Cumulative Effects Analysis of Land-Use in the Carbondale River Catchment: Implications for Fish Management

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Abstract

Recent studies analyzing the cumulative effects of land-use in forested ecosystems show promise for using geographic information systems (GIS) as simple tools for making useful cumulative-effects assessments suitable for routine management applications. We demonstrate that a particular GIS-based watershed analysis approach recently developed for routine use in the interior of adjacent British Columbia, the Interior Watershed Assessment Procedure (IWAP), is applicable to the analysis of cumulative effects of land-use on Alberta's Eastern Slopes, providing results of immediate utility for managing land-uses and fish habitat. We applied a slight adaptation of the IWAP in order to quantitatively document and analyze land-use in the Carbondale River watershed, a representative small river basin on the Eastern Slopes, using existing publicly-available digital geographic data for the area. The results predicted that the basin as a whole, and all of its sub-basins, are at very high risk of damage from increased peak flows, increased surface erosion, or the interaction of increased peak flows and increased surface erosion, resulting from land-use in the basin. The riparian zones of the entire basin and all but one of the sub-basins are predicted to be at high risk of damage as the result of extensive logging of streambanks. These assessments of risk were consistent with previously reported independent observations of extensive damage to stream channels and riparian habitat in the field, with one exception: the procedure failed to predict extensive streambank damage that had previously been independently observed in Gardiner Creek. Delivery of water and sediment are major factors shaping the basin's mainly gravelbed channels, and these basin-wide factors have been fundamentally changed from the natural condition by past and current land-use. The results of this study imply that land-use patterns in the basin must be improved to significantly improve fish habitat in the long term. Accordingly, all roads not required for basic access should be decommissioned and equivalent clearcut area should be reduced to restore the ecological integrity of the Carbondale basin.

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Introduction

The Rocky Mountain region in Canada is under heavy development pressure, particularly for resource extraction, tourism, recreation, grazing and, locally, from intensive urbanization. The Eastern Slopes in Alberta, a 108 000-km^2 area of mountains, foothills, forests and grasslands east of the Continental Divide, is no exception. The 90 000-km^2 portion of the region under Alberta Government jurisdiction is managed under a multiple-use policy that explicitly promotes unlimited growth in resource development while at the same time proposing to maintain key watershed and recreational values (Alberta Energy and Natural Resources 1984). Nevertheless, natural resources in the Eastern Slopes are to be developed, managed and protected "in a manner consistent with principles of conservation and environmental protection" (Alberta Energy and Natural Resources 1984).

Even though these management goals may be met initially when development intensity is low, it is obvious that they must ultimately be incompatible when unstinted development overwhelms natural systems. We endorse an ecosystem-based management approach (e.g., Agee and Johnson 1988; Keiter and Boyce 1991; FEMAT 1993; AFSEEE 1995) as a realistic replacement for this and similar policies. We propose that the goal of ecosystem management in the Rocky Mountains be to accommodate a level of development that maintains natural ecosystems intact in perpetuity. To meet this goal, an evaluation of the existing condition of the landscape relative to its natural condition — a cumulative-effects analysis — is needed as a basis for setting limits to culturally induced change.

We understand cumulative effects to be the total accumulated changes induced by humans in the environment. Individually these effects may be minor, but collectively they can be significant. It is the cumulative effects of all human-induced environmental change that determine the limits within which we can modify ecosystems without destroying their value to us and the essential services they provide. For this reason, we must continually assess the cumulative effects of all human activities in a region if we wish to manage and sustain its renewable resources.

Current views of cumulative-effects assessment see the process as poorly understood, difficult and complex, with few agreed-upon procedures and methods suitable for general application (e.g., numerous papers in Kennedy 1994; Hegmann and Yarranton 1995). Indeed, many of the assessments that have been done have been extensive, tedious, expensive and time-consuming (e.g., Leathe and Enk 1985; Antoniuk 1994; Okrainetz 1994; Smith 1994; Duinker 1994; and Hegmann and Yarranton 1995 describe many other examples). Finally, there is the problem of what to do when the cumulative effects have been identified and quantified. What degree of change is allowed? Some imply that these limits are unreasonably difficult to ascertain (Hegmann and Yarranton 1995). Cumulative effects of many development proposals often are not seriously assessed for these and less savory reasons, even when it is required by policy or law (Nikiforuk 1997).

In our view the many perceived difficulties in assessing cumulative effects are often of little practical importance. For most purposes it is seldom necessary to evaluate every potential interaction for its cumulative effect. Some simple and quick methods are available that, when combined with existing guidelines and standards, can produce results of immediate value for making environmental management decisions.

For example, several recent studies have used computerized geographic information systems (GIS) to assist in the spatial analysis of the cumulative effects of land-use on ecosystems (e.g., Forest Ecosystem Management Recovery Team 1993; Case et al. 1994; several studies cited by Spaling and Smit 1994). These tools are quantitative, fast, cheap and make use of existing, frequently updated, digital map data. GIS-based procedures rank among the better approaches in meeting the objectives of cumulative-effects assessment (Spaling and Smit 1994). At the same time, quantitative or semi-quantitative standards for human disturbance in ecosystems are being developed by some jurisdictions (e.g., B.C. Forest Service 1995a, 1995b). Many important human disturbances in a region can be quantified using a GIS and analyzed according to the existing standards to arrive at defensible decisions about the amount of additional disturbance that can be permitted.

In the study reported here, we demonstrate that a particular GIS-based watershed analysis approach recently developed for the interior of adjacent British Columbia (B.C. Forest Service 1995a) is practical for routine use, and is applicable to the analysis of cumulative effects on Alberta's Eastern Slopes. To do this, we apply the approach to quantitatively document and analyze land-use in a representative small river basin on the Eastern Slopes using existing publicly available digital geographic data for the area. We discuss the applicability of the approach to Alberta based on broad similarities and differences between the characteristics of the study area and the region for which it was specifically designed. We evaluate the potential impacts of land-use on streams in the study basin according to the published standard criteria of the approach, and compare these assessments to independent observations on land-use effects made previously in fish habitat surveys in the same basin. Finally, we comment on the implications of the findings for managing fish habitat in the study basin.

