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Human impacts to mountain streams

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Abstract

Mountain streams are here defined as channel networks within mountainous regions of the world. This definition encompasses tremendous diversity of physical and biological conditions, as well as history of land use. Human effects on mountain streams may result from activities undertaken within the stream channel that directly alter channel geometry, the dynamics of water and sediment movement, contaminants in the stream, or aquatic and riparian communities. Examples include channelization, construction of grade-control structures or check dams, removal of beavers, and placer mining. Human effects can also result from activities within the watershed that indirectly affect streams by altering the movement of water, sediment, and contaminants into the channel. Deforestation, cropping, grazing, land drainage, and urbanization are among the land uses that indirectly alter stream processes. An overview of the relative intensity of human impacts to mountain streams is provided by a table summarizing human effects on each of the major mountainous regions with respect to five categories: flow regulation, biotic integrity, water pollution, channel alteration, and land use. This table indicates that very few mountains have streams not at least moderately affected by land use. The least affected mountainous regions are those at very high or very low latitudes, although our scientific ignorance of conditions in low-latitude mountains in particular means that streams in these mountains might be more altered than is widely recognized. Four case studies from northern Sweden (arctic region), Colorado Front Range (semiarid temperate region), Swiss Alps (humid temperate region), and Papua New Guinea (humid tropics) are also used to explore in detail the history and effects on rivers of human activities in mountainous regions. The overview and case studies indicate that mountain streams must be managed with particular attention to upstream/downstream connections, hillslope/channel connections, process domains, physical and ecological roles of disturbance, and stream resilience.

Keywords: Mountain streams; Human impacts; Colorado; Switzerland; Papua New Guinea; Sweden

1. Overview

Mountain streams have been variously defined using physical characteristics such as average gradient (Jarrett, 1992; Wohl, 2000) or some combination of gradient, confinement, and substrate (Wohl and Merritt, 2005). For the purposes of this review, mountain streams will be simply defined as channel networks within mountainous regions of the world.

Every continent includes some mountainous regions, although mountainous areas are particularly prevalent in the western portions of North and South America, and in a belt extending across southern Europe and central and northern Asia (Fig. 1). Many of these mountain ranges have been occupied by humans for thousands of years, and, thus, have a long history of human effects on watershed processes. Examples of regions with long occupation histories include the European Alps and the Himalaya of Tibet, Nepal, and India. Other mountain ranges, such as the Brooks Range of Alaska or the ranges of northeastern Russia, have had minimal human

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occupation and are relatively unchanged by direct human activities. Even the most remote parts of Earth have of course been indirectly affected by humans through processes such as CO_2-induced atmospheric warming and airborne transport of contaminants including radioactive isotopes and organochlorine pesticides (Colburn et al., 1997; Pringle, 2003).

Human effects on mountain streams may result from activities undertaken within the stream channel that directly alter channel geometry, the dynamics of water and sediment movement, contaminants in the stream, or aquatic and riparian communities. Human effects can also result from activities within the watershed that indirectly affect streams by altering the movement of water, sediment, and contaminants into the channel. Table 1 provides a brief overview of activities that directly and indirectly affect mountain streams. Examples of these effects are discussed in more detail in the regional case studies below.

1.1. Relative impacts of human activities on mountain regions around the world

No single published source provides the information necessary to rank the relative effects of various human

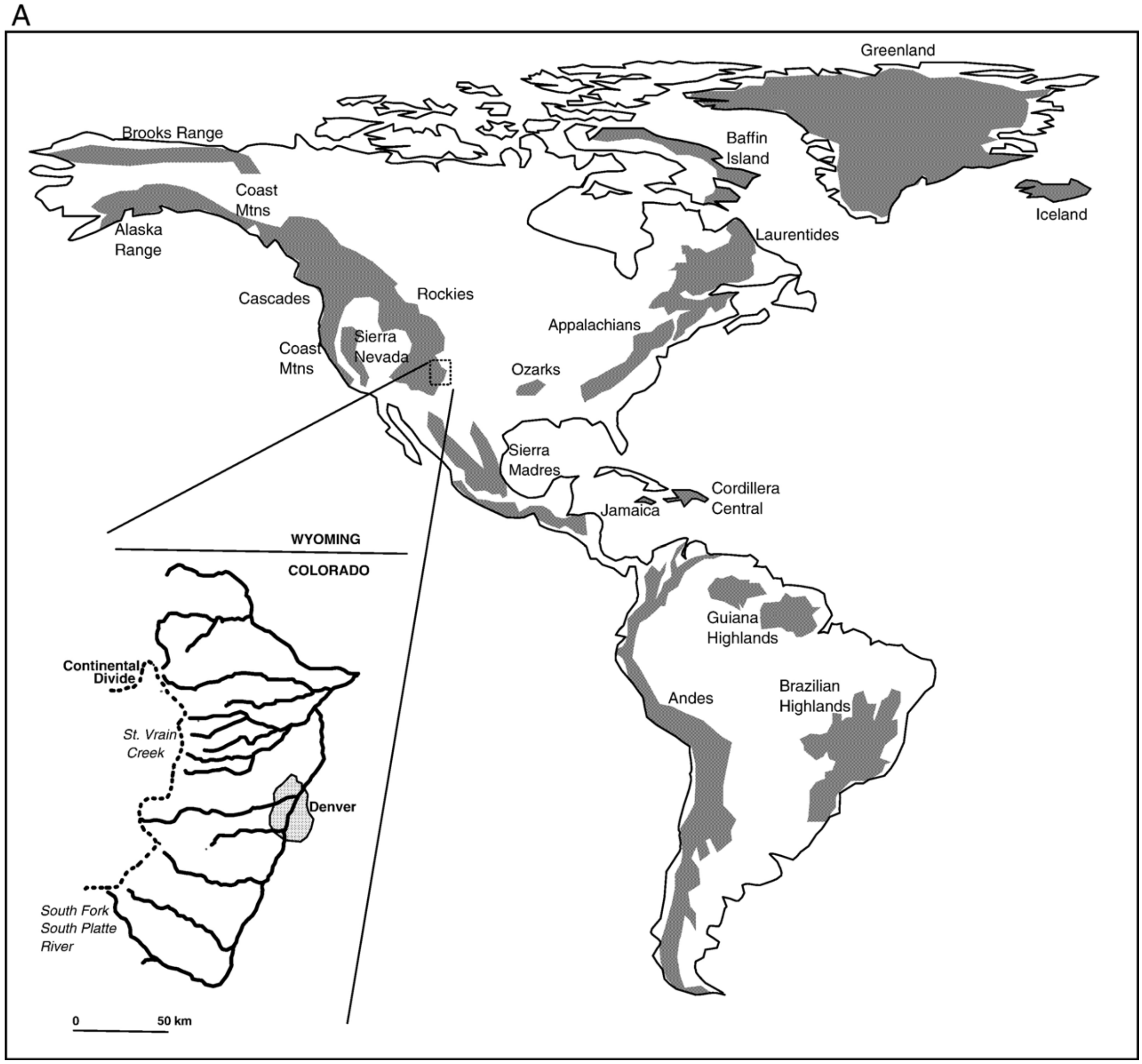

Fig. 1. Map showing mountainous areas of the world included in Table 2 and locations of four case studies shown by dashed boxes. The insert map on 1a shows the Colorado Front Range, which extends east from the Continental Divide to Denver.

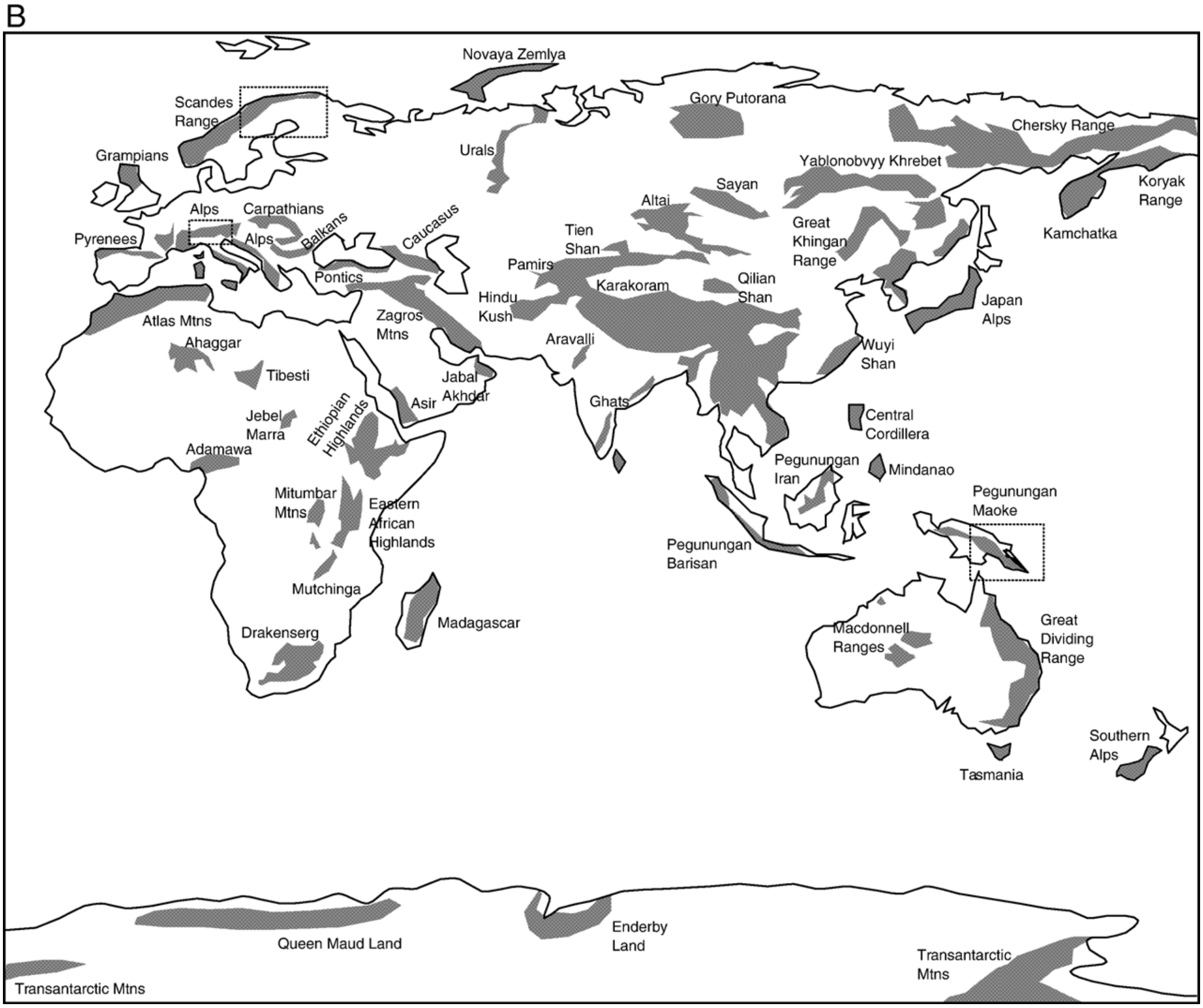

Fig. 1 (*continued*).

activities on mountain streams around the world. As a first approximation of such a ranking, several databases and numerous individual references were used to compile information on five types of human activities that affect mountain streams. Table 2 lists the relative ranking for each of these activities by mountainous region. The rankings in this table are conservative in that they are based primarily on studies in the peer-reviewed, English-language literature. Certainly mountainous regions altered by human activities exist that have not yet been documented by the scientific community.

Many of the cells in Table 2 include a range of numbers because of large spatial variability in impacts. A mountainous region with localized mineralization might have several streams within the mineralized zone that are heavily impacted by mining, deforestation, flow regulation, and urbanization, for example, whereas streams in other portions of the same mountains remain relatively pristine. For each category of human activity, the numerical ranking integrates a mix of spatial extent, duration, and intensity of effects on mountain streams. Regions are also ranked with respect to the amount of effect possible; for example, regulation of flow on streams in the U.S. Rocky Mountains is rated as severe because nearly every river draining an area greater than a few tens of square kilometers is either dammed or diverted. For the same region, biotic integrity receives a moderate rating because, although many native species are endangered and introduced exotic species have proliferated, relatively few native species have gone extinct and recovery of native species remains possible. Water pollution in the U.S. Rocky Mountains is rated 2–3 because limited segments of some streams are severely polluted by 19th century mining wastes or animal wastes associated with heavy riparian grazing, but water quality is generally good.

