

Appendix 3.4.2 Instream background

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Stream Functions Overview

River characteristics vary with the landscape and with stream order. The landscape provides the raw material for the stream channel and flowing water is the sculptor of the channel. Interactions between landscape and flowing water create the physical template within which plants, animals

and microorganisms interact, modifying, stabilizing and creating characteristic ecosystems. Streams that flow over steep bedrock walls typically develop a step-pool structure characterized by cascades and pools. Streams that flow through more gently sloping alluvial deposits develop a channel that is widely meandering with alternating pools, riffles and glides. Alluvial stream channels are formed in sediments previously transported and deposited by the stream and are characterized by the presence of floodplains. Whereas alluvial channels and their floodplains are dependent on vegetation for stability non-alluvial stream channels (those that are formed in bedrock or boulders) tend to be stable and resistant to change. Thus the physical structure of the stream system provides the foundation for and determines biotic community potential.

Channel characteristics and stream structure develop within the context of the landscape and are in a state of dynamic equilibrium with the surrounding landscape. A stream reach that has achieved dynamic equilibrium is stable in that it tends to transport the water and sediment produced by the watershed so that over time it maintains its dimension, pattern, and profile while neither degrading nor aggrading (Rosgen, 1994). This dynamic equilibrium develops out of the complex interplay between the physical, biological, and chemical characteristics of a watershed. Thus stream stability is due to a myriad of self-regulating mechanisms that bring about relatively constant environmental conditions such as stream flow, temperature, amount of oxygen dissolved in the water, in-stream nutrient levels, food availability, and sediment loads.

Stream channels form in response to the amount of flow (discharge) and are shaped by the type, amount and duration of the sediment carried in the water column (Windell, 1992). Flowing water with sediment sculpts the landscape to create specific channel patterns or shapes. Stream channel patterns are straight, meandering, or braided. Straight streams either are in a transitional state and will eventually develop a meandering pattern or, because the channel material is bedrock and boulders or is armored, will remain straight and are highly stable. Braided streams are characterized by numerous channels that continuously divide and rejoin. A braided pattern forms because the channel is overloaded with sediment which drops out of the stream forming small islands and a very shallow stream – to compensate for the shallow depth the channel divides into several small channels (Briggs, 1996). If banks lack stabilizing vegetation the development of multiple channels also causes the stream to widen. Excessive sediment loads increase the erosive power of the stream and frequently scour vegetation from the banks. Consequently braided streams are typically unstable, with simplified instream structure, eroding banks and have the lowest wildlife diversity because of the shifting, unstable sediments that are characteristic of this stream type (Mitsch and Gosselink, 2000).

Meandering stream patterns develop in alluvial deposits (sediment deposited by water) and are characterized by loops and s-shaped bends. Of all the stream pattern types a meandering shape results in the highest habitat diversity and the highest wildlife potential due in part to the diversity of habitats that develop in the river-floodplain system (Mitsch and Gosselink, 2000). Meandering results from the process of erosion, transportation and deposition of the valley floor; sediment is eroded from the concave side of a stream meander where water velocity is greatest and deposited on the convex side where water velocity slows forming a point bar (a deposit of sediment). This process tends to balance erosion from the cut bank side of the channel with deposition on the point bar at the opposite side of the channel, thereby maintaining channel width and elevation throughout the progression of meander migration. Deep pools typically form on the

streams' concave side and shallow riffles downstream of the point bar. Thus the process of meandering enhances stream habitat diversity in 3 dimensions – horizontally, vertically and by creating variations in flow velocity and also enhances stream stability. For instance the formation of depositional bars is essential for the establishment of cottonwood trees which stabilize stream banks; shallow riffle areas are the most productive areas of the stream with regard to aquatic insects which provide food for fish; and meander bends absorb and dissipate floodwater energy.

Stream Functions

Stream Channel Structure

Channel structural characteristics provide mechanisms that promote stream function and homeostasis – more constant environmental conditions such as water temperature, water quality and quantity, dissolved oxygen and nutrient levels, and protected habitat. Under homeostatic conditions energy and nutrients are held onto more tightly, water flow and temperatures are moderated, substrate is stable and the food supply is reliable – thus stream stability and wildlife habitat is enhanced.

Whether a stream is steeply plunging down boulder lined mountains slopes or languidly meandering through a valley bottom a characteristic channel shape and structure develop that are in a dynamic balance with the physical characteristics of the surrounding landscape. These characteristics are essential to stream stability and sustainable wildlife habitat.

Natural channels (and their physical characteristics) maintain stable and sustainable stream ecosystems by dissipating stream energy, balancing erosion with deposition, storing water, maintaining an intimate connection with the floodplain, enhancing wildlife diversity and by developing a diverse velocity-flow regime with heterogeneous in-stream habitat. Characteristics that provide these stream functions include 1) channel complexity, 2) stable stream banks 3) well-vegetated riparian habitat and 4) beaver dams.

Channel Complexity

Structurally complex channels maintain stream stability and increase biotic potential. The frequency and magnitude of floods is the primary driver of structural complexity within stream corridors (Saldi-Caromile et al., 2004) and is instrumental in creating the channel characteristics that enhance complexity. These characteristics include: 1) channel sinuosity, 2) alternating sequences of riffles, pools and glides, 3) diverse flow regimes, 4) variety of stream substrates, 5) coarse woody debris, and 6) streambank roughness.

Channel Sinuosity

Stream sinuosity creates an s-shaped channel configuration that develops in alluvium in lower gradient streams. However, sinuosity also develops in higher-gradient headwater streams, which characteristically have continuous riffles with little lateral meandering, due to the bedrock and boulders that form the channel. Here sinuosity is provided by boulders and riffle cascades which create a vertical form of sinuosity that increases the structural complexity of the stream (Barbour et al., 1999).

Sinuosity (channel meandering) functions to: 1) slow flows and dissipate flood energy by decreasing stream gradient and by absorbing energy at meander bends; 2) decrease bank erosion

by slowing flows; 3) increase water storage by enabling out-of-bank flows into riparian habitat where soils act like a sponge to soak up and store water; 4) replenish riparian habitat with water, nutrients and build floodplains with sediment supplied by out-of-bank flows, 5) enhance instream structural diversity by creating deep pools and shallow riffles; 6) enhance flow diversity by building pools where stream flow is slow and riffles where flow is fast; 7) balance erosion with deposition by reducing erosion and depositing sediment on point bars and onto the floodplain; 8) retain nutrients and enable tighter nutrient cycles (thus less nutrient loss) by slowing flows, and creating backwaters, side channels and oxbows where nutrients are more readily recycled back into plants and animals.

Alternating Sequences of Riffles, Pools, and Glides; and Diverse Flow Regimes

Diverse instream structure increases ecosystem stability by dissipating stream energy, enhancing nutrient cycling and increasing wildlife potential. Stream habitat is made more complex with variable stream depths and flow regimes, diverse stream substrate, abundant woody debris of various sizes and complex, “rough” streambanks that are covered with stabilizing vegetation.

Riffles, pools and runs/glides characterize the three basic stream habitat types and are created by the process of meandering which results in a variety of stream depths and flow regimes. Pools are characterized by deep, slow moving water at low flow. Riffles are characterized by fast moving water in shallow areas where the water surface is broken into waves by the substrate (cobbles, boulders etc.). Often glides, moderately shallow water with an even, unbroken flow, intervene between riffles and pools. The frequency of alternating riffle-pool sequences is an important measure of in-stream habitat heterogeneity – the more frequent the sequence, the greater the habitat heterogeneity. Riffles are critical for maintaining: 1) abundant and diverse macroinvertebrate populations; 2) feeding habitat for fish due to an abundance of macroinvertebrates; and 3) fish spawning and egg incubation habitat. Pools provide: 1) habitat that absorbs and dissipates the energy of flooding flows; 2) environmental conditions that enhance nutrient recycling; 3) resting and feeding sites for fish; 4) refugia for fish and macroinvertebrates during flooding events, during low flow times of the year and during winter;

In Colorado, pool density and pool depth have been found to play an important role in the survival of all cutthroat trout species, particularly during low flow periods (James and Speas, 2005). Herger (1993) found that Colorado River cutthroat trout larger than 152 mm were located primarily in pools, and that pool depth influenced trout density. Behnke (1992) observed that adult trout generally live at depths of 0.3 m or greater in areas of slow water (0.1 m/s) juxtaposed with fast waters (riffles or glides) that carry food and where protective cover is provided by boulders or logs.

Stream Substrates

Stream substrate refers to natural structures in the stream such as gravel, cobble, boulders, fallen trees, logs and branches, overhanging vegetation, undercut banks and thick root mats. These natural substrates provide a variety of wildlife habitat and stream stabilizing functions. A variety and abundance of submerged structures provides macroinvertebrates and fishes with a variety of niches thereby increasing habitat and wildlife diversity and thus the potential for recovery from natural disturbances (Barbour and Stribling, 1991) – thus the maintenance of a healthy fish community and its ability to recover from disturbance is dependent on the variety and abundance

of suitable habitat and cover (Newton et al., 1998). Cobble and gravel of various sizes provides habitat diversity in rifles and glides. Macroinvertebrates use cobble and gravel surfaces for colonization and fish use gravel for spawning and egg laying habitat; female Colorado River cutthroat trout dig their nests (redds) from gravel of a specific size (13.8-15.9 mm pebble size yields the best chance for survival) and eggs are deposited, fertilized, and then covered with gravel (James and Speas, 2005).

