Stehekin River Information Base
Lake Chelan National Recreation Area

White Paper #1 – Stehekin River Corridor Implementation Plan
National Park Service
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January 18, 2008

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Executive Summary

This white paper was developed to summarize the current state of knowledge about the Stehekin River in preparation for a major planning effort. This knowledge is built upon inventory, monitoring, and research conducted primarily on the lower 10 miles of the river above Lake Chelan since the USGS installed a flow gage in 1911.

The Stehekin River drains an area of 220,000 acres (344 $miles^2$) of mostly public lands within Glacier Peak Wilderness Area, Lake Chelan National Recreation Area, and North Cascades National Park (Figure 1). Steep slopes, a dense network of tributary streams, and the location of the river's headwaters along the Pacific crest lead to the frequent and rapid rise of floodwaters on the river, perhaps more so than any other river in eastern Washington.

The shape of the watershed results in the junction of three major tributaries within a five-mile reach above the lower valley. Deep bedrock canyons within this zone deliver water, sediment, and large wood quickly to the wide, lower valley below High Bridge. The narrow box canyons are ideal sites for the formation and failure of temporary debris dams, which add an unpredictable nature to flooding on Stehekin River. Some evidence indicates that the temporary formation and rapid failure of a debris dam on the Stehekin River above High Bridge led to the record peak flow of 26,000 cfs in October 2003.

Analysis of nearly 100 years of flow records indicates that in about 1975 the Stehekin River switched from a system dominated by spring snow melt floods to one dominated by larger, more frequent fall rain on snow floods. The three largest floods on record occurred in the past 12 years and were fall events. Although more research is needed, it appears that this shift is a result of climate change.

The gradient of the river at its confluence with Agnes Creek is about 80ft/mile, decreases to 50 ft/mile above McGregor Meadows, and is 25 ft/mile just above Lake Chelan. However, gradient is steep in the lower valley in reaches with straight, narrow channels where the river encounters large tributary alluvial fans of Company, Rainbow and Boulder creeks (km 2-3, 6-7). The relatively straight, steep reaches are net transport zones for sediment and large wood, and as a result are areas of relative channel stability. Wood and sediment storage zones between these reaches are characterized by the existence of massive log jams, multiple side channels, and channel instability. Examples include the McGregor Meadows area and where the river meets Lake Chelan.

Annual total sediment load of the Stehekin River is estimated at 32,000 yd^3/year; with about 17%, or 5,600 yd^3/year, transported along the bed of the river as gravel. Gravel movement past any one point along the river probably varies annually by 100%, or more, with larger quantities of sediment moved during large flood events.

As recently as 1972, the U.S. Army Corps of Engineers removed most large logjams on the Stehekin River below Harlequin Bridge. Since that time, three comprehensive inventories of large wood accumulations in 1985, 2000, and 2007 have documented a significant increase on the lower Stehekin River. There are currently 166 logjams

consisting of 10 or more pieces on the lower river that contain a total volume of 400,000 cubic yards. In the 2000 survey, there were 101 logjams with a total volume of about 130,000 cubic yards.

Logjams occur at openings to side channels and on gravel bars along the main channel. Main channel logjams form in areas where gravel is deposited, with the largest wood accumulations near McGregor Meadows and where the river meets Lake Chelan. Large wood accumulations are known to play a beneficial role in slowing and spreading floodwater, but also to cause localized bank erosion and higher flood water elevations.

In response to bank instability along the lower Stehekin River, the NPS and private landowners have installed numerous bank protection measures. In 1994, erosion control structures were in place at 28 sites on the Stehekin River along 4,700 ft of shoreline. A recent inventory identifies 42 sites effecting approximately 7, 400 ft. Most erosion control structures are concentrated in the McGregor Meadows and river mouth areas. Most of these sites have rip rap bank protection, but rock barbs have become the favored approach in the past 15 years, with a total of 30 structures at eight sites. Five of the rock barbs placed on the Stehekin River before the 2003 flood are submerged in sediment and ineffective hydraulically less than 15 years after installation.

The U.S. Geological Survey studied the effects of rock groins and rip rap on stream velocity (Nelson, 1986). The National Park Service examined the hydraulic effect of rock barbs using two-dimensional models at upper Company Creek Road and at Stehekin Road mile 2.2. Based on the models and direct observations, barbs decrease bank erosion, but cause increased scour of the channel bed within a few hundred feet downstream of the lowest barb on same side of the river.