The first category, regulation of flow, includes reservoir storage; changes in the hydrograph associated with dams; interruption of upstream–downstream movement of water, sediment, nutrients, and organisms by dams; and off-channel diversion of flow. Individual investigators have compiled this type of information for specific large river basins (e.g. Dynesius and Nilsson, 1994; Nilsson et al., 2005b) or geographic regions (e.g.

Table 1
Types of land use activities that directly and indirectly alter mountain streams (list of sample references follows table)

Land use activity	Effects on mountain streams
Direct land use	
Regulation of flow[1] (dams, diversions)	Changes in: magnitude, frequency, duration, and seasonality of flows; stream temperature, dissolved oxygen, nutrients, and water chemistry; instream habitat availability, quality, and disturbance regime (magnitude/frequency/duration/seasonality of water and/or sediment movement within habitat); riparian disturbance regime (hydraulics and frequency of bankfull and overbank flows); sediment dynamics (entrainment, storage, and deposition) and substrate grain-size distribution; channel geometry
In-channel structures[2] (check dams, grade-control structures, culverts)	Creates segmented longitudinal profile; alters sediment dynamics; bed and bank stability; interrupts longitudinal movement of nutrients and aquatic organisms; alters passage of flood waves
Bank stabilization[3]	Changes in bank erodibility alter sediment dynamics, channel geometry, aquatic and riparian habitat
Placer and aggregate mining[4]	Increases sediment mobility; decreases bed and bank stability and alters channel geometry; degrades water quality (sediment and other contaminants); decreases instream and riparian habitat availability and quality, and alters disturbance regime
Trapping beaver[5]	Increases passage of flood waves and magnitude of hydraulic variables; reduces sediment storage and channel stability; reduces diversity of instream and riparian habitat and alters disturbance regime; results in channel incision
Channelization[6] (levees, wing dams, channel straightening)	Confines flow to central channel, and thus increases magnitude of hydraulic variables and peakedness of flood hydrograph; increases sediment transport and reduces bed and bank stability; reduces diversity and availability of instream and riparian habitat and alters disturbance regime
Log drives[7]	Usually associated with flow regulation and channelization activities; direct physical impacts of logs reduce bed and bank stability, increase sediment transport, degrade instream and riparian habitat
Recreation[8] (fishing, boating)	Fishing can eliminate native species and alter community composition; intense fishing and boating can alter bed and bank stability, sediment dynamics, and channel geometry
Introduced exotic species[9] (aquatic and riparian)	Exotic species can replace native species and change community composition; some species can alter physical properties of channel (e.g. exotic riparian vegetation increasing bank resistance, promoting sediment deposition and channel narrowing)
Riparian grazing[10]	Concentration of wild or domesticated grazing animals in the riparian zone reduces riparian vegetation and, together with animal trampling of banks, decreases bank stability and increases sediment yield to channel, resulting in aggradation, wider and shallower stream geometry, loss of aquatic and riparian habitat, and altered water chemistry (higher water temperatures, excess nitrogen)
Indirect land use	
Deforestation and agricultural land use[11]	Clearing of native vegetation and maintenance of croplands results in increased water and sediment yields to streams, which in turn changes sediment dynamics, bed and bank stability, channel geometry, and aquatic and riparian habitat
Lode mining[12]	Removal of subsurface materials and creation of tailings piles alters hillslope stability, resulting in increased sediment yield to streams; heavy metals and other contaminants of mining enter streams; associated deforestation, urbanization, and transportation corridors further affect streams
Transportation corridors[13] (railroads, roads)	Unpaved roads, traction sand and gravel used during winter on paved roads, cutslopes above and fillslopes below roads and railroads, and changes in surface and subsurface runoff and throughflow that increase mass movements all increase sediment yield to streams; contaminants from road surfaces enter streams in solution or adsorbed to fine sediment; transportation corridor can eliminate riparian corridor, constrict stream, or restrict lateral channel mobility in narrow valleys
Urbanization[14]	Initial phases of urbanization significantly increase sediment yield to streams, subsequent phases reduce sediment yield and increase water yield, resulting in more frequent flooding and more peaked flood hydrographs, bed and bank erosion, changes in channel geometry and aquatic and riparian habitat; contaminants from urban areas enter streams in solution and adsorbed to fine sediment
Altered fire regime[15]	Alteration can involve suppression of fires that results in less frequent, more intense fires, or increase in fire frequency associated with land clearing; in either case, fires increase water and sediment yield to streams, with resulting changes in sediment dynamics, stream geometry and stability, and aquatic and riparian habitat

Hirsch et al., 1990), but these compilations do not differentiate headwater or mountainous regions.

In many parts of the world, the flow of mountain streams is altered through storage, diversion, or generation of hydroelectric power. The case study from the Colorado Front Range illustrates how high-elevation regions that receive relatively abundant snowfall provide water supplies to adjacent regions at lower elevations that are often more arid in climate; this water supply is commonly regulated through diversions from stream channels into storage reservoirs and pipelines. The case study from the Swiss Alps illustrates the extensive regulation of flow in mountain streams associated with generating hydroelectric power for adjacent urban areas. Mountain streams typically have smaller channels than rivers lower in a given drainage basin. As a result, many of the hydroelectric dams and storage reservoirs located in mountainous areas are small relative to dams such as the Aswan in Egypt or the Three Gorges in China. Even a small dam, however, can thoroughly disrupt the flow regime of a small stream, and the cumulative effect of altering nearly every headwater channel in a drainage basin or a region has not yet been effectively assessed. Rankings for regulation of flow reflect primarily contemporary conditions because very few dams or flow diversion structures are being removed in mountainous regions, and because the direct physical effects of dams and diversions on the movement of water and sediments are less persistent than some of the other categories of human impacts once the structures are removed.

The second category in Table 2, biotic integrity, refers to aquatic and riparian communities. This category is based on the presence of non-native species; the percentage of at-risk native species; the presence and status of endemic species; and measures of "original" versus current biodiversity. Setting a standard for original biodiversity is difficult because biodiversity reflects dynamic and successional processes that produced continual fluctuations prior to human effects, and because most regions of the world have been at least minimally affected by humans for thousands of years. In this application, original biodiversity reflects the composition of aquatic and riparian communities prior to intensive regulation of flow, commercial fishing, channel alteration, and introduction of exotic species; depending on the mountain region, this equates to the early 19th or early 20th century. Much of the information necessary to rank the biotic integrity of mountain streams does not exist, even in regions such as the continental United States that have large research communities (Heinz Center, 2002). Global compilations of ecosystem types and status focus almost exclusively on terrestrial systems. The basic field research necessary to identify species present in streams has not yet been carried out in some mountain regions. In areas identified to have severe flow regulation, biotic integrity is assumed to be at least moderately compromised because regulation of flow decreases longitudinal connectivity for seed dispersal of riparian plants (Nilsson and Svedmark, 2002; Merritt and Wohl, 2006) and the ability of aquatic animals to migrate (Brooker, 1981), as well as reducing the diversity and availability of aquatic and riparian habitat (Stanford and Hauer, 1992; Ligon et al., 1995; Bunn and Arthington, 2002; Osmundson et al., 2002). Rankings for biotic integrity reflect contemporary and historical conditions in that, once an endemic species goes extinct or an exotic species is introduced, these changes are essentially permanent. Human-mediated introductions or extinctions of aquatic and riparian species in mountain streams have typically

Notes to Table 1

[1]Williams and Wolman (1985), Stanford and Hauer (1992), Ligon et al. (1995), Kattelmann (1996), Ryan (1996), Graf (1999, 2001), Surian (1999), Wohl (2001), Bunn and Arthington (2002), Nilsson and Svedmark (2002), Osmundson et al. (2002).

[2]Armanini et al. (1991), Willi (1991), Mizuyama (1993), Wohl (2000), Lenzi and Comiti (2003).

[3]Willi (1991), Liu (1992).

[4]Bjerklie and LaPerriere (1985), Wagener and LaPerriere (1985), Van Nieuwenhuyse and LaPerriere (1986), McLeay et al. (1987), Bencala et al. (1990), James (1991, 1999), Kondolf (1994, 1997), Gilvear et al. (1995), Hilmes and Wohl (1995), Wohl (2001).

[5]Naiman et al. (1988), Olson and Hubert (1994), Butler (1995), Butler and Malanson (1995), Wohl (2001).

[6]Ritter (1979), Habersack and Nachtnebel (1994), Wyzga (1996).

[7]Wohl (2001), Törnlund and Östlund (2002).

[8]Scott (1982), Wohl (2001), Bauer et al. (2002), Paul et al. (2003), Maynord (2005).

[9]Graf (1978), Thompson and Rahel (1998), Goodsell and Kats (1999), Adams et al. (2001), Peterson et al. (2004).

[10]Kauffman and Krueger (1984), Myers and Swanson (1992, 1996), Kondolf (1993), Trimble and Mendel (1995), Magilligan and McDowell (1997), Wohl (2001).

[11]Troendle and King (1987), Nik (1988), Luce and Black (1999), Fransen et al. (2001), Wemple et al. (2001), Liébault et al. (2002).

[12]Graf et al. (1991), Starnes and Gasper (1995), Miller et al. (1999), Stoughton and Marcus (2000), Hren et al. (2001), Marcus et al. (2001).

[13]Larsen and Parks (1997), Lorch (1998), Jones et al. (2000).

[14]Wolman (1967), Roberts (1989), Trimble (1997), Bledsoe and Watson (2001), Chin and Gregory (2001).

[15]MacDonald et al. (2000), May and Gresswell (2003), Pierce et al. (2004).

Table 2
Subjective rankings of human impacts to mountain streams based on review of available literature

Region	Regulation of flow	Biotic integrity	Water pollution	Channel alteration	Land use	Reference
Appalachians	2–3	2	2–3	1–2 (placer mining and tie drives in past; urbanization and roads today)	0.06; 1 (extensive deforestation and mining in past, locally extensive mining today)	Flow: Hirsch et al. (1990); Dynesius and Nilsson, 1994; biotic: Heinz Center (2002); pollution: USGS (1999); Wong et al. (2000); alteration: Bolgiano (1998); land use: Schnelling et al. (1992); Bolgiano (1998)
US Rockies	1	2	2–3	2 to 3 (extensive beaver trapping, wood removal, historically intensive placer mining, log drives)	0.00; 2–3 (locally intensive mining, extensive deforestation in past; continuing locally intensive mining, deforestation, grazing today)	Flow: Hirsch et al. (1990); Dynesius and Nilsson (1994); biotic: Heinz Center (2002); Friedman et al. (2005); pollution: USGS (1999); Wong et al. (2000); alteration: Wohl (2001); land use: Wohl (2001)
US coast ranges	Spatially variable; 1 (north) to 2 (south)	2	2–3	1–2 (extensive wood removal)	0.04; 2–3 (extensive deforestation in past and continuing)	Flow: Hirsch et al. (1990); Dynesius and Nilsson (1994); biotic: Heinz Center (2002); pollution: USGS (1999); Wong et al. (2000); alteration: Maser and Sedell (1994); land use: Jackson et al. (2001)
Canadian Rockies	Spatially variable; 3 (north) to 2 (south)	2	2–3	2–3 (beaver trapping, placer mining in past; placer mining, check dams, bank stabilization, channelization today)	0.00; 1–3 (local deforestation and mining, both in past and continuing)	Flow: Hirsch et al. (1990); Dynesius and Nilsson (1994); biotic: Schindler et al. (2001); Paul et al. (2003); channel alteration: Van Dine (1985); Doyle (1992); Pentz and Kostaschuk (1999)
Alaska coast ranges	3	2–3	2–3	3	0.00; 1–3 (locally intense mining and deforestation historically and at present)	Flow: Hirsch et al. (1990); Dynesius and Nilsson (1994); channel alteration: Milner et al. (1997); land use: Swainbank (2002)
Brooks Range	3	3	3	3	0.00; NA	Flow: Hirsch et al. (1990); Dynesius and Nilsson (1994)
Central Am. Cordillera	2	2	1–3	NA	NA; 1–3 (local mining, deforestation, and agriculture)	Flow: Stone and Manrique (2002); Anonymous (2003); biotic integrity: Young et al. (2001); pollution: Willerer et al. (2003): land use: Willerer et al. (2003)
Northern Andes	1–2	2	1–2	1–3 (local placer mining today)	0.03; 2 (variable levels of deforestation)	Flow: Rossinelli et al. (1994); biotic integrity: Junk and Soares (2001); Young et al. (2001); pollution: Herail and Guyot (1989); channel alteration; McMahon et al. (1999); land use: Allan et al. (2002)
Southern Andes	1	2	1–3	2	0.03; 1–3 (local deforestation, urbanization, commercial skiing)	Flow: Brinson and Malvarez (2002); biotic integrity: Young et al. (2001); pollution: Dittmar (2004); land use: Novillo (2002)
Brazilian Atlantic range	NA	2	NA	NA	0.08; NA	Biotic integrity: Junk and Soares (2001); Young et al. (2001)
Northeastern S America	NA	2	NA	NA	NA; 2–3 (some deforestation)	Biotic integrity: Junk and Soares (2001); Young et al. (2001); land use: Revenga et al. (1998)