Study Area

We chose the Carbondale River basin of southwestern Alberta for this demonstration because it is subject to most of the land-uses common on the Eastern Slopes, including logging, mining, grazing, petroleum exploration and development, recreation and off-road vehicle travel (Gibbard and Sheppard 1992). Streams in this basin are regionally important angling waters. The Carbondale River basin is also of considerable interest as a region of high biodiversity, containing many rare species of plants and animals (e.g., Wallis 1994; Alberta Environmental Protection 1995; Gerrand and Sheppard 1995), including two species of fish considered to be at-risk: westslope cutthroat trout and bull trout (Gerrand and Sheppard 1995). The results of a cumulative-effects study in this basin therefore are of broad and immediate practical interest.

Effects of land-use on watersheds are likely to depend on relief, geology, soils, climate and forest cover (B.C. Forest Service 1995a). The significance of these effects on fish will depend on the species present and on their use of the habitat (Hicks et al. 1991).

The Carbondale River is a major tributary of the Castle River in the Oldman River drainage, a part of the South Saskatchewan River system (Fig. 1). The 309-km^2 basin lies in the Front Ranges of the southern Canadian Rocky Mountains on the eastern slopes of the Continental Divide. The basin is topographically rugged, with relief of over 1229 m, from over 2500 m on the divide to 1271 m at the confluence with the Castle River (Fitch 1980a). Bedrock is dominated by shale, sandstone conglomerate and coal of late Triassic to Tertiary age (Gadd 1995). Surficial deposits are mostly moderately to slightly leached silty-sand tills of varying texture, ranging from fine to extremely coarse and silty sand colluvium. Coarse alluvium is associated with stream channels (Bayrock and Reimchen 1980).

Soils, mapped in detail only in the eastern part of the study area, have been described by Twardy and Sehn (1994). Orthic gray luvisols are common, occurring primarily under forests on loam-textured tills, on slopes ranging from 2 to 45%. Water erosion hazard rating of the luvisols is moderate on 5 to 9% slopes, and high on slopes greater than 9%. Orthic dark gray chernozems, particularly common in the eastern portions of the study area under grasslands (Achuff 1992), occur on silty to sandy loam, or on loam- to clay loam-textured till or fluvial veneer over till, on terrain that is gently undulating to moderately rolling (1 to 15% slopes). Water erosion hazard rating of the chernozems is moderate on 9 to 15% slopes and high on slopes greater than 15%. Orthic and lithic regosols, very common on colluvial slopes and on active fluvial landforms, occur on sandy loam to loam-textured weathered bedrock and rock on

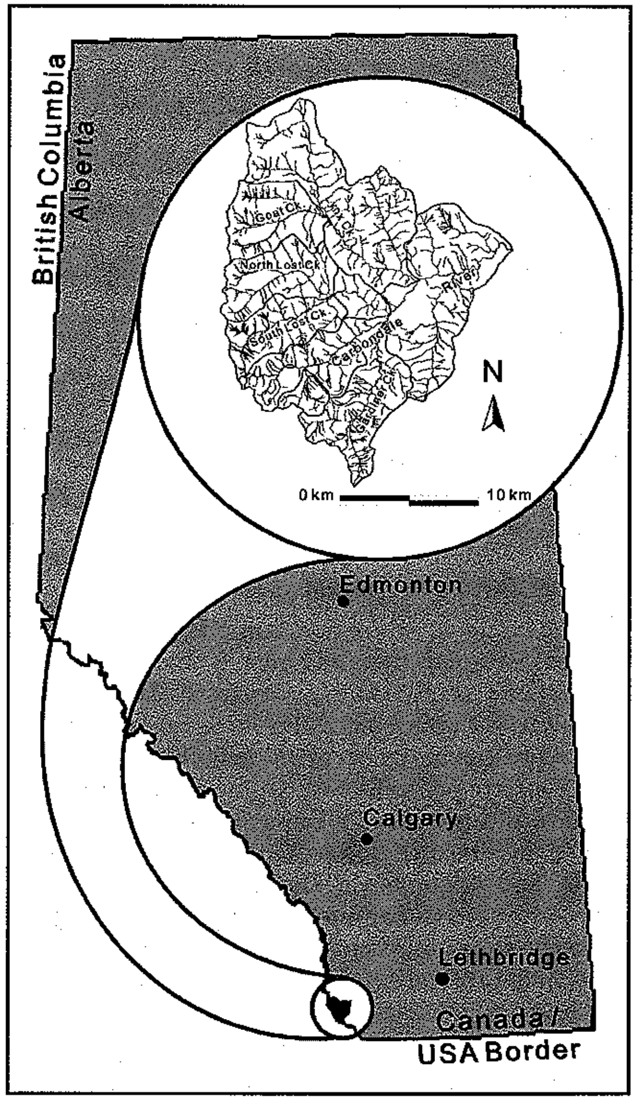

Figure 1. The study watershed: the Carbondale River basin, Alberta, Canada.

strongly to extremely rolling terrain (16 to 70% slopes). Water erosion hazard of regosols is moderate on 9 to 15% slopes and high on slopes greater than 15%

The climate is northern continental, with cold winters and short, cool summers. Mean daily temperatures in January range from -7 to -9°C, and in July are about 16°C (Longley 1972). On average, only 149 days are above freezing (Gadd 1995). The rate of precipitation is among the highest on the Alberta Eastern Slopes: mean annual precipitation ranges from 51 to 107 cm, approximately 30 to 53% of which falls as snow (Longley 1972; Atmospheric Environment Service data for Castle Ranger Station cited by Gadd 1995). The regional snowfall ranges from 221 to 459 cm. Warm, dry and strong chinook winds characteristic of the Eastern Slopes exert a powerful drying influence throughout the year, and are especially prevalent in the study area. These winds are capable of removing most of the snowpack in a matter of days, especially on west-facing slopes. On average, chinooks occur 30 out of 120 winter days (Gadd 1995) but may not occur at all in about one winter out of 10 (Longley 1972).

We did not find streamflow data for the Carbondale River basin, but the hydrology can be expected to display characteristics similar to other Eastern Slopes basins. Streamflows here are highest during spring snowmelt, peaking in late May to early June. Rain-on-snow events during this period have produced large floods, including two greater than 100-year events in the last two decades in the Castle basin. Low flows occur in late winter. Most streams are ice-covered from December through February except during prolonged chinooks, or in areas influenced by groundwater discharge.

The montane sub-region, comprising most of the eastern portion of the study area, is characterized by a savannah of *Pseudotsuga menziesii* (Douglas-fir), *Pinus flexilis* (limber pine) and *Pinus contorta* (lodgepole pine). Subalpine forests dominating the central and western portions vary primarily according to altitude and fire history. Lower subalpine sites disturbed by fire are dominated by lodgepole pine, while *Picea engelmannii* (Engelmann spruce) and *Abies lasiocarpa* (subalpine fir) predominate on cooler, mesic sites not recently burned. At higher elevations *Pinus albicaulis* (whitebark pine) and *Larix lyallii* (subalpine larch) are diagnostic of the transition to the treeless alpine sub-region (Achuff 1992).