Only one extensive flood control project is in place in the lower Stehekin valley. A 400 ft long, 4-5 ft tall levee was constructed by the NPS in the early 1980s along the upper Company Creek Road at mile 5.5. Chelan Public Utility District showed in a 2000 study that the backwater effect of Lake Chelan at full pool extended nearly ¼ mile upstream of the river mouth, raising the 100 year flood elevation ½ foot.

Several features of the Stehekin valley underscore the need for careful land use planning to avoid repeated flood damage. These include the flood prone nature of the Stehekin River, large gravel transport, rapidly growing logjams, channel instability, the potential for the formation and sudden failure of debris dams in canyons above High Bridge, and a history of river manipulation to manage bank erosion and flooding. Further, a shift in the last 30 years from spring floods to larger, more frequent fall floods, and gravel deposition during the three large floods since 1995 makes comprehensive planning even more critical.

Introduction

The lower 18km of the Stehekin River and Lake Chelan are the focal points of Lake Chelan National Recreation Area (Figure 1). The lower valley contains numerous recreational facilities, a public road system, administrative facilities and approximately 100 residences and seasonal cabins. The Stehekin watershed is flood prone due to its climate, steep topography, and other watershed factors. In the past 12 years the three largest floods on record have wreaked havoc on public and private property and degraded scenic values along the river. Massive accumulation of gravel and large wood in the channel has led to proposals to return to the practice of large-scale removal of woody debris and channel dredging.

The first goal of this white paper is to summarize our current state of knowledge about the Stehekin River watershed, particularly those factors that influence the frequency and magnitude of flooding and erosion in the lower valley from Stehekin Valley Ranch to Lake Chelan. The second goal is to identify important gaps in understanding of the river's flood-prone nature.

Stehekin River Information Base

Inventory, Monitoring, and Research

A number of long-term monitoring efforts and basic mapping of the Stehekin River watershed provide important information (Table 1). The most critical of the monitoring efforts has been the measurement of river discharge near the mouth of Boulder Creek by the US Geologic Survey more or less continuously since 1911 (Figure 2). These measurements formed the basis of the 1981 FEMA and 1993 NPS floodplain studies, as well as our current understanding of how often big floods occur (flood frequency, magnitude, and recurrence interval).

These monitoring efforts are supported by a number of inventories of river features in the lower valley (Table 1). A number of these are particularly relevant to our understanding of the lower Stehekin River, including inventories of landforms, river channelization structures, and logjams.

Additional information on habitat was colleted at the reach scale by the NPS for Environmental Assessments of river erosion of public road sites including Coon Run (2005), 8-mile (1993, 2003), upper Company Creek Road (1982, 1998, 2007), and Stehekin Valley Road at mile 2.5 (1998).

Mountain rivers are among the most complex natural systems on earth. Since only a few research projects have been carried out on the Stehekin River (Table 1), some of our understanding about the Stehekin River is based on general observations throughout western North America. In the broadest sense, the Stehekin is typical of a glacial-fluvial river, with a gravel bed and riffle-pool morphology (Montgomery and Buffington, 1998; Rosgen and Silvey, 1998). However, several features of the river's geology, climate, hydrology, and vegetation combine with human influences to make the Stehekin River unique, as discussed below.

Watershed

Stehekin River drains an area of 220,000 acres (344 miles^2) of mostly public lands within Glacier Peak Wilderness Area, Lake Chelan National Recreation Area, and North Cascades National Park (Figure 1). This rugged landscape has numerous peaks above 9,000 ft, while the low point in the watershed is beneath the waters of Lake Chelan at more than 300 ft below sea level. Steep slopes lead to rapid runoff of rain and snow melt water.

The Stehekin's headwaters rise from glaciers located along the Pacific Crest of the Cascade Range. Approximately 103 small glaciers cover about 3% of the watershed, but provide as much s 15% of runoff during the dry summer months, or 21 billion gallons (Post et al., 1971; Figures 2 and 3). Most glacial meltwater comes from the main stem Stehekin River and Agnes Creek, with the largest glacier in the watershed Chickamin Glacier 4.7km^2. Major tributaries to the Stehekin include Agnes Creek, Bridge Creek, Company Creek, Rainbow Creek and Boulder Creek (Figure 2).

