and 4 have predominantly high gradients and snowmelt-dominated runoff. Noncalcareous rocks are more common in cluster 1, whereas calcareous rocks are more common in cluster 4. Streams in clusters 2 and 5 have predominantly high gradients, mixed snowmelt and rainfall runoff, and calcareous rocks. Streams in cluster 6 have predominantly low gradients, rainfall runoff, and noncalcareous rocks.

Physical and Ecological Characteristics of Each Cluster, and Sensitivity to Disturbance

Following cluster analysis, we predicted the dominant physical characteristics and potential response of each driver combination to disturbance. Disturbances evaluated in this context include natural and human-driven changes in water and sediment supply, channel geometry, thermal regime, and water quality. Changes in water and sediment supplied to a stream commonly result from wildfire, flow diversion, timber harvest, and road construction, each of which occurs in the Bighorn National Forest study area. Channel geometry in the study area was changed during historical tie drives along streams (Granum, 1990). Thermal regime can change in response to altered flow volumes or alterations of riparian vegetation and associated shading

Fig. 2 Map showing sixth-level hydrologic unit boundaries (HUBs), including those within the Forest and intersecting the Forest boundaries. Seventy-four sixth-level HUBs intersect the National Forest boundary and 17 of these HUBs are wholly contained within the boundary



of the stream (Poole and Berman, 2001). Water quality can change in response to riparian grazing (Fitch and Adams, 1998; Gary and others, 1983), mineral extraction (Starnes and Gasper, 1996), or motorized recreation (Adams, 1975) adjacent to the channel.

We also assess the ecological potential of each driver combination in terms of instream production, invertebrate diversity, and fisheries, and the sensitivity of these ecological components to potential disturbances (Table 3). The rationale for our subjective ranking of the relative sensitivity of each cluster to disturbance is explained in the following paragraphs.

Physical characteristics

Physical sensitivity to changes in water or sediment supply is inversely proportional to gradient. High-gradient streams are least sensitive to changes in water or sediment supply because these streams have channel boundaries of coarse

clasts and bedrock that are very resistant to erosion that can result from increased water or decreased sediment supply. High-gradient streams also have abundant energy to transport sediment, making these streams less sensitive to decreased water or increased sediment supply (Montgomery and Buffington, 1997). The less resistant boundaries of lower gradient channels, and the greater potential to accumulate excess sediment in localized depositional zones such as pools, render lower-gradient channels more responsive to changes in water and sediment supply (Ryan, 1997).

Streams draining noncalcareous rock types in the Bighorn study area are likely to be more sensitive to disturbances that alter water or sediment supply than streams draining calcareous rocks. Calcareous rocks supply so little sediment in this climatic setting (Ritter and others, 1995) that disturbances such as timber harvest, grazing, or wild-fire are unlikely to produce substantial alterations in sediment supply to streams. In contrast, catchments underlain by noncalcareous granitic rocks may have substantial

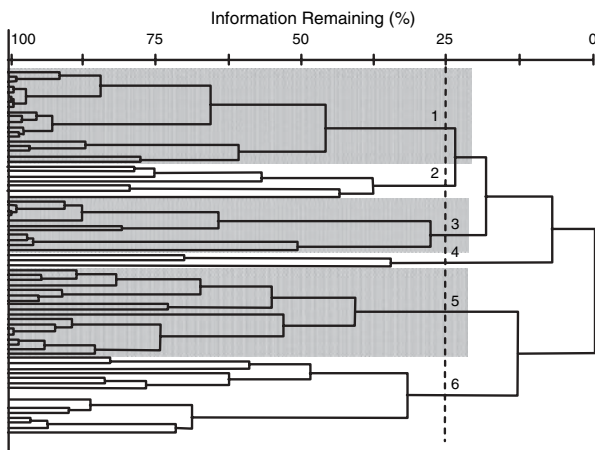


Fig. 3 Management-scale agglomerative cluster analysis of stream ecosystems using the 74 watersheds that intersect the Bighorn National Forest. Geology, flow regime, and stream gradient drivers produced six distinct clusters. The dashed vertical line indicates the level of similarity or cut point used to define the clusters, and the numbers next to the line denote the clusters discussed in the text. Streams in clusters 1, 3, and 5 are highlighted with shading to facilitate distinction of different clusters

amounts of grus, the sand- and gravel-sized sediment produced from weathering granitic rocks, stored on hillslopes that can be mobilized into stream channels following disturbances.

In comparison to larger, lowland drainage basins, all of the streams present in the Bighorn National Forest are relatively ecologically sensitive to changes in flow regime because the watersheds are fairly small and, thus, have a greater proportion of surface runoff and lower subsurface water storage. Low-gradient streams are most sensitive because they provide important habitat (e.g., pool volume) that is particularly sensitive to flow magnitude and duration.

Based on these criteria, physical sensitivity to changes in water supply was evaluated based on gradient (higher-gradient streams have less pool volume and greater boundary resistance, and are less sensitive to changes in flow) and flow regime (reduction of flow volume may have less effect on sediment transport and channel geometry in channels with long-duration, relatively lower-magnitude snowmelt runoff than in rainfall-runoff channels). Sensi-

Fig. 4 Distribution of six cluster groups for stream ecosystems based on management-scale analysis of ecological drivers for 74 watersheds intersecting the Bighorn National Forest. Geology, flow regime, and stream gradient were the drivers used to produce the six clusters