Coarse Woody Debris

Logs, snags and branches are among some of the most productive and essential habitat structures both upland and in the stream. Large, coarse woody debris (logs, downed trees, snags and branches) is a critical element of healthy and diverse riparian and stream ecosystems. Large, coarse woody debris (LCWD) is an essential part of the food web. LCWD contains large stores of carbon and nutrients and during the decay process provides a steady input of energy and nutrients to terrestrial and aquatic ecosystems. Upland, LCWD is important in stabilizing soil on steep slopes, controlling the flow of water and litter across the forest floor and enhancing the organic content of soil (Stevens, 1997). Coarse woody debris also provides habitat for many terrestrial and aquatic plants and animals. On land woody debris provides habitat for nesting, roosting, foraging, and shelter for birds, mammals, amphibians, and reptiles; in the Blue Mountains of Oregon 179 vertebrate species (57 percent of the breeding species) use coarse woody debris with birds dominating that list (Bull, 2002).

Instream, LCWD is also an essential habitat feature. In the stream LCWD slows flows and dissipates energy. Over time LCWD can be incorporated into the streambed creating natural drop structures that lower the streams gradient and help dissipate energy and trap sediment. LWCD also provides some of the most productive habitat for macroinvertebrates and creates deep pools where fish find protected cover. Cover is an important feature for the survival of Colorado River cutthroat trout and large woody debris (LWD), boulders and undercut banks have been described as key cover components (Gregory and Ashkenas, 1990). James and Speas (2005) describe LWD as a key component for the survival of Colorado River cutthroat trout.

Streambank Roughness

Streambank roughness is provided by bank vegetation and roots, boulders, snags, and large woody debris that protrude from the bank. Characteristics such as vegetation and snags decrease near-bank flow velocities and the erosive power of the stream, roots of native vegetation stabilize bank soil, greatly increasing bank stability. All of these characters together increase habitat complexity and enable the development of complex channels that are deep, narrow, and sinuous and that enable frequent out-of-bank flows.

Stable Stream Banks and Well-vegetated Riparian Habitat

Stable banks maintain a stable stream system and stable streams maintain their dimension, pattern and profile over time – thus bank stability is integral to stream stability. Stable streams provide a variety of habitat types and maintain relatively constant, only narrowly fluctuating environmental conditions including water temperature. Stable streams are in a dynamic balance between erosion and deposition – if either is in excess the stream is out of balance. Eroding streambanks result in a change in the physical structure, shape, and function of the stream

channel and contribute to excess sedimentation. Excessive bank erosion is due to channel instability and inappropriate upland and riparian land use practices.

Lateral bank erosion results in channel widening and stream shallowing which frequently leads to channel braiding. Vertical erosion (downcutting) results in straighter channels with steeper gradients. In both cases the condition of the channel is degraded due to structural simplification and loss of habitat complexity. Stream functions including energy dissipation, water storage, and wildlife habitat functions are also degraded by vertical or lateral bank erosion. For instance channel widening often results in structural simplification of the stream channel with the consequent loss of deep pools which provide critical fish habitat. James and Speas (2005) observed that the lack of deep pools in some Colorado streams may limit cutthroat trout survival during low flow conditions in late summer and during winter. Over-wide channels have excessively shallow water that tends to heat up more easily during summer and during winter promotes anchor ice formation during low flow periods. Downcutting results in the stream being confined inside the channel; consequences include accelerated flow velocity that results in increased lateral bank erosion, additional sediment loads to the stream and reduced access to the floodplain.

Downcutting decreases the potential for out-of-bank flows which results in reduced groundwater recharge and the downstream movement of increased sediment loads results in the filling of pools with sediment and the loss of critical pool habitat for trout. Excess sediment also deposits in riffle areas where it smothers macroinvertebrates and reduces trout spawning success. Female Colorado River cutthroat trout tend to locate their redds where velocity, depth, and bottom configuration induce water flow through stream substrate (Young, 1989). Sediment clogged gravels inhibit the flow of water that brings oxygen and removes waste products from developing embryos. Additionally, emergence of fry can be reduced when fine sediments, < 0.25 in., make up >20 percent of the substrate (Reiser and Bjornn, 1979).

Native riparian and streambank vegetation is essential to the stability of alluvial stream channels. In alluvial streams, bank stability depends on the right kind, quantity and cover of native riparian vegetation and on the range of stream flows. Riparian vegetation slows overbank flows, dissipating energy, reducing erosion and increasing the capture and deposition of fine sediments. In turn, the development of soils from sediment deposits promotes the growth of riparian vegetation. The development of soils in the riparian zone provides water storage reservoirs that are recharged during flooding. During dry seasons, water stored in the banks and riparian zone returns to the channels, contributing both quantity and quality to ecologically critical base flows.

Degradation or alteration of bank vegetation often results in the loss of bank integrity and excessive erosion. Any land use that alters riparian or upland vegetation or the natural flow regime can also trigger channel instability. Overgrazing by livestock, road construction, urbanization, channelization, dams, and climate change can alter watershed runoff and erosion characteristics to result in channel instability (Briggs, 1996). Reciprocally, channel instability can degrade riparian vegetation. This can occur in two ways; 1) bank vegetation can be directly destroyed when banks erode and 2) channel erosion that results in downcutting can inhibit overbanking flows thereby resulting in drying riparian soils and insufficient soil moisture to sustain riparian vegetation.

Beaver Dams

The condition of streams and rivers in the Roaring Fork Watershed today is vastly different compared to the historic condition due in great part to the dramatic reduction in the beaver population. Historically, most small to medium sized streams (1st to 6th order streams) in the valley were likely controlled by beaver dams (Saldi-Caromile et al., 2004). Members of the Lewis and Clark expedition from 1804 to 1806 noted that the beaver population in the West was abundant. The expedition opened the West to a variety of development pressures including beaver trapping. When John Charles Fremont traveled through Colorado in 1842-1843 his records indicate that he rarely saw an active beaver lodge (Wohl, 2005). Trapping had been so intense that in a few decades tens of millions of beaver had been killed. Beaver populations have somewhat rebounded and expanded throughout their former range, resulting in the reintroduction of beaver ponds and dams along riparian corridors. However, the continued absence or greatly reduced abundance of beaver ponds in much of the Rocky Mountains throughout the 19th and 20th centuries produced a disequilibrium that has yet to be corrected (Wohl, 2000). In the Roaring Fork Watershed beaver are active on parts of some streams but their abundance and thus their affect is likely much decreased compared to historic abundances and impacts. The continued deficiency of beaver dams along the majority of the streams miles in the Roaring Fork Watershed likely results in ongoing disequilibrium conditions.

Beaver dams and the activities associated with their construction modify stream channel and riparian habitat structure. Beaver dams create ponds that trap sediment, store water, dissipate flood energy and recharge ground water. The dams are often an essential structural element of the stream channel, providing strength and dissipating energy to produce equilibrium conditions (Saldi-Caromile et al., 2004). Beaver dams result in a stepped stream profile that decreases the local stream gradient thereby increasing the interaction between stream and riparian habitat, enhances nutrient cycling, increases bank-water storage, and creates in-stream pool habitat.

As beaver dams fill with sediment they undergo a process of ecological succession to gradually create wet meadows and then forested ecosystems. The process of succession creates a mosaic of habitats that greatly increases wildlife resources and thus biodiversity. Wet meadows and ponds also provide flood control by allowing floodwaters to spread out and infiltrate wetland soils, thereby slowing and reducing flooding flows.

The stepped channel profile that beaver dams produce also creates deep pools and shallow riffles that provide essential fish habitat. In high elevation streams during low flow conditions in late summer and winter, lack of depth may limit cutthroat trout survival (James and Speas, 2005). In this regard beaver dams play a critical role in the survival of many populations of cutthroat trout, by providing good summer and winter rearing habitat (Gregory and Ashkenas, 1990). Pool density and pool depth play an important role in the survival of all cutthroat trout particularly during low flow periods. Large (>152mm) Colorado River cutthroat trout live primarily in deep, slow water pools that are juxtaposed with fast water riffles that carry food to them and where cover is provided by boulders or logs. In the Willamette National Forest in Oregon beaver dams comprised 73 percent of the total volume of fish habitat during summer low flow conditions (Gregory and Ashkenas, 1990).

Stream Flow Characteristics

Flow Regime, Out-of-bank Flooding Flows, and Baseflow

A natural flow regime is essential to stream and riparian functions. Springtime in the Roaring Fork Watershed brings melting snow that results in peak flooding flows in all of our naturally flowing, undiverted streams. As the summer season unfolds snowmelt-influenced flooding flows subside and a period of recession occurs between peak flows and low flows. At the end of the summer and into the fall groundwater-influenced baseflow conditions characterize stream discharge. Thus the amount of water in the stream during low flow is a reflection of ground water discharge, or water released from natural storage features such as wetlands, beaver ponds and lakes.