Stehekin valley is carved out of the crystalline core of the North Cascades, which is composed of very resistant Skagit Gneiss and granite. These quartz and feldspar rich rocks provide abundant amounts of sand and gravel to the Stehekin River system. Relief within the watershed varies from 9511 ft above sea level on Bonanza Peak, to a low of 350 ft below sea level in Lake Chelan, making the valley one of the deepest gorges in North America. Ice age glaciers created most of this relief by erosion of hard crystalline rocks. Two types of glaciers took turns carving the valley, including local alpine glaciers flowing off of the Pacific Crest and the Cordilleran ice sheet from Canada.

Although valley walls of the lower Stehekin were over-steepened by glaciers, the competency of Skagit Gneiss has limited large slope failures in the watershed, and allowed the remarkable development of the Lake Chelan canyon. Thirteen large landslides have been mapped by the NPS in the entire watershed within North Cascades National Park and Lake Chelan NRA. Eight of these features have delivered sediment directly to major tributaries. However, the Agnes Creek watershed has not been examined.

The trend of the Stehekin River follows the NW-SE alignment of most major faults and rivers in the region. However, the Stehekin valley and Lake Chelan do not follow a major fault or other structural weakness in the crust. Rather, geologists believe that the Stehekin River existed when the North Cascades mountains were uplifted, and was superimposed on the crystalline core of the range as it was uplifted and exposed by erosion.

Lower Stehekin Valley

Below High Bridge, the Stehekin River and Agnes Creek emerge from deep box canyons into the broad lower Stehekin valley (Figures 2 and 4). This part of the valley was glaciated by both alpine glaciers and the massive continental glacier from Canada known as the Cordilleran Ice Sheet. During multiple ice ages these glaciers created the valley's characteristic U-shape, straight profile, and flat valley floor. On the southwest side of the valley, the continental glacier left a long, lateral moraine feature 14,000 years ago that can be traced from the Stehekin Valley Ranch to the Orchard (Figure 4).

As they flowed down the Lake Chelan trough and encountered weaker bedrock, the glaciers eroded the floor of the lake valley to a depth more than 2000 feet below sea level. The modern floor of Lake Chelan is covered in a blanket of glacial sediment 1700 ft thick, which thins to a few hundred feet where the Stehekin River meets the lake (Figure 3).

The Stehekin River channel in the lower valley above McGregor Meadows is incised 15-20 ft within sand and gravel terraces, as is typical of rivers in the Western U.S. (Schumm and Brackenridge, 1987). Extensive alluvial fans deposited by major tributaries Company, Boulder, and Rainbow creeks define the area in which the Stehekin River has meandered, which is known as the channel migration zone. The alluvial fans themselves have older upper terrace surfaces that have presumably not been affected by flooding for a very long time, and represent appropriate sites for development to avoid flooding (Figure 4; Ryder, 1971).

The fan terraces grade to elevations more than 20 ft above the modern floodplain, when the level of Lake Chelan was higher following the end of the last ice age. Thus, base level for the lower Stehekin valley decreased until the 1920's, when Chelan PUD raised the level of the lake 20 ft with a hydroelectric dam. The backwater effect of the lake is discussed below. Base level of the river above Buckner Orchard may be bedrock controlled because the river channel is currently superimposed across a bedrock valley spur (Figure 4). The river also flows against the bedrock toe of the valley wall across from the lower field near river kilometer 11.5.

Below the orchard, the lower valley is underlain by a thick silt and clay layer that represents the former bed of Lake Chelan. Evidence uncovered by the National Park Service indicates that the Stehekin River met Lake Chelan just below Buckner Orchard 9,000 years ago. The Scherer cabins sit atop fine sand and silt of what was the river delta at that time. Down valley of the delta deposit, the silt and clay from deeper parts of the former lake bed are exposed near the surface in low-lying areas near the river, and at depths of 25-30 ft in well logs from sites on the Boulder Creek and Rainbow Creek fans. The presence of this layer probably limits channel incision, and along with the water level of Lake Chelan, stream gradient in the lower valley.