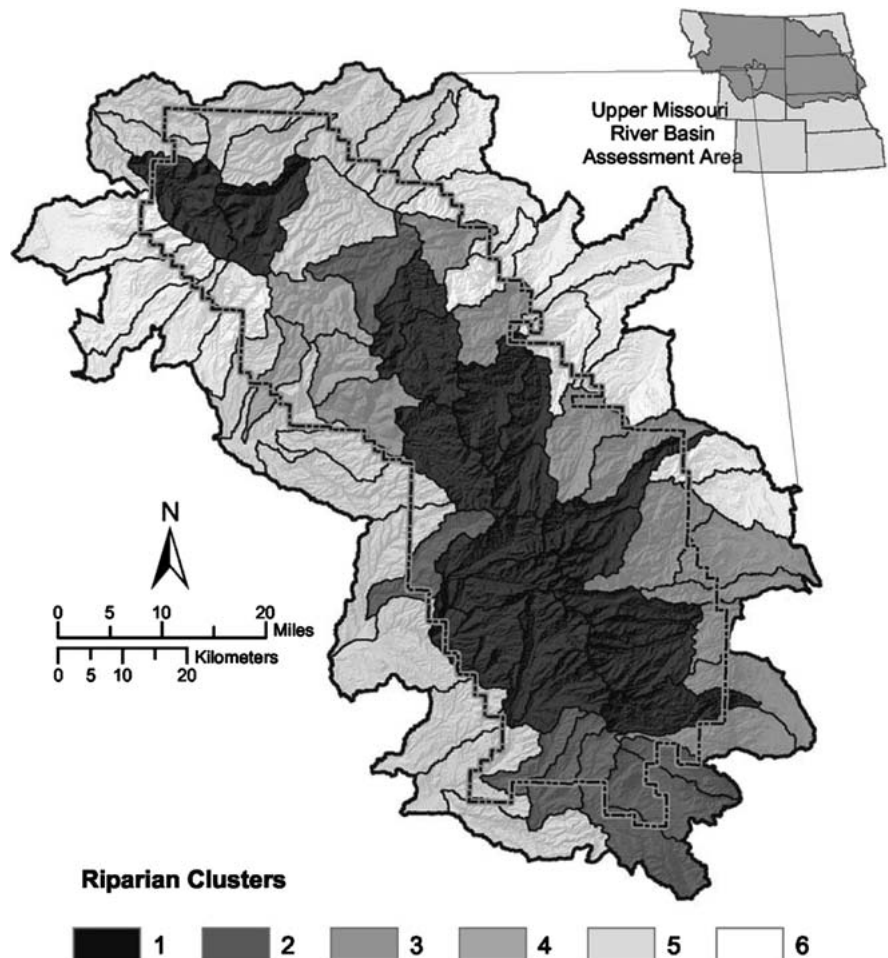


Table 2 Percentage area encompassed by individual ecological driver combinations for the management-scale riparian and aquatic ecosystem assessment of 74 watersheds in the Bighorn study area

Cluster	Percentage area or length encompassed by a specific ecological driver combination							
	Geology		Flow regime			Stream gradient		
	<i>Ca</i>	<i>Cn</i>	<i>Pr</i>	<i>Prs</i>	<i>Ps</i>	Low	Medium	High
1 (19)	11.37	88.63	0.07	21.22	78.71	10.52	32.33	57.16
2 (7)	52.57	47.43	0.46	46.89	52.65	20.92	34.40	44.68
3 (11)	9.86	90.14	17.43	66.09	16.49	29.78	20.09	50.12
4 (3)	58.84	41.16	8.95	21.18	69.87	7.04	13.20	79.76
5 (18)	77.13	22.87	31.34	53.94	14.72	19.78	18.23	62.00
6 (16)	16.79	83.21	76.61	20.61	2.78	39.72	28.38	31.90

Note. Number in parentheses after cluster number indicates number of HUBs in that cluster. *Ca*, calcareous geology; *Cn*, noncalcareous geology; *Pr*, rain-generated runoff; *Prs*, mixed rain and snow; *Ps*, snowmelt runoff. Numbers in boldface indicate the highest percentage in each driver for a particular cluster

Table 3 The relative sensitivity of streams to various disturbances differs among driver categories

Driver	Category	Water	Sediment	Thermal	Nutrient	Nonnative species
Gradient	High	Least	Least	Moderate	Least	Least
	Medium	Moderate	Moderate	Moderate	Moderate	Moderate
	Low	Most	Most	Moderate	Most	Most
Flow regime	Snowmelt	Least	Least	Most	Least	Moderate
	Snow & rain	Moderate	Moderate	Moderate	Moderate	Most
	Rainfall	Most	Most	Least	Most	Least
Geology	Noncalcareous	Most	Most	Moderate	Most	Moderate
	Calcareous	Least	Least	Moderate	Least	Most

Note. These relative rankings were combined to estimate the relative sensitivity of each of the six primary clusters to disturbance in Tables 4a and 4b

tivity to sediment was based on gradient (higher-gradient streams flush excess sediment and resist erosion when sediment is reduced and are therefore less sensitive to changes in sediment) and rock type (calcareous streams are less sensitive to changes in sediment supply because these streams are less likely to have substantial changes in fine sediment input as a result of disturbance).

Instream production and invertebrate diversity

Instream production and invertebrate diversity also reflect controls exerted by flow regime, geology, and stream gradient. Because climate and flow regime in the Bighorn National Forest are largely a function of elevation, temperature correlates strongly with flow regime. Temperature conditions are critical determinants of the growth and developmental rates of invertebrate species (Vannote and Sweeney, 1980). Temperature can also regulate the distribution and abundance of many aquatic insect species within a watershed. There is a distinct faunal zonation

within Rocky Mountain streams that directly reflects the prevailing thermal conditions at particular altitudes (Ward, 1986; Ward and Kondratieff, 1992). Productivity of aquatic invertebrate communities is generally higher in warmer waters (Benke, 1993; Ward, 1992) where metabolic rates are increased.