Streamflow characteristics such as the timing, intensity and duration of flooding play an enormous role in determining the characteristics of stream and riparian ecosystems. Bankfull and flooding flows serve as the principal mechanism for creating and maintaining channel shape and functions such as sediment transport. High flows enhance habitat complexity by creating channel and floodplain features such as pools, islands, bars, oxbows, side channels, and off-channel ponds.

An essential aspect of the flood cycle is overbank flows – water that gets out of the stream channel and flows onto the adjacent floodplain. Over bank flooding supplies backwaters, oxbows and the floodplain with water, replenishes nutrients and removes waste products of soil and root metabolism. Sediment that is carried in the stream is deposited and helps build the floodplain, groundwater is replenished and riparian vegetation receives an adequate supply of water. Junk et al., (1989) developed the Flood Pulse Concept (FPC) to explain the importance of flooding to the river-riparian system. In the FPC the pulsing or periodic flooding of the river discharge is the major force controlling biota in river floodplains and has enormous impact on determining river productivity. The lateral exchange between the floodplain and river channel due to overbanking flows and alternating wet-dry cycles enhances nutrient cycling within the floodplain and optimizes productivity of the riparian zone, decomposition throughout the ecosystem, and fish spawning and feeding (Mitsch and Gosselink, 2000).

In the West the contrast between riparian and upland ecosystems is stark; riparian areas are cool and moist, uplands are warm and dry; riparian vegetation is dense and lush and wildlife is consequently abundant; upland vegetation is more dispersed and so consequently is wildlife. Riparian ecosystems are more productive than adjacent upland systems due to their unique hydrologic condition and periodic flooding which is responsible for the unique environmental condition (Mitsch and Gosselink, 2000).

Stream-riparian Physical Characteristics' Influence on Water Quality

Stream and riparian processes have an enormous influence on water quality. Stream ecosystem processes such as meandering and overbank flooding, and habitat characteristics such as channel complexity, stream bank vegetation, wide and well-vegetated riparian zone and canopy cover tend to stabilize the stream channel and minimize environmental fluctuations.

Sediment and nutrients are the most common nonpoint source water pollutants in the U.S. and stream habitat changes are one of three leading sources of impairment (agriculture and urban runoff are the other two) (USEPA, 2007). Water quality is degraded by excess sediment and by pollutants, such as nutrients, metals, and pesticides that enter the water along eroding banks and move throughout the stream. Additionally many chemical and biological pollutants often adsorb to sediment and are carried into the stream with runoff.

Excess sediment degrades aquatic habitat and impairs water quality in numerous ways. Excessive amounts of sediment can smother bottom-dwelling organisms and bury fish spawning habitat and food resources, fill rearing pools and clog fish gills. Suspended solids increase turbidity thereby reducing the amount of light available to aquatic plants, and increase water temperature, thereby decreasing dissolved oxygen.

Water quality is also impaired by temperature increases and consequent oxygen decreases. Suspended sediment increases turbidity which causes an increase in water temperature because sediment particles absorb heat thereby raising water temperature. Dissolved oxygen concentration in water is inversely related to temperature thus as temperature increases oxygen concentration decreases. Colorado's native fish and aquatic insects typically have narrow temperature limits and require naturally high concentrations of oxygen. Changes beyond the natural temperature and oxygen concentration levels are often lethal to aquatic biota. Increased water temperatures can thereby alter the composition of biological communities. Increased temperatures and solar radiation has been shown to increase algal production and shift the algal community to be dominated by plankton algal communities thereby altering the macroinvertebrate community and disrupting the food chain (USEPA, 2007). Some non-native fish can tolerate temperature extremes and reduced oxygen levels and some tolerant macroinvertebrates can survive reduced levels of oxygen and increased temperatures. Altered stream temperature and dissolved oxygen levels may also lead to alteration in the bioavailability of metals and toxic organics which may result in new or potentially harmful chemicals affecting aquatic biota (USEPA, 2007). Thus a new, pollution tolerant community of animals and plants has come to dominate many stream habitats in the West.

Water quality is also improved by ecosystem characteristics that reduce and treat runoff and maintain bank stability. Structurally complex stream and riparian habitat minimizes the movement of sediment and pollutants into the stream. Riparian vegetation and soil filters sediments and pollutants from surface and sub-surface runoff before reaching the stream. Naturally sinuous, rough channels dissipate stream energy thereby reducing the erosive energy of the stream and protect banks from eroding sediment. Dense, native streambank vegetation improves water quality by increasing bank stability, dissipating stream energy and buffering the abrasive action of suspended solids in the stream thereby reducing erosion and trapping sediment.

Channel shape influences stream temperature. Naturally narrow, deep streams that have less surface area exposed to solar radiation in summer stay cooler – the opposite occurs with wide, shallow streams which rapidly warm up. In winter narrow, deep streams lose less heat to the atmosphere and are less susceptible to freezing – the opposite occurs with wide, shallow streams which are subject to anchor ice formation.

Channel and bank roughness increase dissolved oxygen in the stream by increasing turbulence. Canopy cover shades the stream which is also important in helping to maintain cooler stream temperatures with sufficiently high concentrations of dissolved oxygen. Complex stream structure with frequent riffle-pool sequences enhance nutrient cycling. Organic material such as leaf litter is carried downstream to settle in still pools where decomposition occurs. Nutrients released by decomposition, such as organic fats and carbohydrates, are carried downstream to riffle habitat where the nutrients are filtered out of the stream by periphyton– a complex assortment of microscopic plants and animals that are attached to cobbles and woody debris and other substrate. Larger organisms such as mayflies and caddisflies feed on the periphyton and they in turn become food for trout, dippers and others that are higher up in the food web.

Stresses

Direct Disturbance

Channelization and Channel Modifying Activities

Channelization and channel modifying activities include stream straightening, widening, deepening, relocating existing stream channels, bank armoring and installing culverts and bridge abutments. Channelizing activities simplify stream habitat, increase stream gradient, result in reduced average pool depth and play a critical role in nonpoint source pollution by increasing the delivery of sediment and pollutants that enter the stream; some channelizing activities can also cause higher flows thereby increasing the risk of downstream flooding (USEPA, 2006a). Channelization and modification causes both physical and chemical changes in the stream: channel deepening, straightening and armoring result in increased velocities and flows; channel widening results in shallower depths, increased water temperatures and reduced dissolved oxygen; channel narrowing results in increased erosion and turbidity. Thus channel modifying activities can:

- Disturb stream balance,
- Reduce structural complexity of the stream channel,
- Disrupt riffle and pool habitats,
- Create changes in stream velocities,
- Cause water to flow more rapidly and flood more extensively,
- Eliminate the channel structuring function of floods,
- Alter the base level of the stream (due to downcutting) which prevents out-of-bank flows,
- Increase erosion, sediment load and chemical and biological pollutants,
- Decrease water storage capacity (due to reduced out-of- bank flows),
- Decrease sediment storage on the floodplain (due to reduced out-of-bank flows), and
- Degrade aquatic habitat and decrease wildlife potential.

Many of these impacts are related. For example, straightening a stream channel reduces channel length thereby increasing channel gradient which causes an increase in stream velocities. Increased velocity can destroy downstream pool and riffle habitats and thereby degrade wildlife potential. Straightening and bank armoring also reduces the structural complexity of the channel which reduces the channel's ability to slow down flow velocities. Thus downstream velocities may continue to increase and lead to more frequent and severe erosion which results in increased sediment loads and more flooding.

Bank Erosion

Bank erosion can be caused by channel modification and of itself results in modification to the shape of the channel. Erosion occurs when the force of flowing water exceeds the resisting forces of bank material and vegetation (USEPA 2006a) – thus vegetation removal and “smooth” banks result in increased erosion. The types of erosion associated with channelization and channel modification that produce sediment are (1) destabilization of streambanks (2) increased flow, which carries more sediment downstream at a quicker rate, and (3) gully erosion. Bank erosion also produces sediment which deposits downstream resulting in further degradation to stream habitat and channel function. When more sediment is deposited in an area of a stream, critical habitats can be buried, channels may become unstable, and flooding can increase (USEPA, 2006a). In Colorado the CDOW attributes the most severe cause of aquatic and trout habitat degradation to eroding streambanks and over-width stream channels (CDOW, 2006). Impacts from stream bank erosion include:

- Modification to the shape of the channel – bank sloughing, channel widening & or deepening,
- Habitat simplification – loss of overhanging banks and meanders, loss of pool habitat,
- Downcutting – disconnection from riparian habitat, increased velocity and erosion,
- Lateral cutting – stream widening with consequent shallowing and loss of channel capacity,
- Excess sediment loads,
- Excess sediment deposition,
- Increased flooding,
- Degradation of aquatic habitat – sediment filling pools and embedding riffles, and
- Nonpoint source water pollution (sediment pollution).

Bank erosion can set in motion a series of events with cumulative and negative environmental consequences. For instance, bank erosion results in excess sediment in the stream that can bury critical aquatic habitat, create unstable channels and is a major nonpoint source pollutant due to the deposition and storage of nutrients, metals, and pesticides associated with eroded sediments (Osterkamp et al., 1998). Bank erosion that results in channel widening can decrease stream velocity and thus increase deposition within the channel that then reduces channel capacity; reduced capacity can lead to increased flooding and further erosion (USEPA, 2006). Bank erosion that results in downcutting results in disconnection of the stream from its floodplain which reduces the overbank flows that sustains riparian vegetation and replenishes groundwater stores.

