2. Watershed Geomorphic Processes

Stream channels transport watershed products including water, sediment, woody debris, and nutrients to the lower end of the catchment. Fundamental characteristics of the channel such as plan form, capacity, and width-depth ratio, reflect the quantity and characteristics of watershed products supplied to and eventually transported along the channel. Changes in the quantity or nature of watershed products supplied to the channel are likely to result in changes to channel characteristics. However, the link between a watershed and its channel is complex and a channel's response to watershed changes can be difficult to predict (Lisle 1999).

The supply of watershed products to a stream channel is determined, to a great extent, by geology and climate (Figure 2.1). These factors are termed independent variables in models of channel response. This is because they do not respond to other major factors that govern channel behavior, and they are not influenced by human management. The impact of these independent variables on channel behavior is felt across the watershed. Topography and watershed gradients, which control the rate of erosion, are dictated by tectonic activity and subsequent fluvial erosion, or, in some cases, glacial erosion. The quantity and size of bed load and suspended load sediments available for transport by the channel are a function of how easily rock in the watershed erodes, and their mode of transport from hillside to stream channel. Climate-driven precipitation determines the amount and timing of water and sediment supplied to the channel. Geologic and climatic histories also influence the delivery of watershed products. For example, effects of higher past erosion rates (driven by a wetter climate) still influence how erosion occurs today.

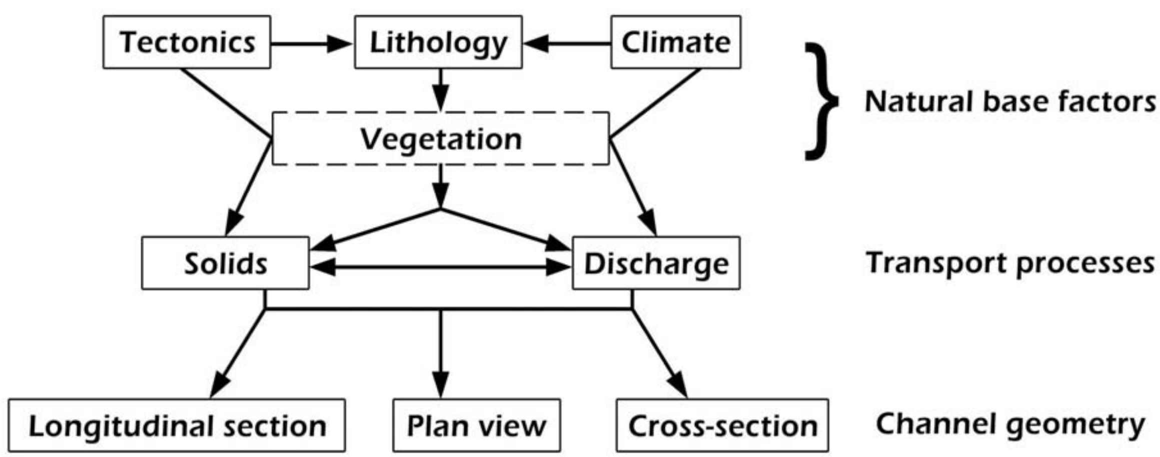


Figure 2.1 Controls on the morphology of river beds. *From Mangelsdorf et al, 1990*

The transport of products through the stream system is also influenced by climate and geology. Large-scale geologic events and features such as faults, landslides, or bedrock constrictions influence the stream profile gradient, the continuity of sediment transport down-valley during floods, and the storage of sediment and wood on the floodplain (Grant and Swanson, 1995; Benda, 1990; Miller, 1994). The magnitude, timing, and duration of floods all have a significant influence on rates of sediment transport.

Although geology and climate are the principle physical factors responsible for channel form, vegetation plays a fundamental role both in regulating the supply of watershed products to the channel and in the transport of those products along the channel (see Figure 2.1). In the watershed, vegetation influences evaporation and infiltration rates, erosion rates, sediment storage, and the supply of wood to the channel. Along the stream channel, vegetation influences channel plan form, hydraulic resistance to flow, cross sectional shape, sediment storage, bank stability, and the transport of large woody debris. The relationship between physical watershed processes and vegetation is complex and variable through time. Many riparian plants are highly adapted to regular disturbance. Over the short term, floods may cause scour and destroy vegetation, yet the scoured surfaces provide important areas for subsequent plant colonization. Over the long term, sediment storage, erosion, and transport during floods can influence soil moisture and groundwater availability to plant communities on the valley floor well after the flood event.

The stream ecosystem is the product of this complex and interconnected set of physical processes acting throughout the watershed**,** modulated by the hydraulic and structural influence of vegetation and wood. To add to the complexity of the aquatic ecosystem, these processes are highly dynamic over time, responding to climatic variability and circumstance.

2.1 Geologic Influences on Geomorphic Process

The Carson River watershed encompasses some 3,966 square miles, of which 606 square miles are located in Alpine County, California (Horton 1996:1). The Upper Carson River watershed within California can be divided into two major sub-watersheds: the East Fork of the Carson River and the West Fork of the Carson River, both of which have their origin in the Sierra Nevada. Of the two, the East Fork is the larger sub-watershed. The channel is about 65 miles in length and its headwater is at about 11,000 feet. In comparison, the West Fork channel is about 33 miles in length and its headwater is at about 9,000 feet. The relative size of the watersheds is reflected by their average annual discharge. At Markleeville, the East Fork has an average annual discharge of 255,560 acre-feet, while the West Fork at Woodfords has a discharge of 79,640 acre-feet (Horton 1996:13).

Figure 2.2 shows channel gradient for the trunk streams and major tributaries within the assessment area. Since the assessment area encompasses only the main stem channels and a few of the major tributaries, most channel gradients are less than 4 percent. Exceptions are found along the West Fork between Woodfords and Lower Hope Valley where local channel gradients can exceed 10 percent, and along portions of Markleeville/Hot Springs and Wolf Creek.

The East Fork of the Carson River is dominated by volcanic and volcaniclastic rock that is Miocene in age (Figure 2.3). These rocks include lava flows, ash, mudflows and volcanic breccias extruded during widespread volcanism in the Sierra Nevada. The West Fork of the Carson River contains a mixture of Tertiary volcanic, extrusive igneous, and granitic formations from the Cretaceous, and metamorphic formations from the Cretaceous and Jurassic. Overlying these rock formations, predominantly along the West Fork, are younger Quaternary fluvial and glacial deposits. These deposits are associated with multiple glaciations that occurred over the past two million years, and with post-glacial erosion and deposition processes of the past 10,000 years.

Table 2.1 summarizes watershed characteristics for each sub-watershed delineated in Figure 2.2. Information presented in this table was derived from the project GIS. Data were first generated relating to the density of drainages and roads in each sub-watershed. In each case, the higher the number, the greater the density of drainages or roads in the sub-watershed. Also, a relief ratio was calculated. Here, sub-watersheds with a higher ratio exhibit more topographic relief. Finally, each sub-watershed was reviewed to determine the abundance (by percentage) of various geologic formations. All of these data are important in understanding the relative sensitivity of sub-watersheds with regard to the potential for erosion and the production of sediments that could be introduced into the area's watershed.

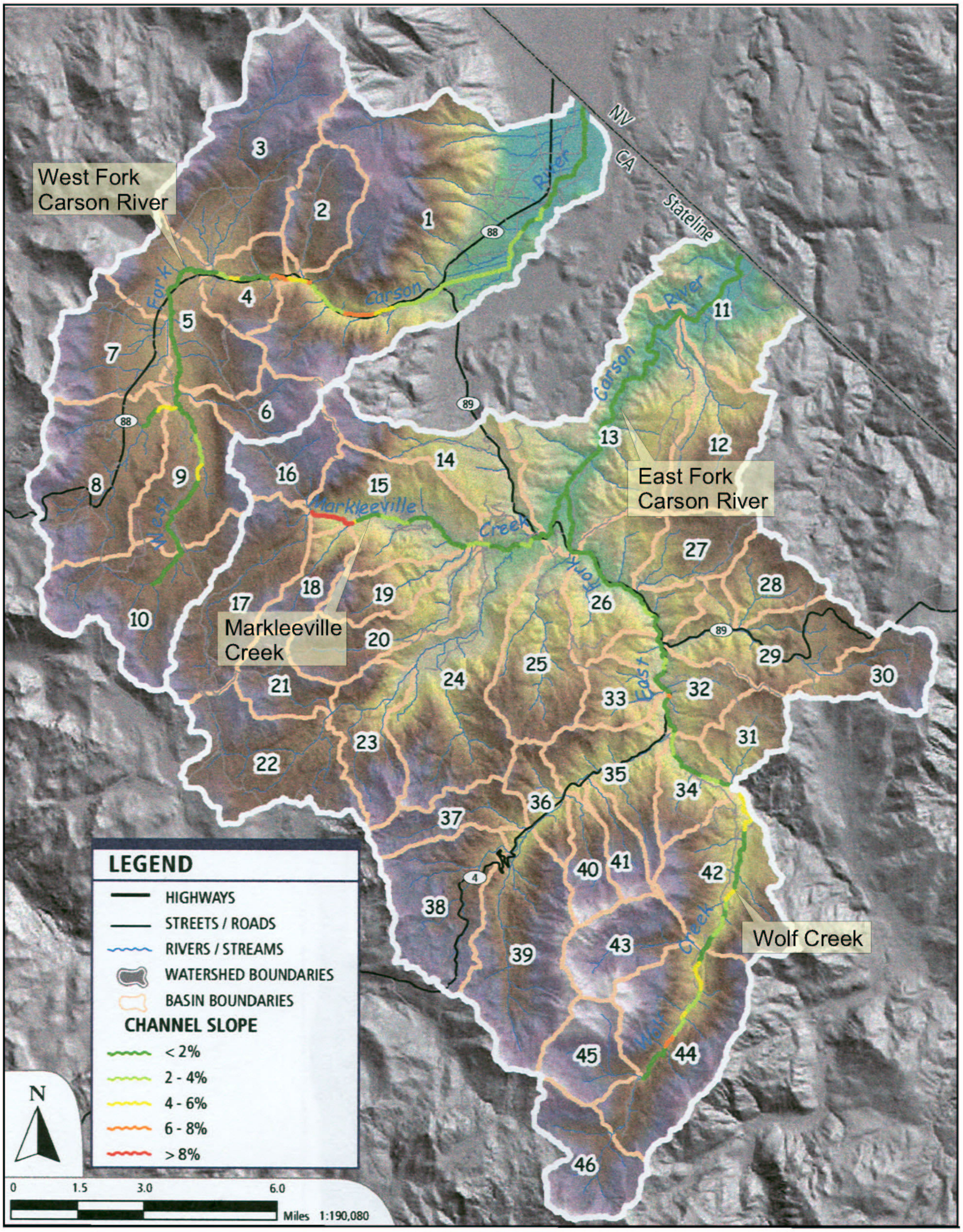


Figure 2.2. Sub-watershed delineation with channel slope, Upper Carson River Watershed.

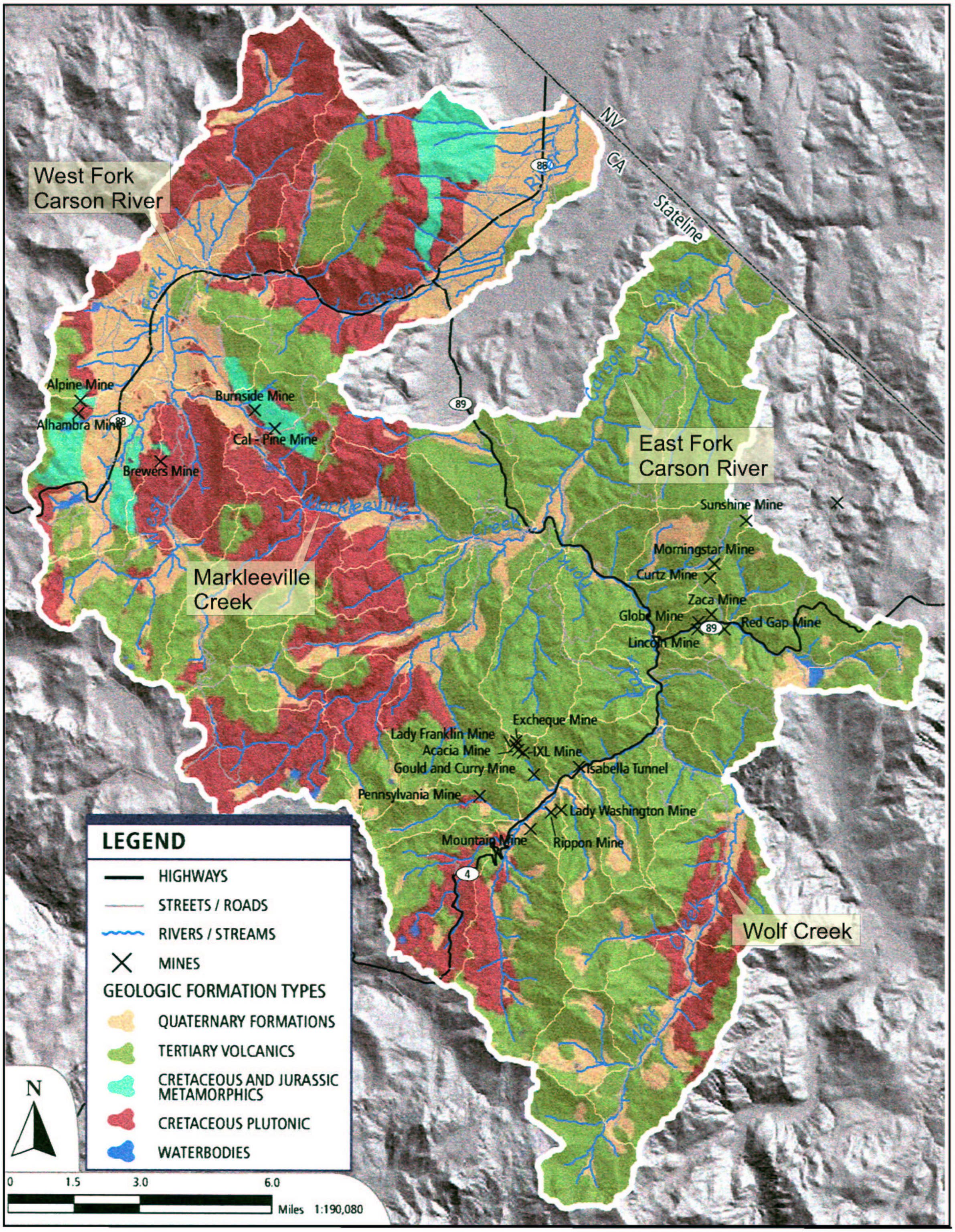


Figure 2.3. Geologic formation types and location of mines within the assessment area.