Table 2 (*continued*)

Region	Regulation of flow	Biotic integrity	Water pollution	Channel alteration	Land use	Reference
Fennoscandia	1–3 (spatially variable)	2	2 (leaks from mine tailings dams; local urban pollution)	1 (log drives, beaver trapping in past; beaver trapping, levees, channelization today)	NA; 2 (extensive deforestation in past, now industrial forestry with short intervals between cutting)	Flow: Dynesius and Nilsson (1994); pollution: Borg et al. (1995); channel alteration: Törnlund and Östlund (2002)
Alps	1	1 to 2	1–2	1	0.05; 1–2 (deforestation, mining, agriculture in past, commercial skiing, agriculture, urbanization at present)	Flow: Baetzing and Messerli (1992); Dynesius and Nilsson (1994); biotic: Friedrich and Müller (1984); Bundi et al. (2000); Landolt et al. (2001); pollution: Tinker (1972); Vilanova et al. (2001); alteration: Baetzing and Messerli (1992); land use: Revenga et al. (1998)
Pyrenees	1–2	1–2	1–2	1 (check dams today)	NA; 1–2	Flow: Lopez-Moreno et al. (2002); biotic: Baran et al., 1995; pollution: Vilanova et al. (2001); channel alteration: Gutierrez et al. (1998); land use: Ives (1992)
Urals	2–3	NA	1–2	1–2 (placer mining today)	0.00; 1 (extensive mining)	Flow: Dynesius and Nilsson (1994); pollution: Standring et al. (2002); channel alteration: Maximovich and Blinov (1996); land use: Badenkov (1992)
Carpathians	1–3	NA	1–2	1–2 (channelization today)	NA; 1–2 (limited mining, extensive grazing and deforestation)	Flow: Dynesius and Nilsson (1994); pollution: Hudacek (1999); channel alteration: Wyzga (2001); land use: Kownacki (1982); Badenkov (1992)
N Middle East (Zagros, etc)	1	NA	NA	NA	0.02; NA	Flow: Sadeghian et al. (2003)
Caucasus	1–2	NA	2	NA	0.04; 2 (moderate mining)	Flow: Dynesius and Nilsson (1994); pollution: Kostyal et al. (1994); land use: Badenkov (1992)
Himalayas	3	2–3	2–3	NA	0.04; 1–2 (extensive deforestation, crops and grazing)	Biotic integrity: Singh and Sharma (1998); Manel et al. (2000); pollution: Khulbe and Durgapal (1994); Jenkins (2002); land use: Bandyopadhyay (1992)
Western Ghats (India)	1	2	NA	NA	NA; 1–2 (deforestation, urbanization, cropping, iron and manganese mining)	Flow: Aswathanarayana and Subrahmanyam (1992); land use: Anonymous (2004)
S Siberia	Mixed; 3 in the Altai	Mixed: 3 in the Altai	Mixed; 3 in the Altai	Mixed; 3 in the Altai	NA; 2 (locally intense mining, some deforestation)	Flow: Klubnikin et al. (2000); biotic: Klubnikin et al. (2000); pollution: Klubnikin et al. (2000); alteration: Klubnikin et al. (2000); land use: Badenkov (1992); Klubnikin et al. (2000)
E Siberia	1	NA	NA	NA	0.00; 1 (extensive mining)	Land use: Badenkov (1992)
Japan	3	1–2	2–3	1	NA; 2 (limited deforestation)	Biotic integrity: Maekawa

(continued on next page)

Table 2 (*continued*)

Region	Regulation of flow	Biotic integrity	Water pollution	Channel alteration	Land use	Reference
						and Nakagoshi (1997); Baxter et al. (2004); pollution: Nagafuchi et al. (2002); land use: Ives (1992)
New Guinea	3	2	2	3	NA; 2	Ives (1992), and references in case study
Indonesia	1–2	1–2	1–3	2	NA; 1–2 (contemporary deforestation and mining)	Flow: Anonymous (1993); Nakayama et al. (1999); biotic integrity: Brook et al. (2003); Iwata et al. (2003); pollution: Green et al. (1978); channel alteration: Anonymous (1982); land use: Revenga et al. (1998)
New Zealand	1	1	2–3	2	NA; 2 (extensive deforestation and mining in past, agriculture at present)	Flow: Carr and Fitzharris (1994); biotic: Read and Barmuta (1999); Harding (2003); Riley et al. (2003); Ling (2004); pollution: Winterbourn and Ryan (1994); land use: Harding (2003)
Australia	1–2	1	2–3	2	NA; 2 (moderate deforestation, local mining historically)	Flow: Crabb (1988); biotic: Arthington (1996); Read and Barmuta (1999); Waters et al. (2002); Arthington and Pusey (2003); land use: Revenga et al. (1998)
Atlas Mtns (Africa)	2 (moderate irrigated agriculture)	NA	NA	NA	NA; 2 (moderate deforestation and grazing)	Land use: Hurni et al. (1992)
Ethiopian highlands	2 (irrigated agriculture, some hydropower dams)	NA	NA	NA	0.03; 1 (extensive deforestation)	Flow: Mirjanic and Slokar (2002); land use: Hurni et al. (1992)
Drakensberg (S Africa)	1	3	2–3	NA	NA; 2 (moderate deforestation and grazing)	Flow: Furstenburg et al. (1997); biotic: Skelton et al. (1995); pollution: Grobbelaar and Stegmann (1987); land use: Hurni et al. (1992)
Gotel Mtns (w-c Af)	NA	NA	NA	NA	NA	
Ruwenzori Mts (Af)	NA	NA	NA	NA	NA; 2 (moderate deforestation and agriculture)	Land use: Hurni et al. (1992)

Categories are severe (1), moderate (2), and limited (3); NA indicates no information found in literature search. Examples of different levels of impact serverity are provided in the text. References listed are in many cases samples from an extensive literature. Population pressure figures are for the population circa 1990/area (millions people/thousands of sq km) from Denniston (1995).

ignored potential effects on the river ecosystem, as when alpine lakes are stocked with game fish. As a result, very few studies detail how past introductions and extinctions have altered the structure and composition of river ecosystems. More attention has been given to changes in stream ecosystems associated with changes to flow regime and habitat, or to water quality.

The third category in Table 2, water pollution, includes organic (human and animal) wastes, nutrients (N and P fertilizers), organochlorine compounds, and heavy metals. These forms of water pollution are based on the National Water-Quality Assessment (NAWQA) program, begun in 1991 by the U.S. Geological Survey, which provides a comprehensive, standardized database of water-quality conditions across the United States (e.g. USGS, 1999; Wong et al., 2000). The mountain streams sampled as part of NAWQA generally have high quality water with relatively little pollution, but the U.S. mountainous regions listed in Table 2 are given moderate ratings because of local sources of contamination from

19th- and 20th-century mining, heavy riparian grazing, commercial skiing, and/or limited urbanization. Sources of non-organic contamination can persist for centuries after the associated land use activity ceases, as in examples of 19th-century placer mining sites with persistent mercury contamination of sediments (Alpers and Hunerlach, 2000; Wohl, 2004), so ratings of water pollution also include a historical component. As with biotic integrity, the field data necessary to assess water pollution do not exist for many mountainous regions of the world.

The fourth category, alteration of channels, includes in-channel structures (check dams, grade-control structures, bank stabilization and culverts), channelization, levees, removal of beavers, log drives, and placer mining and aggregate mining. Channel alteration can occur in sparsely populated areas where natural resources such as beaver furs or timber are being extracted, but alteration is generally most widespread and intensive in areas where floods and/or mass movements along mountain streams are perceived as creating risk for human communities. Countries with high population pressure and limited arable land, such as Japan or Switzerland, exemplify severe alteration of channels. This category has a stronger historical component than many of the other categories in that effects from alteration of channels commonly continue for more than a century after active alteration ceases. Channel geometry and riparian communities in the central Rocky Mountains still reflect alterations associated with log drives that occurred a century ago (Young et al., 1994), for example.

The final category, land use, incorporates land drainage, vegetation changes (timber harvest, grazing, crops), urbanization, lode or strip mining, and road and railroad construction. Each of these activities can alter the magnitude, timing, duration, and quality of water and sediment moving from adjacent uplands into channel networks. At the extreme, such alterations can completely obliterate mountain streams, as in the case of "mountaintop removal" in West Virginia, in which immense quantities of soil and rock removed during coal mining are simply dumped into the nearest small drainage, completely filling that drainage (Peng, 2000). Archeological and sedimentological records indicate that the start of agriculture in a mountainous region is generally accompanied by substantial changes in water and sediment yield to streams. These effects are time transgressive around the world, having occurred thousands of years ago in regions such as the Mediterranean (Davidson, 1980) and Asia (Mei-e and Xianmo, 1994), hundreds of years ago in central Europe (Butzer, 1980), and within the past few decades elsewhere (Clark and Wilcock, 2000).

Many land use activities occur nearly simultaneously in a region, producing greater cumulative effects than would result from any single activity. Timber harvest usually precedes agriculture, and can be accompanied by land drainage, construction of transportation corridors, and local urbanization, as in the case of Switzerland discussed below. Likewise, lode mining promotes timber harvest, transportation corridors, and urbanization, as illustrated by the case study from the Colorado Front Range. Land use rankings in Table 2 reflect extent and intensity of these multiple activities, as well as subsequent recovery of original conditions. In the Front Range, for example, deforestation starting in 1859 was severe and widespread, with very few stands of forest left by 1900. Although much of the pre-1859 forest cover has now regrown in the Front Range, forest ecology has been altered as younger trees replace the diversity of species and stand ages originally present (Veblen and Lorenz, 1991). Changes in land use are the most ubiquitous impact to mountain streams around the world. Even mountainous regions without regulation of flow or direct alteration of channels are likely to have a history of at least localized changes in vegetation associated with clearing forests, planting crops, and grazing domestic animals.

2. Case studies

The case studies presented in this section are chosen to illustrate the diversity of human effects on mountain streams in relation to climate and regional socioeconomic history, and are arranged from high latitude to low latitude. Northern Sweden represents high-latitude regions of industrialized countries, the Colorado Front Range represents mid-latitude arid and semiarid regions of industrialized nations, the Swiss Alps represent mid-latitude temperate regions of industrialized countries, and Papua New Guinea represents the humid tropics in developing countries.

2.1. Mountain streams of northern Sweden

The Scandes mountain chain trends northeast–southwest along the border between Sweden and Norway. The distance from the range crest to the ocean is greatest on the Swedish side, where a dozen roughly parallel drainages run from the mountains down into the Gulf of Bothnia. Rivers at the northern end lie mostly above the Arctic Circle; those at the southern end enter the ocean at 60° N. The region does not have large topographic relief; elevations range from 2100 m to sea level over a distance of approximately 300 km. But the rivers have many steep rapids (Fig. 2) interspersed with

Fig. 2. Upstream view of Storfosen rapids on the Pite River, northern Sweden, August 2004.

lower-gradient segments, and substrate is dominated by the bedrock and coarse clasts characteristic of mountain streams.

Mean annual precipitation across the region is 50–100 cm, much of which falls as snow. The northern rivers have low winter flows with rapid snowmelt and intense flooding in spring–early summer (Nilsson, 1999). Rivers draining the central eastern coast have less intense spring floods, and rivers in the far south have more even discharge throughout the year (Nilsson, 1999). All of the rivers flow across the Precambrian shield, which is dominated by crystalline rocks. Granite and gneiss are the most widespread lithologies, but basic volcanics, gabbro, diorite, and other lithologies are locally present (SGU, 1958).

Glacial erosional forms that influence contemporary river morphology include asymmetrical valleys such as that of the Angermanälven, where the lee-side (in relation to predominant ice movement) valley wall is comparatively steep (Rudberg, 1984). As the glaciers retreated and crustal rebound created down-valley retreat of the coastline and the river mouth, temporary deltas were built, and then dissected at several points along the course of each river. Rivers incising into post-glacial sediments commonly meandered, creating complex landscapes of abandoned meander bends and terraces (Rudberg, 1984). Along substantial portions of the lengths these rivers incised through the sediment cover to the underlying bedrock surface, and bedrock is continuously exposed in contemporary channels along segments hundreds to thousands of km in length.