There is a pronounced asymmetry in the geology of the lower Stehekin valley due to the extreme NE-SW faces of the valley walls (Figure 4). The hot, dry north side (southwest facing) of the valley is characterized by steep streams that are known to carry debris flows to the valley floor. The small, steep streams are also prone to flooding caused by isolated summer thunderstorms. In contrast, forest cover is thicker on the northeast facing side of the valley, and runoff is generally less flashy.

Sediment Movement and Storage

While modern glaciers cover but a small fraction of the Stehekin watershed, extensive deposits were left by ice age glaciers between 30,000 and 12,000 years ago. These deposits are as much as several hundred feet deep in wide, U-shaped tributaries. Some of these deposits are perched adjacent to the channel and active floodplain. Together with deposits from steep tributary streams and landslides, the glacial gravels introduced by bank erosion during modern floods contribute to the gravel load of the Stehekin River, and river channel instability in the lower valley. Identified large glacial gravel sources include the Shady slide one mile below the mouth of Bridge Creek and the Cottonwood terrace eight miles above Bridge Creek. With the exception of numerous river-cut banks in the lower valley below High Bridge, all of the major gravel sources are in designated Wilderness.

Sediment transported through the bedrock-walled Stehekin and Agnes gorges above High Bridge is stored at various points in the lower valley. Major points of deposition include areas where valley width increases, such as McGregor Meadows and between the large alluvial fans of Company, Boulder, and Rainbow creeks. Another major sediment deposition point is where the river enters the slack-waters of the lake. Based on a continual decrease in grain size as the river approaches the lake, only pebble gravel and finer material is transported through the lower valley and deposited in the lake (Figure 5). Cobble and boulder gravel are stored at key points in the upper valley, such as the McGregor Meadows area. The size of gravels is also diminished by erosion as they are transported to the lake (Figure 5).

The grain-size of the Stehekin River bed load undergoes dramatic changes within the lower valley, mirroring changes in the gradient of the water surface profile (Figure 5). At its confluence with Agnes Creek, the Stehekin River gradient is about 80ft/mile. Above McGregor Meadows, the river moves cobbles and small boulders along its bed, and its gradient is approximately 50 ft/mile (1%). By the time it reaches Lake Chelan, seven miles down-river, the gradient decreases to about 25 ft/mile (0.5%) and the bed load is sand and pebble gravel. Within straight, narrow reaches in the lower valley, including between river kilometers 2-3, 6-7, and 11-12, the Stehekin transports clasts with median diameters of 15-25 cm. These areas correspond with the wood transportation zones discussed below, while areas of smaller-diameter gravels correspond with areas of increased floodplain and channel width and wood storage zones (Figure 5).

Several studies have attempted to estimate the amount of sediment that the Stehekin River moves annually (Table 2). In a survey of sites in the upper Columbia River basin of Washington State, Nelson (1974) estimated annual suspended sediment load on the Stehekin River (silt, clay and fine sand) at about 15,000 tons per year, which was comparable to the Methow River near Pateros. Nelson measured suspended load concentration as high as 22mg/l during a 7,000 cfs flow event on the Stehekin River in June of 1970, however, he did not attempt to measure the total load of the river (bed load and suspended load).

In 1999, the NPS used growth of the delta from Buckner Orchard to the landing over a 9,000 year period to estimate mean annual total sediment yield at about 25,000 cubic yards (Table 4). This estimate does not include silt and clay carried deeper into Lake Chelan and not deposited on the growing delta. This may explain why this value is low compared to other rivers in the region shown in Table 4. Considering the indirect method of measurement used by the NPS, the 25,000 cubic yard per year estimate should be viewed as a first-order approximation. Whether the actual value is significantly lower or higher, the amount of sediment the Stehekin River moves is impressive, and comparable to other large rivers in the Pacific Northwest.

The bed load (gravel) component of steep rivers such as the Stehekin is typically greater than 11% (Schumm, 1963; 1977). Use of the total and suspended load estimates of Nelson (1974) indicate that the bed load of the Stehekin River comprises about 17% of the total load, or 5,600 yd^3/year. Bed load discharge at a given cross section probably varies annually by 100%, or more, with larger quantities of sediment moved during large flood events. Considering a relative lack of change in the position of the channel at the river mouth and other locations, it appears that much of this sediment was being transported through the lower Stehekin valley prior to deposition of gravel during the 2003 flood.