Table 2.1 General sub-watershed characteristics.

Basin ID	Drainage Density	Road Density	Relief Ratio	Percent of Geologic Formation Types in Each Basin				
				Cretaceous and Jurassic Metamorphics	Cretaceous Plutonic	Quaternary Formations	Tertiary Volcanics	Waterbody
1	1.36	1.39	0.10	13.4%	35.0%	31.2%	20.4%	0.0%
2	0.74	0.98	0.17	0.0%	33.9%	8.6%	57.6%	0.0%
3	1.36	0.76	0.12	0.0%	76.4%	23.1%	0.5%	0.0%
4	0.89	1.84	0.25	0.0%	45.5%	17.0%	37.6%	0.0%
5	1.14	2.33	0.14	4.8%	12.2%	63.5%	19.4%	0.0%
6	1.39	1.23	0.18	27.1%	15.1%	25.7%	32.1%	0.0%
7	1.64	1.51	0.17	1.6%	19.0%	60.6%	18.0%	0.7%
8	1.10	1.35	0.13	23.6%	14.5%	42.5%	18.2%	1.2%
9	1.33	1.55	0.09	2.7%	85.8%	10.0%	1.5%	0.0%
10	1.41	0.57	0.13	0.0%	14.8%	24.3%	60.5%	0.4%
11	2.02	0.91	0.17	0.0%	0.0%	14.4%	85.6%	0.0%
12	1.62	0.40	0.12	0.0%	0.0%	1.4%	98.6%	0.0%
13	1.40	1.08	0.08	0.0%	0.0%	11.1%	88.9%	0.0%
14	1.34	1.70	0.15	0.0%	23.9%	8.9%	67.1%	0.0%
15	1.60	0.86	0.16	0.0%	48.1%	18.5%	33.4%	0.0%
16	1.21	0.99	0.15	12.3%	69.8%	5.7%	11.7%	0.5%
17	1.28	0.96	0.08	0.0%	42.7%	10.9%	46.3%	0.0%
18	1.29	0.00	0.20	0.0%	43.8%	9.5%	46.7%	0.0%
19	1.15	0.00	0.16	0.0%	63.6%	0.5%	36.0%	0.0%
20	1.07	1.30	0.11	0.0%	36.4%	17.0%	46.6%	0.0%
21	1.30	0.55	0.16	0.0%	15.1%	14.3%	70.6%	0.1%
22	2.00	0.81	0.10	0.0%	71.9%	5.7%	20.8%	1.6%
23	1.78	0.00	0.18	0.0%	53.0%	6.8%	39.9%	0.3%
24	1.53	0.91	0.19	0.0%	13.0%	19.6%	67.4%	0.0%
25	1.09	0.59	0.12	0.0%	0.0%	0.0%	100.0%	0.0%
26	1.47	1.09	0.15	0.0%	0.0%	3.6%	96.4%	0.0%
27	1.69	0.76	0.15	0.0%	0.0%	28.9%	71.1%	0.0%
28	1.14	0.45	0.20	0.0%	0.0%	2.9%	97.1%	0.0%
29	1.21	1.66	0.10	0.0%	0.0%	9.9%	89.3%	0.8%
30	1.08	1.09	0.11	0.0%	0.0%	16.3%	80.6%	3.2%
31	0.88	1.08	0.16	0.0%	0.0%	0.0%	100.0%	0.0%
32	1.88	1.79	0.20	0.0%	0.0%	3.8%	96.2%	0.0%
33	1.44	0.52	0.28	0.0%	0.0%	0.0%	100.0%	0.0%
34	1.36	1.20	0.30	0.0%	0.0%	1.0%	99.0%	0.0%
35	1.46	0.65	0.26	0.0%	0.0%	6.2%	93.8%	0.0%
36	1.67	0.49	0.39	0.0%	0.0%	14.0%	86.0%	0.0%
37	1.09	0.00	0.17	0.0%	3.7%	5.3%	91.0%	0.0%
38	1.46	0.72	0.14	0.0%	47.5%	3.7%	47.0%	1.8%
39	1.64	0.29	0.14	0.0%	23.9%	11.9%	64.2%	0.1%
40	1.21	0.01	0.30	0.0%	0.0%	17.1%	82.9%	0.0%
41	1.71	0.05	0.25	0.0%	0.0%	30.4%	69.6%	0.0%
42	1.73	0.93	0.18	0.0%	33.3%	13.8%	52.9%	0.0%
43	0.71	0.00	0.25	0.0%	6.2%	13.3%	80.4%	0.0%
44	1.37	0.53	0.16	0.0%	23.5%	18.1%	58.4%	0.0%

2.1.1 Glacial Morphology

The morphology of stream channels within the East and West forks of the Carson River was strongly influenced by a series of glaciations that occurred in the watershed over the past 2 million years. The most apparent remnants of past glacial events include a series of terminal moraines and large deposits of unsorted sediment, all left at the terminus of each glacial advance. These glacial deposits often formed at natural points of constriction that impeded sediment transport and resulted in the establishment of glacial outwash valleys - like modern Hope Valley. These valleys were most likely preceded by broad, shallow lakes. The transition from lake to alluvial valley to meadow probably occurred quickly as retreating glaciers delivered large amounts of outwash sediment. Because the meadows are relatively unconfined and have a low gradient, the modern stream channel is relatively sinuous and tends to migrate slowly across the meadow over time.

Where the stream is confined by adjacent canyon walls, material deposited by glaciers and glacial processes included very large boulders. High stream flow from glacial melt water provided the energy to incise deep canyons. Smaller material was transported out of the canyons, leaving behind larger boulder deposits. The current stream flows over these materials, which it cannot move. Material transported out of the Woodfords Gorge during periods of rapid incision created large alluvial fans at the mountain front. The modern stream is incised into these deposits.

Glacial erosion still influences sediment production in the watershed today. Glacial cirques eroded in volcanic rocks in the upper portions of the watershed are over steepened and produce sediment for stream channels through gully formation, debris flow, and other hill slope processes. These processes are important today in the upper West Fork above Charity Valley and in the Upper Hot Springs Creek watershed. Glacial erosion also appears to have steepened valley walls upstream of the meadow section along Wolf Creek, contributing to high sediment production.

The degree to which glacial processes affect current channel and valley morphology depends on the extent and magnitude of glaciation. The West Fork of the Carson is wetter than the East Fork since it is closer to the Sierra crest and has a higher average elevation. The wetter condition of the West Fork suggests that glaciation would have played a more prominent role in its morphological development. For example, glacial outwash and canyon morphology occur throughout Hope and Faith Valleys. In the East Fork, glaciation dominated channel morphology is limited to Hot Springs, Pleasant, and Wolf Creek Valleys, and upper portions of the main stem of the East Fork (outside of the assessment area).

2.2 Hydrologic Influences on Geomorphic Process

2.2.1 Precipitation

Over 80 percent of the total annual precipitation within the Upper Carson River watershed falls between November and April, primarily as snowfall. During summer months (from July through September), localized heavy rainfall from monsoon driven thunderstorms can occur. During most years, however, individual summer months usually have little or no rainfall. Precipitation varies considerably across the watershed depending primarily on elevation and proximity to the Sierra Crest. Winter storms consist of meso-scale storm systems that originate in the Gulf of Alaska. These storms are driven by jet stream winds and entrain moisture as they pass over warm waters of the eastern Pacific Ocean. Typically, rain-on-snow events occur when a deep layer of moist air is entrained from near the Hawaiian Islands, a climatic pattern referred to as the "Pineapple Express." Precipitation is enhanced on the western slope of the Sierra through orographic dynamics with reduced precipitation on the east side of the Sierra Crest. This "rain shadow" effect is more pronounced the further east you go with areas immediately east of the crest receiving spill-over moisture from orographic precipitation.

Figure 2.4 provides mean monthly precipitation values for two gages located in or near the assessment area. One gage is located at Woodfords (period of record, 1948-1990) with an average annual precipitation of 21.2 inches. Mean monthly precipitation during a typical winter month averages between 2 and 3.5 inches. The second gage is located at Twin Lake (period of record, 1948-2000), just over the ridge from the Upper West Fork in the Mokuleme River watershed. The high elevation of this site and its location near the Sierra Crest results in an average annual precipitation of 49.6 inches. Mean monthly precipitation during a typical winter month at Twin Lake averages between 6 and 9 inches, or approximately three times the amounts observed at Woodfords.

Average annual hydrographs for the West Fork at Woodfords (USGS Gage ID #10308200; period of record, 1960-present) and the East Fork near Markleeville (USGS Gage ID #10310000; period of record, 1901-1920 and 1939-present) are shown in Figure 2.5. Snow pack development and melt are dominant factors in producing runoff. During most years, precipitation falls as snow from November through April, most of which remains in place until the snowmelt season. The snow pack begins to melt in March, typically reaches a maximum in May, and then recedes through the remainder of the summer. Rainstorms that occur during the spring and summer have essentially no influence on the mean hydrograph (see Figure 2.4). Because of dry conditions, most rainfall that does fall during summer months merely recharges soil moisture; very little translates into stream flow.

Spring and summer precipitation does not typically contribute to stream flow.

Figure 2.6 is a summary of the annual and monthly mean daily flow values at these gages. The data show the probability of flows exceeding a given value over a period of record. Given the limited importance of summer thunderstorms, stream flows during late July through October are derived from subsurface lateral flows and from the exfiltration of groundwater from the alluvium filled valley bottom.

Beginning in the fall, frontal storms begin passing over the watershed. Typically, early storms recharge soil moisture depleted through evapotranspiration over the previous growing season. As the temperature drops, a greater percentage of precipitation falls as snow. Declining temperatures result in reduced evapotranspiration, allowing for efficient soil moisture recharge. Buildup of the snow pack increases soil moisture through the melting of snow in contact with the ground surface. This process, in conjunction with influent groundwater, is the source of base flow over the winter. As total precipitation increases over the season, the watershed becomes more responsive to individual storms. For example, rainstorms in the fall and early winter can produce moderate to high stream flow. Responses by individual large storms are evident in Figure 2.5, even though these storms are averaged with the entire data set.

2.2.2 Peak Flows

Peak flows impart hydraulic energy to channel and floodplain surfaces. This energy drives geomorphic processes such as sediment transport, erosion, and deposition. Hydraulic forces associated with peak flow can mobilize the bed, cause channel incision, recruit new bed load through lateral erosion, form and erode bars, and change channel shape and alignment.

To confidently describe the magnitude of peak flows within the Upper Carson River watershed, data must be drawn from a monitoring site that has a long-term record of instantaneous peak-flow measurements. Two such sites occur in the assessment area. They are located on the East Fork near Markleeville (USGS Gage ID #10308200; 1960-present) and the West fork at Woodfords (USGS Gage ID #10310000; 1901-1920 and 1939-present). Peak values for these gages over their period of record are provided in Figure 2.7.

Flash floods occur infrequently and may not be captured at gages.