Flow regime determines how much water is in the channel at any given time. Drying of streams (intermittency) has serious consequences for aquatic communities, severely reducing diversity and limiting production (Larimore and others, 1959; Stanley and others, 1997). Perennial streams in the Big Horn Mountains are associated with headwaters having heavy snow accumulations and/or springs. Streams that head at lower elevations in the foothills and plains are likely to be seasonally influenced by runoff from rainfall, which may provide the main source of stream flow. These systems tend to be more temporally intermittent during periods of low precipitation because the streams lack the storage characteristic of snowmelt streams. Lower-elevation streams thus have a very

different fauna because of seasonal drying and late-season disturbance, in addition to other factors such as warmer summer water temperature (Ward and Kondratieff, 1992).

Geology influences instream production and invertebrate diversity through the type and volume of sediment produced, as well as the quantities of nutrients available for dissolution and transport to streams. Rock type also influences rates and pathways of runoff to stream channels, thereby regulating stream thermal and flow regimes. Coarse-grained gravel-bed streams typically have greater production than fine-grained channels formed in silt or clay (Allan, 1995; Waters, 1995). Invertebrate production is generally higher in streams draining calcareous geology than in streams draining noncalcareous geology as a result of a combination of greater dissolved nutrients and more stable thermal and flow regimes in calcareous streams (Huryn and others, 1995; Krueger and Waters, 1983). This effect may be enhanced at very high elevations, where cold temperatures can interact with low nutrient levels to further limit invertebrate production potential.

Sediment transported during higher flows often serves as a source of disturbance that induces mortality in benthic invertebrate populations (Resh and others, 1988; Poff, 1992) and scours benthic algae (Peterson, 1996; Peterson and others, 2001). The frequency and timing of bedload movement influence the types of species that occur in a stream. Frequently disturbed streams, for example, are dominated by highly mobile species that are good at recolonization (Richards and others, 1996; Robinson and Minshall, 1998; Scarsbrook and Townsend, 1993; Townsend and others, 1997a). Invertebrate diversity can reach a maximum at intermediate levels of disturbance (Townsend and others, 1997b), possibly because disturbances reduce the abundance of superior competitors that might otherwise eliminate “weedy species” (Hemphill and Cooper, 1983; Hildrew and Giller, 1994; Townsend and others, 1997a). Interannual variation in population sizes for lotic species can also be attributed to interannual variation in disturbance or other environmental conditions (Feminella and Resh, 1990; Voelz and others, 2000). Disturbances caused by high flows also have a direct influence on invertebrate production because mortality reduces population size and biomass.

Lower gradient stream reaches tend to retain more sediment and dissolved nutrients and thus have greater habitat complexity and local production than higher gradient streams (Huryn and Wallace, 1987). Lower gradient reaches of mountain streams may also have more varied thermal regimes as a result of hyporheic flow patterns. Hyporheic flow provides winter thermal refugia for invertebrates (Stanford and Ward, 1988) and fish (Baxter and Hauer, 2000), and can also promote nutrient transformations such as mineralization of dissolved organic nitrogen, nitrification, and denitrification (Grimm, 1987).

Sensitivity to disturbance: stream productivity

Relative sensitivity of stream productivity for streams in each cluster to changes in water, sediment supply, thermal regime, and nutrient input is summarized in Table 4a. The snowmelt runoff, high-gradient streams in clusters 1 and 4 will support some unique, cold-adapted invertebrate species (Ward, 1986) and therefore an increase in thermal regime would be expected to diminish available cold-water habitat for these species. Overall invertebrate production might, however, increase in response to warmer water temperatures. Streams in both of these clusters are likely nutrient limited and probably sensitive to nutrient additions, although the cluster 1 streams underlain by noncalcareous geology would probably be more responsive to nutrient input concentrations.

The sensitivity of streams in cluster 2 is difficult to assess because habitat heterogeneity is likely to be high. Streams in this cluster of mixed snowmelt and snowmelt-rainfall runoff might be vulnerable to reduced water supply that converts permanent streams to intermittent streams, with a subsequent large change in biological composition. A warming of currently cold water temperatures might eliminate certain cold-adapted invertebrate species, but overall invertebrate production might increase.

A change in water temperature would probably enhance invertebrate production in streams of clusters 3 and 5, although invertebrate diversity might not be sensitive to thermal change. Streams in cluster 3 that are underlain by noncalcareous rocks could be considered more responsive to the same concentrations of nutrient input than streams in cluster 5 that drain watersheds largely underlain by calcareous rocks.

Addition of nutrients to streams in cluster 6 would probably greatly enhance algal production, possibly including nuisance algae, given the high residence time of water in these low-gradient channels. Warmer temperatures

Table 4b Relative sensitivity of stream productivity to changes in hydrologic and thermal regime, sediment and nutrient input, and nonnative biota

Cluster	Hydrology	Sediment	Thermal	Nutrient	Nonnative species
1 (<i>Ps, Cn</i>)	***	**	***	***	***
2 (<i>Prs, Ca</i>)	***	**	**	***	**
3 (<i>Prs, Cn</i>)	***	**	**	***	0/*
4 (<i>Ps, Ca</i>)	**	*	***	**	**
5 (<i>Prs, Ca</i>)	***	**	**	**	0/*
6 (<i>Pr, Cn</i>)	0/*	***	0/*	***	0/*

Note. The sensitivity scale ranges from completely insensitive or not applicable (0) to very sensitive (***). Driver categories that are most prevalent within each cluster are indicated in parentheses (see also Table 2)

in streams of this cluster would probably not affect the resident warm-adapted fauna.