Processes associated with glacial advance and retreat dominate the topography of river basins across Fennoscandia. Models of regional Pleistocene glaciation postulate a maximum ice thickness of 2000 m over northern Finland and the Gulf of Bothnia (Lambeck et al., 1998). Deglaciation began circa 12,500 yr BP in southern Sweden. As the crust rebounded from the weight of glacial ice, relative sea level fell rapidly until circa 9000 yr BP, and then fell at a lower rate. The maximum land uplift relative to the geoid during the past century is 10.2 mm/yr (Ekman and Mäkinen, 1996), although uplift rates directly measured during the past 2–3 years exceed this value in northern Sweden (Scherneck et al., 1998). The rate of contemporary land uplift drops to about 1 mm/yr in southern Sweden (Ekman and Mäkinen, 1996). Eustatic sea level has increased at an average rate of 0.5 mm/yr during the past 6000 years, for a total increase of 3 m, but this effect is dwarfed by relative sea level fall associated with crustal rebound (Lambeck et al., 1998).

Mountain streams in arctic and alpine environments of northwestern Sweden have the lowest numbers of benthic macroinvertebrate taxa found in a national survey, but taxon richness increases downstream (Sandin, 2003). Swedish streams have low fish diversity and the fauna is dominated by a few species (Degerman and Sers, 1992). Brown trout (*Salmo trutta*) are by far the dominant species, although European minnow (*Phoxinus phoxinus*), burbot (*Lota lota*), northern pike (*Esox lucius*), and bullhead (*Cotus gobio*) are also fairly common. Headwater streams generally contain Arctic char (*Salvelinus alpinus*) and brown trout.

Swedish riparian ecologists distinguish turbulent and tranquil segments of rivers. Rapids formed on bedrock or boulders constitute the turbulent segments. Aquatic vascular plants are very limited along these segments, and riparian vegetation is open but can be very species-dense. Tranquil segments have much finer substrate, with local deposits of silt and clay among the predominantly sand- to cobble-sized substrate. Aquatic vascular plants are present, although not abundant, and long stretches of continuous riparian vegetation zoned as a result of water-level fluctuations include a range of plant types from lichens and bryophytes through woody species of *Alnus*, *Betula*, *Salix*, and *Pinus* (alder, birch, willow, pine). The distributions of riparian species also reflects hydrochory, the dispersal of plant propagules by water (Nilsson et al., 1991a; Johansson et al., 1996). The diversity of plant species is greatest along the middle portions of the rivers where they pass the former high coastline and change from coarse, morainic, stable substrate to finer, easily eroded, less stable substrate (Nilsson et al., 1989). The higher diversity probably reflects an intermediate disturbance regime, maximum habitat heterogeneity, and colonization by plant species up- and downstream from the former highest coastline (Nilsson et al., 1991b).

Human effects on Swedish rivers are associated primarily with floating of logs and regulation of flow, although diversions, species introductions, deforestation, and pollution, including acidification, have also affected

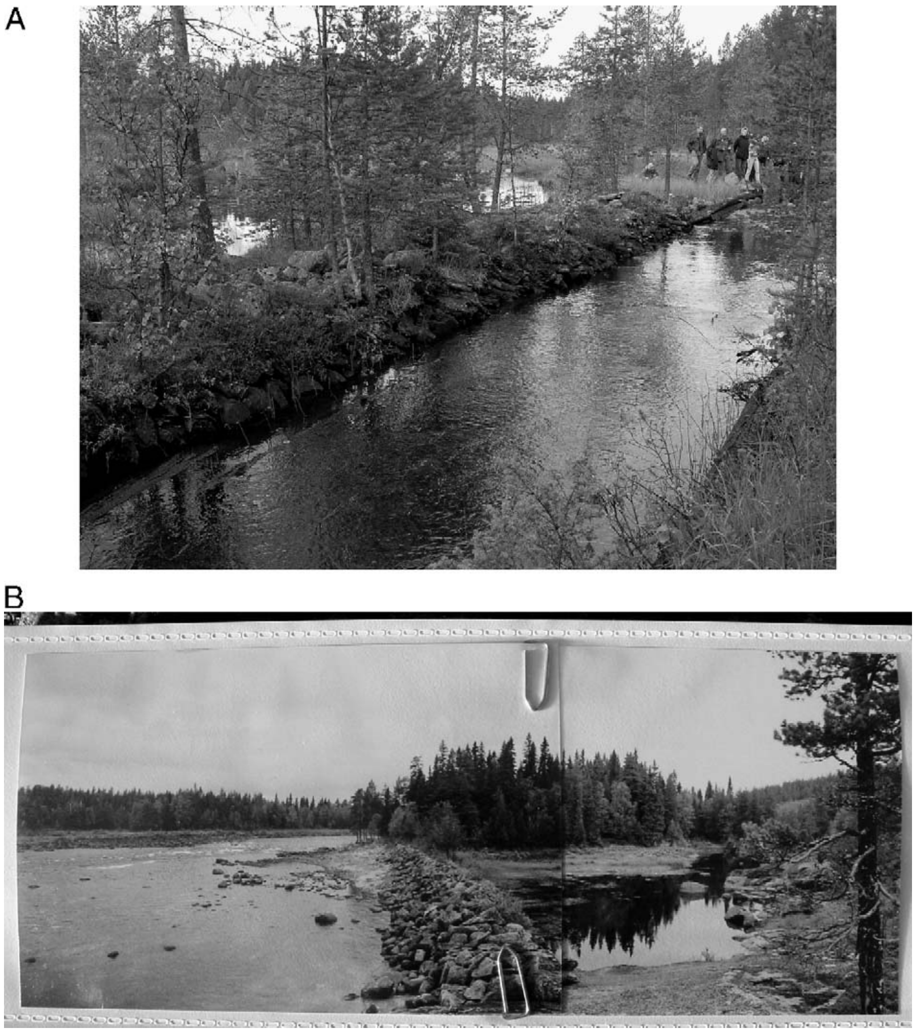

Fig. 3. (A) Modification to a small stream to promote log floating. This portion of the stream flows through a low-gradient wetlands (background left), but the stream has been channelized with riprap and wood, and isolated from the adjacent wetlands, August 2004. (B) Upstream view of structure blocking connection between main channel and secondary channel along Vindel River, northern Sweden, 2002. (This photograph is of two snapshots clipped together to provide a panoramic view of the channel section, courtesy of Christer Nilsson.) (C) View of left-half of the same reach along the Vindel River in October 2003, following removal of log-floating structure.

C

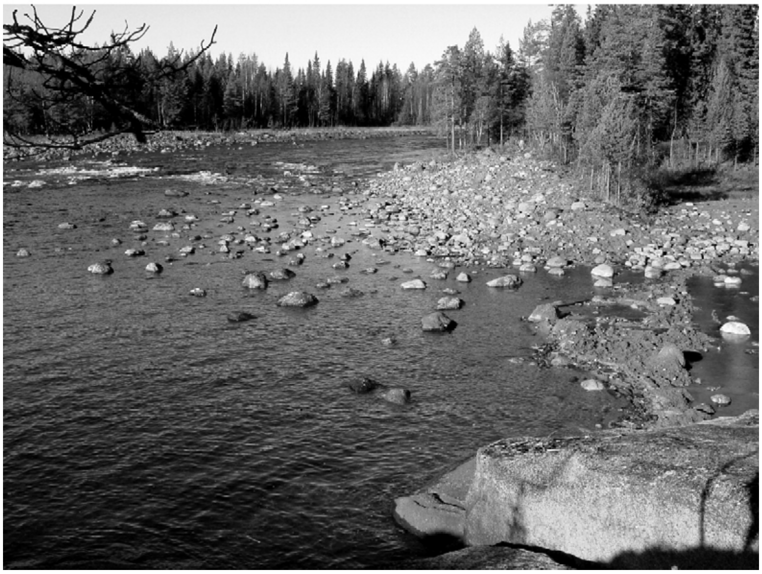

Fig. 3 (*continued*).

the rivers (Nilsson, 1999). Land drainage has also affected hydrology and aquatic habitat. The water table of about 2500 lakes was lowered to produce farmland, and more than 600 lakes were completely drained before lake drainage was halted at the end of the 1950s (Svensson, 2000). Ditching across wetlands, and dredging and channelization of rivers continue today.

Rivers from major channels to small tributaries were used to float cut timber downstream to collection points from the first decades of the 19th century until the 1970s (Törnlund and Östlund, 2002). The length of floatways grew, rapidly during the latter 19th century, from 1000 km in 1860 to nearly 20,000 km in 1890, and more than 30,000 km by the early 1900s. Modifications to rivers used for floatways, designed to facilitate downstream passage and avoid logjams, included splash dams, off-channel flumes, stone levees that blocked off overbank areas and secondary channels (Fig. 3), reinforcement of banks with stone piers and wing dams, and dredging, blasting, and removal of naturally occurring bedrock knobs and large boulders in rapids. These modifications substantially reduced habitat diversity and terrestrial-aquatic interactions, as well as increasing average velocity of flows and the erosion of gravel and finer sediments from the streambed (Nilsson et al., 2005a).

Streams modified for floatways lost riparian vegetation through direct cutting and through loss of suitable germination sites as channelized streams became incapable of lateral movement. Higher velocities and coarse substrate also reduced aquatic plants in streams modified for floatways. Decreased retentive capacity for allochthonous detritus adversely affected macroinvertebrate communities in these streams, and loss of spawning and rearing habitat contributed to declining numbers of fish (Nilsson et al., 2005a).

The majority of Swedish rivers are now regulated, following a period of intense hydroelectric development from the 1950s to 1970s (Nilsson, 1999). The 5290 dams present throughout the country range from the 125-m high Trängslet dam on the upper Dal River through smaller, run-of-river impoundments. Less than 200 large hydroelectric dams and less than 1000 smaller hydroelectric dams are present. Even the run-of-river impoundments are used for the generation of hydroelectric power, however, and create 24-hour cycles of up to 1-m variability in stage. Several storage reservoirs experience 20–35-m fluctuations in water level. Annual flood peak has been reduced on most rivers. The most common longitudinal pattern is now a series of reservoirs with low-gradient river segments between; rapids are largely submerged, and dry channels are present in former bedrock anastomosing segments associated with rapids and falls. Comparison of regulated and free-flowing boreal rivers indicates that although the total species richness of vascular plants in the riparian zone is similar, many plant populations are locally extinct along the regulated rivers, and the remaining small, isolated populations are at increased risk of complete extinction (Nilsson and Jansson, 1995). These changes result from reduced hydrochory and altered magnitude, duration, and timing of water-level fluctuations along the margins of regulated rivers (Jansson et al., 2000).

Salmon spawned in 60–70 rivers in the Baltic region at the end of the 19th century (Eriksson and Eriksson, 1993). Many of the large salmon rivers were dammed from 1940 onwards, mostly below the lowest spawning rapids for salmon. The inundation of almost all mainstem spawning habitat for migratory brown trout (*S. trutta*) and Atlantic salmon (*Salmo salar*) in the regulated rivers required artificial rearing of these species in hatcheries, with release of smolts at river mouths (Svensson, 2000). High survival rates of stocked fish indicate that the annual release of approximately 3 million smolts is successful, but natural spawning runs are weak on the 20 remaining suitable rivers in the Baltic region (Eriksson and Eriksson, 1993). Although water quality is generally good in Sweden compared to other industrialized nations, rivers contaminated with PCBs from industry, such as paper mills, result in the concentration of PCBs in the flesh of fish (Bremle et al., 1995).

Regulation of flow has affected many other species that use river corridors (Nilsson and Dynesius, 1994). Eurasian beaver (*Castor fiber*) require stable water levels during winter, and many beaver living along reservoirs have died as a result of the fluctuations in water-level. Areas of open water provide important resting areas for migrant birds during spring, and the flooding of rapids that now lie beneath ice during spring has reduced habitat for these migrant birds, as well as for resident birds such as the dipper (*Cinclus cinclus*) and fishing animals such as European otter (*Lutra lutra*). The frequency of ice fog during winter increases downstream from power plants, leading to hoar frost and rime ice on forage plants needed by species as diverse as black grouse (*Tetrao tetrix*) and moose (*Alces alces*).