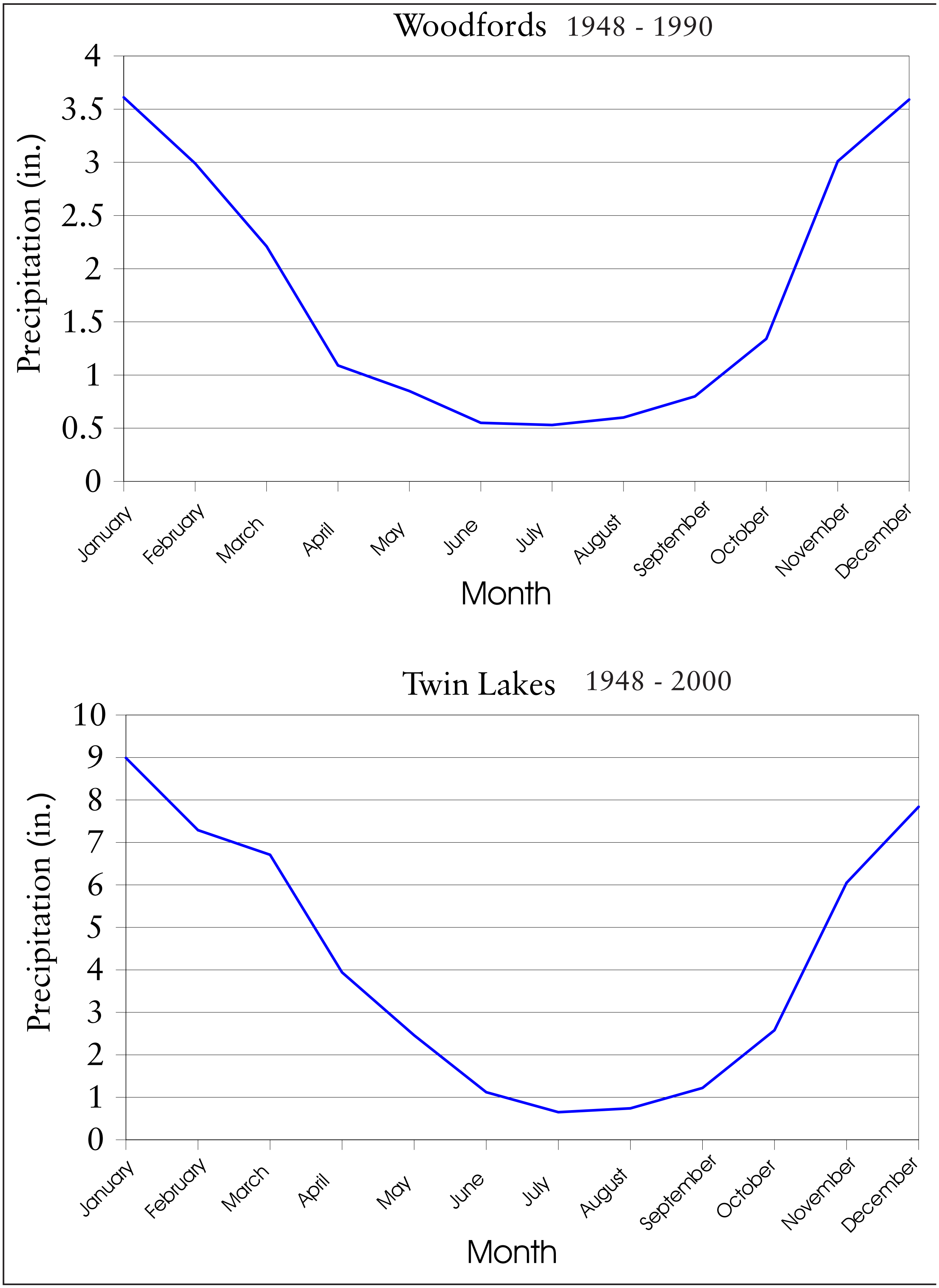
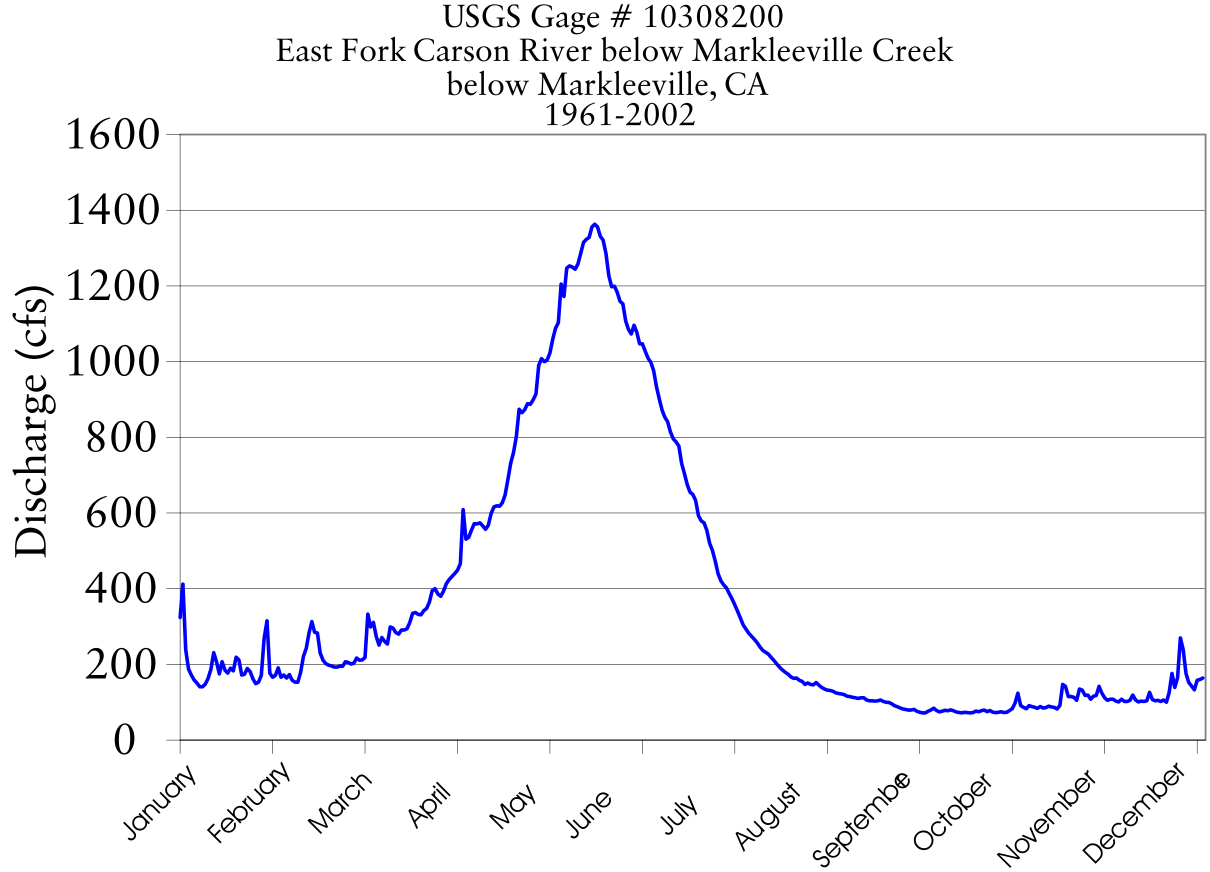


Figure 2.4. Mean monthly precipitation for two locations in the assessment area.



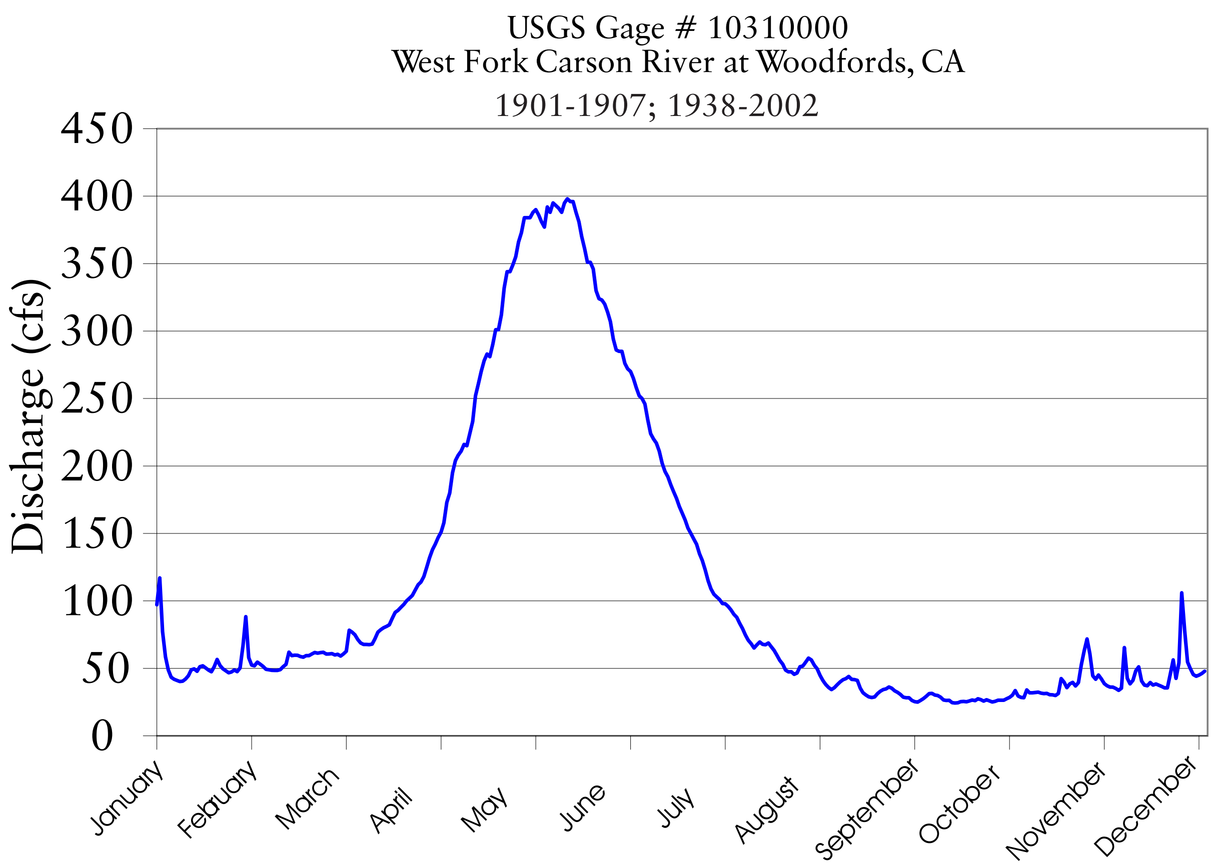
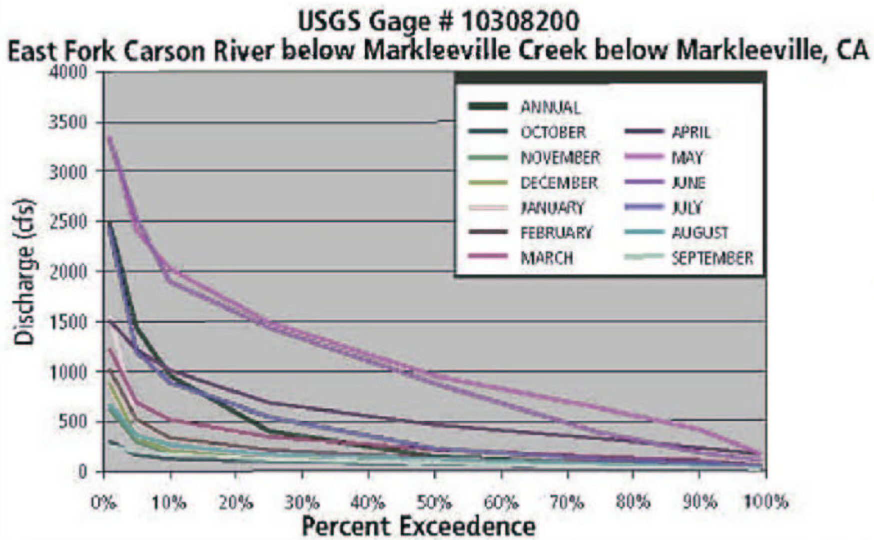
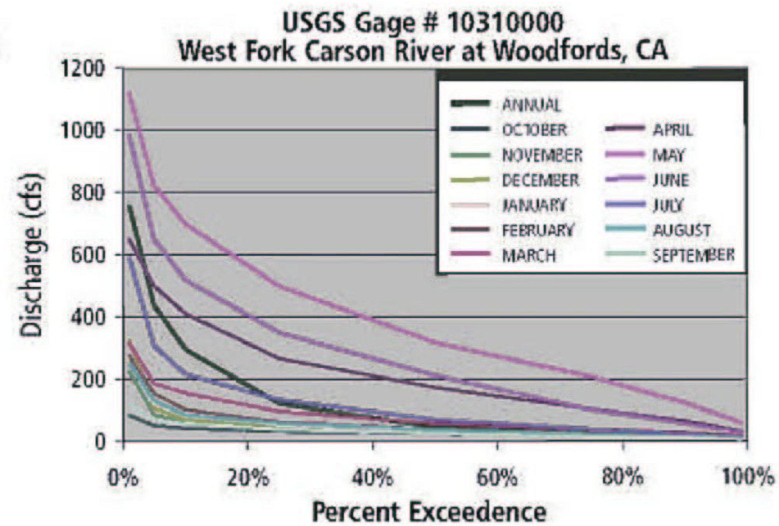


Figure 2.5. Average annual hydrographs for the East and West Forks of the Carson River within the assessment area.





USGS Gage # 10308200 Percent Exceedence Discharge Values (cfs)								
	1%	5%	10%	25%	50%	75%	90%	99%
Annual	2483	1440	959	400	143	76	50	26
October	296	161	123	95	68	45	32	23
November	618	293	183	105	77	58	41	28
December	876	339	205	120	80	64	50	31
January	1558	497	321	173	100	65	50	35
February	1016	519	335	215	130	90	62	39
March	1220	689	517	342	215	141	103	54
April	1504	1220	1011	684	462	321	230	165
May	3340	2410	2029	1490	953	626	410	173
June	3318	2540	1900	1440	877	379	184	103
July	2430	1199	892	541	224	117	79	48
August	661	355	262	170	120	71	46	22
September	256	196	169	118	75	44	30	16

USGS Gage # 103010000 Percent Exceedence Discharge Values (cfs)								
	1%	5%	10%	25%	50%	75%	90%	99%
Annual	758	437	296	122	45	25	17	10
October	84	51	42	32	24	17	13	8
November	224	86	61	38	27	21	16	12
December	327	107	69	45	28	21	17	12
January	250	122	92	53	30	22	17	13
February	276	154	102	62	38	25	20	14
March	315	187	156	96	57	38	27	17
April	650	500	411	267	173	103	65	32
May	1120	824	700	500	317	207	123	59
June	985	650	520	350	212	101	57	28
July	590	307	216	134	69	38	23	12
August	250	130	86	58	37	22	14	9
September	117	70	57	38	25	15	12	6

Figure 2.6. Flow duration curves and selected flow statistics for the East and West Forks of the Carson River within the assessment area.

An exceptionally long flood record has been kept for the West Fork at Woodfords (see Figure 2.7). Two separate types of floods are obvious in this record. Floods under about 1,000 cfs are due to snowmelt, and tend to occur in May or early June. The other type of flood can occur from November through February, and is the result of intense rainfall when snow is on the ground (rain-on-snow event). All floods in the West Fork record over 3,000 cfs represent rain-on-snow events, with the exception of the May 1996 snowmelt flood.

Rain-on-snow events appear to occur in clusters and may be tied to El Niño conditions in the Pacific Ocean. Several decades may pass without a single rain-on-snow event, as from 1964 to 1997. The period from 1950 to 1964, on the other hand, saw four rain-on-snow events. Based on longer-term Tahoe City rainfall records, strong El Niño conditions probably occurred in 1850-1860, the mid 1880's, and the first decade of the 1900's. Rain-on-snow events are important to the geomorphology of the Carson River watershed due to their magnitude. The average snowmelt flood is about 750 cfs; the average rain-on-snow event is at least five times larger. Substantial quantities of sediment are moved during rain-on-snow events, and extensive channel change can occur. The relative magnitude of rain-on-snow events may be somewhat larger in the West Fork watershed due to its proximity to the Sierra crest and its higher elevation. For example, the rain-on-snow event in 1997 was especially pronounced in the West Fork. It was nearly twice the size of any other floods recorded at the West Fork gage.

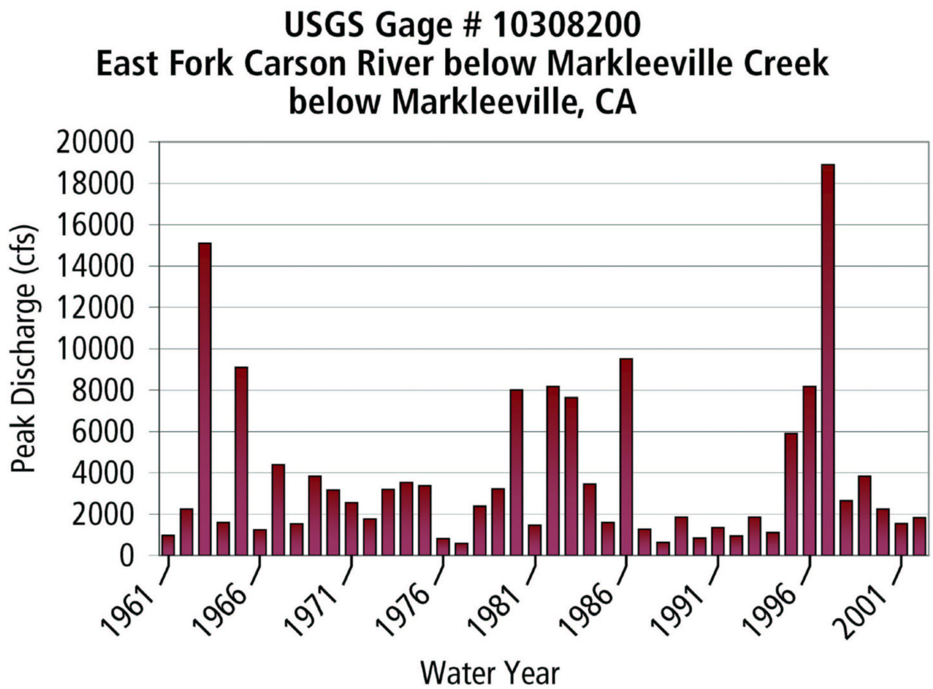
Large winter floods are well documented and seem to be tied to El Niño events.