Flood Hydrology

Climate of Stehekin watershed varies by elevation and distance from the Pacific Crest. High elevation headwater areas along the crest receive about 150 inches of precipitation a year, including approximately 20-30 ft of snowfall. At the opposite extreme at the low elevation eastern end of the watershed in Stehekin, annual rainfall is about 35 inches. Most of the precipitation within the watershed falls as snow between November and March.

The geology and shape of the Stehekin River watershed contributes to the valley's frequent and large floods (Figure 6). Resistant bedrock, and a steep, well-developed drainage network feed rain and snow melt water rapidly to trunk streams. The three main branches of the Stehekin River, Agnes, Bridge Creek, and Stehekin River, join within five miles, bringing floodwaters together in deep bedrock canyons that deliver it rapidly to the lower valley.

The location of the Stehekin River's headwaters along the wet Pacific Crest has a strong influence on flooding. Unlike nearby rivers on the east side of the Cascade Range, the upper Stehekin River, Flat Creek, and Agnes Creek valleys are prone to fall and early winter rain-on-snow floods because their headwaters are so far west (Figure 2). These floods are known for rising quickly and having relatively short durations of a few days (Figure 7).

The exceptional flood of 2003 was a fall rain-on-snow flood that occurred early in the flood season on October 20. It was triggered by heavy rainfall beginning on October 10, and was remarkable not only for its size, but for how quickly it rose early in the flood season. The 2003 event had a peak discharge of 25,900 cfs, and is by far the largest flood on record for the Stehekin River, with a discharge about 30% greater than the other large floods since 1911. The magnitude of the flood in the Skagit, Entiat, or Methow rivers did not approach the 100-year level (0.01 probability), while it far exceeded this probability on the Stehekin. Comparison of the Stehekin 2003 flood hydrograph with those of adjacent streams indicates that an unusual event led to the Stehekin undergoing a larger flood than its neighboring streams, even though its drainage area is much smaller (Figure 8).

The narrow box canyons on lower Bridge Creek, lower Stehekin River, and lower Agnes Creek, are ideal sites for the formation and failure of temporary debris dams. Review of available airphotos and satellite images, and inspection of the Stehekin river canyon above High Bridge, did not reveal any evidence of a temporary dam. However, failure of a forested, 50 ft tall bank four miles above High Bridge at Shady Camp, and evidence of water on top of the tall Tumwater Bridge two miles downstream, may support the inference of a debris dam failure as the cause for the unusually high peak discharge of October 2003. Future planning should take into account the likelihood of future debris dam failure events and their impact on development and land use in the lower valley.

Like their drier east side counterparts, the Stehekin River and its tributaries also flood during periods of rapid snow melt in May and June. Spring floods rise relatively slowly, but last for many days or even weeks (e.g. the 1997 spring flood had several peaks above 10,000 cfs through June into July). The largest spring floods occur when an above average snowpack persists late into the spring, and is melted rapidly by high temperatures and/or heavy rainfall. The largest flood on record for Stehekin River prior to 1995 was a spring flood that occurred in 1948 with a peak discharge of 18,900 cfs (Figure 9). In the Columbia basin, this was the largest flood on record since the 1894 event (Paulsen, 1949), which was also triggered by rapid spring snowmelt. Stehekin River tributaries Bridge, Rainbow, Boulder, and Company creeks are currently dominated by spring snowmelt floods. In fact, none of these ‘eastern’ tributaries underwent substantial flooding in 1995, 2003, or 2006, and the flood of record for these streams remains the spring 1948 event.

Small, steep first and second order tributaries in the valley are prone to flash flooding in summers as a result of intense thunderstorms. Those streams in southwest-facing valleys are particularly prone to debris torrents triggered by heavy summer rainfall.

Flood Magnitude and Frequency

Stehekin River has been gauged almost continuously since 1911. The flood history on the river contains both fall rain-on-snow and spring snow melt floods (Table 3). Until 1995, the largest flood on record was the 1948 spring event, and six of the seven largest floods occurred during the spring (Table 3; Figure 6). On November 29, 1995, a flood equaling the 1948 event passed down the Stehekin River. It was followed by large spring floods in 1997 and 1999, and two large fall floods in 2003 and 2006.