Sensitivity to disturbance: fisheries

Relative sensitivity of fishery resources for streams in each cluster to changes in water, sediment supply, thermal regime, and nutrient input is summarized in Table 4b. Flow regime correlates with thermal conditions in streams of the Bighorn study area, and thermal conditions determine the type of fish species likely to occur. The coldwater fish guild is not likely to persist in the Rocky Mountain region, for example, in areas where mean July air temperatures exceed 22°C (Keleher and Rahel, 1996). Streams in the Rocky Mountains show a characteristic transition from dominance by various species of trout in headwaters to dominance by minnows and suckers at lower elevations because of the general inverse relationship between elevation and temperature (Rahel and Hubert, 1991).

As with instream production and invertebrate diversity, geology influences fisheries through coarse-scale patterns of water fertility and susceptibility to acid precipitation. The abundance of calcareous rocks, for example, influences stream alkalinity, a measure of nutrient content often correlated with the abundance of aquatic organisms (Krueger and Waters, 1983; Kwak and Waters, 1997).

Stream gradient influences fisheries through the type of habitat units present and substrate characteristics. Low-gradient stream reaches are generally more conducive to fish production and are especially important for larger individuals that are typically associated with deep pool habitats (Chisholm and Hubert, 1986). High-stream gradients can prevent fish from colonizing or maintaining populations in some streams (Kruse and others, 1997).

Based on these considerations, streams in cluster 1 would be extremely cold and unproductive for fisheries. Fish assemblages would nonetheless be susceptible to invasion by nonnative coldwater fish. Streams in cluster 2

likely have a mix of habitat conditions and abundant coldwater fish populations, especially in areas with calcareous geology and moderate to low gradients. Of all the clusters, cluster 2 has the highest proportion (11%) of driver combinations most conducive to coldwater fish production (calcareous geology, mixed snowmelt and rainfall runoff, and low or moderate gradient streams). Excess sediments could accumulate in the low-gradient segments of these streams, which are typically mountain meadow environments that support high abundances of fish. Fish assemblages in cluster 2 would be susceptible to invasion by nonnative coldwater fish. Historically, this has involved brook trout (*Salvelinus fontinalis*) that thrive in small, high-elevation streams and brown trout (*Salmo trutta*) or rainbow trout (*Oncorhynchus mykiss*) that become established in midsized streams at moderate elevations. All three of these species have detrimental effects on native cutthroat trout in streams of the western United States through competition, predation or, in the case of rainbow trout, hybridization (Kruse and others, 2001; Novinger and Rahel, 2003).

Streams in cluster 3 would likely have limited aquatic productivity and fish biomass. These streams are likely to represent a transition from mainly coldwater fish at upper elevations to a mixture of coldwater and warmwater fish at lower elevations. Changes in thermal regime could have negative consequences for coldwater species at the lower-elevation portion of these drainages. Streams in cluster 3 are also located in areas where water development activities are extensive and thus stream flows and water quality are often altered. Because these streams are mostly underlain by noncalcareous rocks, aquatic systems in these watersheds would be more affected by nutrient additions than streams in cluster 5, for example, which are underlain by calcareous rocks. Fish assemblages in streams of cluster 3 would be susceptible to invasion by nonnative coldwater fish.

Streams in cluster 4 should contain coldwater fish species, but the cold temperatures and high gradients would limit fish production. The small size of these streams makes them sensitive to reductions in stream flow.

Streams in cluster 5 are at the transition between the Big Horn Mountains and the surrounding prairie. These streams are similar to those in cluster 3 in having high to moderate stream gradients and mixed snowmelt-rainfall or rainfall runoff, but the streams of cluster 5 differ in being underlain primarily by calcareous rocks, which would enhance aquatic productivity. Streams in this cluster are second only to streams in cluster 2 in having conditions most suitable for coldwater fish production. At lower elevations within the watersheds in cluster 5, streams likely would have more diverse fish assemblages that include non-game fish such as suckers and minnows. Fish assemblages in streams of

Table 4a Relative sensitivity of fishery resources to changes in hydrologic and thermal regime, sediment and nutrient input, and nonnative biota

Cluster	Hydrology	Sediment	Thermal	Nutrient	Nonnative species
1	**	*	0	***	***
2	**	*	*	*** or **	***
3	***	**	**	***	***
4	**	*	0	**	***
5	***	**	**	**	***
6	***	***	***	***	*

Note. The sensitivity scale ranges from completely insensitive or not applicable (0) to very sensitive (***)

cluster 5 are vulnerable to water development, changes in thermal regime, and invasion by nonnative coldwater fish.

Streams that originate in cluster 6 likely would be warmwater systems, but larger streams that originate in higher-elevation watersheds would still provide thermally suitable habitat for coldwater fish. Streams in cluster 6 should have the most diverse fish assemblages that include both introduced coldwater game species and native warmwater nongame species. Smaller streams may experience intermittency, which would limit the number and types of fish species that could persist in these systems.

Implications of Cluster Analysis and Sensitivity Assessment for Watershed Management on the Bighorn National Forest

The landscape-scale analysis indicates that watersheds in the Bighorn National Forest are unique in providing snowmelt-driven, cold water, high-gradient habitat relative to the surrounding region. Like headwater streams elsewhere, watersheds on the national forest provide hydrologic connectivity—the water-mediated transport of matter, energy, and organisms within or between elements of the hydrologic cycle (Pringle, 2001)—that is critical to the ecological integrity of the surrounding region. High-elevation watersheds in the forest provide much of the surface flow to adjacent lower elevation portions of regional drainage networks. High-elevation watersheds also substantially increase regional habitat diversity and biodiversity of aquatic and riparian species. Small headwater streams collect organic matter from the surrounding landscape, and organic detritus and invertebrates exported from headwater channels can substantially subsidize food resources for downstream aquatic communities (Freeman and others, 2006).