Estimating recurrence values from peak flood flows requires careful consideration of regional data and the assignment of appropriate parameter values (USIAC 1982). To provide consistency to the assignment of recurrence values, the assessment team compiled information from existing flood frequency efforts assembled by the U.S. Geological Survey. Results of that effort are summarized in Table 2.2.

Table 2.2 Selected flood recurrence interval values.

Recurrence Interval (in years)	West Fork at Woodfords (in cfs)			East Fork at Markleeville (in cfs)	
	1961-2002	1938-2002	1997 Analysis[1]	1960-2002	1997 Analysis[1]
1.5	517	565	NA	1,731	NA
2	728	784		2,468	
5	1,513	1,588		5,218	
10	2,292	2,378		7,943	
25	3,661	3,758		12,720	
50	5,027	5,126		17,450	
100	6,750	6,848	6,270	23,390	26,200

1. Taken from "Flood of January 1997 in the Carson River Basin, California and Nevada," USGS, Fact Sheet FS-183-97, December 1997. The skew values used in this analysis differ from those used elsewhere.



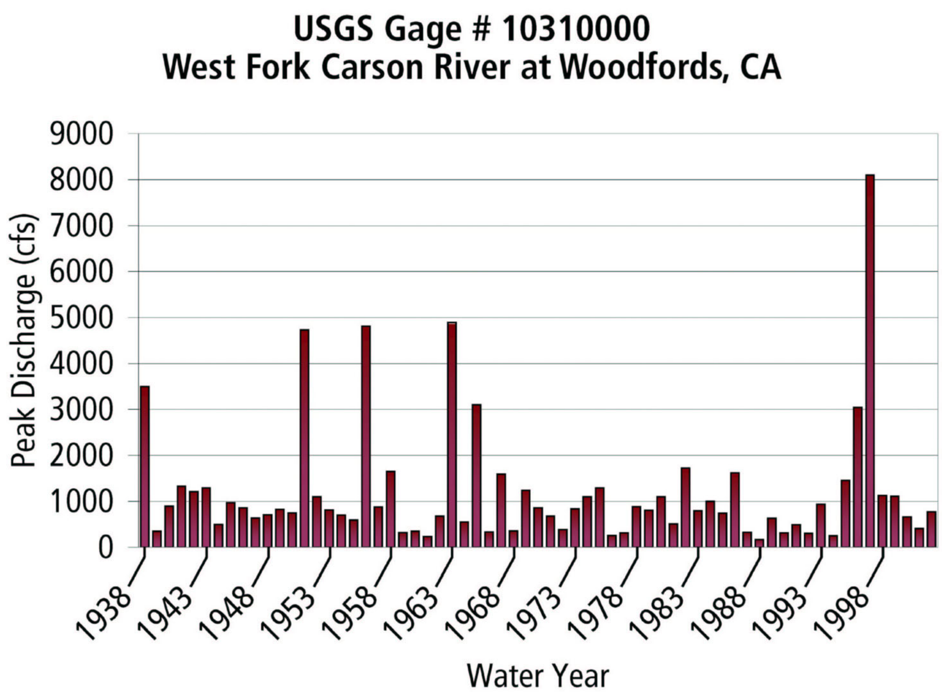


Figure 2.7. Annual maximum floods at stream gages on the West and East Forks of the Carson River.

Although they never produce the highest peak flows at gages on the main stem rivers, summer rainstorms produce localized high flows in higher parts of the watershed. Intense thunderstorms that occurred over a four-day period in August of 2003 produced flows well in excess of bankfull in upper portions of Charity Valley Creek. Flows along lower reaches of the West Fork during this same period were substantial but well below bankfull. This type of storm occurs infrequently and is highly localized. Anecdotal information suggests that storms of this intensity have not occurred in decades.

2.2.3 Low Flows

Low-flow hydrology is of primary importance to ecosystem quality. It is a limiting factor for fish habitat and it exerts considerable control over vegetation communities within the floodplain. This occurs through the interaction of channel flow and groundwater elevation in adjacent valley alluvium. In general, summer base flow is quite low in both the East and West Forks of the Carson River (see Figure 2.6). Although an early winter rainstorm might prompt a brief increase in flow, such rains are rare. The general trend is for low base flows to continue through the winter. Notable exceptions occurred in 1982 and 1983. Residual snow packs held base flows high during or immediately proceeding September 15.

> The West Fork experiences very low flows in late summer.

The long-term mean daily flow data at the Woodfords and Markleeville gages suggest that some base flow always exists. The 50th percentile flow for September and October at the East Fork gage is 75 and 65 cfs, respectively. Flows downstream of the Markleeville gage approximate this value since there are few, if any, diversions through the lower portion of the assessment area. On the West Fork at Woodfords, the summer low flow is about one-third of that seen on the East Fork. The 50^{th} percentile flow for September and October at the West Fork gage is 25 and 24 cfs, respectively.

2.3 Erosion and Sediment Supply

A major factor influencing channel morphology and geomorphic function is how sediment is supplied to the stream. The amount, type, and frequency of sediment supply have important effects on the character of the channel (Dunne and Leopold 1978; Rosgen 1996). Figure 2.8 shows the generalized relationship between sediment supply, channel gradient, channel sinuosity (how much the channel bends), channel stability, and basic plan form.

With high supply rates of coarse sediment, channel patterns tend to be braided or dynamically meandering. Channel sinuosity is relatively low, as is stability. Much of the East Fork of the Carson River exhibits these characteristics. As the supply of coarse sediment is reduced, channels tend to be more sinuous with large, looping bends. Overall gradient is lower, and channel stability is higher. The West Fork in Hope Valley exhibits these characteristics. As can be seen, sediment supply has an important influence on channel form.

2.3.1 Geologic Influence

Background geology strongly influences the rate and type of sediment supplied to stream channels. Extrusive volcanic rock is poorly consolidated and tends to be friable and very erosive. Material may be transported to channels from steep volcanic surfaces by overland flow or gullying. These factors (volcanic lithology and steep slopes) can be employed to assess relative erodability (Figure 2.9). This exercise illustrates the prevalence of highly erosive terrain in the East Fork. In the East Fork, adjacent slopes are extremely steep and channels are strongly incised into volcanic material. Some similar terrain is present along the West Fork, but it is confined to upper portions of the watershed.

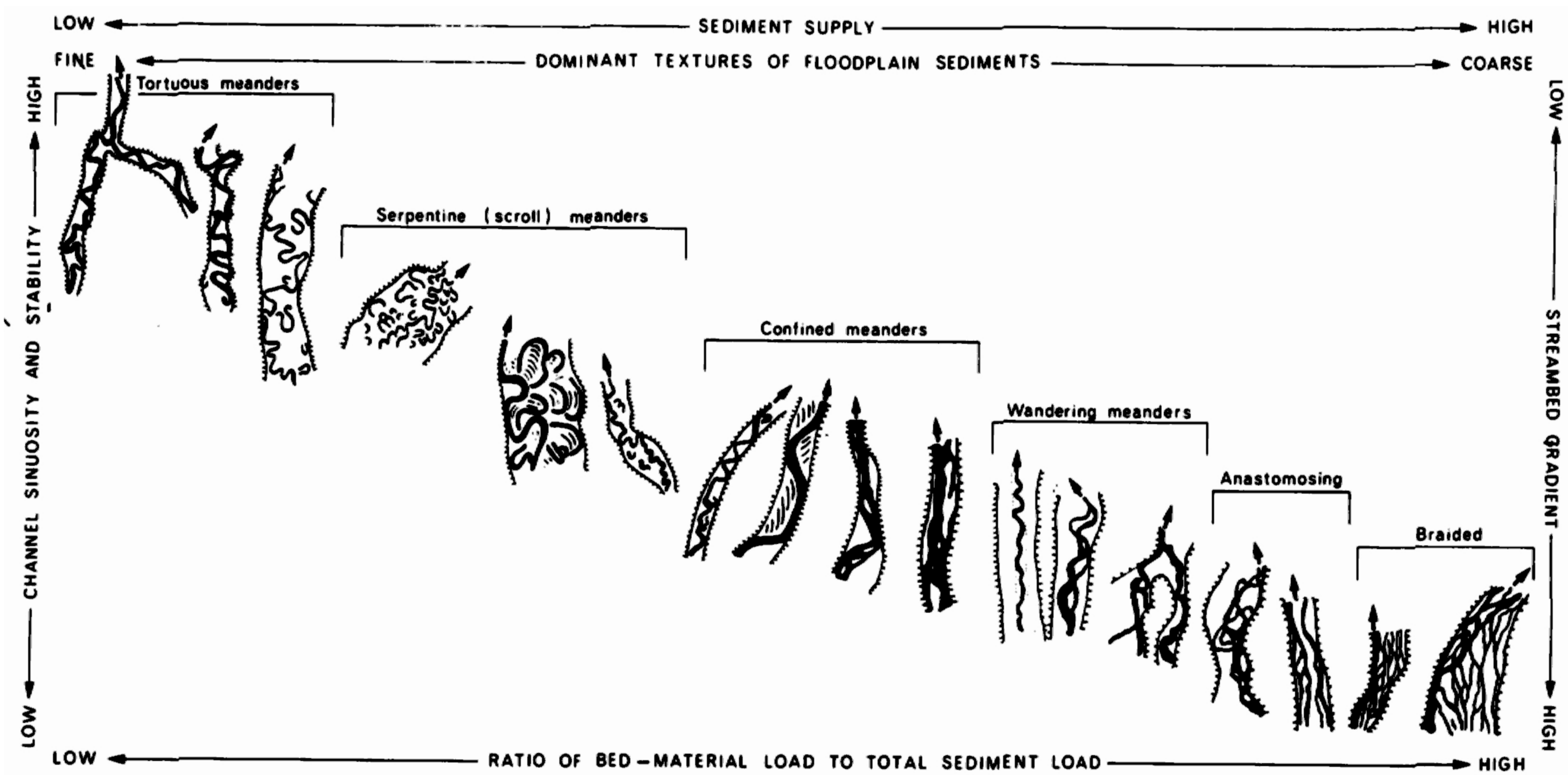


Figure 2.8. The influence of sediment supply on channel form. Modified from *Selby (1985)* in *Gordon et al (1992)*.

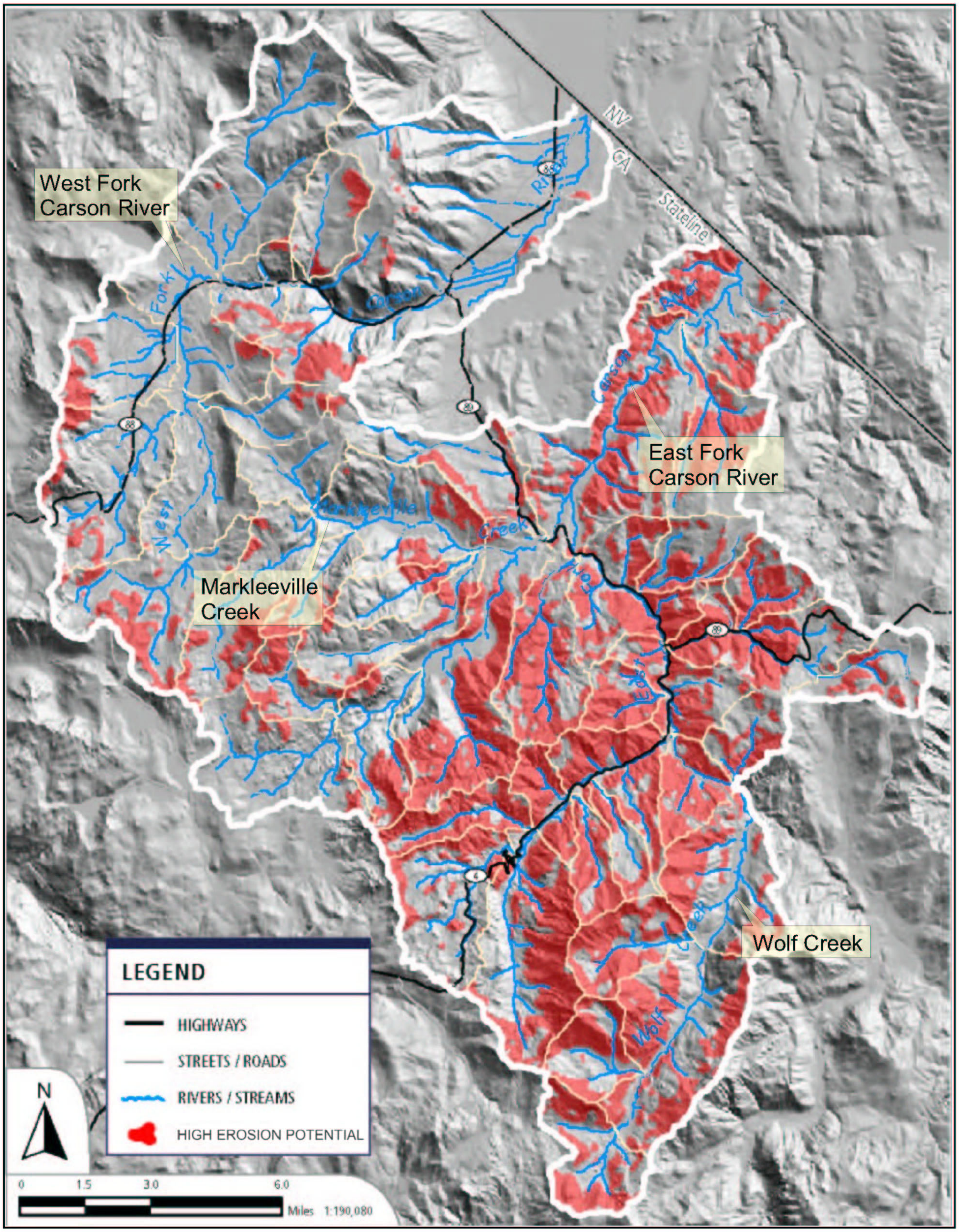


Figure 2.9. High erosion potential areas within the West and East Fork of the Carson River.