A research project written for the relicensing of the Lake Chelan Hydroelectric Project has added some perspective to our understanding of Stehekin River hydrology. In 1999

Bob Jarret of the U.S. Geological Survey estimated the largest flood on the Stehekin River since the last ice age at 36,000 cfs, about 50% larger than the 2003 event. However, this estimate is based on geologic data and should be considered a first-order estimate. Further, it is possible that a flood of this magnitude occurred many thousands of years ago under different climatic conditions, or that it was related to failure of a natural dam as discussed above.

Table 4 shows the recurrence interval for floods of different magnitudes based on the 90+ year gauging station record. This analysis was based on data recorded at the gauge between 1911 and 1927 and 1927 and 2007. Passage of the large floods in 1995, 2003, and 2006 has shifted the magnitude-frequency relationship toward larger, more frequent floods. This coincides with a general shift in about 1975 from a spring snowmelt dominated system to one dominated by fall and early winter rain on snow flooding.

The shift to a fall rain-on-snow dominated flood regime on Stehekin River means that events like 1995 and 2006 may be typical for this system in the foreseeable future. Jarrett, (1999) noted that probable maximum floods on west slope Cascade streams are larger than their east side counterparts. How far the Stehekin River watershed moves toward a west-slope magnitude flood system remains to be seen. Considering the flood-prone nature of the Stehekin system, a shift toward larger, more frequent fall flooding, and channel changes caused by the three large recent fall floods underscores the need for careful land use planning.

Channel Geometry, Hydraulics and Stability

The lower Stehekin valley is an alluvial valley with varying levels of confinement. It is characterized by a wide floodplain and gravel-dominated channel containing an island-bar pattern (Schumm, 1977). The river has this pattern because of the voluminous gravel load that it carries, its large-scale transport and storage of woody debris, and the effective resistance provided by dense stream-bank vegetation, including willow and red osier dogwood. Despite the resistant imparted by large wood and dense stream-side vegetation, the instability of the Stehekin River streambanks was recognized long before the large floods of the past 12 years (Nelson, 1986).

Stehekin River is not a glacially dominated stream like the rivers on Mt. Rainier. Figure 10 illustrates the island-bar pattern of the river in several reaches. Areas standing above the floodplain, and limiting channel migration, include a large lateral moraine on the north east side of the valley and the extensive alluvial fans of Company, Rainbow, and Boulder creeks (Figure 4). Over the past several hundred years, the Stehekin River has meandered across most of the valley floor between these landforms. Two sites in the lower valley have more of a single, straight channel, including the reach above Harlequin Bridge, and the reach near the mouth of Boulder Creek. As discussed above, these relatively straight channel reaches function as large wood and sediment transport zones. They have been stable features of the floodplain for the last 50 years. In all three of the transport zones, there are large side channels (Figure 10). These channels carry fast, deep flood waters, and may be preferred sites for the main channel to shift to when it becomes obstructed.

Channel geometry varies considerably within the two types of lower valley reaches (Table 5). In the narrow, straight reaches, bank-full width is as low as 50 ft, but increases to more than 250 ft. in deposition/storage reaches. Channel sinuosity is generally near 1.3, but in areas of recent sediment deposition such as McGregor Meadows reaches 1.8. Three relatively large meander loops have formed down stream from Harlequin Bridge, where sinuosity increases to 2.5 (Figure 11). The first is located near Frog Island (river kilometer 6), where the channel has migrated into the left bank. A second is below Buckner Orchard. This unusually large meander formed in-part because a right bank side channel was blocked by Chelan PUD in the 1930s to prevent water from bypassing the stream gauge. Growth of this meander was exacerbated by removal of native vegetation and the presence of weak sand and silt soils (ancient river delta) on the left bank below the mouth of Rainbow Creek. Another large channel meander has formed just above the mouth of the river, and is discussed below.

Channel hydraulic conditions in the two different reaches were assessed by the NPS (1993) with a HEC-2 hydraulic model. Channel flood water velocity generally decreases downvalley, while widt-depth ratio and sinuosity increase. Superimposed on this general pattern, within narrower, straighter sediment transport zones adjacent to alluvial fans and above McGregor Meadows, 100 year flood channel velocities are on the order of 9-12 feet per second (fps). Within sediment storage zones between the big alluvial fans and at McGregor Meadows, 100-year flood velocities in the main channel are typically 6-7 fps, but more variable due to the presence of multiple side channels. Flow depth, flood-prone width, entrenchment, width-depth ratio, and stream power also vary systematically between these zones (Figure 11; Table 5). Overbank velocities during 100-year flood events vary between 2-4 ft, with flood depths of 6 ft or more in many side channels.