Westslope cutthroat trout (*Oncorhynchus clarki lewisi*) and bull trout (*Salvelinus confluentus*) are the only widespread native fishes in the basin. Mountain whitefish (*Prosopium williamsoni*), longnose suckers (*Catostomus catostomus*) and longnose dace (*Rhinichthys cataractae*) are native in the lower reach of the Carbondale River below a waterfall barrier. Rainbow trout (*O. mykiss*) have been widely introduced within the drainage, and appear to have introgressively hybridized with the cutthroats (Fitch 1980a–g, D. Mayhood unpublished data).

Methods

We adapted slightly the B.C. Forest Service's Level I Interior Watershed Assessment Procedure (IWAP) to assess the cumulative effects of existing human disturbance in the Carbondale watershed. The IWAP was developed for use in the interior forested watersheds of British Columbia, including the west slopes of the Rocky Mountains immediately adjacent to the study area (B.C. Forest Service 1995a). The procedure is intended to help land managers understand the type and extent of water-related problems in a basin and to recognize the possible hydrologic implications of proposed future developments in that basin.

The IWAP assesses potential for certain hydrological impacts in a watershed, specifically the potential for (1) changes in peak flows, (2) accelerated surface erosion, (3) changes to riparian zones, and (4) mass wasting, from the 13 indicators of cultural disturbance listed below.

Peak Flow Indicators

1. peak flow index
2. road density above the H_{60} line (elevation above which 60% of the watershed area lies)
3. road density in the entire basin

Surface erosion indicators

4. road density on erodible soils
5. density of roads within 100 m of a watercourse
6. road density on erodible soils within 100 m of a watercourse
7. stream crossing density
8. road density in the entire basin

Riparian buffer indicators

9. proportion of watercourse banks logged
10. proportion of banks of fish-bearing watercourse logged

Mass-wasting

11. landslide density in the watershed

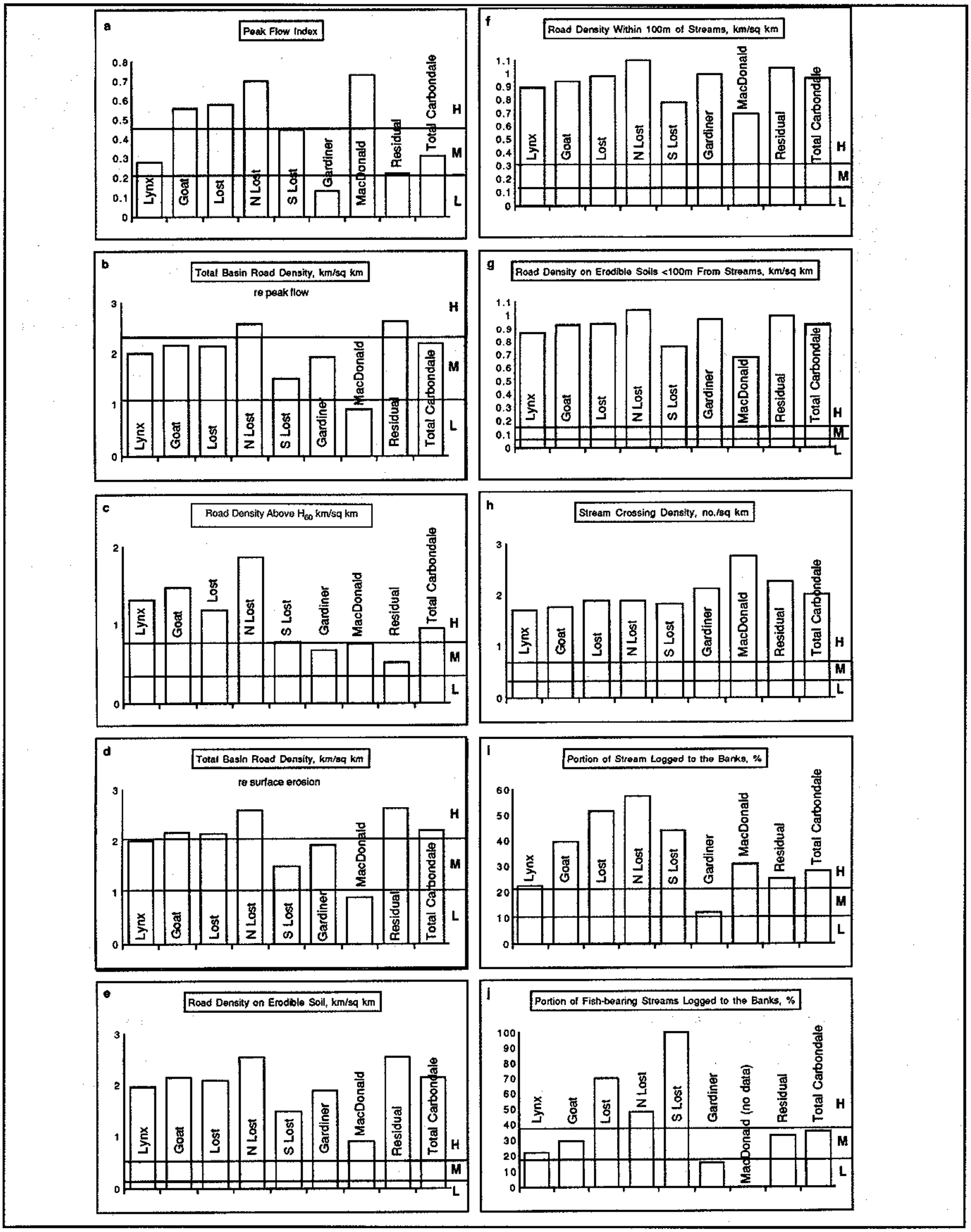

Figure 2. Indicators of environmental impact produced by the IWAP analysis, Carbondale River basin and its sub-basins. H, high; M, moderate; L, low potential impact.