Granitic rock is found predominantly in the West Fork watershed and also tends to be highly erosive. However, the weathering products of volcanic and granitic landscapes differ. Granite tends to weather in place to sand. A large portion of the material supplied to channels in granite-dominated area will be the size of small gravel or smaller. Some portion of the sediment supplied in volcanic terrain will also be sand-sized, but coarser material tends to be more prevalent.

The East Fork has significantly higher natural sediment transport than the West Fork

2.3.2 Climatological Influences

Climate strongly influences sediment production. Through out the watershed, infrequent but intense rain-on-snow events can supply large amounts of sediment to the channel. Channel erosion during these events also may be high, producing additional sediment from within the channel and the adjacent floodplain. Infrequent summer thunderstorms are another important climatological event for sediment production in upper portions of the watershed, producing substantial runoff in short periods of time.

Another influence of climate is the role it plays in the distribution of vegetation communities. As one moves across the watershed from west to east, vegetation communities reflect increasingly drier conditions. Along the East Fork, plant communities have adapted to drier conditions and provide less ground cover, resulting in increased erosion. Similarly, high elevation slopes in both basins are steep, harsh vegetation environments. They exhibit low summer precipitation levels, a short growing season, and high winter snowfall. As a result, ground cover is often sparse, leading to increased erosion in these areas as well.

Rain-on-snow events create significant amounts of sediment.

2.3.3 Mass Sediment Movement

Mass movements of sediment can supply large amounts of coarse bed load to discrete locations. This can occur during rain-on-snow events, snowmelt floods, or summer thunderstorms. During field reviews, the assessment team saw evidence of two mass movement types – debris flows and landslides.

Debris flows occur when material is sufficiently liquefied to allow substantial internal deformation during movement. Flows are moving masses of water, fine sediment, larger sediment clasts and woody debris. Sediment clasts can be large, including boulders. Large amounts of sediment may be transported fairly quickly.

Debris flows strongly influence the morphology of Wolf Creek. Upstream of the assessment area, steep volcanic terrain on the west side of the watershed can produce debris flows during large precipitation events. In 1997, coarse sediment supplied from these drainages via debris flow resulted in destabilization and erosion of the Wolf Creek floodplain upstream of the assessment area. Large amounts of sediment were transported to the meadow reach within the assessment area, resulting in substantial channel dynamics. Between flow events, alluvial fans at the base of debris flow drainages become incised. Evidence of debris flows is found throughout the East Fork. Debris flows also occur in the upper portion of the West Fork drainage, particularly in association with volcanic geology.

Sediment mobilized during debris flows may be derived from outside the channel or from within it. At higher elevations, rills and gullies on adjacent steep slopes may provide sediment to channels, where the material moves in a debris flow. At lower elevations, material stored in the channel from previous flows may again mobilize during subsequent floods.

Large landslides throughout the East Fork watershed also cause the episodic delivery of sediment to the channel. These events alter localized segments of the channel through changes in local channel slope, the creation of temporary landslide dams, and the transport of large amounts of coarse and fine sediment downstream. On the East Fork, just downstream of the Wolf Creek confluence, a massive landslide is evident that dates back to at least the 1960's. This landslide remains active; additional movement occurs during high magnitude events when the landslide is undercut, causing instability and subsequent movement. The most recent movement occurred in 1997 when the undercut landslide failed, blocking the entire channel. This resulted in channel aggradation upstream and incision of the landslide mass.

> Landslides are common along the East Fork

The West Fork watershed is less prone to mass movement of sediment. However, the uppermost portion of the watershed, above Charity Valley, is surrounded by volcanic rock and there is evidence of debris flows in this area. Much of the sediment derived from this area appears to be stored in a lower-gradient portion of the watershed just downstream of the headwaters. However, the presence of volcanic rock as streambed material throughout Charity Valley attests to the transport of at least some material derived from headwater sources to downstream reaches. Some isolated drainages on the east side of Charity and Hope Valleys, again draining volcanic geology, also produce debris flows. One unnamed tributary, which enters the West Fork in Charity Valley, produced enough sediment as debris flow during the 1997 floods to cause substantial erosion along the Blue Lakes road.

2.3.4 Proximity to Sediment Supply

Channel response to sediment supply depends on the proximity of the channel reach to the source of the sediment. Throughout much of the East Fork watershed, sediment sources tend to be relatively close to the channel. This is due to the steep, confined valley walls, which consist of highly erosive volcanic material. Debris flows and landslides provide for the direct input of coarse bed load into the channel at regular intervals throughout the assessment area. Sediment supply and its proximity to the channel are both reduced downstream of the river's confluence with Markleeville Creek.

Much of the sediment supply along the West Fork is located high in the watershed. As this material is transported through the system, some is stored within the channel, providing a protective buffer for downstream reaches against large pulses of sediment. The Charity Valley area, at the upstream end of the watershed, is the most likely to receive large, episodic pulses of coarse sediment. Hope Valley, further downstream, is buffered from pulses of coarse sediment, and probably derives much of its sediment load from stream banks and the surrounding floodplain. This gradient of channel proximity to sediment source is likely reflected in channel pattern and dynamism.

2.4 Natural Geomorphic Dynamism

Dynamism is a fundamental, inherent characteristic of natural streams. Seasonal changes in flow, annual channel scour and the deposition of sediment, and large floods may rework entire reaches of a channel. To understand ecosystem function it is important to consider how channel dynamics occur over different time scales.

Human life spans, decades long, are short when compared to geomorphic processes. Over decadal time scales (10 to 100 years), rivers tend to exhibit steady state equilibrium (Figure 2.10). Channel pattern and form may change slightly, but they tend to vary around an average condition (hence the term equilibrium). Though changes may occur at specific locations, sediment supply and erosion tend to remain relatively constant. Significant increases and decreases do not occur, especially when considering reaches of a channel rather than specific locations. Pools may form and disappear in specific locations, or individual banks may erode, but the general form of the channel remains constant over reach-wide spatial scales. This is the short-term model of channel behavior depicted on the left in Figure 2-10.

The picture becomes more complex over longer time periods. Consider changes along the West Fork of the Carson River since the end of the Pleistocene. As the glacial ice melted, the stream probably exhibited characteristics typical of glacial outwash environments; stream channels were most likely braided. Sediment supply and discharge were both much higher than today. As the climate warmed and vegetation began to invade formerly glaciated terrain, sediment supply began to decrease. Precipitation and stream flow also decreased. Invading vegetation promoted relatively stable gravel bars and the once braided channels gradually changed to single-thread channel. Deposition of fine sediments on adjacent floodplains promoted the development of stable herbaceous plant communities.

Over this transition period, climatic variability resulted in large floods and extended droughts that temporarily increased or decreased sediment supplied to the system, causing short-term changes in channel form or pattern. However, dominant trends from the Pleistocene to the present have been a reduction in the amount of sediment supplied to the channel, and a transition from braided to single-thread channels. This model of channel dynamics is termed dynamic equilibrium (the middle graph in Figure 2.10). The equilibrium is dynamic because average channel behavior changes slowly over time (from braided to single-thread channels, for example).

A new understanding of the importance of rare, catastrophic events to river systems has helped to refine this model of channel dynamics especially over long time scales. Over a long period of time, it is more likely that a large flood, landslide or some other disturbance will occur that results in a substantial change to channel form. When these disturbances are large enough, the steady evolution from one channel condition (from high to low loads of sediment, for example) may be disrupted and the equilibrium condition of the system changed. This model of dynamic behavior is termed dynamic metastable equilibrium (see the graph at the right of Figure 2.10). Large landslides in the Upper Carson watershed may be reflective of dynamic metastable equilibrium. The disruption in equilibrium may result in a different channel pattern such as occurred upstream of the landslide along the East Fork. This type of fundamental change occurs over a short period of time but has a profound affect. Over a longer time scale, the evolution towards lower sediment yield and meandering channel patterns continues, but from a different equilibrium.

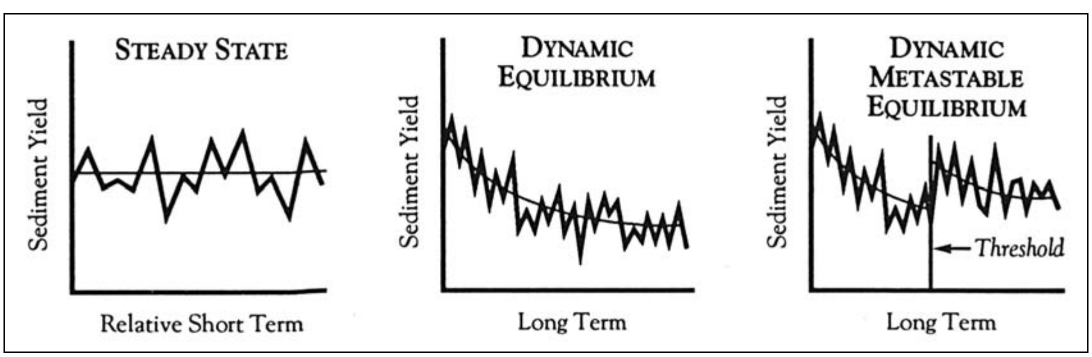


Figure 2.10: Types of equilibrium over different time scales in river systems. *Source: Mount 1995.*

2.4.1 Equilibrium

A fundamental characteristic of this conceptual model of channel equilibrium is that channels tend to oscillate around some average condition. Deviations from the average condition may occur due to periodic, random flood events that impart tremendous erosive energy on uplands and the channel, and which can also trigger landslides or debris flows that supply large volumes of sediment to the channel. The concept of equilibrium suggests that the channel will tend to return to some median condition following extensive disturbance caused by large floods or other landscape-altering events. In other words, the channel will tend to recover following major disturbances. In models of upland watershed stability, this tendency toward an average condition has been termed inertia and is commonly considered a characteristic of ecosystem function. Inertia can be viewed as a property with two components: resistance to change and recovery from disturbance over time, or resilience. Resistance to change and resilience following change allow for a "central tendency" behavior. In basic terms, the equilibrium model is one of force and resistance, but also of recovery.

2.4.1.1 Resistance to Change

Perhaps the most important factor resisting change in watersheds is the influence of vegetation. Vegetation reduces the supply of sediment from upland sources, makes floodplain far less susceptible to erosion, and greatly stabilizes stream banks. In forested watersheds such as the upper portions of many parts of the Carson River watershed (especially along Hot Springs Creek), large trees are an important component of the vegetation community, providing resistance to change. Extensive root networks of large trees stabilize banks and the floodplain. Also, woody debris in the channel tends to store sediment and stabilize the channel plan form.

Another important factor in resistance to change is the form of the channel and its relationship to the floodplain. The ability of especially large floods to produce change is reduced when much of the discharge is carried onto the floodplain. In situations where most of the flood is contained within the channel, the channel is much more likely to be modified. Trees and woody debris have an important influence on channel form in forested watersheds, serving as hydraulic controls that promote floodplain connectivity during large floods.

2.4.1.2 Resilience Following Disturbance

Vegetation is a dominant influence affecting resilience of the system following disturbance. Colonization of vegetation reduces sediment supply in uplands, and stabilizes stream banks and floodplains. The return to average channel conditions following a disturbance is promoted by the influence of vegetation. Again, as in resistance to change, large trees and resulting woody debris are major components of resilience in forested streams. The recruitment of large trees by bank erosion, for example, tends to stabilize the system by promoting sediment storage. The same process occurs on floodplains during large floods. Stabilization of stream grade by logjams also tends to promote sediment storage, the storage of floodplain water, and short-term stability, all processes that promote subsequent colonization and stabilization by other plants.

2.5 Characterizing Dynamism of the Historic Channel

Floods and other disturbances act across wide spatial and temporal scales. Some disturbances cause little change in the fluvial system. Others result in changes that are short temporal deviations from the average condition. Still others cause threshold changes in equilibrium. Large rain-on-snow events can cause threshold level changes in channel condition and behavior at some watershed locations, particularly lower gradient meadows. Channel form may change entirely following such an event, substantially altering the stream and surrounding floodplain for years to come. The influence of rain-on-snow events can clearly be seen in Wolf Creek. The 1997 flood substantially altered the channel in some areas and caused extensive erosion. On first examination this appeared to be a relatively unusual event. However, aerial photos of the channel taken in 1963 and 1997 (Figure 2.11) show very similar channel morphologies (extensive erosion, widening). The 1963 photo was taken just after a rain-on-snow event. These data suggest that large floods routinely cause substantial changes in Wolf Creek. Channel condition tends to improve between flood events.

Snowmelt floods and lower magnitude rain-on-snow events, which occur more frequently than larger floods, also cause changes in the channel. However, these changes are smaller and do not persist as long. For example, gravel bars deposited by the 1997 flood are still apparent along both the East and the West Forks. Subsequent snowmelt floods have reworked the deposits somewhat, but the influence of a single snowmelt flood is not nearly as significant or long lasting as the effect of a larger flood. Within the model of dynamic metastable equilibrium discussed above, average annual floods represent minor variations from equilibrium, or the spikes and troughs around the lines on the right graph in Figure 2.10. Larger rain-on-snow events, however, may cause enough disruption in the system to cause threshold level changes in behavior characteristics typical of dynamic metastable equilibrium.

The magnitude of geomorphic change at a particular location in the watershed depends on a number of factors. These include the confinement of the channel, the nature of the bed material, and proximity to the supply of coarse sediment. As noted previously, some sections of the West Fork are relatively immune to change due to very stable streambeds and banks. In the canyon above Woodfords, the West Fork is highly confined and has a very stable bed composed of large boulders. The surrounding canyon shows little evidence of the mass movement of sediment, such as debris flows. As a result, the channel in this area is relatively resistant to morphological changes during larger floods.