Removal of Large Wood

Clearing and snagging or the removal of large wood and is one of the most destructive practices for aquatic habitat in forested alluvial streams (Saldi-Caromile et al., 2002). Forested alluvial streams are often heavily dependent on large woody debris for the development of complex channel structure and for stability. Tree and shrub roots stabilize stream banks. Large woody debris is a floodplain builder – logs that fall into the stream help build broader floodplains. Flooding behind logs helps recharge the floodplain. Sediment that is trapped and removed from the stream then helps build floodplain soil. In smaller streams where downed logs span the width of the stream natural drop structures are created that lower stream gradient, dissipate energy and

capture sediment. In larger streams large woody debris forms log jams that increase habitat complexity, dissipate energy and capture sediment. Large woody debris increases aquatic habitat value by creating deep pools, side channels, islands and point bars. Impacts from the removal of large wood include:

- Stream bed erosion,
- Decreased structural complexity,
- Increased stream gradient,
- Increased stream energy,
- Increased bank erosion,
- Increased sedimentation,
- Degraded aquatic habitat, and
- Decreased over bank flows and decreased recharge of the floodplain.

Beaver Extirpation

Beaver extirpation brought about a major alteration of the Western landscape (Grahame and Sisk, 2002). Beaver are a keystone species whose activity is integral to stream and riparian ecosystem sustainability. Beaver dams represent structural elements within the stream channel (Saldi-Caromile et al., 2002) and their removal has had severe and negative consequences for streams throughout the West. Beaver dams decrease stream gradients by creating a stepped profile, dissipate flood energy, control seasonal flooding, reduce erosion, capture and store sediment and nutrients, store water, increase bank storage, elevate local water tables, increase the interaction between the stream and floodplain, build floodplain soil, create deep pools and a myriad of habitats that support a wide diversity of wildlife. The environmental mosaic created by beaver ponds provides valuable habitat for wetland-dependent plants and animals (Wohl, 2000), open water breeding and rearing habitat for waterfowl, shorebirds and fish, and a variety of successional habitats for terrestrial mammals and birds.

In spite of their beneficial effects beaver dams continue to be deliberately removed or destroyed in many streams in the Roaring Fork Watershed. Beaver dams have been removed on Cattle and Fourmile creeks and the Roaring Fork River. Cattle grazing on stream banks have destroyed beaver dams on Snowmass, Fourmile and Cattle creeks. Impacts from beaver extirpation in the intermountain West include:

- Loss of stream structural complexity (lower habitat diversity,)
- Increased stream gradient,
- Increased stream velocity,
- Increased flooding flows and decreased base flows,
- Increased bank erosion – downcutting,
- Increased sediment loads in the stream,
- Increased nutrient loads in the stream (especially when dams are breached),
- Decreased out-of-bank flows,
- Decreased water storage,
- Lowered water table – soils drying – change in riparian plant community,
- Aquatic and terrestrial habitat simplification,

- Loss of wetland habitat – declines in fish, bird, amphibian and mammal populations that depend on these habitats,
- Disconnection between stream and riparian habitat – degradation & loss of riparian habitat, and
- Altered plant communities with upland and drought tolerant species becoming dominant.

Beaver and the dams that they build provide a wonderful example of the interconnectedness of the natural world and how removing just one thing impacts other parts of the ecosystem. For instance, removal of beaver dams increases the stream gradient which increases flow rates and bank erosion and downcutting which then inhibits the over bank flows that supply moisture to sustain riparian habitat. As the channel cuts deeper the water table is lowered and surface riparian soils and wet meadows dry out. Vegetation that was dependent on high soil moisture is replaced by plants tolerant of drier conditions. Animals that were dependent on wetland and riparian habitat also decline or are lost due to habitat alteration.

Dams and Diversions

Anthropogenic dams and diversions can alter natural flow regimes by altering the natural flow regime thereby affecting environmental conditions, habitat structure and biological communities. In the West the majority of streams have been modified for human use; streams have been dammed; instream flows have been depleted by diversions; and return flows are always altered with increases in temperature, nutrients, salts, and a variety of chemicals that enter the stream as effluent from sewage plants or as runoff from agricultural fields, golf courses or roadways (Wohl, 2001). Entire communities of wildlife have been destroyed by dams. Dams flood narrow canyons and destroy habitat for cliff-nesting raptors, swifts, swallows, canyon wrens, American dipper and a host of riparian song birds (Kingery, 1998).

In the Roaring Fork Watershed most of the headwater streams, including those of the Roaring Fork and Fryingpan Rivers, have been dammed, diverted or degraded by historic and current human development. Transmountain diversions dewater the watershed and in-basin diversions; although they eventually return some of the diverted water to the stream, severely alter water quality. Water development (dams and diversions) can disturb streams by altering the timing, quantity and frequency of flooding flows, by altering base flows, by altering water temperature and chemistry and by altering stream habitat structure. In response, aquatic wildlife communities are typically altered due to the individual and cumulative impacts of dam-induced changes to the stream environment.

Human population growth has been a major driver of water development. Dam building as a measure of water development, has kept pace with human population growth in the West: in the U.S. Rocky Mountain States in 1890 the human population was less than 500,000 and there were about 250 dams, by 1940 the population had grown to about 5 million and the number of dams to about 3,000, by 2000 the population was about 12 million and about 7,500 dams had been constructed (Pepin et al., 2002). Water impounded by dams is used for irrigation, water supply, flood control, and hydroelectric power generation. In Colorado agriculture has been the primary purpose for water development. For example, within Colorado's national forest and extending out as far as 10 km there are 67,747 points of diversion; water from 35 percent of the diversions is used exclusively for irrigation and 55 percent primarily for irrigation (Solley et al., 1998).

These diversions have decreed water allotments totaling more than 1.8 billion acre-feet annually (USDA, 1999); the historical mean annual runoff for the entire state of Colorado is only 10.7 million acre-feet (CDWR, 2007). Clearly water in Colorado is over-appropriated.

Stream Structure

Dams change the natural flow regime and interrupt the movement of water and sediment along the entire stretch of river that the dam affects thereby changing stream structure and function. Dams store and release water in increments over the course of the year according to societal needs rather than in a natural pulsed pattern (Pepin et al., 2002). Irrigation impoundments divert, reduce and store spring flooding flows and release water in the growing season whereas hydroelectric impoundments release water to match the energy needs of the human population.

Natural stream flow regimes are essential to maintaining stream structure and function. Flooding flows create and maintain channel shape and function and maintain physical habitat for aquatic plants and animals. Flooding flows erode the channel, flush sediment from pools and riffles and redistribute cobbles and boulders to form pool and riffle habitat, and they create oxbows, side channels and off channel ponds. When flood waters recede, sediment carried by the stream is trapped by vegetation and deposited on point bars, mid-channel islands and onto the floodplain thereby re-building the channel and replenishing riparian habitat with soil, nutrients and moisture. Thus erosion is balanced by deposition and equilibrium is maintained.

Hydroelectric releases result in flashy, short-term fluctuations that drastically change the natural flow regime to one few native wildlife species can tolerate. Irrigation, flood control and municipal dams reduce the variability in flow regime and magnitude of discharge so that the peaks are reduced and base flow is elevated. Because peak flooding flows are reduced flushing and out-of-bank flows are reduced in magnitude, duration and frequency. Thus channel substrate becomes smothered with sediment (Windell, 1992) and riparian areas and floodplain ponds are not replenished (Pepin et al., 2002). Additionally, with these types of dams base flows are elevated so that sediment eroded during flood stage is not re-deposited and rivers cut (incise) into their beds when they are starved of the sediment trapped behind the dam (Windell, 1992; Pepin et al., 2002). Channel incision is a common phenomenon downstream of dams. Above a dam, the sediment carrying capacity of a stream is decreased due to a drop in velocity. The reduction in velocity causes the stream to drop its sediment load. As the stream starts flowing below the dam, it regains its ability to carry sediment. The channel will start to incise because sediment is being removed and little new sediment is being deposited. A more incised channel disconnects the vegetation on the stream banks from the channel, which, in the worst case scenario, leads to replacement of a riparian vegetation community with an upland vegetation community.

Water Temperature

Dams alter the temperature regime of tailwater (below the dam) reaches with tailwater temperature typically much different from temperatures in the dam or in the upstream inflowing unregulated tributary (Windell, 1992). Deep-water releases (water released from the bottom of a dam) provide drastically colder water in summer and warmer water in winter than was originally present in the stream whereas surface releases can have a warming effect; each can alter stream ecology and result in changes in the fish and macroinvertebrate community (Pepin et al, 2002).

In winter, dams that result in excessively low base flows maximize the development of frazil (slush) and anchor ice which covers feeding areas, creates physical obstacles for fish and when it breaks loose can result in significant scouring of the streambed and stream bank (Windell, 1992).

Biological Functions

Dams interrupt the movement of wildlife and alter aquatic wildlife communities along the entire stretch of river that the dam affects. Only two percent of the rivers in North America are free flowing (Benke, 1990) – considering the environmental changes and consequent loss of native wildlife, elimination of wetland and riparian habitat and water quality degradation that result from dams and diversions the negative impacts from dams and diversions far outweigh the benefits.