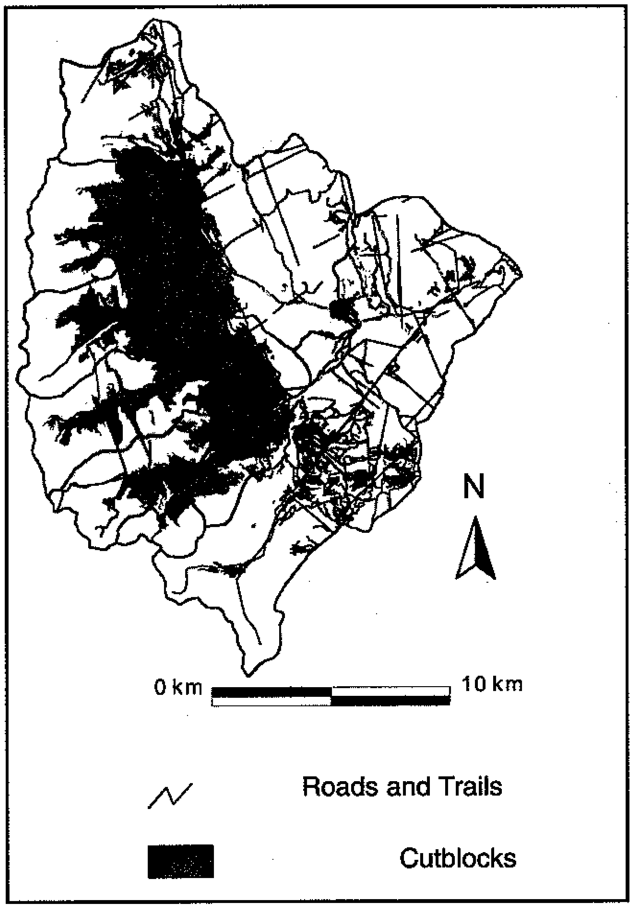

Figure 3. Principal human disturbances from land-use in the Carbondale River basin.

12. road density on unstable or potentially unstable slopes
13. proportion of watercourses logged on slopes exceeding 60%

These indicators are standardized to values between 0 and 1 according to results of studies on 40 watersheds in interior B.C. The indicators in each category are evaluated together to arrive at a hazard index score for that category, then the hazard indices are interpreted in several pairwise matrices to assess the potential for environmental impact arising from their interactions. We undertook to assess peak flow, surface erosion and riparian buffers in this reconnaissance-level study, but did not have the resources to do the landslide counts and acquire the terrain stability data required to make an assessment of mass-wasting potential. Omitting the mass-wasting assessment will tend to underestimate the cumulative effects of human development on the study area.

All digital data necessary for the analysis were purchased from Alberta Environmental Protection and were not modified for this study. Linear data (roads, trails, streams, lakes) and digital elevation models (DEMs) were obtained from 1:20 000 provincial digital base map files. Vegetation data, including species composition and stand disturbance modifiers, were derived from digital Alberta Vegetation Inventory (AVI) files. The data sets are accurate to ±5 m. The linear and DEM data are current to 1994 and vegetation data are current to mid-1995. The data were managed, analyzed and displayed with ArcInfo 3.4.2 (Environmental Systems Research Institute 1995), a personal computer-based GIS. The Unix version of ArcInfo 7.0 was used for some complex analyses not available in version 3.4.2.

We used the calculation and analysis methods detailed in the IWAP Guidebook (B.C. Forest Service 1995a), with only the modifications outlined below. It is critical to be aware that, under the IWAP calculating methods, all density figures are standardized to the total area of the basin or sub-basin in question, even those related to some restricted area. For example, road density within 100 m of a stream is calculated as the length of road within 100 m of a stream divided by the total area of the basin, not just by the area of the 100-m buffer. The resulting figure therefore is not the actual road density within the buffer,

Table 1. Standard IWAP (B.C.) hydrological recovery criteria for partially cut areas, and the Alberta equivalents used in the calculation of equivalent clearcut area in this study

	100% recovery	50% recovery	0% recovery
IWAP	<30% basal area removed	30–60% basal area removed	>60% basal area removed
Alberta	1–25% loss of crown closure	26–75% loss of crown closure	76–100% loss of crown closure

but the overall density of road in that category in the basin in question. The true densities within the restricted areas thus will always be higher—usually much higher—than the figures calculated according to the IWAP.

Equivalent clearcut area (ECA) is used in the IWAP to calculate a peak flow index, a ratio of ECA to total basin area, weighted to account for the greater influence on peak streamflows of clearcuts at higher elevations. The method of calculating ECA had to be slightly modified to accommodate the Alberta data. ECA is the area that has been clearcut, reduced by a factor to account for the hydrological recovery due to forest regeneration (B.C. Forest Service 1995a). The hydrological recovery factor was obtained from the AVI data, which provide the height of regeneration and the loss of crown closure in each logged polygon. Because the IWAP recovery criteria for partially cut sites are based on three categories of basal area removal, whereas the AVI data provided a five-category classification of loss of crown closure, we adjusted the IWAP criteria to suit our data (Table 1). Because restocking in our study area was very low, this adjustment tends to underestimate ECA (i.e., shows greater recovery) relative to that derived from B.C.'s three-category data. Our ECA estimates are therefore somewhat conservative.

Trails for seismic exploration were considered roads in our analysis. Virtually all seismic trails in the study area are used—often heavily—by recreational off-road vehicles (M. Sawyer and M. Judd, unpublished data). Our procedure still underestimates the extent of road and trail development, because recreational off-roaders continually create their own trails throughout the basin (Gibbard and Sheppard 1992; Sheppard 1995; M. Sawyer unpublished data), and these do not necessarily show up in the digital database.

The IWAP uses various calculated watershed indicators (primary indices) to establish hazard index scores (secondary indices) used in bivariate matrices, termed interaction matrices, to create interaction matrix values (tertiary indices). It is these highest-order indices that are used to make recommendations about watershed management. We were able to calculate an interpretation matrix only for the interaction of peak flow and surface erosion. This was a Level 1 analysis, so we did not have the necessary channel stability data collected in a Level 2 analysis (B.C. Forest Service 1996) to calculate values for the three interpretation matrices requiring those data, and as noted above, we did not have the mass-wasting data that would have allowed us to calculate an interpretation matrix for mass-wasting versus peak flow. Instead, we initially rated potential for watershed damage directly from the primary indices in the "watershed report card" (B.C. Forest Service 1995a). We used the ranking scheme of the relative impact guidelines and the scoring conversion table in the IWAP document, which is based on results from 40 test watersheds representing the four interior forest regions in British Columbia (B.C. Forest Service 1995a). We also rated the secondary indices (hazard indices) for the peak flow, surface erosion and riparian buffers impact categories according to the low-medium-high hazard criteria established in the IWAP (B.C. Forest Service 1995).