The intensity and extent of new human impacts to Swedish streams are decreasing, even as efforts are underway to restore streams by removing 19th-century log-floating modifications. Although removal of these structures is expensive and labor intensive, Swedish streams not contaminated by toxins such as PCBs have a high restoration potential if the operation of dams can be modified to restore some of the natural flow regime. Swedish ecologists hypothesize that restoration measures currently being undertaken will increase channel width, sinuosity, and bed roughness, and thereby improve terrestrial–aquatic exchanges and the retention of water, sediment, organic matter, and nutrients (Nilsson et al., 2005a). The components of the historical river system most difficult to restore at present are the flow regime and large roughness elements, such as very large boulders and wood. Public awareness of human-induced changes to mountain streams, and support for restoration measures, is increasing in Sweden, but has not yet reached the level of removing dams or modifying the operation of dams.

2.2. Mountain streams of the Colorado Front Range

The Front Range forms the eastern-most part of the Colorado Rocky Mountains and is drained by streams of the upper South Platte River basin. More than ten streams heading close to 4300 m elevation along the Continental Divide flow east toward the base of the range at 1520 m elevation, joining beyond the mountain front to form the South Platte River. The history of land use changes and associated changes in mountain streams of this region is representative of many mountainous regions in North America (Wohl, 2001). Mountains in North American were sites of fur trapping, deforestation, mining, construction of riverine (e.g. floating of logs) and terrestrial (e.g. railroads) transportation corridors, and introduction of exotic fish species, primarily during the 19th and 20th centuries, and 20th century urbanization. Mountain streams in semiarid and arid regions are also heavily affected by the regulation of flow.

Front Range streams are underlain predominantly by crystalline igneous and metamorphic rocks, and streams commonly flow in bedrock canyons with only a thin veneer of cobble–boulder alluvium on the streambed. Pleistocene glaciation affected the upper third of major drainages. Climate, vegetation, and flow regime vary strongly with elevation. Mean annual precipitation drops from approximately 100 cm at the highest elevations to 36 cm along the base of the range. Alpine vegetation in the headwaters gives way downstream to subalpine spruce–fir forest, montane pine forest, and eventually steppe vegetation.

The major streams are perennial, with a snowmelt peak in late spring and early summer. Convective storms also generate summer rainfall that produces infrequent flash floods below approximately 2300 m elevation. These rainfall floods can generate a peak discharge as much as forty times the size of snowmelt flood peaks (Jarrett, 1989). Only these floods have sufficient stream power to mobilize the coarse surface streambed and to substantially reconfigure channel and valley-bottom morphology. Flooding can also be exacerbated by a hillslope disturbance, such as a forest fire, that introduces large quantities of sediment into the river. The rivers are normally stable, with relatively low sediment loads, but they periodically exhibit dramatic response to disturbance from floods and hillslope instability.

Organisms adapted to cold, oxygenated water, coarse stream substrates, and turbulent flow are most common in the Front Range streams. Macroinvertebrate abundance and species richness are low in the headwater reaches, and increase from the montane zone down to the foothills as a result of increasing water temperature and habitat diversity (Ward, 1992). Fish diversity also increases downstream. Salmonids include native greenback cutthroat trout (*Oncorhynchus clarkia stomias*) in the highest elevation stream segments, and nonnative brook trout (*Salvelinus fontinalis*), rainbow trout (*Salmo gairdneri*) and brown trout (*S. trutta*) in the middle and lower stream segments (Campbell et al., 1984; Raleigh et al., 1986).

People have lived in the Colorado Front Range for at least 12,000 years (Eighmy, 1984; Grant, 1988; Benedict, 1992), but no evidence exists that population densities or land-use patterns produced changes in the rivers of the region until the middle decades of the 19th century. Once people of European descent began to settle the region, numerous types of land use swiftly became widespread and substantially altered hillslopes and stream channels.

Fur trapping removed most beavers in the Front Range by the early 1840s. Beavers exert a strong influence on water and sediment movement along a river by building low dams of woody debris (Naiman et al., 1986, 1988). These dams create ponds that act as sediment traps, gradually filling to create swamp or meadow environments. The ponds and meadows also slow the passage of flood waves and reduce associated channel erosion. The stepped profiles of beaver-influenced rivers, with narrow, deep, sinuous reaches above the ponds and shallower reaches of swifter flow below the ponds, maximize the diversity of riparian and aquatic habitats (Fig. 4).

Between 1810 and 1860, tens of millions of beavers were trapped along rivers in the western U.S. Once fur trappers discovered an area, the majority of the beavers were usually trapped within a few decades (Olson and Hubert, 1994). With the removal of beavers, the beaver dams were breached, and some of the rivers probably rapidly incised to become gullies. Incised channels have larger, more flashy, floods; increased sediment yield from unstable and eroding streambed and banks; and less diverse habitat (Brayton, 1984; Maret et al., 1987).

We can infer river response to 19th-century trapping from modern analogs. Contemporary studies indicate that flow downstream from beaver ponds contains 50–75% fewer suspended solids than that of equivalent stream reaches without these ponds (Parker, 1986). When beavers were reestablished along Currant Creek, Wyoming, during the 1980s, daily sediment transport decreased from 30 to 4 metric tons (Brayton, 1984). Downstream channel slope decreased, as did bank erosion during spring high flows, which was the main source of sediment to the river.

The net effect of the removal of beaver along rivers in the Front Range was probably a reduction in diversity and stability as channels incised, flood peaks and sediment transport increased, and riparian and slow-velocity habitats were lost. The channel changes caused by removal of beaver, however, were probably much less substantial than those associated with changes in regional land use that began with wide-scale mining during the 1860s.

Fig. 4. Upstream view of river where multiple beaver ponds create stepped longitudinal profile and habitat diversity, Rocky Mountain National Park, Colorado, July 1995.

Placer metals, such as gold and silver, were removed from streambed sediments throughout the Colorado mountains from 1859 into the early 20th century using either hydraulic systems or dredge boats. Two people operating a hydraulic system can process 2–4 m^3 of sediment in 10 h. A dredge boat can process 6000–6600 m^3 of sediment during 10 h (Silva, 1986) (Fig. 5). The usual practice in either hydraulic or dredge boat mining was to remove and process the streambed sediment down to the bedrock contact and back to the valley side slopes.

The effects of placer mining on river form and function are threefold. First, the disruption of bed and bank sediment renders the sediment more susceptible to being moved by flow in the river. This can cause downcutting of the river at the location of the mining (Graf, 1979), or change a meandering river to a braided river (Hilmes and Wohl, 1995). Smaller sediments are preferentially mobilized from the disturbed area and accumulate downstream. Downstream accumulation can reduce the river capacity and cause enhanced flooding. Water quality is degraded by the increase in suspended sediment, further degrading aquatic habitat for a variety of species (Wagener and LaPerriere, 1985; Van Nieuwenhuyse and LaPerriere, 1986). The remaining coarse lag can be too large to provide spawning gravels for fish, whereas the finer sediment carried downstream can preferentially fill pools and cover downstream spawning gravels. The river at the mining site remains less stable for decades after mining has ceased because the fine-grained bank sediment that formerly supported stabilizing riparian vegetation is now gone (Hilmes and Wohl, 1995). Placer mining along the mountainous headwaters of Clear Creek, Colorado, produced so much excess mobile sediment that an 1894 photograph taken from a balloon clearly shows sediment deposition along the creek well beyond the mountain front. This sediment in turn caused problems for newly built irrigation intake structures along the downstream portion of Clear Creek flowing through the Great Plains.

Second, toxic materials, such as heavy metals or mercury, used during mining are introduced to the stream and valley-bottom sediments. These materials are very persistent in the environment, as shown by the contemporary correlation between 19th century mining sites and 20th century Superfund sites (EPA, 1994). The most general effect of any pollutant is to reduce community diversity within and along a river (Mackenthun and Ingram, 1966). Toxic materials interfere with the respiratory, growth, and reproductive functions of members of the entire river food web. The toxic materials are “time bombs” because initial introduction is followed by processes of bioaccumulation and biomagnification over a period of years to decades. The toxins may be adsorbed onto clay or silt particles, lie buried in a sediment deposit, and then be remobilized decades later by streambed erosion or lateral channel shifting during a flood (Graf et al., 1991).

Third, placer mining indirectly affects rivers by altering the amounts of water and sediment entering the rivers. These alterations usually result primarily from destabilization of the valley slopes as a result of timber harvest associated with settlement of the region. During 19th century mining in the Front Range, lumber was

Fig. 5. A 1995 view of tailings piles left from dredge-operations during the 1950s, Middle Fork of the South Platte River near Fairplay, Colorado.

needed for sluices, flumes, stamp mills, mine timbers for lode mines, houses and other buildings, cooking and heating, and the fires that drove steam-operated stamp mills and smelters. After Congress passed the Free Timber Act of 1878 to protect forests by prohibiting the cutting of live trees on the public domain for commercial purposes, mining communities reacted by setting forest fires to create standing charcoal and dead trees that could then be legally harvested. Placer mining also redistributed sediment in valley bottoms, often removing lateral support at the base of hillslopes. Construction of roads, railroads and buildings along hillslopes compacted slope surfaces and increased the weight over portions of the slopes, further destabilizing slopes and increasing sediment yield to rivers. Widespread deforestation and slope instability caused an increase in debris flows and landslides that was noted by contemporary observers (Clark, 1861; Tice, 1872).

As with beaver trapping, the net effect of placer mining and associated activities in the Colorado Front Range was to reduce river diversity and stability. The contemporary activities of floating railroad ties to collection booms, regulating and diverting streamflow, and constructing transportation corridors further impacted rivers (see Table 1). These activities affected almost every stream in the Front Range, and effectively overwhelmed the channel alterations associated with beaver trapping. Subsequent, primarily 20th-century land uses include urbanization in the mountains, increased recreational fishing and whitewater rafting, increased diversions arising from water demands associated with urbanization in the adjacent plains, and climatic change, as well as localized riparian grazing (Wohl, 2001).

Every stream in the Colorado Front Range was affected by at least one of the land-use activities summarized above. A few streams were primarily affected by trapping beaver, but most stream segments were altered by the combined effects of trapping beaver, regulation of flow, construction of transportation corridors, and associated recreation and urbanization. In the absence of detailed historical records pre-dating the start of trapping beaver, the characteristics of the stream prior to the 19th century cannot be known with certainty or precisely quantified. Reference conditions can be

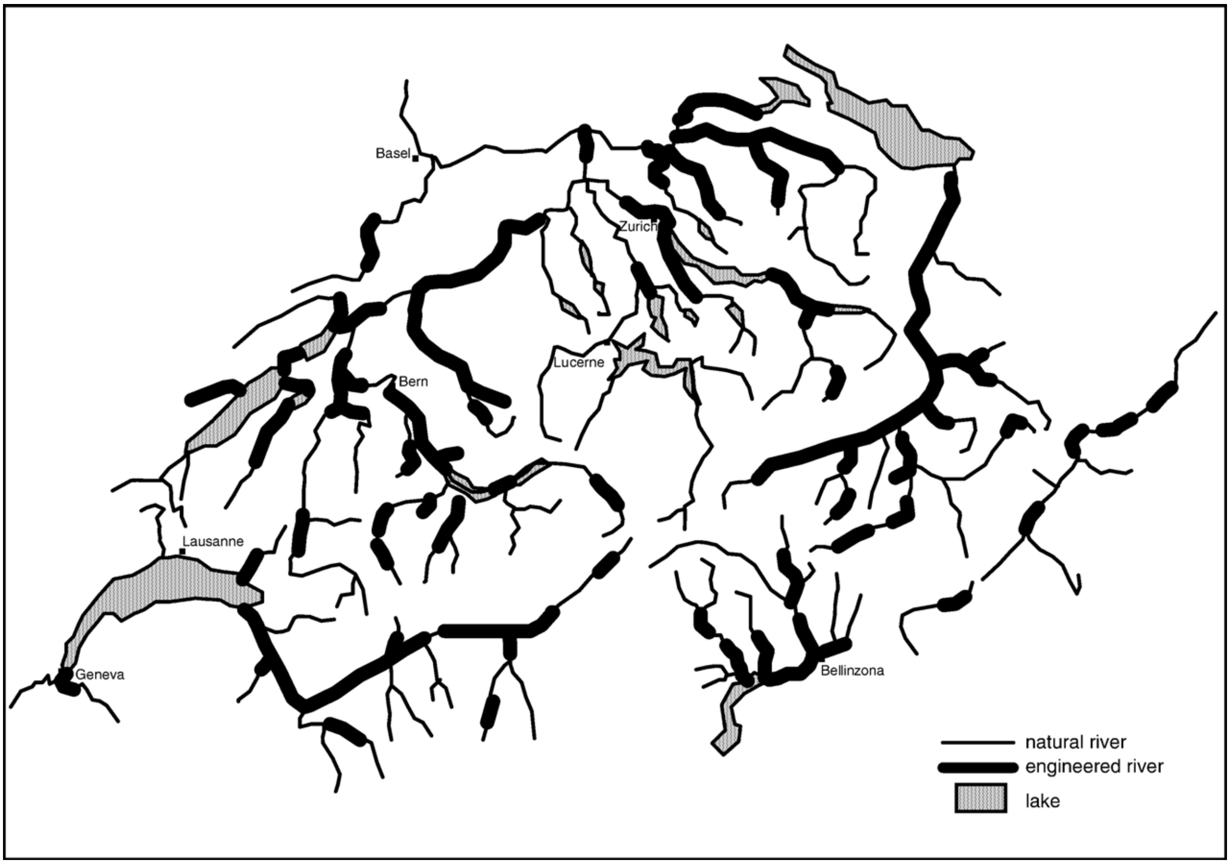

Fig. 6. Map of river reaches in Switzerland altered by humans during the 19th century (after Baetzing and Messerli, 1992, Fig. 3.10).