Native wildlife has co-evolved over thousands of years with local environmental conditions including the flooding and temperature regime. Dams and diversions have radically altered most of the streams in the West and consequently local environmental conditions. Sudden changes in the physical or chemical environment, that are outside the range of natural variability, can and has resulted in the extirpation of native wildlife from many riparian and stream systems in the West.

Fish require adequate space in which to live and reproduce, they require protective cover from predators, tolerable temperatures and sufficient food and oxygen. Stream flow and channel morphology is critical in providing trout with adequate living space and conditions. Stream carrying capacity is related to the timing and amount of high and low flows; high flooding flows sculpt the stream channel creating essential pool habitat and low summer flows are major limiting factor for fish populations (Larsen, 2007a). Fish also need adequate conditions to reproduce. Successful spawning, incubation, hatching and emergence of fry requires appropriate water velocity, temperature, and oxygen and substrate (stream bottom material) that is the right size and is not overly covered with sediment – emergence is reduced when fine sediments make up >20 percent of the gravel (Larsen, 2007a). The environmental conditions that trout require depends on the species and size of fish – requirements are specific and the range of tolerance is fairly narrow; for instance for successful spawning cutthroat trout need a water depth of 0.2 ft, a stream velocity of 0.4-2.4 ft/second, substrate size from 0.2-4.0 inches and water temperatures 43.0 – 63.0° F (Larsen, 2007a; Larsen 2007 b). These environmental conditions are typically altered by dams and diversions.

Wildlife relies on natural seasonal changes in the environment, such as temperature or day length, to signal the start and end of life history activities such as breeding, migration or hibernation. If environmental cues and conditions are not in sync with biological rhythms disaster can result; fish may spawn at the wrong time or not at all and birds may migrate only to find that their insect food base has not yet emerged. Prolonged constant conditions – such as occurs in streams that are controlled by dams – disrupts those cues resulting in the loss of sensitive native species and the invasion of non-native species (Pepin et al., 2002). Increased variability – such as occurs with hydroelectric dams – leads to extreme environmental conditions and fluctuations that are outside the tolerance range of most native species.

In each case wildlife communities are altered with sensitive native species replaced by species that are tolerant of modified conditions. For example a diversion on a stream in the Fraser River basin in Central Colorado resulted in prolonged low flows downstream of diversions. Rader and Belish (1999) found that mayfly and stonefly species richness was lower downstream compared to upstream of diversions; ten abundant taxa were locally extirpated from reaches downstream of diversions and the relative abundance of invertebrates shifted below diversion structures from an even mix of mayflies, stoneflies, caddisflies and midges to a community dominated by midges and ostracods (non-insect invertebrates).

Sudden changes in stream flow and temperature can modify fisheries and result in the elimination of native fish. The impact of impoundments on stream fishes is generally negative but is ultimately dependent on the tolerance of a fish species to change – more highly adapted species tend to be less tolerant of change and often sustain the greatest impact from regulated tailwater streams (Windell, 1992). Water that is too cold may eliminate warm water species and too warm water may eliminate cold water species and both may cause reproductive failure. High water temperatures can cause increased incidence of disease, increased metabolism and increased food demand (Larsen, 2007b). If water temperatures are too high trout may not migrate upstream for spawning. Water temperatures at the spawning site also have to be right for spawning to occur and an increase in water temperature after spawning may adversely affect incubation, hatching time and emergence and survival of fry (Larsen, 2007b).

Fluctuating flows cause stress by periodically eliminating critical habitat and protective cover. Reduced flows or complete dewatering simply eliminates habitat. Excessive water velocity, as frequently occurs with a dam or diversion release, results in torrential flows that eliminate fish and macroinvertebrate species by removing protective cover (Windell, 1992).

Flow alteration sets in motion a cascade of processes and events that alters stream channel structure and environmental conditions that result in ecosystem degradation, and habitat loss with a consequent decline of native plant and animal species. Habitat loss is the primary reason for the decline of native fish in Colorado (Pepin et al., 2002). Dams and diversions fragment rivers isolating fish populations and prevent or delay migration to spawning streams. Flow alteration has simplified stream structure and reduced the diversity of stream habitats. Historically, flooding flows maintained a diversity of habitats which supported a diverse and abundant fish community. Since regulation, fish fauna in Colorado has become depauperate and non-native species dominate; one native fish is extinct and fifteen of the original thirty two natives occur only in small, fragmented populations (Pepin et al., 2002). The introduction of exotic fish species that are tolerant of the altered environment, has further contributed to the decline of native fish biodiversity (Stanford and Ward, 1986). Fish introductions are implicated in the decline of 25 percent of fish species: in Colorado total native fish species = 33, non-native species = 99, federally listed/at-risk species = 17 and candidates for listing as endangered = 1 (Tomback and Kendall, 2002).

Although not federally listed as endangered, native Colorado River cutthroat trout are clearly threatened with extinction – they currently occupy only five percent of their historic range; as of 2001 in the Colorado River watershed 159.6 miles of stream contained 76 conservation populations of Colorado River cutthroat (CRCT Task Force, 2001). Streams in the Roaring Fork

Watershed with conservation populations of cutthroat trout (genetic purity rating of B or better) include Difficult Creek, Express Creek, Cattle Creek, South Fork of the Fryingpan River, Rocky Fork Creek, Lost Trail Creek, Yule Creek and the Middle and North fork of Thompson Creek (CRCT Task Force, 2001). The severe contraction of the cutthroats' range and population size is due to the cumulative effects of habitat loss and the stocking and spread of non-native fish (The Center for Biological Diversity, 2007). Dams and diversions have severely degraded cutthroat habitat by: 1) stream dewatering which results in habitat loss and overcrowding that stresses fish and results in increased egg and fry mortality by exposing redds; 2) fragmenting habitat which reduces genetic exchange and population expansion; and 3) resulting in excess sedimentation that smothers spawning habitat (The Center for Biological Diversity, 2000). Native cutthroat trout require clear and cold water, naturally-fluctuating stream flows, low levels of sediment, well-distributed pools, stable streambanks, and abundant stream cover – all characteristics which are degraded by dam-induced flow modification. Introduced non-native fish are an added blow to the potential survivability of native fish species. One reason for the success of non-native trout species is dam-altered environmental conditions which give non-native brook and brown trout a competitive advantage over native cutthroats (The Center for Biological Diversity, 2000).

Riparian Habitat

Dams and diversions have also been a major factor in the large-scale elimination and degradation of wetland and riparian habitat (Grahame and Sisk, 2002). Rivers downstream of large dams experience fewer and smaller floods (Pepin et al., 2002). Altered flooding regimes that reduce out-of-bank flows result in riparian soils drying, lowered water tables and riparian vegetation being replaced with more drought tolerant plants. Plants that are more tolerant of the altered conditions invade regulated stream systems – these are often invasive, difficult-to-control plants such as tamarisk or Russian olive (Pepin et al., 2002). Cottonwood are especially susceptible to water stress and decline as groundwater becomes less available (Grahame and Sisk, 2002). Additionally, cottonwood recruitment is dependent on a naturally flooding and receding stream flow regime. With less flooding, there is less channel shifting and less suitable habitat for establishment of cottonwood and willow seedlings, which are dependent on recently inundated sediments to become established (Grahame and Sisk, 2002). Additionally, riparian and stream ecosystem stability is degraded wherever riparian forests have aged without young trees and shrub regeneration to replace dying individuals.

Physical effects and ecological consequences of dams and diversions include:

- Altered flow regime – reduced flooding flows, prolonged constancy or increased variability of flows;
- Fluctuating flows: periodically eliminate critical habitat, alter wildlife community composition, result in the elimination of native fish & invasion of non-natives more tolerant of altered environmental conditions, and alter macroinvertebrate community composition to be dominated by species more tolerant of the altered environment;
- Habitat loss: lower base flow results in a smaller portion of the channel suitable or available for wildlife with consequent population declines;
- Dewatering: often results in fish stranded in disconnected pools where water temperature is rapidly rising and oxygen is rapidly depleted;
- Altered stream structure: loss of natural flooding flows leads to habitat simplification, loss of habitat diversity with consequent declines of native wildlife populations;

- Reduced flushing flows: results in excess sedimentation and embeddedness which smothers macroinvertebrate and fish habitat, smothers fish eggs and bottom dwelling organisms and blocks sunlight which reduces the growth of beneficial aquatic plants;
- Altered sediment transport and deposition – excessive bank erosion and/or excessive deposition;
- Altered stream temperature: results in wildlife community alteration with natives declining and non-natives becoming dominant; reduced reproductive success of native trout with consequent population declines;
- Increased anchor and frazil ice formation with ice jam formation: results in fish kill and bottom scouring;
- Habitat fragmentation: dams and diversions are a barrier to wildlife dispersal. Consequences include population isolation and loss of genetic exchange;
- Habitat connectivity is truncated with stream-riparian connections consequently being lost;
- Reduced out-of-bank flows: results in wetland and riparian habitat degradation due to reduced moisture-replenishing flows, soil drying, lack of cottonwood, willow etc. recruitment, invasion of drought tolerant and non-native and weedy species; and
- Riparian and upland habitat lost to inundation with commensurate loss of wildlife.