Soils and their susceptibility to water erosion have been mapped only for the eastern portion of the study area (Twardy and Sehn 1994). Because soil types are closely correlated with surficial geology and the surficial deposits of the study area have been mapped (Bayrock and Reimchen 1980), we identified soil types based on the known distribution of surficial deposits. The erodibility of each soil type is strongly related to slope (Twardy and Sehn 1994). We therefore mapped slope classes using the DEM, and used these together with the map of surficial deposits to map soil erodibility for those areas where site-specific erodibility data were not available.

Results

The IWAP analysis produced a total of 10 indicators of the impact of human disturbance on peak streamflows, surface erosion and riparian buffers. These indicators are summarized in Figure 2 together with the levels of potential low, moderate and high impact. The GIS data from which the ten indicators were calculated are presented in Table 2. Figure 3 maps the total amount of human-induced surface disturbance in the Carbondale basin. Whenever possible, the results for larger basins incorporated those for all included sub-basins. The Goat Creek drainage is a sub-basin of Lynx Creek, and North and South Lost creeks are sub-basins of Lost Creek. MacDonald, Gardiner, Lost and Lynx Creeks are direct tributaries of the Carbondale River.

The sub-basins not included in any of the named basins in the tables or figures were grouped and referred to as the residual Carbondale sub-basin (cf. B.C. Forest Service 1995a).

Peak Flows

Peak flow index. The peak flow index is intended as a measure of the sensitivity of a basin to increases in peak flows resulting from clearcutting. Higher values indicate a greater sensitivity to increased peak flows. The index is calculated as a weighted measure of the proportion of the basin that has been clearcut, the weighting depending on the fraction of clearcutting in a particularly sensitive zone, the upper 60% of the basin that is still snow-covered at the time that streamflows begin to rise in the spring. The elevation of this snowline (the H_{60} line) in the Carbondale basin was calculated from the DEM to be 1622 m.

The peak flow index for the Carbondale basin suggests a moderate potential for increased peak flows from clearcutting overall, but the index for five of the sub-basins was high, and could be described as extremely high in two (Fig. 2a). Two sub-basins had moderate potential for increased peak flows from clearcutting, and only one had a low potential.

Road densities and peak flows. The potential for increased peak flows also increases as the road density increases, because roads act in part as an extension of the surface drainage network, effectively increasing drainage efficiency. The effect is likely to be especially pronounced above the H_{60} line, where most of the meltwater contributing to spring peaks in flows originates.

The potential of overall road densities to increase peak flows was generally ranked moderate in most sub-basins and in the total Carbondale basin, but was rated as high in North Lost Creek and in the residual Carbondale basin (Fig. 2b). In contrast, the potential for road densities above the H_{60} line to increase peak flows could be described as extremely high in four sub-basins, high in one, and moderate in three (Fig. 2c). The potential for increased peak flows from road development above the H_{60} line was rated as high for the Carbondale basin overall.

Surface Erosion

Based on its potential for increasing surface erosion, the overall road density was considered to be high in the Carbondale basin and in several of the sub-basins (Fig. 2d). Potential surface erosion due to roads as measured by all other indicators could reasonably be rated extremely high for every sub-basin (with the exception of road density on erodible soils in the MacDonald sub-basin) and for the Carbondale watershed as a whole (Figs. 2e–h). The two indicators incorporating soil erodibility are extremely high in part because 97% of the Carbondale drainage had erosion hazard ratings of moderate (17%) or high (80%) based on slope, surficial geology and soil type.

Riparian Buffers

Overall, 28% of the total length of watercourse in the Carbondale basin has been logged on at least one bank, leaving little or no buffer strip; 40 to 58% of total watercourse length was logged to at least one bank in four sub-basins (Table 2). The potential for resulting riparian damage was rated high to extreme in the Carbondale watershed and all but one of its sub-basins (Fig. 2i).

Thirty-five percent of the known fish-bearing stream length in the Carbondale basin was logged to the banks on at least one side; this proportion ranged to as high as 70% in the Lost Creek sub-basin and 100% in the South Lost Creek sub-basin (Table 2). Nevertheless, the values overall suggest only a moderate potential impact from logging on streambank fish habitat in the Carbondale basin as a whole, even though the potential impact in the Lost Creek sub-basin is high to extreme (Fig. 2j).

Hazard Indices

Hazard indices summarize the overall potential for impact from the two to five indicators in each impact category. Hazard indices for surface erosion ranked uniformly high throughout the basin (Table 3). Hazard indices for peak flows rated high for the Carbondale basin overall, and for all but two of the sub-basins. Riparian buffer hazard indices were high for the Carbondale basin and all but one of its sub-basins, being low in Gardiner Creek.

Peak Flow–Surface Erosion Interaction

We created an IWAP interaction matrix for the two indicator classes for which we had sufficient data to do so: surface erosion and peak flow. Tertiary index values of 4, the highest possible, indicating very high potential for channel damage from erosion and sediment deposition, were obtained for the total Carbondale catchment and all sub-basins (Table 3).

Table 2. GIS-derived data on the Carbondale basin used in the IWAP analysis

Parameter	Lynx Creek	Goat Creek	Lost Creek	North Lost Creek	South Lost Creek	Gardiner Creek	MacDonald Creek	Residual Carbondale Basin	Total Carbondale Basin
Total area of basin (km^2)	103.43	29.35	65.23	29.99	26.26	36.26	6.49	97.68	309.08
Area above H_{60} line (km^2)	74.11	24.36	46.56	25.17	20.19	25.12	6.07	33.42	185.28
Total ECA (km^2)	22.54	11.96	29.56	15.31	9.55	4.29	4.27	18.65	79.31
ECA above H_{60} (km^2)	12.88	8.90	15.99	11.19	4.39	0.96	0.93	4.92	35.67
Road length (km)	207.94	63.56	139.63	78.02	39.73	69.75	5.88	259.03	682.22
Road length above H_{60} (km)	136.17	43.55	77.18	56.08	20.61	24.48	4.84	50.17	292.83
Road length on erodible soils (km)	203.23	63.01	136.03	76.25	39.05	68.25	5.83	248.20	661.53
Road length ≤ 100m from stream (km)	92.15	27.50	63.81	32.98	20.59	36.08	4.45	101.34	297.84
Road length ≤ 100m from stream on erodible soils (km)	90.05	27.26	61.28	31.25	19.96	35.30	4.41	96.56	287.61
Stream crossings	177	52	123	56	48	77	18	222	617
Total stream length (km)	206.44	57.64	141.86	59.77	66.51	105.45	18.49	204.58	676.82
Length of stream logged (km)	46.54	22.95	73.17	34.42	29.24	12.59	5.72	51.81	189.83
Total fish-bearing stream length (km)[a]	35.84	6.49	24.55	10.50	8.23	16.92	?[b]	25.39	102.70
Length of fish-bearing stream logged (km)	7.85	1.92	17.18	5.05	8.23	2.64	?	8.35	36.02

[a] Minimal estimates. Many tributaries undoubtedly hold fish, but have not been adequately surveyed.