Changes in any one key factor can lead to substantial changes in channel behavior. While the East Fork in the vicinity of Wolf Creek is confined by valley walls much like the West Fork above Woodfords, the mass movement of material (i.e., debris flows) is more common and the bed material is smaller. As a result, the East Fork in this area, like the portion of Wolf Creek described earlier, is subject to substantial changes during larger floods. Aerial photographs of the channel following rain-on-snow events in 1963 and 1997 show extensive gravels bars, evidence of substantial channel dynamism (Figure 2.12).

Lower gradient meadows throughout the watershed are likely to be highly dynamic, though the response to floods in meadows is variable. For example, the Wolf Creek meadow near the East Fork confluence is located downstream of several tributaries draining volcanic geology. Debris flows are common in these tributaries during large floods, providing a large supply of coarse sediment to the meadow. As a result, a dynamic alluvial fan has developed at the upstream end of the meadow, and the channel is highly dynamic within the meadow. The lower portion of the Hope Valley meadow, on the other hand, is buffered from episodic pulses of coarse sediment by upstream meadows, and the West Fork channel appears to be substantially less dynamic than Wolf Creek.

This gradient of potential natural dynamism, which varies based on channel type, substrate, and sediment supply, is important to understanding effects of human disturbance on fluvial geomorphic process and ecosystem integrity. Human disturbance tends to increase instability and dynamism in natural channels (Dunne and Leopold 1978; Mount 1995). Human disturbance has certainly played a role in the dynamism of channels throughout the Carson River watershed. When analyzing the effect of human disturbance, however, it is first necessary to characterize natural disturbance. The assessment team classified channels throughout the watershed in terms of their relative inherent natural dynamism (Figure 2.13), demonstrating that many stream segments exhibit a relatively high rate of natural dynamism.

1963 **1997**

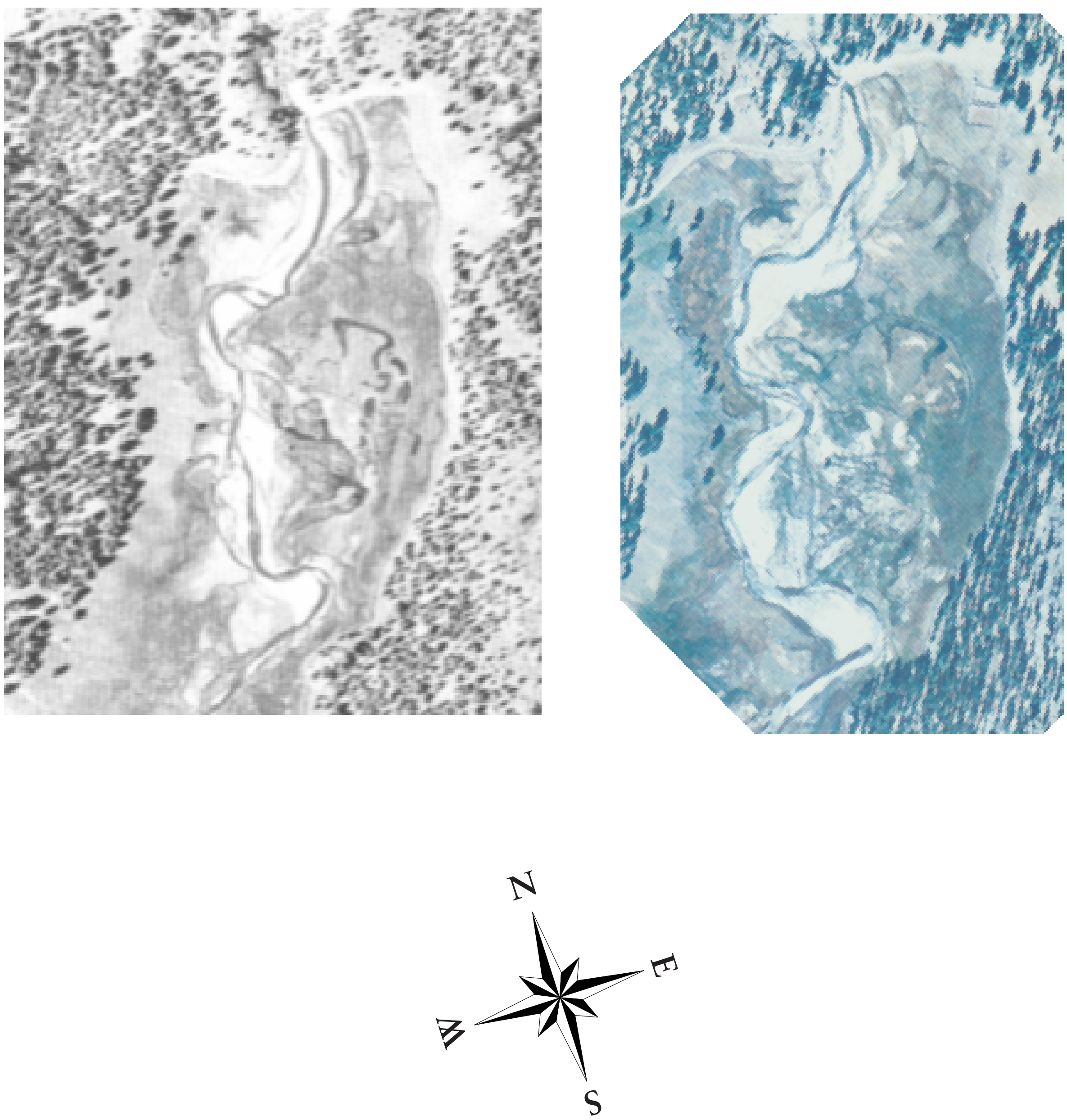


Figure 2.11. Wolf Creek near the confluence with the East Fork Carson River, 1963 and 1997.

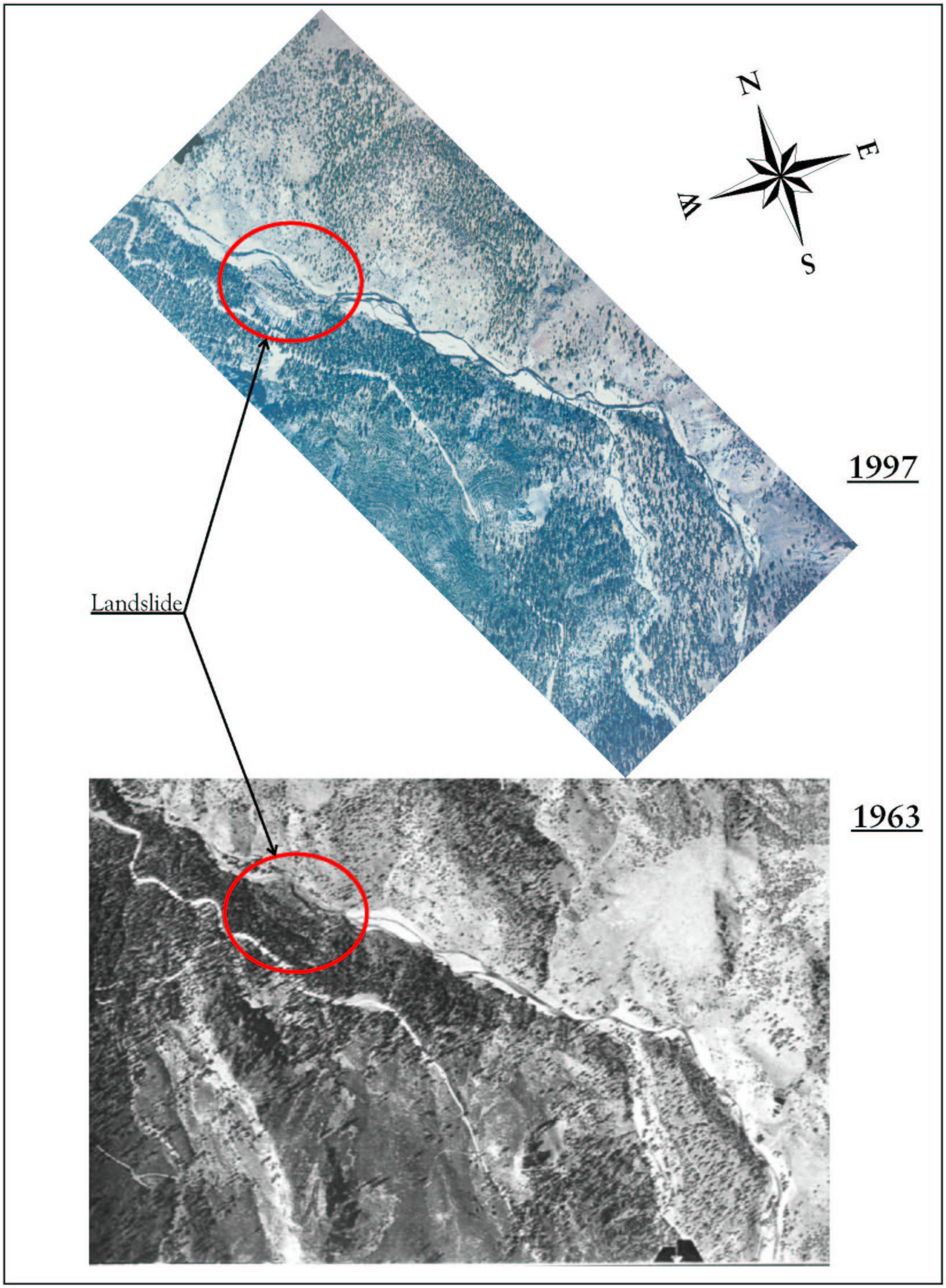


Figure 2.12. East Fork Carson River at the Wolf Creek confluence, 1963 and 1997.

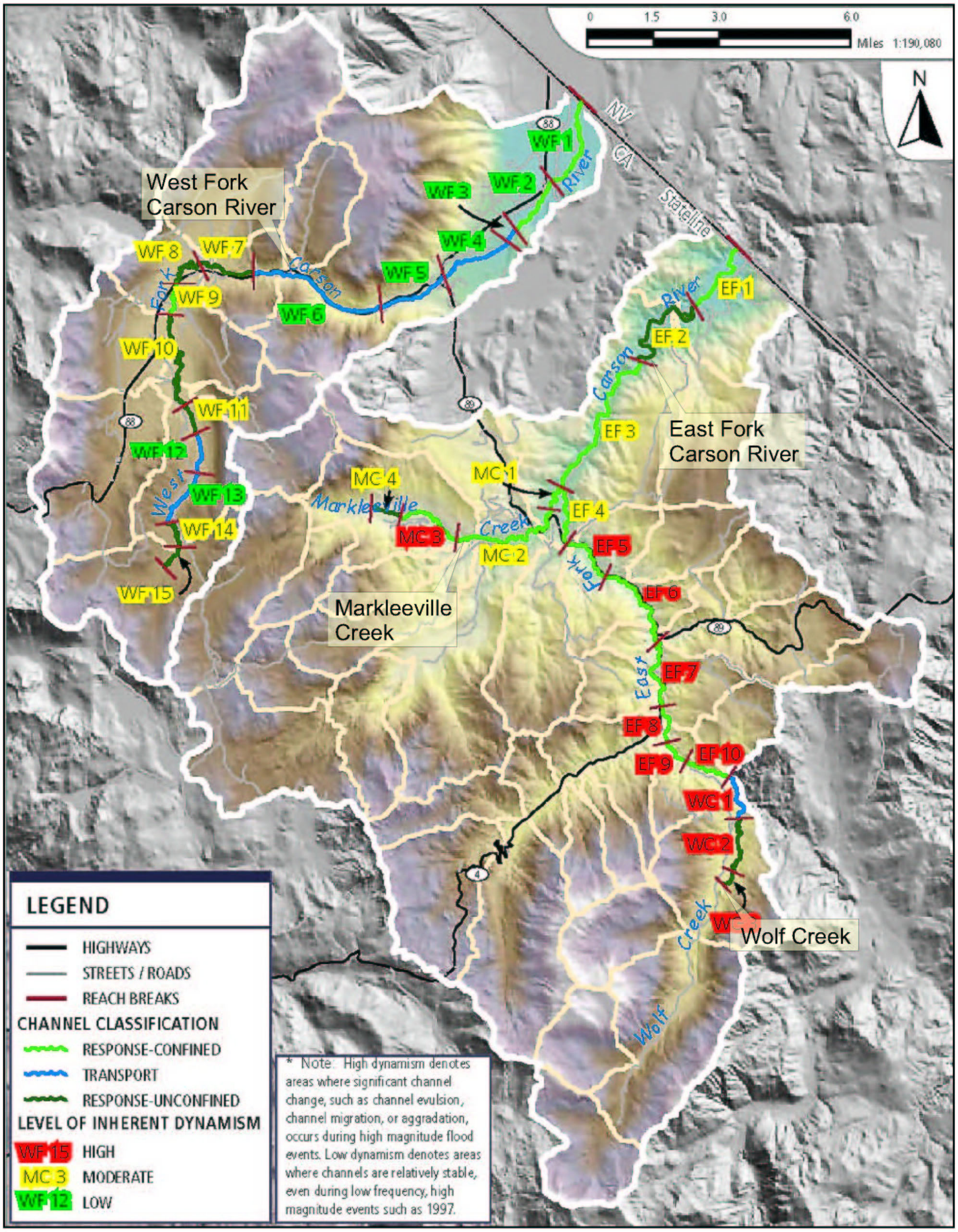
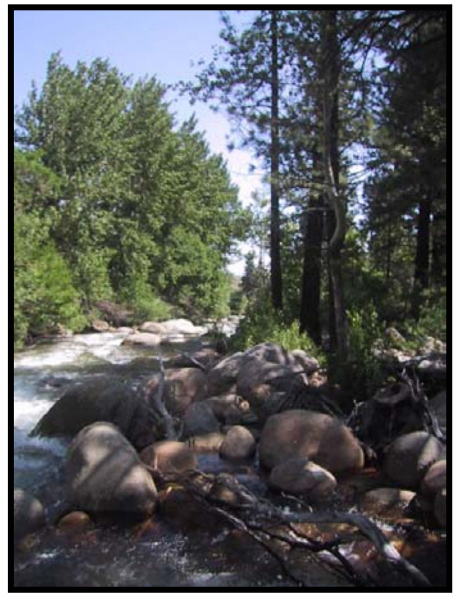


Figure 2.13. Channel classification.