estimated by comparing streams with multiple and continuing land-use effects to streams with relatively few historical or contemporary alterations. In the Front Range, North St. Vrain Creek and the South Fork of the Poudre River are relatively unaffected by land use. Although beaver were trapped along both rivers, and timber was harvested in the catchments, neither river had placer mining, regulation of flow, extensive tie drives, roads or railroads along the length, or extensive grazing or recreational use. The characteristics of these rivers can, thus, be used to calibrate estimates of likely condition of the river (e.g. pool volume (Goode and Wohl, in press), wood loading, substrate grain-size distribution and stability), given the geologic and climatic setting of the Front Range.

Another approach to estimating change from reference conditions is to assess ecological indicators, such as habitat quality and availability, biotic diversity (e.g. macroinvertebrate distributions), or presence of endangered species such as the greenback cutthroat trout. Aquatic and riparian communities integrate the effects of changes in the physical and chemical environment, as well as the influence of introduced species. The limited contemporary distribution of native greenback cutthroat trout, for example, may reflect the presence of brook trout as much as the loss of habitat diversity, pool volume, and wood in the Front Range streams. Use of species distribution to estimate change from reference conditions depends on knowledge of the habitat (substrate, flow, water chemistry, etc) required by a species. Absence of the species when suitable habitat is available may reflect competition from introduced species. Detailed studies of the habitat requirements of various aquatic and riparian species native to the rivers of the Colorado Front Range are ongoing, but results to date suggest that some native species, such as the cutthroat trout, would have wider geographic distributions than at present in the absence of introduced competitors, whereas other organisms, such as river birch (*Betula fontinalis*) (Merritt and Wohl, 2006) or macroinvertebrates (Rader and Belish, 1999), are compromised primarily because of physical changes such as altered flow regime.

Except in cases of persistent contamination, the physical processes and aquatic biota of Front Range streams appear to have recovered relatively well from 19th-century activities such as mining and deforestation. Although beaver have not returned to pre-19th-century levels, they are once again present along streams. Channel stability and habitat diversity are sufficiently recovered to support diverse aquatic and riparian species. This level of recovery illustrates the resilience of these mountain streams. Physical processes and biological communities in Front Range streams, however, continue to be severely affected by the regulation of flow and introduced fish species. Societal pressures to further regulate surface water in this region steadily increase as population grows in the urban corridor along the eastern base of the mountains, which is one of the fastest growing regions of the United States (Wohl, 2001). In addition, the deposition of atmospheric nitrogen from agricultural fields and feedlots, automobile emissions, and coal-fired power plants surrounding the Front Range is now creating measurable changes in high-altitude lake chemistry and biota, as well as soil and stream chemistry (Baron et al., 2000; Fenn et al., 2003). In all of these historical and contemporary characteristics, the Colorado Front Range exemplifies human effects on mountain streams in mid-latitude arid and semiarid regions.

2.3. Mountain streams of Switzerland

Mountain streams in Switzerland lie within the western Alps, the central Swiss Plateau, or the Jura Mountains. An arc of fold mountains forms the western Alps, which reach elevations of 4800 m in Switzerland (Leser, 1984). Regional geology is quite complex, and includes belts of flysch, calcareous rocks, schists, and the crystalline rocks of the High Alps. The central plateau forms a part of the Alpine foreland bordered on the south by the Alps and on the north by the folded calcareous rocks of the Jura, where elevations reach 1700 m. Much of Switzerland was affected by Pleistocene glaciation (Leser, 1984). Mean annual precipitation for all of Switzerland is 150 cm, divided among snowfall, rain-on-snow, and summer rainfall although, as in most mountainous areas, spatial variation in precipitation is very high.

The most common downstream progression in channel morphology is from steep, laterally confined channels with coarse substrate, accumulations of woody debris and narrow riparian corridors, to braided channels with moderate floodplain development, and then alluvial floodplain rivers (commonly meandering) in broader, lower gradient valleys (Jungwirth et al., 2000).

Water temperature in alpine headwaters tends to be relatively cold in summer and warm in winter because of groundwater input (Jungwirth et al., 2000). Diversity of macroinvertebrate species decreases with increasing altitude because of the shorter timespan since deglaciation, the limited food supply, and the extreme physical conditions (variability of flow, temperature, etc.) at higher elevations (Landolt and Sartori, 2001). Brown trout (*S. trutta forma fario*) is the dominant, and in many cases the only, fish species in the uppermost channel reaches, although bullhead (*Cottus gobio*) can also be present. Both species rely on longitudinal stream connectivity for spawning migrations as well as seasonal or stage-specific habitat shifts (Jungwirth et al., 2000). Grayling (*Thymallus thymallus*) are the dominant fish species in the middle braided zones, although habitat diversity and, thus, diversity of aquatic and riparian species increases progressively from the alpine headwaters to the alluvial meandering streams.

The history of changes in land use and streams in Switzerland is representative of many mountainous regions in Europe, as summarized by Baetzing and Messerli (1992). Many aspects of this history are also shared by mountainous regions in Japan. Evidence of human habitation in the Alps occurs as early as 1 million years BC, and year-round occupation of agricultural

A

B

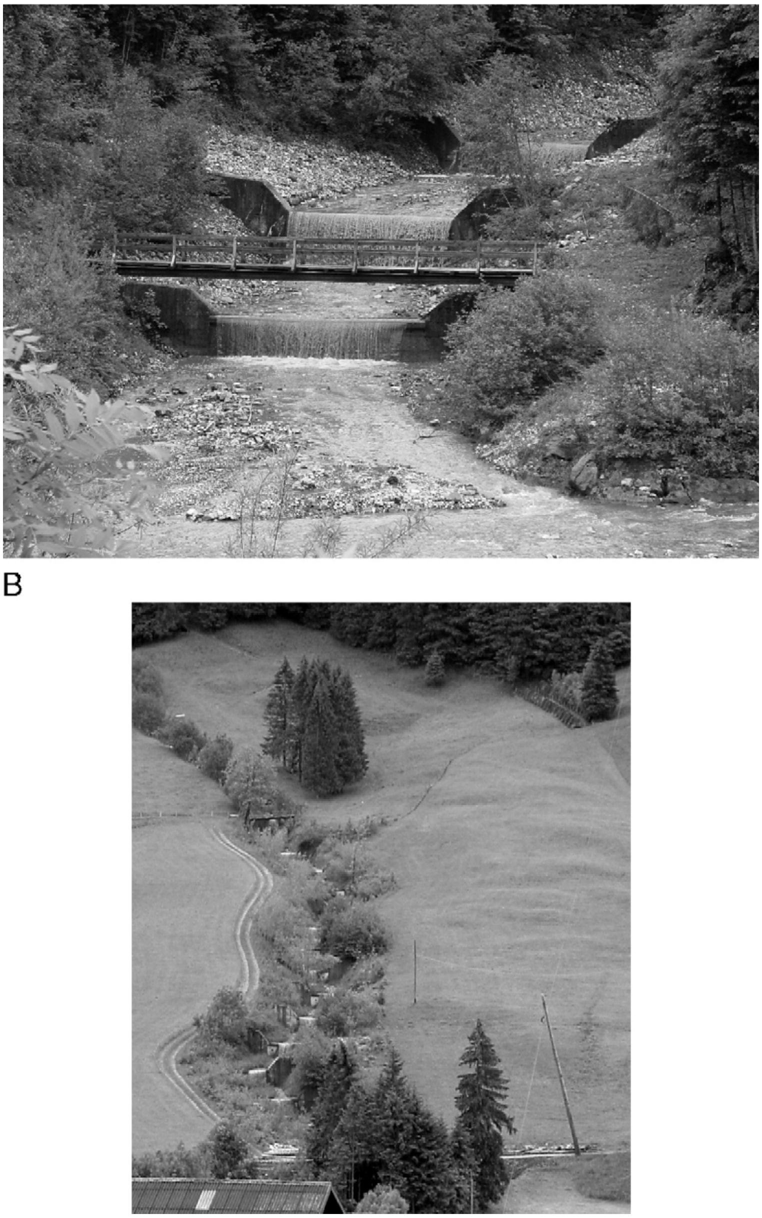

Fig. 7. (A) Upstream view of some of the numerous grade-control structures along the Vogelbach, a Swiss mountain stream, June 2004. (B) Upstream view of numerous grade-control structures along the Lumpenenbach, a Swiss mountain stream, June 2004.

villages dates back to 3000–2000 BC. Accounts by Roman historians indicate heavy settlement and intensive land use by 200 BC, although settlement in the northern and western Alps may not have been intense prior to 500 AD. In general, the Alps and other European mountains have experienced deforestation and agriculture for at least a thousand years. Particularly heavy demand for lumber during 19th-century industrialization left Swiss forests so depleted that severe flooding in the latter half of the century was widely perceived to result from deforestation. This perception fostered laws for forest protection and the initiation of studies of forest influence on hydrology in 1876 (Hegg, 2004).

The limited land suitable for agriculture in Switzerland has been subdivided among farming families for centuries. This has led to increasing demand for arable land, to the point where many first-order channels on the central Swiss Plateau were piped underground during and after World War II to improve land access for growing crops (Hegg, 2004). At present, an estimated 27% of the channels throughout Switzerland are underground in artificial conveyance structures (Bundi et al., 2000).

Construction of riverine and terrestrial transportation corridors and in-channel structures during the 19th and 20th centuries also affected Swiss streams. Valley-bottom rivers with floodplain suitable for farming and settlement were straightened and deepened (Fig. 6), and steeper tributary streams were lined with check-dams and bank stabilization (Fig. 7). The first railroad through the Alps was completed in 1850, and the first through-highway in 1955, resulting in substantial increases in alpine tourism.