Alteration of the Natural Disturbance Regime

Alteration of an ecosystem's natural disturbance regime also alters the ecosystem. Natural ecosystems evolve with and depend on a natural disturbance regime which increases habitat variability and resiliency: "When the range of natural variation in a system is reduced, the system loses resilience" (Meffe and Carroll, 1997). Human development has frequently altered natural disturbance regimes. Natural disturbances with characteristic frequency, intensity, duration and scale are critical to maintaining ecosystem function and habitat diversity. A diversity of habitats creates the potential for diverse wildlife communities. Natural, intermediate-level disturbances create a mosaic of habitat patches that increase potential wildlife diversity by preventing any one species from becoming dominant. Alteration to natural disturbance regimes diminishes potential wildlife diversity and degrades ecosystem function and resilience.

Flooding is the primary disturbance factor in stream ecosystems (Saldi-Caromile et al., 2004). Flooding shapes and maintains channel capacity and is the principle mechanism creating a diversity of aquatic habitat by redistributing boulders and cobbles to form pool and riffle habitat, and by creating side channels and oxbows. Flooding is also essential to maintaining habitat quality by flushing excess sediment from riffles and pools and out-of-bank flooding is important in maintaining wetland and riparian habitat. Periodic floods are vital to the maintenance of biodiversity within many riparian zones (Hansen et al., 2003). Flooding processes maintain a dynamic steady-state of riparian vegetation with a suite of successional stages that create a mosaic of vegetation types that may support a variety of wildlife species (Hansen et al., 2003). Many species of plants and animals are dependent on a particular successional stage therefore the presence of a mosaic of various successional stages enhances wildlife potential. In terrestrial communities disturbance also plays a dominant role in shaping the vegetative community and so plays a critical role in watershed function: For instance fire frequency and intensity affects species composition and structure of the plant community which in turn affects precipitation runoff and infiltration (Saldi-Caromile et al., 2004).

Human development of the landscape changes the natural disturbance regime of an ecosystem. Disturbances such as flooding, fire, and even small disturbances, such as a tip-up mound from a tree blow-down or pocket gopher activity are relevant to local ecology, increasing habitat patchiness and diversity (Meffe and Carroll, 1997). Flood regimes have been altered by diversions and dams, reducing the range of variability and resulting in less frequent and lower magnitude floods that are not able to maintain aquatic and riparian habitats. Agricultural and urbanization activities have resulted in widespread soil compaction which reduces infiltration and soil moisture, affecting vegetative communities, erosion and runoff patterns such that peak flooding flows are increased and base flows decreased. Agriculture and urbanization are also major disruptions of native plant communities that alter natural disturbance regimes which thereby affects groundwater, stream flow, and soil stability.

Impacts of altering natural flood regimes include:

- Loss of ecosystem resiliency: reduced potential for habitat maintenance and recovery from natural perturbations;
- Habitat simplification – reduced frequency of pools, side channels and oxbows, and riparian vegetation degradation due to loss of species and age class diversity;
- Habitat degradation – pools and riffles filling with sediment, riparian soils drying with consequent loss of riparian vegetation; and
- Reduced diversity and abundance of native wildlife species – loss of cutthroat spawning habitat, loss of bird species that depend on early- or mid-successional stage riparian vegetation.

Wildlife Species Assemblage Change

Changes in the assemblage of wildlife species in a community can alter trophic cascades – the way energy flows through the ecosystem. The deliberate introduction of non-native fish has dramatically altered the composition of the aquatic wildlife community in most Rocky Mountain rivers and has resulted in the extirpation of native fishes, amphibians, zooplankton and benthic invertebrates (Bowman et al., 2002). Further, impacts to one species may ripple widely throughout the aquatic community even extending to terrestrial species (Cole and Landres, 1995). For instance, lake trout were illegally introduced into Yellowstone Lake in 1994. Lake trout are large, predatory fish that are known to displace smaller western trout such as cutthroat. Whereas Yellowstone cutthroat trout provide an important prey base for animals such as grizzly, bald eagle and osprey, lake trout tend to occupy deep water and are unavailable to most of these fish-eating mammals and birds (Tomback and Kendall, 2002).

Wildlife community diversity sets up patterns of energy flow and nutrient cycling. Habitat disturbances or species introductions or extirpations that alter community structure and diversity can change these fundamental ecosystem processes (Malone and Emerick, 2002), often with negative impacts on those remaining species. For instance, fish introductions are implicated in the decline of 25 percent of native fish species and can greatly alter invertebrate communities (Tomback and Kendall, 2002). Most high elevation lakes evolved without fish. Without fish, alpine lakes developed complex food webs that included a diversity of invertebrates such as daphnia, copepods, amphipods, fairy shrimp, rotifers, clams and snails (Bowman et al., 2002). Today these aquatic invertebrates are particularly at risk because of fish stocking (Tomback and Kendall, 2002). Further, in some high-elevation lakes, fish introduction has increased lake

primary production (algae) and decreased wildlife diversity due to predation on (invertebrate) algal grazers and by increasing availability of the vital nutrient phosphorus (Bowman et al., 2002).

Impacts to aquatic and terrestrial ecosystems from changes to the composition of the aquatic wildlife community include:

- Changes in the way energy flows and nutrients are cycled;
- Extirpation of native fish, amphibians, macroinvertebrates and zooplankton; and
- Reduced food and habitat resources for native terrestrial and semi-terrestrial mammal and bird species.

Indirect Disturbance

Streams are laterally connected to upland terrestrial habitat. Modifications to upland habitat thus impacts stream ecosystems. Three major land uses affect Rocky Mountain ecosystems: residential development, extractive land uses such as logging and grazing and infrastructure development such as roads (Travis et al., 2002). These land uses and their impacts are reflected in the condition of stream ecosystems that drain the surrounding watersheds. Land use inevitably alters native plant communities, compacts soil, and typically reduces the resistance to water as it moves through the watershed, speeding runoff, increasing peak flows and decreasing low flows so that there is more water when it is not needed and less water when it is in short supply (Saldi-Caromile et al., 2004).

Land uses and alterations that impact stream condition include:

- Urbanization, impervious surfaces, recreation, fragmentation;
- Extractive uses: Grazing, agriculture, logging, mining;
- Infrastructure: Roads, power lines; and
- Non-native plant species – both a consequence of habitat modification and a habitat modifier.

Residential Development and Urbanization

Urbanization

Urbanization of mountain ecosystems poses unique environmental challenges. Mountain ecosystems are the source of water in the West and the functionality of those ecosystems determines stream health throughout the watershed. In the Colorado River watershed, mountains generate over 90 percent of the total discharge (Viviroli et al., 2003). Thus urbanization of the Rockies has consequences to streams and rivers throughout the Colorado River watershed. Human built environments have typically decreased water quality and quantity, fragmented the landscape and increased flooding and urban heat island effects. These negative environmental effects are largely due to impervious surfaces and habitat alteration. In the Roaring Fork Watershed the valley bottom is rapidly becoming a strip development roughly 40 miles long by 5 miles wide (Travis et al., 2002).

Impervious surfaces are those surfaces that are impenetrable by water including sidewalks, parking lots, roof tops, compacted soil, and lawns. The urbanization of watersheds increases the amount of impervious surfaces which then increases precipitation runoff, decreases infiltration, changes the runoff pattern by diverting runoff to storm sewers and preventing it from infiltrating

soils, alters the chemical characteristics of runoff, and alters the shape and stability of stream channels. Collectively these factors upset stream balance, degrade water quality and wildlife habitat values and result in drastically fluctuating stream flow and water temperature.

The problem with impervious surfaces is that water runs over them, not through them, and that creates numerous other problems. Water running off impervious surfaces, such as roads, collect nitrogen oxides from car exhaust, metals from brake linings, bacterial contamination, particulate matter from the atmosphere, phosphates from residential and agricultural fertilizers, sediment and road salts – and deliver these pollutants to the stream. In natural systems, or on roads of open-graded road aggregate, much of the pollutants would seep into soil where soil microbes would break down, detoxify or filter out pollutants – but pollutants can't penetrate an impervious surface and so end up in the stream (Frazer, 2005).

Impervious surfaces disrupt the hydrologic cycle. Impervious surfaces prevent precipitation and snowmelt from infiltrating back into soil. In natural systems soils and vegetation soak up, slow and store runoff and then slowly release that stored water back into the stream thereby decreasing flooding flows and maintaining base flows. In urban areas 30-40 percent of rainfall runs directly into the stream compared to the amount of runoff in forested areas which is typically less than five percent (Frazer, 2005). Collectively then “not only do you have too much water, all moving too fast, you have polluted water that kills fish and makes water unfit for drinking or recreation” (Frazer, 2005).

Runoff from impervious surfaces also increases stream temperature. Impervious surfaces, such as roads and parking lots, absorb heat which heats the rainfall that runs over those surfaces. Runoff can be heated by as much as 10° F and can raise stream temperature enough to harm aquatic wildlife and decrease levels of dissolved oxygen (Frazer, 2005).

Building and paving materials contribute to stream pollution. Asphalt contains carcinogenic chemicals such as benzopyrene, that are carried into the stream with runoff, and roofing materials shed cadmium, copper, lead, zinc and PAH's (polycyclic aromatic hydrocarbons) into runoff (Frazer, 2005). All of these chemicals have harmful impacts on the environment and potentially human health: while some of these chemicals are toxic others can disrupt physiologic functions by, for instance, acting as a pseudoestrogen (Frazer, 2005).