The sensitivity assessment of clusters in the management-scale analysis suggests that most watersheds on the Bighorn National Forest are ecologically sensitive to alterations in water supply because of the relatively small size of streams. Although watersheds are generally less sensitive to changed sediment supply, low-gradient stream segments create sensitive sites within the watershed, where greater sediment supply would likely result in siltation of riffles and loss of pool volume, and decreased sediment supply would likely result in erosion of the stream bank and bed. Watersheds in cluster 6, which represents 16 of the 74 HUBs in the analysis, include the greatest length of stream segments sensitive to changes in sediment supply.

Most watersheds in the Bighorn National Forest are also sensitive to changes in thermal regime as a result of small stream size and limited capacity for thermal buffering. The high-gradient streams that dominate most watersheds in the forest are sensitive to changes in nutrient input and in-

stream productivity because these streams are less likely to retain fine sediment and organic materials, and less likely to have substantial hyporheic inputs. Because of the high capacity for these steep streams to flush nutrients downstream, continued input of terrestrial detritus such as leaf litter and terrestrial insects is critical to maintaining instream productivity. Disturbances such as wildfire or timber harvest that alter these inputs can substantially alter stream health.

Most streams in the Bighorn National Forest are highly sensitive to the effects of nonnative fish species. Streams in clusters 1 and 4 are at high elevations where cold water temperatures may limit even coldwater fish species. However, Mullner and Hubert (2005) found that nonnative brook trout (*Salvelinus fontinalis*), was able to establish naturalized populations in headwaters of the North Tongue River on the eastern slope of the Bighorn Mountains. In fact, reproducing brook trout populations were found at colder summer temperatures than populations of cutthroat trout, the native trout species in the region. Brook trout were also widely distributed in headwaters of the Little Bighorn River drainage at the northern end of the Bighorn National Forest (Stichert and others, 2001). Brook trout are known to compete with native cutthroat trout and have been implicated in the loss of many cutthroat trout populations (Peterson and others, 2004). Streams in clusters 2, 3, and 4 are at moderate elevations but still have coldwater dominated fish assemblages. Stream temperatures would be warmer at these elevations and are suitable for two other nonnative trout species: rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*). Both species are widespread throughout the Bighorn Mountains at middle elevations and can be detrimental to native cutthroat populations through competition and predation. Rainbow trout also readily hybridize with cutthroat trout. Streams in cluster 6 are at the lowest elevations and would contain more complex fish assemblages containing a mixture of trout, minnow, and sucker species. The lower reaches of the Powder River in Wyoming contain a regionally unique assemblage of turbid-water fish that are threatened by nonnative fish but these nonnative species are not likely to occur as far upstream as the Bighorn National Forest (Hubert 1993).

Testing the Stream Ecosystem Assessments for the Bighorn National Forest

Two aspects of the stream ecosystems assessments described here can be tested using field-derived data. First, do the predicted physical characteristics and biological communities correspond to what is actually present in the

field? Second, do HUBs within each cluster vary in sensitivity to disturbances relative to HUBs in other clusters in the manner predicted in Table 4? Addressing the second question is beyond the scope of this paper, but would involve quantifying the changes in stream ecosystems through time following human-induced disturbances. We did undertake field verification to determine whether the predicted physical and biological characteristics occurred as predicted.

Correspondence Between Predicted and Actual Characteristics

Field verification of physical characteristics was based on determining whether (i) the associations of channel forms and processes that were predicted as a function of drivers do in fact occur (e.g., *CnPs high gradient* is predicted to produce step-pool channels with cobble and boulder substrates of noncalcareous rocks and a snowmelt-runoff regime), and (ii) the boundaries of driver combinations as mapped using published data match the actual boundaries of these combinations present in the field.

Twenty-eight stream reaches that together include all of the combinations of driver variables present in the study area were chosen as field sites at which to verify geologic unit and gradient. At each site, a hand-held GPS unit was used to determine the geographic coordinates. Visual assessment was used to characterize geologic unit (calcareous or noncalcareous), and channel morphology (step-pool, pool-riffle, or transitional between step-pool and pool-riffle). A metric tape and stadia rod were used to measure cross-sectional geometry, as represented by average bankfull-channel top width and bankfull depth. (Bankfull level was judged using high-flow indicators such as bank-slope change, vegetation, debris lines, and water stains or lichen limits on boulders.) Streambed grain size was measured using random-walk clast counts of 100 clasts at each site. Streambed gradient was measured using a hand-held clinometer.

Table 5 summarizes the map designations and the field-measured characteristics for each site chosen. Only 3 of the 28 sites (11%) showed discrepancies between map-designated and field-designated characteristics. In each case, a stream segment predicted to have a low or medium gradient actually had a high gradient. Predicted associations between channel forms and processes were present. High-gradient stream segments generally had step-pool morphology, medium-gradient segments had transitional morphology, and low-gradient segments had pool-riffle morphology. Low- and medium-gradient channels were more likely to be meandering, whereas high-gradient channels were straight. High-gradient channels had coarser streambed substrates, regardless of lithology.

Actual locations of specific driver combinations matched mapped combinations very well. Geologic unit (*Cn*, *Ca*), for example, was always correctly predicted. The only discrepancies between actual and mapped driver combinations occurred where a very short (usually <200-m-long) stream segment had a higher gradient than the stream segments immediately up- and downstream. In this case, the short stream segment had step-pool morphology, rather than the pool-riffle or transitional morphology predicted from the map.