[b] Creek holds fish, but the fish-bearing stream length is not known.

Table 3. Hazard indices and interaction matrix scores for three classes of cumulative effects in the Carbondale Basin. Hazard indices, reported to the number of significant figures supported by the data, are interpreted as < 0.5, low; 0.5–0.7, moderate; > 0.7, high potential for watershed damage. Peak flow vs. surface erosion (interaction matrix) values can be interpreted as indicating very high potential for impact from the combined effects of increased peak flows and surface erosion (B.C. Forest Service 1995).

	Lynx Creek	Goat Creek	Lost Creek	North Lost Creek	South Lost Creek	Gardiner Creek	MacDonald Creek River	Residual Carbondale Basin	Total Carbondale
Peak flows	0.73	0.9	1.0	1.0	0.8	0.50	1.0	0.60	0.70
Surface erosion	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Riparian buffers	0.8	1.0	1.0	1.0	1.0	0.4	1.0	0.8	0.9
Peak flow vs. surface erosion	4	4	4	4	4	4	4	4	4

Discussion

Is the IWAP Applicable to the Carbondale Basin?

The climatic, pedological, geological and vegetational conditions of the Carbondale basin are sufficiently similar to the region for which the IWAP was developed to render it applicable to our study area as well. The IWAP model was developed for use in the B.C. interior, including the eastern slopes in northeastern B.C. and the western slopes of the Rocky Mountains immediately adjacent to the Carbondale basin. Based on similarities in climate, soils and vegetation, the Carbondale drainage is in the same ecological region as the Elk and Flathead drainages of B.C., the southern ecological region of the Canadian Rockies (Gadd 1995). There are some differences between the eastern and western parts of the region, but even greater differences are noted among the southern, central and northern regions of the western slopes. If the IWAP is generally applicable using these criteria to all of the western slopes of the Rockies, and the northern east slopes as well, it is applicable using these criteria to the Carbondale area as well.

Climate is expected to have the largest effect on the results of watershed analyses; that is why a somewhat different procedure has been developed for the rain-dominated watersheds of coastal B.C. (B.C. Forest Service 1995b). There is a substantial overlap in most climatological measures for the western slopes of the Rockies and for the Carbondale area (Table 4). Although the Castle weather station, representative of the Carbondale basin, is at a higher elevation than all but four of 37 stations on the Rocky Mountain west slopes (Gadd 1995), the Carbondale region falls well within the climatological range for which the IWAP procedure was designed. Annual precipitation and annual snowfall are relatively high in the Carbondale area, probably because most weather stations on the west side of the Rockies have been placed at lower elevations there. It is possible, however, that the strong chinook winds of the Carbondale basin may significantly modify the effects of the area's greater snowfall. The effect of chinooks on IWAP results should be considered in future modifications of the procedure for the Rocky Mountain eastern slopes.

Potential Effects on Channels, Riparian Zones and Fish Habitat

Increases in peak flows and surface erosion, and logging in the riparian zone can be expected to affect channel morphology, bank stability, riparian and aquatic ecosystem function, and fish habitat. In alluvial channels, such as those that predominate in the Carbondale basin, the physical effects are broadly predictable from basic principles of stream geomorphology, although the details are often highly complex and unpredictable (Schumm 1977; Rosgen 1978; Heede 1980; Gordon et al. 1992). In general, any change in the supply of water or sediment to alluvial channels can be expected to force the channel to adjust its bed or morphology to accommodate the change.

High values for the peak flow–surface erosion index indicate that there is a high probability of damage to stream channels from increases in peak flow and surface erosion. Higher peak flows will increase the erosive power of the stream and its ability to transport sediment, including suspended particles, bedload and large woody debris. Greater surface erosion contributes more sediment to channels. High riparian hazard potentials suggest that there is a high potential for bank erosion and, in the case of fish-bearing reaches, a high potential that erosion and/or loss of large woody debris, cover and shade will damage fish habitat. Logged streambanks are potentially more erodible, and slash is likely to be dumped in the channel during streamside logging operations (Chamberlin et al. 1991, Swanston 1991).

Results reasonably to be expected from increased peak flows in the alluvial channels of the Carbondale basin are flooding or bank erosion with consequent logjams and channel widening (Rosgen 1978; Heede 1980; Chamberlin et al. 1991). Reasonably expected results of increased surface erosion are in-channel sediment wedge and bar formation and channel infilling, causing streams to flood and erode their banks, creating further logjams (Heede 1980; Chamberlin et al. 1991; Swanston 1991; Gordon et al. 1992). Riparian logging might reasonably be expected to result in increased water temperatures,

Table 4. Number of Rocky Mountain west slope (interior B.C.) weather stations recording higher and lower values than the Castle weather station (Rocky Mountain east slope, Carbondale area) for selected climatological criteria. Tabulated from Environment Canada data summarized by Gadd (1995).

	Higher	Lower	Identical	No. of stations
Elevation, m	4	33	0	37
mean annual temperature	16	19	2	37
frost-free days	23	12	0	35
daily Jan. low temperature	22	15	0	37
daily Jul. high temperature	12	25	0	37
annual precipitation	4	33	0	37
annual snowfall	3	34	0	37
no. of days with rain	22	14	0	36
no. of days with snow	11	26	0	37

increased autotrophic production, short-term increases in fine particulate organic matter, eroded banks and logjam formation from slash left in the channel, with a later longterm reduction in large woody debris contributed to the channel (Chamberlin et al. 1991; Murphy and Meehan 1991). The cumulative result of increases in peak flow, surface erosion and riparian logging will depend on the relative increases in the peak flows and surface erosion, and for riparian logging, on the nature of the streambank soils and the quality of the logging operation (Chamberlin et al. 1991; Swanston 1991). Our analysis suggests that the potential for these kinds of damage is generally high, and often extreme, in the Carbondale basin.