Urbanization causes eutrophication (nutrient enrichment) of streams by adding nutrients to previously oligotrophic (nutrient poor) streams (Pepin et al., 2002). Golf courses, ball fields, ski areas and lawns all add nutrients to streams. Excessive nutrients result in excessive algal growth that consequently decreases levels of dissolved oxygen in water and which is harmful to fish and other aquatic wildlife.

Habitat Fragmentation

Habitat fragmentation disrupts life processes. Many animals require a variety of habitats to meet their life history needs – if barriers exist between essential habitats population viability will suffer. For instance, habitat connectivity is essential to enable access to forage resources that change with the seasons of the year; to enable access to reproductive habitat that is in a different

location from winter habitat; and is critical to enable long-term population viability by ensuring genetic exchange.

What constitutes a barrier varies between species. Paved highways and roads constitute a barrier for many species and urbanization is a driving factor in increased road density and use. In the Roaring Fork Watershed roads parallel many streams and rivers and act as a barrier to terrestrial mammals and even birds attempting to access open water or attempting to move between winter and summer habitat. Road-killed deer, elk, bear, mountain lion, and songbirds and raptors are common along most of the roads that run parallel to streams including the Roaring Fork, Crystal and Fryingpan rivers, and Castle and Snowmass creeks.

Development induced habitat fragmentation also occurs in aquatic systems. Streams are fragmented whenever the connection is disrupted between up- and downstream reaches or between stream and riparian habitat. Dams, dewatering, and polluted stream reaches act as barriers to fish attempting to reach spawning grounds or recolonize stream segments. Human development activities in the riparian zone and in upland habitat have frequently fragmented and disrupted essential ecosystem processes. For instance terrestrial vegetation and soils play a key role in maintaining water quality and nutrient cycling. Urbanization of the landscape severs the connection between upland, riparian, and stream habitat thereby altering ecosystem processes.

Recreational Use

Recreational use of remaining natural habitats is one effect of urbanization. As the human population grows we can expect the growth and impact of recreation to also increase. The Rocky Mountain region is experiencing some of the largest human population growth in the U.S. and Canada—Douglas County in Colorado and Summit in Utah, grew faster than any other in the U.S. in the 1990s. In the 2000s resort areas such as Aspen, Colorado, have become “growth poles” due primarily to the attraction of the region’s environmental amenities (Travis et al., 2002). Resorts represent the most quickly expanding residential and commercial land use in the Rocky Mountain bioregion and human growth rates along the forest fringe now outpaces statewide growth rates (Travis et al., 2002).

Recreational use of mountain habitats can have both direct and indirect impacts on stream ecosystems. Direct impacts include stream dewatering for recreational activities such as snowmaking and golf course irrigation. Stream dewatering results in the loss of aquatic habitat, creates dangerously low winter streamflows for fish and degrades water quality by preventing sufficient dilution of nutrients and pollutants (Pepin et al., 2002).

Indirect impacts occur from degradation to riparian and upland habitats. Recreationists pose a real and significant threat to the very resource they so cherish (Marion, 1998). One of the most impactful recreational abuses occurs when soil function is degraded, soils are compacted or soils are lost through erosion or displacement. This is particularly true at picnic areas, campsites and along trails and streams where use is concentrated. Consequences of recreational use include trampling and subsequent loss of ground vegetation, shrubs, tree seedlings, erosion of surface litter and humus, erosion, and compaction of soil and exposure of tree roots and damage to tree trunks.

Vegetation trampling along streambanks is common along many rivers in the Roaring Fork Watershed and has resulted in soil compaction, streambank erosion and stream sedimentation and the loss of overhanging vegetation that shades the stream and provides protective cover for fish. Soil compaction reduces water infiltration, increases runoff, limits the ability of vegetation to reestablish, and results in an overall loss of soil productivity (Joslin and Youmans, 1999).

Ski areas impact streams indirectly by deforesting upland slopes and by “grooming” that compacts snow on the deforested ski slopes. Snow compaction lowers soil temperatures, reduces the survival of plants and soil microbes (Joslin and Youmans, 1999), reduces the insulating properties of snow and negatively impacts each major level in a food web including producers, consumers and decomposers. Temperatures beneath snow compacted by snowmobiles are considerably colder than those under undisturbed snow cover (Kuss et al., 1990) and compaction tends to increase retention of snow cover during spring and early summer. Thus the growing period for early spring plants is shortened which may result in the reproductive failure of these plants. In high altitude ecosystems the growing season is relatively short and further shortening of the growing season may eliminate some native species and select instead for fast-growing weedy species. Loss of protective, native vegetation, especially in severe climates, can lead to rapid soil erosion and increased surface runoff.

Other indirect impacts from ski areas include changes in the soil decomposers. Significant reductions in soil bacteria and soil fungi have been reported to occur with heavy recreational use (Kuss et al., 1990). Additionally snow compaction eliminates the subnivean habitat that small mammals depend on during winter; small mammals are a critical link between the grazing and detritus food webs. Ski area deforestation both eliminates vegetation and degrades soil function. Together snow compaction and deforestation result in the elimination of native habitat, altered plant community composition, eroding, degraded and compacted soils, altered runoff patterns, reduced infiltration and increased and rapid runoff. Additionally, ski areas are frequently located on north-facing slopes which are especially important water-storage landscapes. Taken together, impacts from ski area development have especially severe consequences to stream health.

Urbanization impacts include:

- Increased impervious surfaces,
 - Increased runoff, decreased infiltration
 - Increased flooding flows and decreased base flows
 - Decreased water quality: pollutant-laden runoff moves directly into the stream
 - Increased stream water temperature
 - Stream imbalance
- Increased stream nutrients (eutrophication) with a consequent decrease in dissolved oxygen,
- Habitat fragmentation, and
 - Wildlife population declines, local loss of native species, loss of genetic variability
 - Loss of ecosystem integrity
 - Loss of ecosystem function
- Recreational development
 - Stream dewatering from ski areas, golf courses, etc.: impacts include the loss and degradation of aquatic habitat and water quantity and quality

- Soil and vegetation degradation by trampling: results in bank erosion, stream sedimentation,
- Ski area development - deforestation and snow compaction result in altered runoff patterns and nutrient cycling, increased erosion, reduced water storage and degraded water quality.

Extractive Land Uses

Grazing

Overgrazing by domestic livestock has extensively altered and degraded riparian habitat and stream quality across the West and in many areas of the Roaring Fork Watershed. Overgrazing compacts soil, destroys vegetation, destabilizes streambanks, degrades water quality and reduces stream flows frequently below what is essential for wildlife survivability. Water quality is degraded by excess nutrient and excess sediment delivery to the stream. Overgrazed upland and riparian habitat results in vegetation destruction and compacted and eroding soil. Due to soil compaction more water runs over the ground instead of through it, carrying pollutants and eroding soil to the stream. The latest *National Water Quality Inventory* indicates that agriculture is the leading contributor to water quality impairments, degrading 60 percent of the impaired river miles and half of the impaired lake acreage surveyed by states, territories, and tribes (USEPA, 2006).

Improperly managed grazing in riparian habitats is detrimental to stream sustainability. Cattle spend a disproportionate amount of time in riparian habitat as compared to drier, and hotter, upland habitat and consequently have a disproportionate impact on riparian vegetation. Riparian vegetation plays a major role in streambank stability and maintaining water quality by trapping and removing sediment. Excessive grazing destroys vegetation and destabilizes streambanks. In Colorado on most CDOW properties, livestock grazing has been reduced or eliminated because, when not managed properly, grazing can be detrimental to river bank stability and increase sediment loads to the stream.

Grazing negatively impacts the fishery. While vegetation can usually recover from excessive grazing within 5 to 15 years, impacts on fish habitat and on the fishery may continue long after grazing has ceased and may not improve. Fishery sustainability is limited by factors including bank morphology, stream stability and sediment. Maintenance of bank and channel structure and function is essential to sustainable fisheries. Sloughing and eroding banks and structural simplification of stream habitat eliminates protective cover and foraging and resting habitat and increases sedimentation which smothers stream macroinvertebrates and degrades spawning habitat.

Selective grazing by domestic livestock on the most palatable and nutritious plant species such as cottonwood and willow has dramatically altered plant community composition and in so doing diminished riparian function. Often palatable species have been reduced or eliminated leaving non-palatable species to dominate riparian areas. Frequently these non-palatable species are also non-native species such as tamarisk (*Tamarix ramosissima*.) and Russian olive (*Elaeagnus angustifolia*). Vast areas of riparian habitat throughout the West are now dominated by non-native invasive plant species due to the cumulative impacts of over grazing, stream dewatering, irrigation-induced salted out soils, and channel downcutting with resultant lowering of the water

table. The result of over 100 years of grazing in has been the virtual eradication of many of the most biotically productive plant communities in the West (Jacobs, 1992).

Indirect grazing impacts result from activities such as diversion-induced stream dewatering. Raising crops to support cattle has resulted in-basin and transmountain diversions that have severely dewatered mountain streams. In the upper Colorado River basin states, Wyoming, Colorado, Utah, and New Mexico, 90 percent of the water is used to irrigate land for crops. Of the 1.6 million acres irrigated in the upper basin, feed for livestock is raised on 88 percent of the irrigated land (Grahame and Sisk, 2002).