We examined discharge records from U.S. Geological Survey stream gages at various elevations in the region to test predictions about (i) correlations between flow regime and elevation and (ii) seasonal and interannual variability of *Pr*, *Ps*, and *Prs*. Figure 5a shows average annual hydrographs for several sites; Figure 5b shows mean daily discharge over 10-year intervals for several sites. Stream flow regimes as recorded in the discharge records correspond to stream flow characteristics predicted in relation to elevation. The snowmelt runoff (*Ps*) sites at 2529- and 2476-m elevation, respectively, have more gradual recession from the annual peak, and the annual peak values have less interannual variability than the other flow regimes. The mixed snowmelt-rainfall runoff sites (*Prs*) at elevations of 2195, 1737, 1578, and 1541 m, respectively, exhibit more secondary peaks superimposed on the rising and falling limbs of the annual peak, and more symmetrical annual peaks with greater interannual variability. The rainfall site (*Pr*) at 1240-m elevation, which is beyond the boundaries of the Bighorn National Forest on the adjacent plains, exhibits numerous, short duration peaks during an average year and very large interannual variability.

The general results suggest that the protocol provides a very robust means for predicting channel characteristics on the Bighorn National Forest, with the channel configuration of 89% of the sample sites being predicted correctly, and all site checks of geologic unit and flow regime correctly predicted. Problems in using map predictions arise only for very short stream segments that differ from adjacent stream segments, and these very short segments are not likely to be crucial for habitat management at the scale of the Forest unit as a whole, at least not at the “management unit” scale. Such finer heterogeneity in gradient at subreach scales could, however, represent “special” habitat types that could be relevant for management at scales smaller than entire management units.

Sampling populations of aquatic organisms to test field associations was also beyond the scope of this study, but a recently completed M.S. thesis by M. Pyne that was designed to test the predicted biological associations found a strong correspondence between our predictions and populations in the field (R. Rader, Brigham Young Uni-

Table 5 Description of sites chosen for field verification of physical channel characteristics at reach scale

Site	Mapped drivers	Geology	Morphology	Width/depth (m)	Substrate	Gradient
1	<i>CnPrs, m</i>	<i>Cn</i>	Transitional	6.0/0.7	Cobble/small boulder	4%
2	<i>CnPrs, m</i>	<i>Cn</i>	Transitional	6.0/0.5	Cobble/small boulder	3%
3	<i>CnPrs, m</i>	<i>Cn</i>	Transitional	6.0/0.5	Cobble-boulder	4%
4	<i>CnPs, m</i>	<i>Cn</i>	Transitional	1.0/0.2	Gravel-cobble	3%
5	<i>CnPrs, l</i>	<i>Cn</i>	Step-pool	1.5/0.4	Gravel-boulder	6%
6	<i>CaPrs, h</i>	<i>Ca</i>	Step-pool	20/0.7	Cobble-boulder	5%–6%
7	<i>CnPs, h</i>	<i>Cn</i>	Transitional	20/0.5	Boulder	4%
8	<i>CnPs, m</i>	<i>Cn</i>	Step-pool	7.0/0.5	Boulder	4%
9	<i>CnPs, h</i>	<i>Cn</i>	Step-pool	1.0/0.4	Sand-boulder	5%
10	<i>CaPrs, l</i>	<i>Ca</i>	Step-pool	20/0.7	Cobble-boulder	5%–6%
11	<i>CnPs, h</i>	<i>Cn</i>	Step-pool	2.5/0.4	Boulder	8%
12	<i>CnPs, m</i>	<i>Cn</i>	Transitional	4.0/0.5	Gravel-cobble	3%
13	<i>CaPs, h</i>	<i>Ca</i>	Step-pool	15/0.7	Cobble-boulder	8%
14	<i>CaPs, m</i>	<i>Ca</i>	Transitional	15/0.7	Cobble-boulder	4%
15	<i>CaPr, l</i>	<i>Ca</i>	Pool-riffle	15/0.7	Cobble-boulder	2%
16	<i>CaPr, m</i>	<i>Ca</i>	Transitional	15/0.7	Cobble-boulder	4%
17	<i>CaPr, l</i>	<i>Ca</i>	Pool-riffle	15/0.7	Cobble-boulder	2%
18	<i>CaPr, h</i>	<i>Ca</i>	Step-pool	15/0.7	Cobble-boulder	8%
19	<i>CnPs, l</i>	<i>Cn</i>	Pool-riffle	2.0/0.3	Cobble	1%–2%
20	<i>CnPs, m</i>	<i>Cn</i>	Transitional	1.0/0.2	Cobble	3%
21	<i>CaPs, m</i>	<i>Ca</i>	Pool-riffle	5.0/0.5	Gravel-cobble	3%
22	<i>CnPs, m</i>	<i>Cn</i>	Pool-riffle	5.0/0.4	Gravel-cobble	2%
23	<i>CnPs, h</i>	<i>Cn</i>	Step-pool	1.0/0.4	Boulder	4%–5%
24	<i>CnPs, m</i>	<i>Cn</i>	Pool-riffle	2.0/0.3	Gravel	2%
25	<i>CnPs, m</i>	<i>Cn</i>	Pool-riffle	2.0/0.4	Gravel	2%
26	<i>CnPs, l</i>	<i>Cn</i>	Pool-riffle	25/1.0	Gravel-cobble	2%
27	<i>CnPs, m</i>	<i>Cn</i>	Transitional	2.5/0.4	Boulder	4%
28	<i>CnPs, h</i>	<i>Cn</i>	Step-pool	1.0/0.2	Boulder	4%–5%