The effects of such damage to the stream channels are likely to be generally unfavourable fish (Hicks et al. 1991). On the positive side, moderate increases in water temperature, autotrophic production and fine particulate organic matter might tend to improve fish abundance or growth in small streams (Murphy and Meehan 1991). Moderate short-term increases in large woody debris also temporarily increase cover for fish, and channel widening may increase shallow-water habitat for young-of-the-year and young juveniles.

These positive factors, however, are likely to be more than offset by many negative consequences. Bank erosion, channel widening and channel infilling reduce deepwater habitat required by late juveniles and adults, especially during the critical overwintering period. Bank erosion and longterm decreases in the supply of large woody debris reduce cover. Increased sedimentation of fine particles reduces the quality of spawning and incubation substrate and fills in interstitial cover for early juveniles (Leathe and Enk 1985). Finally, road crossings of streams, especially where culverts are used, can impede or block movements of fish, especially juveniles. Road crossings also play a role in directing eroded sediments into watercourses (Furniss et al. 1991).

These expected effects of increased peak flows, surface erosion and riparian logging in the Carbondale basin can now be used at least in a qualitative way to help determine whether the IWAP evaluations obtained for the watershed are realistic.

Are the IWAP Hazard Evaluations Realistic?

The hazard assessments in this study are, with few exceptions, consistent with independent observations of erosion, sediment deposition and channel changes previously reported in the Carbondale basin. In particular, the 1979 fish habitat surveys of Fitch (1980a–g) documented pervasive, widespread channel damage in the Carbondale River and its major tributaries that he attributed to logging and road effects. His observations will be discussed and compared to our independent assessment in downstream order, from headwaters to the mainstem, to reflect the direction of influence of watershed disturbance on the channels.

Gardiner Creek. Numerous fords on the road paralleling the creek contributed to sedimentation (Fitch 1980b). Clearcuts on the floodplain near the mouth created unstable streambanks and a wide and meandering channel. Some sections of the stream were damaged by flooding. Fitch (1980b) calculated that 23% of the banks of Gardiner Creek were unstable as a result of logging.

Our IWAP analysis for this sub-basin indicated a high potential for channel damage from surface erosion, and the combined effects of surface erosion and peak flows (Fig. 2, Table 3). It is therefore consistent with the previously observed sedimentation and flooding problems. In contrast, the IWAP hazard index for riparian buffers suggests a low potential for streambank damage, inconsistent with Fitch's observations of considerable streambank damage. We are uncertain of the reason for this inconsistency. It is possible that there has been sufficient recovery in this small basin since it was logged that older bankside cutting no longer affects the riparian buffer calculations. Field observations of current conditions could help to resolve the matter.

South Lost Creek. Logging had a major impact on this creek (Fitch 1980c). Clearcut banks, blowdown, poor road alignment, poor bridge placement and numerous trail crossings contributed to increased bank erosion, sedimentation and flooding. Logjams from logging and blowdown had created some good fish habitat, but increased bank erosion. Fully 30% of the banks of the stream were unstable as a result of logging.

The watershed assessment of this sub-basin in the present study indicated high to very high potential for channel and riparian damage from increased peak flows, surface erosion and bank instability (Fig. 2, Table 3). Many of the effects we would expect from such changes (see section of this paper entitled Potential Effects on Channels, Riparian Zones and Fish Habitat, above) were observed by Fitch (1980c).

North Lost Creek. This drainage basin was extensively logged with a major impact on the stream (Fitch 1980d). Bank erosion was increased along the stream by clearcuts, road alignment, bridge placement, trail crossings and logjams. Nineteen percent of the banks were unstable as a result of logging.

The present watershed analysis indicated a uniformly high potential for channel and riparian damage from increases in peak flows, surface erosion and streambank logging in this sub-basin (Fig. 2, Table 3). The bank damage observed by Fitch (1980d) is consistent with what could be predicted from these high indices (see section of this paper entitled Potential Effects on Channels, Riparian Zones and Fish Habitat, above).

Lost Creek. Fitch (1980e) drew attention to the influence of the logging haul road that paralleled the creek for most of its length. The road occupied the floodplain and sidehill cuts above the stream, and was a major source of sediment. In fact, 26% of the banks were unstable due to logging roads.

The high hazard values for increases in surface erosion in our watershed analysis of this sub-basin (Table 3) reflects in part the high near-stream road density in the basin (Fig. 2f), and is consistent with Fitch's (1980e) road sediment observations. On the other hand, this indicator does not precisely reflect the bank stability problems associated with roads encroaching on streambanks noted by Fitch (1980e), because it includes all roads within 100 m of the streambanks.

Goat Creek. Clearcuts extended to the edge of the banks near the headwaters, rendering them unstable (Fitch 1980f). Overall, 8% of the banks of the creek were unstable due to logging. Braided channels and unstable banks attributed to flood damage were found near the middle and at the mouth of Goat Creek (Fitch 1980f). More recently, Sheppard (1994) documented several instances of stream damage from logging and roads in the Goat Creek drainage. These included unculverted tributary crossings that diverted watercourses down roads—or cut through them—to deposit silt in Goat Creek; an undersized culvert crossing of Goat Creek that had washed out, depositing considerable silt in the creek; and blowdown depositing trees and silty rootwads in the creek from logging to the streambank.

The watershed analysis of Goat Creek basin in this study indicated high potential for damage from increased peak flows, surface erosion and riparian logging (Fig. 2, Table 3).The channel braiding and unstable banks reported by Fitch (1980f) are consistent with the channel infilling, flooding and bank instability expected from increases in sedimentation arising from increased surface erosion and peak flows, and from streamside logging (see section of this paper entitled Potential Effects on Channels, Riparian Zones and Fish Habitat, above).

*Lynx Creek:*Fitch (1980g) stated that extensive logging in the headwaters and tributaries has had a major influence on this stream. He noted that some sections of the creek have been rerouted to accommodate a road, and the road parallels the stream, in some areas encroaching onto the floodplain. Trout habitat below the Goat Creek confluence has deteriorated due to flooding. Overall in Lynx Creek, 22% of the banks were unstable as a result of logging.