2.6 Channel Sediment Transport, Erosion and Deposition

Different types of channels have characteristic patterns of sediment transport, erosion, and deposition (Leopold et al. 1964; Rosgen 1994; Mount 1995). The assessment team identified three classes of channel behavior with respect to erosion and deposition in the assessment area: transport, confined response, and unconfined response channels. Transport channels (Figure 2.13 provides locations of each channel type) are highly efficient at moving sediment, exhibit very low bank erosion, and store little of the sediment in transport within the channel or on the adjacent floodplain. Response channels are less efficient at moving sediment, show moderate bank erosion, and store some of the transported sediment within the stream banks and on the adjacent floodplain. There are two types of response channels in the watershed: confined response channels with moderate gradients and smaller floodplains, and unconfined response channels with low gradients and large, meadow floodplains.



2.6.1 Transport Channels

Transport channels are higher gradient, highly confined (valley walls close to the channel) Rosgen A and B-type channels. They are found predominantly in the lower portion of the West Fork. Plan form is straight. They tend to have very little associated floodplain and are often incised in Quaternary glacial deposits. Channel morphology is generally step-pool or plane bed. Streambed substrate is large.

Coarse sediment may be supplied to these channels, but transport capacity is high and even larger particles are transported readily with little deformation of the streambed or banks. Some of the supplied sediment is stored temporarily within the channel, behind large boulders or in other flow shadows. Point bars and other alluvial formations are absent. Stream banks and the streambed are resistant to erosion.

2.6.2 Confined Response Channels

Confined response channels are found between higher gradient transport channels (upstream) and lower gradient response channels (downstream). They have moderate gradient (around 1 to 4 percent) and moderate confinement (Rosgen classifications of B, C, and F). These channels constitute most of the mainstem of the East Fork, Markleeville/Hot Springs Creeks, and lower Wolf Creek. Plan form is straight to confined meandering. Associated floodplain is variable, but is generally less than two times the width of the bankfull channel. The channel and floodplain are composed primarily of sediment with recent origin. The processes of channel erosion and deposition can be described as fill-cut. These streams steadily rework bed load on the valley floor during normal flow years. This process is punctuated by massive, episodic inputs of bed load from tributaries and hill slopes to the valley floor during severe floods.

Massive erosional events, primarily associated with rain-on-snow events or following fire, result in extensive channel aggradation. The amount of sediment delivered exceeds the capacity of the channel to move the supplied load. Evidence of large-scale aggradation events is apparent along the main stem as terrace bar surfaces with a slope that approximates overall valley slope. Subsequent low to moderate magnitude events, such as the annual snow melt flood, result in re-incision of the aggraded rain-on-snow surface. The characteristic "bankfull" channel is formed with a cut face and flat terrace surface abandoned by the recent incision. Terrace and bar surfaces are re-colonized by pioneer species of riparian vegetation, reinitiating the familiar pattern of succession that leads to later seral stages.

2.6.3 Unconfined Response Channels

Unconfined response channels are found in larger meadows within the assessment area. They are low gradient, meandering Rosgen C- and E-type channels. Valley walls do not confine meanders, and bed substrate is relatively small.

These channels have extensively worked valley floor sediment deposited during recent times. The channels are associated with wide, flat floodplains on both sides of the river. Erosion and deposition in these channels follows classic alluvial models described by Leopold et al. (1964). Outer bends are slowly eroding, migrating outward and down valley (meander translation). Point bars are deposited on inside bends, and represent floodplain being constructed by the channel.

Much of the sediment in transport within unconfined response channels may be derived from within the channel itself. However, larger floods are obviously capable of supplying large amounts of sediment from upstream sources. Thus, the upstream ends of unconfined meadows tend to be depositional and dynamic. Material supplied during larger floods may then be slowly transported through the system during smaller floods.

2.7 Channel and Floodplain Morphology

Substantial differences in sediment transport and erosion among the three general types of channels (transport, confined response and unconfined response) were discussed in the preceding section. Given these differences in geomorphic processes, it is not surprising to note that there is substantial variability in channel and floodplain form.

Interaction between the stream channel and the adjacent floodplain is an important component of riparian ecosystem function. Regular flooding creates conditions required for riparian plant communities to reproduce and remain vigorous. Groundwater conditions, mediated by the channel level with respect to the floodplain, are important to plant communities adapted to high levels of available moisture through the growing season. These very conditions are the ones that promote equilibrium resistance and resilience. Moreover, functioning floodplains reduce the energy of large floods, again promoting inertia to equilibrium changes. The relationship between the floodplain and the channel is therefore important to understanding how the system functions. In general terms, understanding channel morphology may be simplified conceptually by considering them to be composed of three stages: low flow, bankfull and flood.

The low flow channel contains flows that occur over 95 percent of the time. It is the portion of the channel, which is wet nearly year-round and provides stable habitat for aquatic organisms. The morphology of the low flow channel is dependent on all flows, from low flows to snowmelt floods and rain-on-snow events. The low flow channel is also highly influenced by vegetation.

Dunne and Leopold (1978) defined the bankfull stage as follows:

> "The bankfull stage corresponds to the discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or reforming bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels."

They note that, based on research elsewhere, the bankfull stage is associated with a momentary maximum flow, which, on average, has a recurrence interval of 1.5 years. Although these definitions are relatively precise, the bankfull stage is often difficult to identify in the field, and the recurrence interval of bankfull discharge may vary widely from the 1.5-year recurrence flood (Williams 1978). Nonetheless, several indicators are used to identify the bankfull stage, including new floodplain development, other channel forming features such as scour lines or point bars, or the growth of certain species of riparian vegetation (BLM 1998). Note that the bankfull stage is not always at the top of the banks.

The flood channel contains the largest floods and is the area of the valley floor that exhibits evidence of sediment transport (scour, sediment deposition, etc.). Throughout the assessment area, flows accessing the entire flood channel are primarily generated by rain-on-snow events.

Between the stages of the bankfull and flood channels lies the floodplain. The size of the floodplain varies significantly between the three general channel types in the assessment area. These channel stages are shown on photographs of the three channel types in Figure 2.14. Floodplain area is smallest in the transport channel and largest in the unconfined response channel. Dunne and Leopold (1978) define the floodplain as the

> "flat area adjoining a river channel constructed by the river in the present climate and overflowed at times of high discharge."

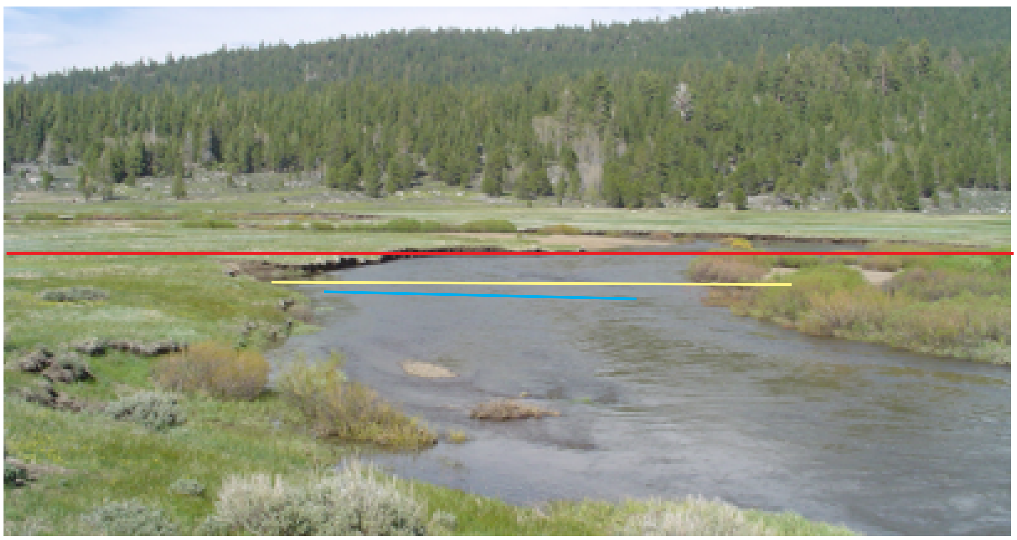
Again, although this appears to be a simple definition, closer examination suggests that reality is more complex. For example, the flat area in this definition is a landform constructed primarily by slow lateral migration and overbank deposition. Dunne and Leopold (1978) note:

> "The valley flat in some regions may not be formed in this manner. Hack and Goldlett (1960) found that mountain valleys of the central Appalachians are subject to recurrent debris flows associated with extreme storm events…levels, berms, or terraces may be distinguished and even ascribed to particular years, but a floodplain, as defined here and having a constant frequency of overflow, cannot be identified or does not exist."

Well-developed flat areas or floodplains exist in unconfined response reaches in the assessment area. In other locations, where the channel is more confined (such as Hot Springs Creek) the floodplain is highly variable, probably due to the episodic transport of large, coarse bed load.

Extensive flat areas near the channel may or may not function as floodplain. For example, the wet meadow associated with Red Lake Creek is floodplain in the sense of the description provided above. Average annual floods reach the meadow. On the West Fork of the Carson River, in Hope Valley, although there is extensive meadow next to the channel, these meadows tend to function as elevated stream terraces rather than floodplains that experience "… a constant frequency of overflow".

East Fork Carson River - Response-Confined



West Fork Carson River - Response-Unconfined

West Fork Carson River - Transport

KEY

Flood Stage

Bankfull Stage

Low Flow Stage

Figure 2.14. Channel stages in three general channel types.

These meadows are only rarely flooded by larger rain-on-snow events. Snowmelt floods are generally carried within the channel. Evidence that these meadow systems may have historically been the floodplain is provided by the presence of relic, mature willows located in low, topographic remnants of old channels. Given that willow regeneration requires plant establishment on fluvial substrate within the active floodplain, this indicates that the meadows were once active floodplains. The continued presence of these willows suggests that the supporting hydrology is provided by groundwater recharge via lateral flow from the adjacent channel.

2.7.1 The Role of Woody Debris

Where watershed channels occur in forested areas, resistance and resilience were probably promoted by large, live trees and by woody debris. The presence of large, relatively immobile woody debris or trees in the channel, on channel banks, and on the floodplain made system-wide threshold changes less likely. Within the channel, large woody debris likely occurred both as individual trees, partially or entirely within the channel, and as larger woody debris jams. Large trees and woody debris serve a number of functions, which provide resistance to change and resilience from change. These functions include:

- stream bank stability;
- floodplain connectivity;
- floodplain erosion resistance; and,
- floodplain heterogeneity.

Several processes involving woody debris improve stream bank stability. Woody debris works as a hydraulic roughness element within the channel, reducing stream power and erosion capability. Trees and large woody debris also directly stabilize stream banks, either by root structure or by directly protecting the banks from erosive force. In some situations, trees and woody debris stabilizing one bank promote erosion on the opposite bank. These effects tend to be localized, however, because in forested environments trees and woody debris are likely to found in almost all locations, and will limit the amount of erosion that can occur. Where localized bank retreat does occur, banks erode more slowly because of the high density of vegetation on the floodplain.

While trees and debris jams can deflect flows into easily eroded banks, limited local erosion is offset by the beneficial effect of maintaining channel grade and capacity. That is, woody debris forces floods onto the adjacent floodplain by helping to maintain a minimal hydraulic capacity of the main channel. The channel is more resistant to change because large floods are incapable of attaining the power needed to produce widespread erosion of the bed and banks.

Greater connectivity with the floodplain promotes vigorous floodplain plant communities, a factor in providing resistance to and resilience from change. During floods, localized erosion and deposition occurs on the floodplain, resulting in a highly varied microtopography. Sediment deposition on the floodplain is a key element in establishing new riparian vegetation, as is localized erosion, which provides growing areas in proximity to the water table. Also, log jams and woody debris act as hydraulic controls in the channel, influence groundwater elevation throughout the floodplain, increase the amount of time that soil moisture is available during the growing season, and increase the overall density of vegetation.

Woody debris also plays a key role in stabilizing the floodplain by providing resistance to erosion in flood channels, storing and sorting sediment in localized areas, and preventing widespread erosion by resisting the tendency of flood flows to concentrate. Individual trees or downed logs break up floodplain flow paths. In forested areas, this effect can be very important, ensuring that flood forces do not concentrate, which could result in channel incision and erosion. Moreover, individual logs store sediment, and are particularly effective at sorting sediment into fine lee deposits that become important areas for riparian vegetation colonization. The assessment team noted this process occurring throughout the Upper Carson River watershed today, and it was certainly important in the historic channel.

The heterogeneous nature of the floodplain prompted by these processes contributes to the future recruitment of large trees and woody debris. Recent deposits of flood sediment may be well drained at a locally high elevation, thus providing suitable establishment areas for conifers. Though they may be surrounded by riparian vegetation, these sites favor the regeneration of large trees providing for the next generation of large woody debris. This perpetuates the long-term supply of woody debris, encouraging the persistence of a resilient, steady state system.

2.7.2 Beaver

Beaver (*Castor canadensis*) are generally considered to be non-native to the high Sierra (Graber 1996). In a summary of beaver distribution and ecology in California, Tappe (1942) stated that beaver were not present in the Sierra above 4,000 feet prior to their introduction by Euro-Americans. However, the issue remains controversial. The Tappe paper included a footnote that described a claim by an individual in Carson City to have seen extensive beaver sign in the upper Carson watershed:

> "Since the above was written [the actual report], the writer, through the courtesy of Mr. G.H. Hansen of the Fish and Wildlife Service, Reno, Nevada, on October 1, 1941, interviewed Mr. Roy Mighels, who was born in Carson City, Nevada, in 1872 and now lives in Reno. Mr. Mighels spent much of his time between the ages of 14 and 20 riding the range in Alpine County, California, and in Ormsby and Douglas counties, Nevada. He said that in these years (1886-1892) beaver cuttings were plentiful on the upper part of the Carson River and its tributaries in Alpine County. He attributes the disappearance of beaver from the Carson River drainage to the heavy trapping done in that area prior to 1900. It seems, therefore, that beaver actually did inhabit at least part of the eastern slope of the Sierra south of Lassen County."

Today, there is some evidence for both views. A recent Tahoe Basin watershed assessment concluded that beaver did not occur in the Lake Tahoe basin until some time in the early 1900s, when they were introduced by both agencies and by individuals (Fox 2003). An important part of the evidence cited in this assessment is that beaver are absent from traditional Washoe Indian heritage, as reported by elders who recollect memories of beavers only from the 1930s-1950s (Lindstrom and Rucks 2003).