Hydroelectric power was introduced in 1880, and is now one of the most extensive and intensive impacts to alpine streams (Figs. 8 and 9). Alpine water is used for drinking-water supplies, irrigation water, production of electricity in run-of-river power stations, and storage of electricity. Power storage stations rely on artificial enlargement of natural high-altitude lakes and conversion of flat valley floors into lakes. The water is commonly used to produce electricity during winter, so that stream flows are thoroughly altered from natural patterns of spring-summer high flows to regulated patterns of winter high flows and summer low flows. Power production of high-altitude stations has also been expanded via tunnels that completely divert streams over extensive areas. Proposals to expand power production by pumping water upwards into high-altitude reservoirs would quadruple

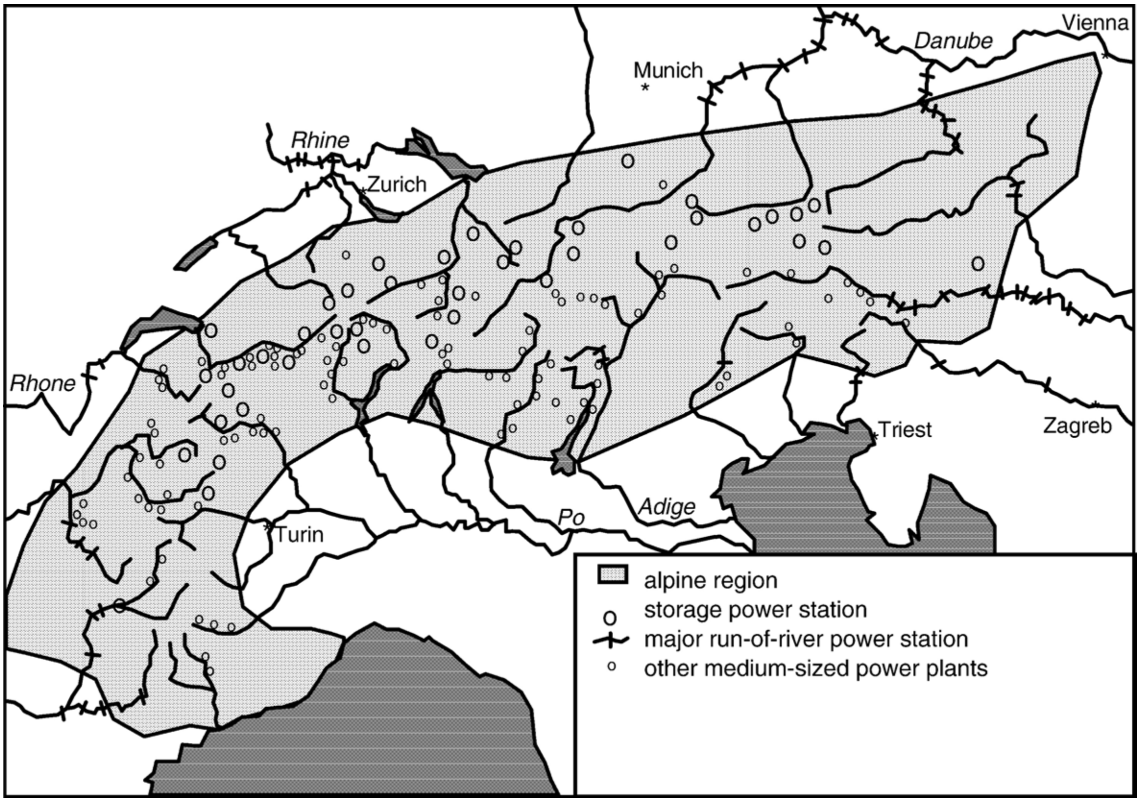

Fig. 8. Map of hydroelectric power stations in the Alps as of 1980 (after Baetzing and Messerli, 1992, Fig. 3.13).

water storage in the Alps. At present, no single major river flows for its entire course in a natural condition, and there fewer than ten alpine rivers exist whose courses are uninterrupted for more than 15 km (Baetzing and Messerli, 1992). Comparison of regulated and unregulated rivers in Switzerland indicates low macroinvertebrate (Landolt et al., 2001) and fish (Jungwirth et al., 2000) faunal diversity in regulated rivers.

Increases in power generation fostered the movement of industrial branch operations into the Alps during the 1960s, and the growth of urban areas and ski resorts. Along with continental increases in air pollution and increased highway traffic, these changes increased air pollution to the point that forests regionally began to suffer dieback, leading to increased avalanche danger and the abandonment of some settlements (Baetzing and Messerli, 1992; Grassl, 1994), and presumably altering sediment yield and water quality of adjacent mountain streams.

Formerly braided sections of Swiss rivers have been especially affected by the regulation of flow and

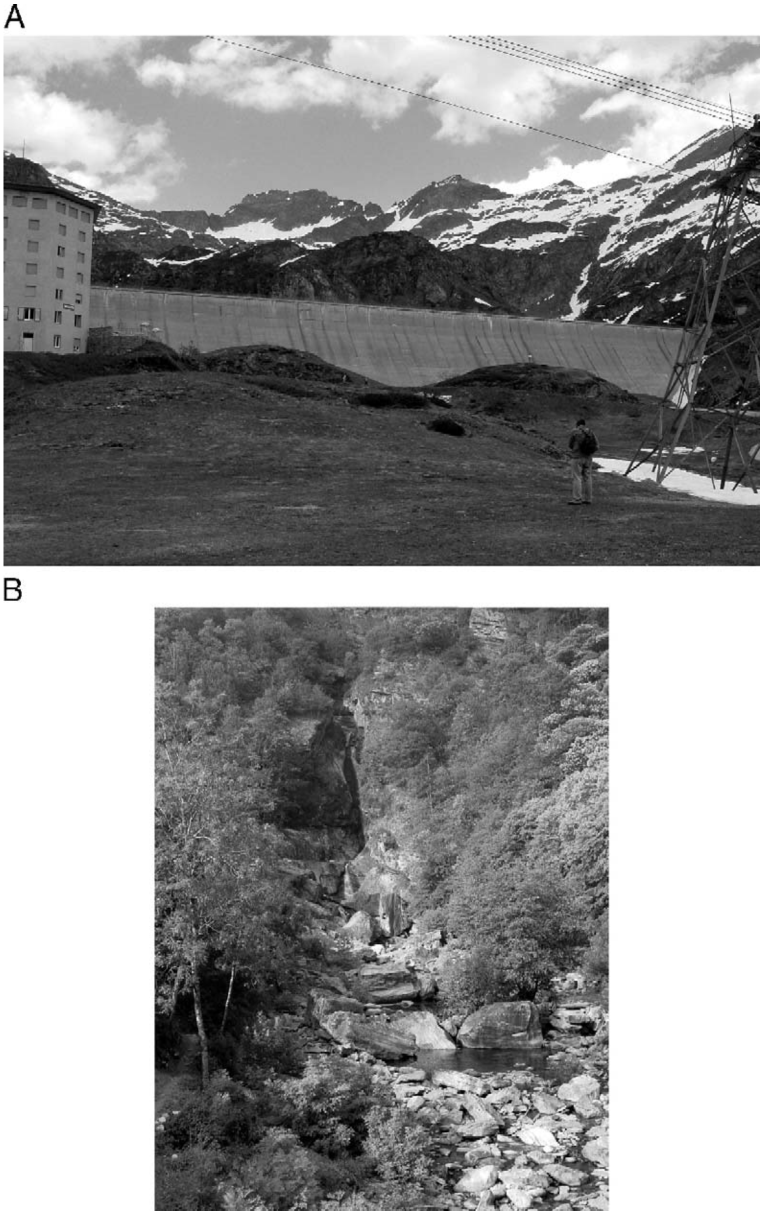

Fig. 9. (A) A hydroelectric dam at the headwaters of the Maggia Valley, Switzerland (structure is above timberline), June 2004. (B) View of a headwater tributary in The Maggia Valley, Switzerland during snowmelt season, June 2004; channel is nearly dry because flow is diverted into a collection pipeline that goes to a hydroelectric station.

channelization (Tockner et al., in press), as in much of the Alps. A recent survey of Austrian rivers with drainage basins > 500 km^2, for example, found that 25% of high-gradient confined sections remained intact, but only 1% of braided sections were intact (Muhar et al., 1998). In a natural state, braided rivers are characterized by a shifting mosaic of channels, ponds, bars, and islands with large spatial variability in substrate type, flow depth and velocity, thermal regime, nutrient availability, and physical disturbance. Large wood and surface–hyporheic exchanges exert important influences on the habitat of a braided river. Biotic and abiotic components of the river ecosystem have rapid rates of turnover. Although braided rivers are harsh environments because of frequent physical disturbances, such as floods and low-flow periods, low organic content, and large fluxes of temperature and humidity, braided rivers have very high overall biodiversity. As braided rivers in the Swiss mountains have been converted to incised, single-thread channels, most of the complexity and dynamic character of riparian and aquatic habitats have been lost. Restoration projects, undertaken to date, focus primarily on increasing the complexity and diversity of channel planform by creating secondary channels and more irregular banks, or by allowing flow to re-occupy secondary channels that were artificially closed. These projects have largely been unsuccessful where they do not restore the underlying hydrogeomorphic dynamics that produce braiding (Tockner et al., in press). Thus, as in Sweden, ability to restore streams is limited where the intense regulation of flow remains in place.

The Spöl River in Swiss National Park provides an example of the effects of regulation of flow, and of attempts to restore river function (Mürle et al., 2003; Ortlepp and Mürle, 2003). The natural mean annual discharge of 6–12 m^3/s was reduced to a constant discharge of 0.3, 0.6, 0.9 or 1.4 m^3/s, depending on river section, after the construction of two large reservoirs in the late 1960s. Natural floods now occur only in the lower Spöl where it is joined by a large unregulated tributary, the Cluozza River. Following flow regulation, the residual flow on the Spöl was too low to transport organic and inorganic inputs from tributaries and valley-side talus slopes. The channel aggraded and narrowed, with woody forest species colonizing gravel bars. Alluvial fans and talus slopes extended into the river channel. These changes degraded habitat for brown trout, the only fish that lives and reproduces in the Spöl, by clogging the gravels in spawning areas. Six experimental flood releases were conducted during 2000–2002 with peak discharges of 55–15 m^3/s. These floods flushed fine sediments from the streambed; eroded vegetated gravel bars, alluvial fans and talus slopes; and enhanced the variation in channel depth. The condition of adult trout remained relatively constant following the floods, but the number of redds (fish spawning grounds or nests) increased three-fold.

Although many of the mountain streams in Switzerland are severely altered by the regulation of flow and in-channel structures, the uppermost segments of river networks are generally in good condition. The middle, braided segments are increasingly the focus of new management strategies designed to restore stream ecosystem function. A 1994 government decree, for example, requires that cantons must define the space for a river based on its ecological functions and the need for flood protection of human communities (Peter et al., in press). This represents an important advance on past regulations, which focused solely on flood protection. Restoration methods employed to date include experimental floods; local setbacks on levees and other flood-control structures to allow channel–floodplain connectivity and more lateral channel mobility; and removal of in-channel structures (Peter et al., in press).

Despite high population pressure in Switzerland, Swiss mountain streams have a high potential for restoration if periodic high flows are released and natural vegetation and channel mobility are allowed to return in riparian areas. This high potential for restoration reflects the relatively low biodiversity and lack of endangered or extinct species, and the lack of serious water quality problems.

2.4. Mountain streams of Papua New Guinea

Papua New Guinea (PNG) is located at a complicated intersection among the Philippine, Pacific, and Indo-Australian tectonic plates. Adjacent convergent boundaries create high uplift, accompanied by frequent earthquakes and active volcanism. Approximately 40 active volcanoes are present along the north coast of the mainland and adjacent smaller islands. The primary trend of the drainage divide on PNG is roughly northwest–southeast, with a series of rivers draining away from the divide and into the Pacific Ocean on both sides. Lithologies present in the mountains reflect the complex tectonic history, and include felsic to mafic intrusive and extrusive rocks, metamorphic rocks, subduction-zone complexes of deformed nearshore clastic sediments, and carbonate platform sediments. Warm sea-surface temperatures, seasonal migration of the Intertropical Convergence Zone, and orographic effects resulting from steep topography combine to create high rates of rainfall (Hall, 1984). Mean annual precipitation is extremely spatially variable, in part because convective thunderstorms are the dominant type of storm (Hall, 1984); values can exceed 10 m at elevations of 1500–2000 m, but then decrease to 8 m at 200 m elevation, and 2 m near sea level (Dietrich et al., 1999). The regional tectonic setting produces steep, massively unstable topography with large sediment inputs to rivers and high sediment loads in the headwaters; mechanically weak sediment that rapidly disintegrates during fluvial transport; a rapid downstream decrease in stream gradient; and possible tectonic influence on river orientation (Dietrich et al., 1999). The mountain streams of New Guinea (PNG and Irian Jaya; total area 800,000 km^2) discharge approximately 1.7×10^9 t of sediment annually, which is about the same as the combined sediment loads of rivers draining North America (Milliman, 1995).

One of the most well-studied drainages in PNG is that of the Fly (75,000 km^2), primarily because of concern about effects from gold and copper mining in the upper basin. The Ok Tedi, Fly and Strickland, the three major tributaries of the Fly River system, originate in the steep, rapidly uplifting Southern Fold Mountains, which reach 4000 m in elevation. Dense rainforest covers most of the Fly drainage basin (Pickup, 1984). The streams descend steeply through narrow canyons and are locally braided, before meandering across coastal lowlands to the Fly River delta (Higgins et al., 1987). Although the upper stream reaches have a flashy discharge regime (Dietrich et al., 1999), the catchment as a whole has very little interannual hydrologic variability; the 100-year flood is only about twice the size of the 2-year flood (Pickup, 1984). These characteristics are shared by many other drainages in PNG.