Domestic livestock directly and indirectly impact stream ecosystems. Indirect effects from diversions and stream dewatering occur everywhere streams are diverted for agriculture. Direct affects of overgrazing depend on where grazing occurs. Overgrazing in riparian areas results in ecosystem level changes in plant communities and in adjacent aquatic communities (Rueth et al., 2002) including:

- Reduction or elimination of native riparian and upland vegetation due to selective grazing,
 - Altered plant community composition
 - Reduction or elimination of filtering and water storage functions and of wildlife habitat
- Bank erosion due to vegetation degradation
 - Excessive stream sedimentation due to bank and upland erosion,
 - Degraded water quality due to diminished riparian functions
- Higher stream water temperatures due to the removal of streamside vegetation,
 - Depleted levels of dissolved oxygen
 - Rising water temperatures are lethal to fish
- High coliform bacteria counts from polluted runoff ,
- Soil compaction,
 - Reduced infiltration,
 - Increased runoff
 - Increased pollutants and nutrients delivery to the stream,
- Channel widening from erosion and trampling-induced bank sloughing,
- Channelization and stream habitat simplification,
- Elimination of riparian habitat due to lowering of the water table and to channel degradation,
- Stream channel downcutting or braiding depending on soil and substrate with concurrent replacement of riparian vegetation with drought tolerant vegetation, and
- Invasion of non-native invasive plant species.

Logging

Extensive logging in the Rocky Mountains was first initiated by mining, then settlement and currently continues with commercial logging, urbanization and recreational development. Vast areas around mines and towns were deforested leaving a “wilderness of stumps” (Wohl, 2001). This legacy of stumps and the absence of old growth forest are still visible at the townsite of Independence and throughout the Roaring Fork Watershed. Although commercial logging is infrequent in the Roaring Fork Watershed, recently logged landscapes are visible on ski areas and urbanized areas which sprawl into wildlands effectively deforesting the landscape.

Logging eliminates vegetation, alters forest structure, composition and function, fragments the landscape, compacts soil and eliminates the litter layer. Stream effects from forest harvest include altered soil, water, and nutrient cycling properties (Rueth et al., 2002). Impacts to the stream include increased peak flows and decreased base flows, degraded water quality, and impaired stream habitat. Forested ecosystems exercise strong regulatory functions over the chemistry of water passing through it (Likens and Borman, 1995). Long-term research at the Hubbard-Brook experimental forest has demonstrated that in forested watersheds internal nutrient cycling conserves most of the mineral nutrients whereas in deforested watersheds water quality is degraded by excessive nutrients such as nitrates.

An indirect impact of forest harvest occurs from associated road building. Road building results in the removal of vegetation, alters runoff patterns, interrupts and redirects the flow of shallow groundwater thereby increasing erosion and decreasing soil water storage and creates impermeable surfaces. Additionally roads provide corridors for the invasion of noxious weeds and channel the flow of pollutants into receiving streams.

Effects of timber harvest and associated road building on stream ecosystems include:

- Vegetation reduction which results in nutrients leaching out of soil thereby decreasing soil fertility and increasing stream nutrients,
- Soil disturbance, removal of the litter layer and vegetation removal which destabilizes hill slopes resulting in increased erosion and sediment yield to receiving streams,
- Soil compaction which reduces infiltration and soil water storage thereby resulting in increased peak flows and decreased base flows,
- Noxious weed invasion,
- Altered runoff patterns with consequent increased erosion and reduced soil water storage,
- Aquatic habitat degradation due to excess sedimentation, and
- Water quality degradation due to excess nutrient enrichment.

Infrastructure

Road Building

Road building removes vegetation, exposes soils, creates impermeable surfaces and can drastically alter the routing of water through watersheds (Saldi-Caromile, et al., 2004). Roads directly change the hydrology of slopes and stream channels by intercepting and re-routing shallow groundwater flow paths and diverting water along the roadway to surface-water systems and streams (Trombulak and Frissell, 1999). Changes in the routing of shallow groundwater and surface flow may cause unusually high concentrations of runoff on mountain slopes that can trigger erosion through channel downcutting, new gully initiation, slumping or debris flow (Trombulak and Frissell, 1999).

Roads and trails also result in compacted soil, encourage erosion and reduce the quality of animal habitat by increasing human presence (Bowman et al., 2002). Erosion and sedimentation can severely and negatively impact aquatic ecosystems downstream for long periods of time. Roads and railroads that are built adjacent to rivers and streams change the flow pattern of rivers, cutting off side-channels where fish spawn and truncating meanders that dissipate energy and enhance out-of-bank flows. More water and sediment in stream channels can alter stream physical characteristics such as bank stability, sinuosity, and riffle-pool ratio, usually with

negative effects. These changes lead to changes in the fishery and in riparian and wetland vegetation (Schindler, 2002).

The presence of roads nearly always indicates habitat degradation and loss of ecological integrity. Roads cause erosion, damage roots of nearby trees, change soil density, temperature, soil water content, light levels, dust, surface waters, patterns of runoff, and sedimentation, as well as adding heavy metals, salts, organic molecules, and nutrients to roadside environments (Trombulak and Frissell, 1999). These effects extend beyond the road to penetrate and negatively impact surrounding terrestrial and aquatic habitat.

Non-native, Invasive Species

The invasion of non-native plant and animal species threatens native biodiversity and ecosystem functions. Non-native plants and animals adversely interact with native plants and animals and can damage resources, result in the decline of native species, alter ecosystem functions and even fundamentally change ecosystem type. Adverse effects of invasive exotic species often include the displacement, or replacement, of native plant and animal species, disruptions in nutrient and disturbance cycles such as the natural fire regime, and changes in the pattern of plant succession (Lovich, 1996). Human habitat alterations that disturb the landscape such as road building, livestock grazing, logging, and urbanization often create environmental conditions that enable invasion of non-native plant and animal species. Habitat alteration coupled with deliberate and accidental introductions of exotic species has resulted in widespread habitat degradation, decline of native species and, in the case of river systems, reduced flows.

For example, human alteration of riparian habitat has enabled the overwhelming invasion of non-native species such as tamarisk (*Tamarix ramosissima*). Tamarisk is an introduced riparian plant species that has deep tap roots that allow the plant to access deep ground water as well as adventitious roots that enable the plant to survive where there is no ground water. Human-induced alterations to riparian and stream habitat that have resulted from grazing, irrigation diversions, beaver extirpation and other channelizing activities has often resulted in stream downcutting with a consequent inability of stream to access the floodplain and resultant drying riparian soils. Thus native riparian vegetation such as willow and cottonwood, that requires moist soils and periodic flooding, are at an environmental disadvantage. Given the altered environmental conditions, species such as tamarisk, can out compete and replace native species.

Negative impacts of non-native species are many. The introduced tamarisk (salt cedar) has come to dominate hundreds of miles of riparian habitat in the West. Dense stands of tamarisk channelize, narrow and deepen stream channels so that backwaters are eliminated and carrying capacity of streams are reduced and flooding potential increased. Tamarisk is fire prone and introduces a regime of episodic fire which is uncommon in native riparian woodlands (Grahame and Sisk, 2002) and shortens the fire return intervals so that native shrubs are eliminated (Tomback and Kendall, 2002). Tamarisk has excessively high rates of water consumption which contributes to ground water depletion. Additionally, tamarisk is salt tolerant and increases soil salinity which decreases regeneration potential for many native plants.

Consequences of tamarisk invasion on native ecosystems are severe. Tamarisk invasion has led to the decline of native cottonwood communities and associated native birds and reptiles

(Lovich, 1996). Outside of its natural range tamarisk does not provide suitable habitat for wildlife and has little forage value to native wildlife. Thus as tamarisk displaces native vegetation the value of the habitat is diminished for many native animal species (Lovich, 1996).

In the arid west native riparian plant communities support the most productive and diverse wildlife populations of any community type. Although western riparian habitats represent less than 1 percent of the total acreage of public lands in the 11 western states, about 72 percent of all reptiles, 77 percent of all amphibian species, 80 percent of all mammals, and 90 percent of all bird species routinely use riparian areas for food, water, cover or migration routes (Grahame and Sisk, 2002). For instance, in Colorado riparian lowland habitat (below 6000') supports 302 native wildlife species while similar elevation sagebrush habitat supports 86 species; riparian transition habitat (6000-9000') supports 222 species while similar elevation aspen forest supports 70 species (CDOW, 2007).

This disparity between small land area and large wildlife value is due to the unique environmental conditions and rich habitat resources that are created by the interactions between water, soil and vegetation – soil moisture is high, air temperatures are cooler, habitat variety and structure is diverse and foraging resources are diverse and abundant. Noxious weeds such as tamarisk degrade these environmental conditions that are essential to native wildlife – habitat structure is simplified and variety is reduced, soils become saline and dried out, shade is reduced and forage is limited to the few plants that can tolerate salted-out soil. An extreme example of ecosystem alteration has occurred on the Colorado Plateau where tamarisk has replaced thousands of acres of riparian gallery forest, resulting in a significant decrease in biodiversity and ecosystem health (Grahame and Sisk, 2002).