On the other hand, beaver dams and other sign are well distributed across the Sierra landscape. Much of this beaver sign appears to be quite old. Beaver may have influenced landscape morphology in many Sierran meadows over long time-scales (decades to hundreds of years). Areas where beaver have been active in the past tend to have a distinctive morphology, consisting of small flats that are the remains of ponds that have filled in with sediment. The flats are bounded on at least one side by willow-covered ridges that are the remains of the dams themselves. Researchers in Plumas County excavated these features in a small stream in the Plumas National Forest (James 1990). Radiocarbon dating of willow stems interpreted to be part of the dam gave dates as far back as A. D. 580. Although there is considerable uncertainty about the validity of age dating remains of beaver dams, this evidence suggests that it is possible that beaver were native to at least parts of the Sierra.

Whether or not beaver were originally native to the Sierra, they were certainly introduced by the early part of the 20th century. Tappe (1942) provides the first documentation on the introduction of two pairs of beavers to Lake Tahoe (in Meiss Meadow, near the Carson Pass) by the U.S. Forest Service in 1938. Federal agencies introduced beaver to uninhabited locations because of their value as a fur resource, as an aid in water conservation, and to control soil erosion (Tappe 1942). Individuals who wanted to establish an additional income source from trapping may have introduced beaver prior to activities conducted by agencies. Conflicts between beaver, irrigation systems, and cattle grazing were noted in the 1920s in North Canyon Creek (near Spooner Summit in the Lake Tahoe Basin). In this area, beaver would likely have been introduced informally, by individuals interested in either fur or watershed stabilization.

There is just as much controversy over whether beaver are beneficial to a watershed. Dams are known to provide stream stabilization and sediment storage, to raise water tables, and to increase riparian vegetation (Muller-Schwarze and Sun 2003; Naiman et al. 1988). Beaver have often been introduced into degraded watersheds to restore stability; it is likely that beaver were introduced to Meiss Meadows to restore and stabilize range that was considered impacted by grazing.

On the other hand, potential negative impacts of beavers are often cited (Muller-Schwarze and Sun 2003; Naiman et al. 1988). They are most commonly associated with the failure of abandoned dams, which results in substantial erosion, channel dynamism, and can supply excess sediment to the channel. Other impacts are associated with beaver feeding and foraging. Aspen is a preferred food, and beaver can eliminate stands of aspen through foraging. Willow stands can also be heavily utilized for both food and dam materials, and cottonwood trees are sometimes girdled, either for dam material or for food. Another impact is decrease in water quality due to the ponding of water and an increase in biological activity within ponds. Beaver dams are also sometimes considered to be barriers to fish migration, although most studies suggest that fish pass dams readily during high water (Muller-Schwarze and Sun, 2003).

For example, during the 1940s the Dangberg Land and Cattle Company aided federal agencies by reintroducing beaver above Dumont Meadows in the Upper East Fork. The goal was to stabilize the meadow and reduce erosion. Floyd Brown is a descendant of the Koenig family, one of the earlier families to settle in the Alpine County area. While attending high school during the mid 1940's, Mr. Brown worked for the Dangberg Land and Cattle Company as a seasonal ranch hand. As part of a recent oral history (Zeier 2001: A-11), Mr. Brown spoke of his role in the reintroduction of beaver into Dumont Meadows.

> "Earle Leslie and I, we met the guys (*federal or state agents*) at Wolf Creek and had some saddle horses…and we took them clear up by the falls…what they called the White Meadows, above Dumont Meadows. I was just a kid and I thought it was great. Jeez. They told me how they're going to build all of these dams and they gonna…you know, everything. We get up there and he (*Earl Leslie*) said, "you know if we took an axe and knocked these buggers in the head, we'd be doing the country a great favor." And I was saying…oh, no, no, no…he was just an old guy. In later years, we'd be going through some of the aspen thickets and them beaver had fallen them trees just like you'd dump a thing of toothpicks, you know. And sure, they built dams, but as soon as they ran out of material…there was no more aspen to feed them…they left. Well then, years later, the higher water come through and broke the dams out and they just destroyed a lot of nice little meadows."

Because of their enormous potential to alter a watershed, effects of beavers on stream environments, either negative or positive, are likely to be substantial. In analyzing the role of beaver within the watershed it is useful to consider the place of the animal within the context of the ecosystem. Fox (2003) identified several important aspects of beaver ecology in the Sierra Nevada.

- Areas with sufficient forage to support beaver colonies over the long-term may be relatively rare in high Sierra streams. On the Upper Truckee River in the Tahoe Basin, less than 10 percent of the available habitat was considered to be high quality, capable of supporting continual occupation by a colony.

- Aspen stands appear to be important to supporting continual occupation. However, foraging by beaver may significantly disturb aspen stands, particularly if stands are not actively reproducing. Because aspens stands may rely on frequent, low-intensity fire to support reproduction, alteration of fire regimes may be a factor in beaver-aspen interaction.

- The occurrence of large rain-on-snow events in the Sierra is an important factor in the stability of dams. Dams on the Upper Truckee that were the most stable over time were those constructed on tributaries or side channels. Dams constructed in the main channel were often stable during typical snowmelt floods, but prone to failure during rain-on-snow events.

- Where dams are constructed in stable locations, and environmental conditions allow for reproduction of willow, beaver colonies can persist over long periods with little negative impact. One colony located on a spring source adjacent to the Upper Truckee River, has been in the same location for at least 10-15 years. Willow adjacent to the colony is vigorous and well distributed, and nearby aspens stands show no sign of overgrazing.

2.8 Vegetation Dynamics

Vegetation assemblages in place today are the result of processes initiated over several million years. Climate is the major driver for vegetation dynamics at the evolutionary scale (Woolfenden 1996). For example, the paleoecological record (macrofossils and pollen grain samples) indicates that during the early Tertiary (60-45 million years ago) area flora consisted of tropical and neotropical plant species. During this period, the Sierra Nevada were low plains and hills, bordered by the Pacific Ocean to the west and a high plateau to the east. High temperatures and rainfall characterized the climate. This resulted in flora similar to that found today in rainforests of Malaysia and southern Mexico.

While there is no record available for the Sierra Nevada during the Oligocene, climate on a worldwide basis became drier, with more seasonal variance and extremes in annual temperature. Neotropical vegetation at mid latitudes died out. It is postulated that cool-season conifers and angiosperms replaced them in our area. During the Miocene, the Sierra Nevada uplift continued, and rainfall was a year round occurrence.

By the end of the Pliocene, a climate similar to the Mediterranean emerged, with gradual declines in temperature and seasonality of rainfall. Remnants of neotropical vegetation disappeared from the Sierra Nevada, and forest species from the eastern plateau emigrated westward. The zonation of vegetation assemblages by region, latitude, and elevation was evidenced by the distribution of subalpine and mixed conifer vegetation associations in broad bands across the landscape. Those vegetation assemblages became further differentiated and are today found in the upper montane and subalpine zones (e.g. red fir, western white pine and bristlecone pine) (Millar 1996).

Climactic change continued to influence the distribution of vegetation assemblages as elevational limits of vegetation distribution fluctuated due to variations in temperature and precipitation experienced during the comparatively unstable Holocene. Currently, the area is experiencing a warming trend that is wetter than what occurred during the mid-Holocene Amelioration (8000 to 4000 years ago) when widespread drought occurred, as evidenced by Lake Tahoe submerged tree stump dating and other paleo-environmental data (Unknown 2000).

Various processes have and continue to influence the vegetation composition, structure, and abundance seen today in Sierra Nevada ecosystems. Vegetational change is most influenced by:

- disturbance events like fire, flood, volcanic eruption;
- variations in precipitation and temperature; and,
- the amount of atmospheric carbon dioxide (Woolfenden 1996).

The co-evolvement of plant species with these disturbance regimes is evidenced by species adaptation to fire and fluvial disturbance. This allows species the flexibility to change given site specific conditions.

The paleo-ecological record shows evidence of fire as an important ecological process even before current vegetation patterns were established (Skinner and Chang 1996). Fire aides the regeneration of plant species by providing a mineral soil seed bed and openings for shade intolerant species, it affects stand structure and composition, it regulates thermal and chemical effects, and it facilitates nutrient cycling (Weatherspoon 1996). Furthermore, individual plant species exhibit fire adaptive characteristics that demonstrate coevolution with the presence of fire. These traits include sprouting after fire, thick bark to retard damage to the cambium, and successional regimes that require the burning of decadent growth to regenerate the species (Chang 1996).

As discussed earlier in the chapter, erosion and sediment supply within the watershed influence geomorphic processes, which in turn affect riparian vegetation. Processes associated with the upland environment, including fire regimes, can exert a strong influence on riparian process and function. Prehistoric (before 1850) fire regimes have been identified by the U.S. Forest Service. In general, lightening strikes caused most fires. The Jeffrey pine and Sierra Mixed conifer cover classes were subject mostly to non-lethal ground fire regimes with return intervals of 5 to 35 years (Arno 2000) or a 15-year median fire return interval (SNEP 1996). This type of fire consumed herbaceous growth, litter and branches on the forest floor, lower branches of mature trees, and eliminated competition from young age class shrub and conifer species. As a result, forest stands were fairly open, with fire selecting large, heavily barked, fire resistant trees like Jeffrey and Ponderosa pines.

Pine regeneration occurred when large trees died, and shade intolerant conifer seedlings grew in the subsequent tree fall clearings. Alternatively, conifer seedlings would regenerate in fire gaps if the fire return interval was long enough. By the time the next fire came through, the saplings would have enough bark to resist the effects of fire.

An alternative view held by some scientists is that a mixed fire regime was probable. Some productive sites escaped fire for longer intervals, accumulating large fuel loads. Small pockets of stand replacement fires could occur in these areas (SNEP 1996). Lodgepole pine was subject to a mixed fire regime, characterized by a combination of the understory ground fire (described above) at shorter intervals and stand replacing fires at longer intervals. The range of available fuels and the frequency of fire determined which type of fire regime would prevail at a given site and time. At longer intervals, stand replacing fires would occur on more productive, mesic sites that produced more ground, ladder, and canopy fuels. For example, a thick duff layer could ignite and smolder for days. If temperatures continued warm and winds commenced, a crown fire could ensue. Thus, pre-1900 succession with fire return intervals of 60–80 years resulted in a variable, fine-grained landscape created by both understory and stand replacement fires (Arno 2000).

Aspen stands were subject to stand replacing fire as well (Duchesne and Hawkes 2000). In stands where less than 25 percent of species composition was aspens, the fire return interval was 35 years or less and tended to favor conifer regeneration. Conversely, in stands with greater than 25 percent aspen cover, fire return intervals were 35-200 years. The determining factor for stand replacing fire in this cover type was fuel availability. Fire is more probable the higher the percentage of shrub and herbaceous fuels. Skinner and Chang (1996) present an alternative viewpoint. They suggest that aspen stands in the central Sierra Nevada appear to be relatively stable.

Upper montane red fir/white fir cover types were subject to frequent, lightning induced ground fire regimes. The projected median fire return interval was 26 years (SNEP 1996). The presence of naturally occurring fire breaks (rock outcrops and snow pockets) slow biomass (fuels) accumulation due to the short growing season. Cooler weather prevented extensive stand replacing fire as the normal circumstance (Chang 1996).

Within subalpine meadows, fire regimes were of the ground fire type, returning at short intervals. Grasses and sedges were fire adapted and would resprout after fire. Encroachment of lodgepole pine into the meadows was regulated, in part, by frequent burning (Chang 1996). Effects of fire on riparian areas have not been well documented in the Sierra Nevada, but data collected in Klamath Mountain riparian areas identified a fire return interval of 49-102 years (Skinner and Chang 1996). Agee (1993) suggests that fire will burn more frequently in narrow riparian and in drier areas.

Of equal importance to riparian vegetation communities are disturbance processes associated with the fluvial environment. Riparian community types develop as the result of general elevation, climate, valley bottom gradient and substrate, and valley bottom width, features and patterns that are fairly stable and repeatable within a given time frame (Winward 2000). Most riparian areas are continually redefining the balance between the development of a buffering line of vegetation along the water's edge and the naturally occurring, eroding force of water to move this vegetation as the stream adjusts to its bedload and essential geomorphology.

Fluvial processes affecting vegetation include sediment sorting by lateral channel migration, flooding, and fine sediment capture (Weixelman et al. 1999). Flooding initiates the sediment sorting process. Coarser, heavier material is deposited as gravel bars, while lighter fines are eventually deposited on top of the bar as the elevation of the bar increases in relation to the channel bottom. Eventually, the gravel bar is converted to floodplain, with a vertical cross section identifying the layer of coarse gravels overtopped by fine sediment deposition. Geologic processes and other disturbances may result in channel incision, with the old floodplain becoming elevated above the existing channel.

Regeneration of riparian plant species demonstrates co-eveolution with fluvial processes. For example, the *Salicaceae* family includes willows, cottonwoods, and mountain alder. These species regenerate on disturbed soils and in openings, taking advantage of little or no competition from other plant species for soil moisture, sunlight, and nutrients. Grass and sedge sods become reestablished due to bank sloughing and re-anchoring in streams, and also due to seeds and rhizomes dispersed by channel flows (Winward 2000). Consequently, riparian community types do not stay fixed in place, but fluctuate over time and space in response to fluvial processes.

Fire and fluvial disturbance regimes described above influence changes in vegetation including regeneration of plant species, vertical and horizontal structure, and species composition within plant communities. Changes in plant species composition at a specific location that occur over time are termed plant succession. Stages of plant succession range from the very early seral stage to the potential natural community (PNC) stage. The PNC

> "is the biotic community that would be established if all successional sequences were completed without additional human-caused disturbance, under present environmental conditions" (Weixelman et al. 1999).

Succession is the process that begins with the colonization of bare soil by annual forbs and grasses, and extends through the establishment of stands of grasses, forbs, shrubs, and trees on a site – all subject to disturbances and subsequent soil development. As an example, within a fluvial disturbance regime, stream bars formed by newly deposited gravels provide the substrate and hydrologic parameters necessary for willows and cottonwoods to become established. As the stream channel migrates laterally and perhaps vertically in response to fluvial processes, the hydrologic gradient fluctuates as well. Over time, the stream bar may become an elevated stream terrace. This would occur as vegetation stabilizes transported sediment, fines accumulate, and the elevation of the bar increases. Eventually cottonwoods become the dominant overstory, and willows die out. An equally plausible successional trajectory would be that heavy flooding occurs, and stream bar sediments are relocated downstream where they are once again revegetated by willow and cottonwood. Plant succession has traditionally been defined as resulting in a "stable" plant community. Within Sierra Nevada upland and riparian systems, it is more accurate to state that community types become established in dynamic equilibrium with disturbance processes at work.