Note. Site numbers in boldface are those that did not match predicted channel characteristics. Sites 5 and 10 were predicted to have a low gradient and pool-riffle morphology but had a high gradient and step-pool morphology. Site 8 was predicted to have a medium gradient and transitional morphology but had a high gradient and step-pool morphology. Mapped drivers refer to map designations; all other columns refer to field-designated characteristics. Substrate: dominant grain size is boulder (>400 mm), small boulder (200–400 mm), cobble (20–200 mm), gravel (1–20 mm), and sand (<1 mm). Characteristics such as substrate, channel morphology, and width/depth ratio were also measured to test the assumed correlations between these parameters and gradient

versity, personal communication, January 2006). In that work, 132 riffles from 15 watersheds were sampled. Pyne measured algal and invertebrate biomass, macroinvertebrate richness and relative abundance, and brook trout growth in order to test the assumption that our management-scale classification could account for much of the variation in biological characteristics at the reach scale. Pyne found that statistically significant amounts of variation in the biomass of algae and invertebrates, fish growth rates, and macroinvertebrate community composition were explained by the management-scale classification, but he recommended that additional local-scale habitat information is needed to further explain biological variation present at the reach scale. Short segments of low stream gradient that are vulnerable to sediment accumulation, for

example, would not appear in broader-scale averaging of stream characteristics.

Management Implications of These Results

The limited field verifications discussed above suggest that the management-scale analysis based on gradient, flow regime, and lithology as ecological drivers can be of use to resource managers. The assessment procedure described here can be used to identify watersheds with similar driver combinations that should have broadly similar biological characteristics and react to disturbance in a similar manner. This would simplify the task of managers who must do environmental impact assessments with little time to collect new data on a given watershed. The assessment can

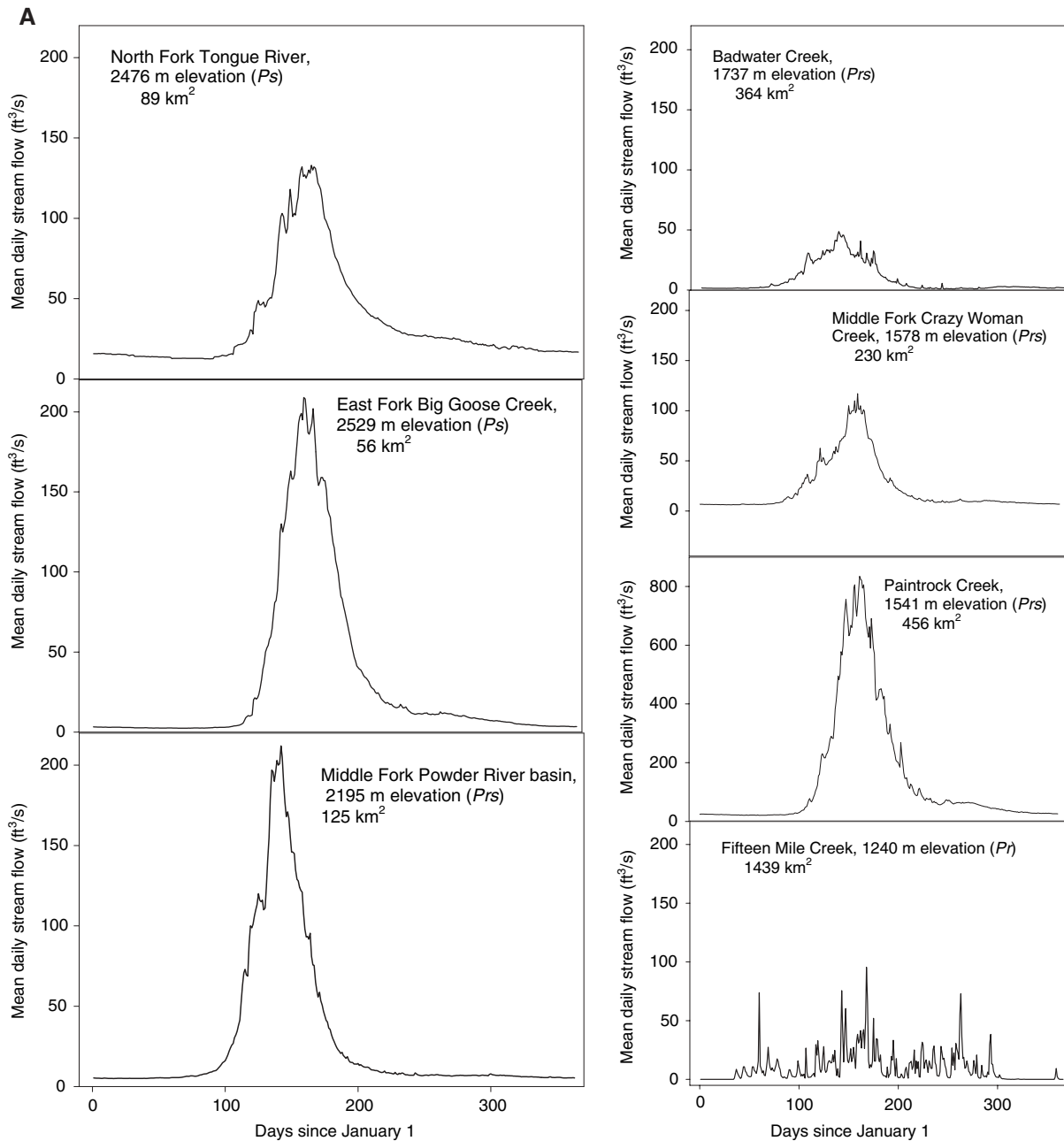


Fig. 5a Average annual hydrographs for seven sites at various elevations in and near the Bighorn National Forest. All sites except Paintrock Creek are plotted at the same scale

also be used to identify watersheds with driver combinations that make the watersheds especially susceptible to certain types of disturbance but not others, allowing managers to focus their efforts on controlling the highest impact anthropogenic activities while not investing as much effort in controlling other activities. Managers might put more emphasis on limiting flow diversions than on limiting road building, for example, in watersheds dominated by high-gradient streams that are relatively sensitive to changes in water yield and relatively insensitive to

changes in sediment yield. Such decisions should also consider the watershed context of the high-gradient streams, however, because the adjacent steep terrain might be especially sensitive to the effects of road building. Finally, the assessment can be used to identify watersheds with unusual combinations of drivers that make the watersheds regionally rare and/or distinctive and thus worthy of special attention from managers. Each of these aspects of identifying the specific characteristics and regional abundance of sixth-level watersheds can also be