In contrast, Pisces Environmental Services Ltd. (1992) took issue with Fitch's interpretation (1980g) that extensive logging in the headwaters of Lynx Creek has had a major influence on that stream. The company felt that in the absence of historical streamflow data it was not possible to determine if the flood damage to Lynx Creek is related to hydrological changes resulting from clearcut logging. Pisces (1992) further stated that there was little evidence of direct impacts of logging: the streambanks had been left intact adjacent to cutblocks, and the most evident effects are related to increased sediment and turbidity loads caused by surface runoff from roads. Pisces (1992) observed that, for approximately 3 km below Goat Creek, Lynx Creek is unconfined, exhibiting evidence of lateral instability and high bedload movement. Above the Goat Creek confluence, debris jams cause channel changes. Woody debris was abundant in a reach of dense, unlogged mature spruce, and was more common there than elsewhere in Lynx Creek. The company attributed the abundance of woody debris in the stream to logging.

Of concern to us in this study is the cumulative impact of cultural disturbance. In his study of the Lynx Creek watershed, Fitch (1980f,g) systematically collected quantitative data on bank stability along almost the entire length of Lynx Creek and most of its main tributary, Goat Creek, looking specifically for any obvious causes for it. His data convince us that streambank logging has been a significant factor creating bank instability in the basin. There appears to be agreement on the point of channel instability in Lynx Creek below the confluence of Goat Creek. Neither investigator attributed a cause to this, but it is at least not inconsistent with impacts to be expected from several of the logging-related disturbances quantified above (see section of this paper entitled Potential Effects on Channels, Riparian Zones and Fish Habitat, above). The abundant woody debris from logging in Lynx Creek, and of siltation from roads noted by Pisces (1992), are human disturbances primarily attributable to logging. Finally, Pisces (1992) reported that shallow-water habitats (riffles and runs) comprised 93 percent of the total autumn habitat of a 9.5-km reach of Lynx Creek, while less than one percent of the reach consisted of deep pools, runs and flats. These observations are evidence of channel aggradation and widening that is consistent with the effects to be expected from the logging and road development noted by Fitch (1980f,g; see section of this paper entitled Potential Effects on Channels, Riparian Zones and Fish Habitat, above).

Carbondale River: Fitch (1980a) noted that the percentage of sand-silt substrate increased below Lost and Lynx creeks. Overall, 9% of the banks of the Carbondale River mainstem were unstable as a result of logging.

As noted above, the results of the IWAP indicated high potential for damage from increased peak flows, surface erosion and riparian logging in all sub-basins of the Lynx and Lost Creek watersheds (Table 3). Deposition in the Carbondale mainstem of sediments eroded from upstream sites is a result reasonably to be expected (see section of this paper entitled Potential Effects on Channels, Riparian Zones and Fish Habitat, above); thus our watershed analysis is consistent with Fitch's (1980a) observation of an increased proportion of fines in the mainstem substrates below Lynx and Lost creeks.

In short, the IWAP hazard estimates calculated in this paper are consistent with the extensive channel damage in the Carbondale basin documented by Fitch (1980a–g) and others, and attributable primarily to roads and logging. This is perhaps not surprising, given the intensity and extent of human disturbance in the basin. The principal exception was the failure of the watershed analysis to predict the extensive damage to streambanks on Gardiner Creek previously observed by Fitch (1980b). Additional field observations are needed to resolve this issue.

Appropriate Management

This study provides several concrete examples of how the IWAP can be used to guide management in watersheds.

1. The IWAP document presents specific recommendations for action when hazard indices exceed certain values. In this study, the hazard indices were sufficiently high in various combinations that a more detailed Level 2 watershed analysis (B.C. Forest Service 1996) is recommended for all sub-basins and the Carbondale watershed as a whole (Table 3, cf. B.C. Forest Service 1995a). The Level 2 watershed analysis is a channel assessment involving field and office studies intended to estimate the actual level of channel disturbance associated with land-use practices in the subject basin. Where appropriate, the channel impact scores obtained from the Level 2 analysis are used in the interaction matrices to arrive at specific recommendations for management action, as in (2), below.
2. The IWAP document recommends specific management actions when risk assessments are moderate, high or very high as indicated by the interaction matrix scores. The interaction matrix of peak flow versus surface-erosion hazards for all sub-basins and the Carbondale basin as a whole had extreme risk values of 4 in this analysis. For catchments with interaction values of 4 in the peak flow–surface erosion matrix, B.C. Forest Service (1995) recommends the following responses:

   a. initiate an assessment of sediment sources;

   b. permanently deactivate as many roads as possible, consistent with access requirements;

   c. disallow additional roads in sensitive areas; and

   d. reduce the equivalent clearcut area over the entire watershed.

   Given the high peak flow–surface erosion interaction scores of our analysis (Table 3) and the independent observations of channel degradation previously documented by others in the Carbondale basin (Fitch 1980a–g; Pisces 1992; Sheppard 1994), immediate action on these recommendations is justified. Channel assessments conducted concurrently under (1), above should be used to guide this work. It is especially important for fish management that the amount of road be substantially reduced in this basin. The amount of road is the single most important disturbance measure in the IWAP, undoubtedly because roads have such profound effects on sediment and water delivery to channels, with correspondingly far-reaching impacts on fish habitat (Furniss et al. 1991; Waters 1995; Rieman and Clayton 1997). Several studies have related various measures of the amount of road directly to negative effects on fish and their habitats (Furniss et al. 1991 provide a review; see also Leathe and Enk 1985; Eaglin and Hubert 1993; Myers and Swanson 1995).
3. By using the GIS and IWAP as a simple analytical model together with cost estimates, it is possible

to estimate which combination of restoration approaches would provide maximum restoration (minimize IWAP impact indicators) at the least cost. Roadbeds can be satisfactorily decommissioned for perhaps $5000/km (Harr and Nichols 1993). If the entire 682-km road and seismic trail network of the Carbondale basin were to be restored to a more natural condition, the cost could conceivably be in the order of $3.4 million. If the work focused on selectively decommissioning only the most damaging roads and trails, the cost could be substantially reduced. Decommissioning all of the 288 km of roads and trails on erodible soils within 100 m of a watercourse, for example, would reduce the cost to perhaps $1.4 million.

4. Currently efforts are being made in the Carbondale basin to improve fish habitat with instream structures (Pisces 1992). This study suggests that such an approach is likely to fail, because the channel is not the problem; it simply displays the symptoms of widespread watershed degradation. The watershed analysis presented here strongly suggests that in-stream work will provide only short-term improvement at best. The delivery of water and sediment are major factors shaping the basin's mainly gravelbed channels, and these basin-wide factors have been fundamentally changed from the natural condition by past and current land-use. The results of this study imply that land-use patterns in the basin must be improved to improve fish habitat significantly in the long term.

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