Very little information exists on the ecology of streams in PNG (Dudgeon, 1994). Substantial turbidity and bed instability reduce biological productivity to low levels (Swales et al., 1998). Diverse macroinvertebrate communities are present and population densities compare to those recorded elsewhere in tropical Asia, but morphospecies richness is lower than in comparable tropical Asian rivers (Dudgeon, 1994; Yule, 1995). Most fish species present in PNG are diadromous. Three hundred and sixteen native fish species are present, so the freshwater fish fauna as a whole is not especially species-poor. The rivers generally have low fish biomass, although totals vary among individual rivers. The recently uplifted drainage of the Sepik, the largest river in PNG (drainage area 78,000 km^2), has about half the diversity and abundance of freshwater fish species as the Fly River (Dudgeon, 2003). Mining-related effects to fish in the Fly River system include significant reductions in fish catches at most sites in the upper and middle portions of the drainage (Swales et al., 1998).

Protein malnourishment is common among people living in the highlands of PNG, and the Food and Agriculture Organization of the United Nations introduced a suite of exotic fish species to the Sepik River during 1993–97 to increase fish stocks for subsistence fishing. Species of Tilapia and Cyprinidae were stocked at higher elevations, but the response of stream ecosystems has not yet been documented (Dudgeon, 2003).

The Ok Tedi mine in the headwaters of the Ok Tedi River is the second largest copper-producing mine in the world. Mining for gold began in 1984 and copper production started in 1987. Construction of a tailings dam was considered unfeasible, and the mine operates without waste retention. Approximately 80,000 t/day of waste tailings and 121,000 t/day of mined waste rock are dumped directly into the Ok Tedi (Fig. 10). Metals travel downstream throughout the drainage network in dissolved and particulate form (Yaru and Buckney, 2000). Elevated levels of copper, zinc, lead and cadmium are found in tissues from a range of fish species, with metal concentrations decreasing with distance downstream from the mine. Significant reductions in fish catch biomass, ranging from 65% to 95%, were recorded at most sites in the Ok Tedi and middle and upper Fly River following the start of mining (Swales et al., 2000). No evidence exists that metal levels recorded in the fish, however, indicate lethal or sub-lethal effects of mine wastes on fish survival. Swales et al. (1998) attribute the declines in fish abundance instead to greatly increased rates of bed aggradation and associated loss of fish habitat and elimination of other forms of aquatic life. The streambed aggraded over 6 m in parts of the Ok Tedi during the decade following the start of mining. The introduction and subsequent wide range and abundance of two species of introduced fish, the climbing perch (*Anabas testudineus*) and walking catfish (*Clarias batrachus*), may also be reducing native fish stocks (Swales et al., 1998).

Mining also occurs on some of the smaller islands, such as Bougainville, that form part of PNG. Copper mining began on the headwaters of the Jaba/Kawerong River on Bougainville in 1968. By 1974, tailings had spread over 1700 ha on either side of the river, destroying large areas of rainforest and killing fish (Brown, 1974). By mid-1976 an estimated 226 Mt of sediment had been introduced to the naturally braided river (Pickup and Higgins, 1979; Pickup et al., 1983). Tailings discharges of up to 140,000 t/day continued until 1989. The mine is now closed. As a result of mining wastes, the fish fauna were completely destroyed in the main channel, and partly destroyed in the tributaries which, although not directly affected, were biologically isolated from the ocean by

Fig. 10. Mining wastes entering headwater streams of the Ok Tedi, Papua New Guinea. Photograph courtesy of Bill Dietrich.

high suspended sediment loads in the main channel (Powell and Powell, 1999).

In addition to mining-related impacts, mountain streams in PNG are affected by the regulation of flow and hydroelectric power development for both municipal and industrial use. Port Moresby, the capital of PNG, relies on a single large reservoir for power and water (Hall, 1984). The Ok Tedi mines are served by a 50-MW hydroelectric plant completed on the Ok Menga River in 1988 (McCreath et al., 1990). Problems associated with flashy hydrographs, unstable bed and banks, and large and unpredictable sediment loads have thus far not stopped construction of hydroelectric plants (Pickup, 1980; Ponta and Mobiha, 2002), although most of the larger reservoirs are located at lower elevations. Run-of-river intakes and no storage reservoirs are more common at higher elevations (McCreath et al., 1990).

Although PNG contains some of the least disturbed tropical forests in the world, the annual rate of deforestation (0.36%) has threatened an estimated 266 species with extinction as of 2002, and deforestation locally increases sediment yields to streams (Ulack, 2004).

In general, mountain streams in Papua New Guinea are relatively unaltered by human activities except where they drain areas being mined. Many of the effects of mining and hydroelectric development are more severe in the lowland, coastal portion of stream networks. Mountain streams affected by mining have even higher sediment loads than those that occur naturally in this geomorphically unstable region, resulting in streambed aggradation, decrease in water quality, and loss of aquatic habitat. The limited studies conducted to date indicate severe reductions in aquatic biota as a result of these changes. Increasing population density and industrialization in PNG could exacerbate deforestation and hydroelectric development along mountain streams, as is presently occurring in neighboring Irian Jaya, the western half of New Guinea that is part of Indonesia. Irian Jaya is experiencing rapid population growth as a result of the resettlement policies of the Indonesian government, as well as large-scale mining and industrial-scale deforestation. A large hydroelectric project to power an aluminum smelter is also planned for Irian Jaya.

In contrast to the case studies from Sweden, Colorado and Switzerland, the greatest human effects to mountain streams in PNG are probably yet to occur. Mountain streams in industrialized regions, such as Europe and the United States, have a long history of intensive impacts, as well as continuing effects, but, relatively high public and governmental awareness exists that mountain streams must be protected and to some extent restored. PNG exemplifies much of the developing world, where high rates of population growth, attempts to raise the standard of living, and largely unregulated exploitation of natural resources combine to create locally intense effects on mountain streams. The best strategies for protecting streams in these regions are to develop and enforce regulations governing land use, and to develop preserves, such as national parks, where intact stream ecosystems can continue to function.

3. Implications of the global status of mountain streams

The physical and ecological importance of mountain streams is disproportionately greater than the extent of these streams within the river basins of the world. Although mountain streams drain an estimated 20% of global land area, they contribute nearly 50% of the sediment that rivers carry to the global oceans (Milliman and Syvitski, 1992). Headwater streams are also particularly important in controlling nutrient exports to larger rivers, lakes and estuaries. The most rapid uptake and transformation of inorganic nitrogen occurs in the smallest streams and, during seasons of high biological activity, headwater streams export downstream less than half of the input of dissolved inorganic nitrogen from the watersheds (Peterson et al., 2001).

Although many people are likely to consider mountainous regions relatively unaffected by human land uses, Table 2 indicates that very few mountains have streams not at least moderately affected by land use. The least affected mountainous regions are those at very high or very low latitudes, although our scientific ignorance of conditions in low-latitude mountains in particular means that streams in these mountains might be more altered than is widely recognized. Mountain streams might be resilient to a variety of land use effects in that these streams typically have: (i) lower biodiversity than stream segments in middle or lower portions of drainages (Vannote et al., 1980); (ii) both physical processes and aquatic and riparian biota adjusted to periodic severe disturbances resulting from small drainage areas, close coupling with hillslopes, and absence of extensive floodplains that buffer disturbances (Wohl, 2000); (iii) steep gradients and relatively high sediment transport capacity so that excess sediment is transported to depositional zones downstream (Montgomery and Buffington, 1997); and (iv) channel boundaries of bedrock or coarse grains that resist erosion, so that changes in discharge are less likely to cause channel erosion than in downstream channel segments. On the other hand, relatively simple aquatic trophic systems and less diverse riparian communities, along with the absence of physical and chemical buffering mechanisms associated with extensive groundwater flow paths, riparian zones, floodplains, and valley-bottom storage of water and sediment, can also make mountain streams vulnerable to the immediate consequences of land use activities (Wohl, 2000). The scientific community does not yet have sufficient understanding of mountain versus lowland river systems to make broad generalizations about the relative vulnerability of mountain streams to human activities.

In the absence of such comprehensive understanding, and knowing that most mountain streams are affected by land use to some extent (Table 2), human communities must manage mountain streams within an integrative conceptual framework that recognizes the multiple and complex connections between any particular stream segment and the greater environment. Management in this context includes stream restoration, which is too often undertaken at the scale of a single channel reach, without considering greater spatial and temporal controls on the success of restoration (Wohl et al., 2005). Specifically, mountain streams must be managed with cognizance of:

- Upstream/downstream connections: Sediment transported from mountainous headwaters exerts an important control on downstream channel stability, and increases or decreases in sediment supply can destabilize downstream channel segments. Numerous species of fish and aquatic invertebrates rely on ability to move up- and downstream to complete their lifecycle (Stanford and Ward, 1993; Gomi et al., 2002), and longitudinal connectivity is important to nutrient cycling (Newbold et al., 1982). Similarly, many species of riparian plants rely on water transport of propagules (Nilsson et al., 1991a; Nilsson and Jansson, 1995; Merritt and Wohl, 2006).
- Hillslope/channel connections: As mentioned previously, mountain streams are particularly vulnerable to changes in hillslope processes because of close coupling with adjacent hillslopes. Changes in hillslope vegetation cover or exposure of mineralized rock are, thus, likely to have immediate consequences for the discharge and quality of water and sediment.
- Process domains: Numerous investigators have suggested that mountain streams have distinctive types of morphology and substrate, rate/manner of dissipating flow energy, and response to water and/or sediment yield as a function of characteristics such as gradient, proximity of tributary junctions, hillslope stability and sediment supply (Montgomery, 1999; Miller and Benda, 2000; Chin, 2002; Benda et al., 2003; Grant, 2003; Montgomery et al., 2003).
- Physical and ecological roles of disturbance: Just as increased instability can reduce the functioning of mountain streams, increased stability can also be detrimental to physical and biological diversity (Reice, 1994). Loss of seasonal flood peaks as a result of the regulation of flow, for example, removes cues for spawning or release of plant seeds.
- Stream resilience: The resilience of mountain streams reflects physical and biological parameters. Physical parameters influencing the resilience of mountain streams include reach-scale gradient and habitat diversity. Higher gradient stream segments are less responsive to increased water and sediment yield than lower gradient channel segments (Montgomery and

Buffington, 1997). Consequently, lower gradient pool-riffle channel segments flowing through a glaciated trough will be less resilient to increased sediment yield, for example, than steeper, step-pool or plane-bed segments located in other portions of the channel network. Streams with diverse habitats are likely to have higher biodiversity (Voelz and McArthur, 2000), and are less vulnerable to physical disturbances such as increased sediment supply (Nilsson and Grelsson, 1995). Ecologists characterize environments with intermediate levels of disturbance as having the greatest habitat and biodiversity. Physical controls on the resilience of mountain streams can, thus, be characterized along a spectrum of gradient and disturbance regime analogous to the process domains described above. Biological parameters influencing the resilience of mountain streams include species diversity and percentage of endemic species. Streams with diverse aquatic and riparian species are less vulnerable to extinction of native species and complete ecosystem disruption as a result of introduced species (Pimm, 1989). Streams with a high number of endemic species are more susceptible to species extinction (Reid and Miller, 1989). Species diversity and percentage of endemic species reflect habitat availability, as well as geologic and evolutionary history. Because historical conditions tend to be very site-specific, it is difficult to develop general characterizations of biological controls on stream resilience analogous to the characterization of physical controls. The different influences on stream resilience to chemical, physical, or biological disruption can be used to rank stream sensitivity to various types of land use within a particular mountain region (e.g. Winters et al., 2004).

People have recognized the connection between watershed conditions and stream stability in mountainous regions for centuries. Governmental regulation of timber harvest along mountain streams so as to maintain channel stability dates to 806 AD in Japan, for example (Wohl, 2000). Scientific study of the effects of human activities, however, developed more slowly. In his 1864 classic *Man and Nature*, George Perkins Marsh (1965) described "displacements of earth and rocky strata" in the form of landslides in mountain regions as being of "… rare occurrence in countries still covered by primitive forest, so common where the mountains have been stripped of their native covering …" (p. 230), yet the classic 1956 text *Man's role in changing the face of the Earth* (Thomas, 1956) did not address effects of land use activities in mountains as a distinct environment. Systematic investigations of human effects on mountain environments date to the 1970s, yet very little is known of the rivers in many mountains (e.g. Table 2). Continued geomorphic and ecological investigation of the characteristics that govern the ecosystems of mountain streams will facilitate the development of conceptual and quantitative models of mountain streams that can provide a predictive framework for understanding and mitigating human impacts.

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