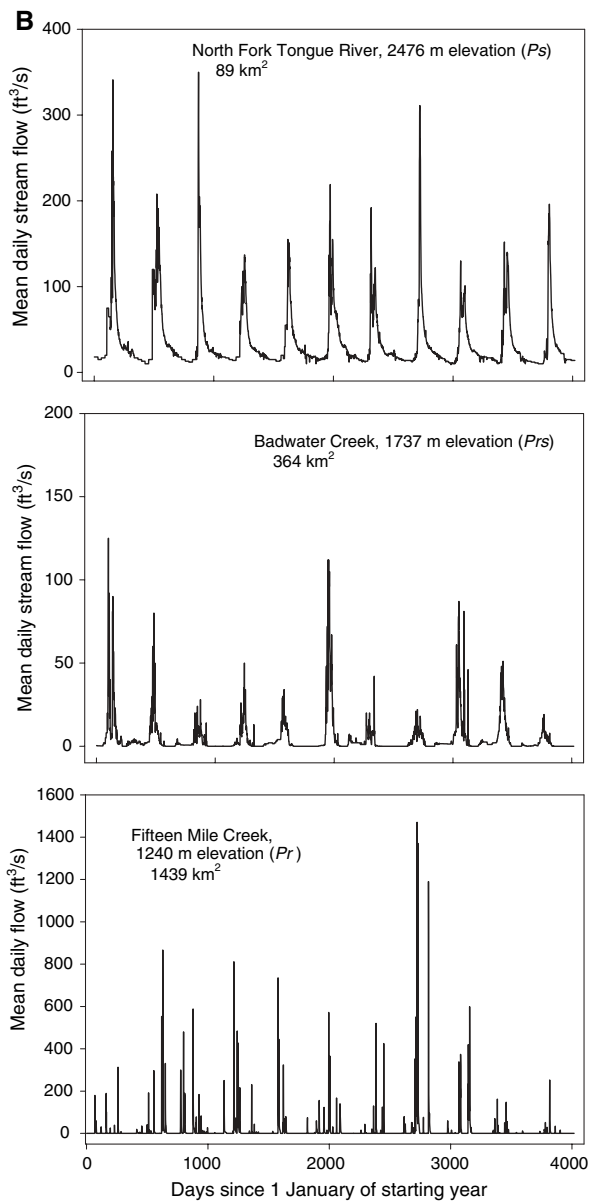


Fig. 5b Mean daily discharge for three sites at various elevations in and near the Bighorn National Forest, plotted for 10-year intervals. Note that vertical scales differ among the three graphs

used as a starting point for more detailed characterizations of stream processes and biological communities at finer spatial scales.

Conclusions

Aquatic and riparian resources can be managed at many scales, ranging from the landscape scale of a continental river basin such as the Mississippi River, through sixth-level watershed HUBs, to the stream reach. Managers do

not necessarily want to manage for each stream reach given limited resources, and they cannot ignore the larger scale constraints imposed by the contributing watershed. Consequently, we have developed an assessment procedure for the spatial scale at which many managers work, i.e., the sixth-level HUB. We classified management units according to reach-scale attributes such as gradient and flow regime, but we did not examine the within-HUB heterogeneity of reach-scale driver combinations, and we cannot assume that reaches are homogeneous within a HUB. This reflects an inherent principle of hierarchical systems, in which the higher level category (management unit) averages across the heterogeneity present at lower level categories (stream reaches). The percentages of each driver combination within each of the six clusters in Table 2 indicate that some HUBs are quite variable in reach characteristics. As a result, our inferences about abundance and sensitivity of watersheds are most appropriately applied to the management scale rather than to individual stream reaches. Because of heterogeneity among reaches within a management unit, we do not expect to explain all of the physical or biological variation using only a single scale of classification (see Poff, 1997).

With these reservations, the hierarchical assessment of stream ecosystem function and sensitivity described in this article develops testable hypotheses based on existing knowledge of environment-ecological relations. The assessment procedure provides a relatively simple and accurate means to predict the spatial distribution of watershed characteristics within the study area. The assessment also provides an objective means to assess the abundance and sensitivity of watersheds, and thus provides a basis for management decisions. The assessment of the Bighorn National Forest in Wyoming highlights the regional uniqueness and importance of watersheds within the Forest, which contain predominantly high-gradient streams dominated by snowmelt and mixed snowmelt and rainfall runoff. The techniques described here should be readily applicable to other mountainous regions of the western United States, with site-specific adjustments to the driver categories used to characterize gradient, flow regime, and lithology.

Future research can build on the results presented here by assessing the heterogeneity of channels within larger-scale management units. Variation within larger-scale management units can influence unit-wide ecological potential, and our approach here was to average across the management units rather than focus on the heterogeneity. Thus the next level down in the hierarchy would be to representatively sample this within-unit heterogeneity. The need to conduct such studies will be driven by management questions.

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