Flood hazard conditions on the floodplain away from the main channel vary widely in the lower valley. In general, areas above Buckner Orchard can be exposed to higher overbank flood velocities. The area near McGregor Meadows is particularly hazardous due to deep, fast overbank flows and the presence of enlarging side channels where flood depths during a 100 year event are greater than 5 ft. In contrast, flood waters in overbank areas near the Bakery and Silver Bay move more slowly. Any areas in the lower valley isolated between the river and large side channels are particularly hazardous. As a general rule, as flood depths approach 3 ft and flood water velocities reach 3 feet per second, cars can be swept off roadways.

Manning's hydraulic roughness values for the Stehekin River channel have been estimated at 0.045 by the U.S.G.S. (1986) and N.P.S. (1993). Overbank flooding areas in the deposition zones, with dense forests and large wood accumulations, have 'n' values as high as 0.125. The high degree of roughness in most overbank areas reduces flood water velocities in floodplain developed areas. Lower velocity results in less erosion and scour damage to structures and roads.

Until passage of the recent large floods, evidence indicates that the Stehekin river's channel geometry was fairly well adjusted to a spring mean bank-full discharge of about

9,000 cfs (Leopold and Wolman, 1957; Southerland, 2003). Deposition of massive amounts of gravel and channel widening in different reaches during the recent floods has initiated multiple channel changes on the lower Stehekin River.

Large bed load, rapid sediment movement, and rapid changes in stream capacity to move material of different sizes creates instability in the deposition zones of the lower Stehekin River channel. Often, coarse material deposited during a large flood is abandoned by the river as it erodes into finer –grained material, a process known as lateral replacement. This often leads to bank erosion in reaches that are characterized primarily by channel deposition, such as McGregor Meadows and the river mouth at Lake Chelan.

The position of the Stehekin River Channel has been monitored using an old map made in 1902, and from aerial photos taken in 1957, 1962, 1978, 1988, 2004 and 2007 (Figure 10). The 1902 channel location is suspect due to mapping scale and a lack of landmarks, however, in several areas there are old river channels where the map placed the river. Furthermore, it is interesting that the channel appears to have been straighter in 1902, and its sinuosity has generally increased since 1962 (Figure 10).

Major channel changes observed at three locations by the NPS in the past 50 years have been gradual, given the magnitude of recent flood events. At several locations, including the Lower Field and near the mouth of Wilson Creek, the river has jumped from one side of its channel to the other with deposition of gravel during large floods (Figure 10).

Qualitative observations indicate that the slower process of channel change begins with deposition of large amounts of gravel in the main channel during floods, which reduces channel capacity and results in accelerated bank erosion and over-bank flooding. Over-bank flooding and channel erosion of stream banks exploit weaknesses in the floodplain, but generally follow and enlarge former river channels. The process of channel migration is complicated by the presence of large wood, as discussed below for McGregor Meadows.

Due to changes in valley width, stream gradient, and obstructions, there are two main areas of stream bank instability in the lower Stehekin valley. One is where the river loses its energy in the half-mile above Lake Chelan. The other is at McGregor Meadows, where the valley width increases three-fold. In the McGregor Meadows reach, the increase in valley width is accompanied by a drop is valley gradient, which in turn results in loss of stream power and pronounced deposition of sand, gravel, and large wood. Channel instability is also occurring throughout the valley on the outside of channel bends.

Long-term studies of similar river systems like the Stehekin suggests that events in the upper valley can trigger a cascade of river channel adjustments downvalley. The idea is that once a major channel realignment/straightening event occurs, that the increased energy results in the movement of a large wave of gravel downstream, where it triggers another channel adjustment, and so forth downstream. In Stehekin, it is possible that McGregor Meadows is a key site in initiating this process. Once the channel realigns itself through the meadows and becomes faster and straighter, it could trigger changes all the way to Lake Chelan.

Large Wood Accumulations

As recently as 1972, the Corps of Engineers removed most large wood piles on the Stehekin River below Harlequin Bridge. Three comprehensive inventories of large wood accumulations in 1985, 2000, and 2007 have since documented rapid movement and storage of wood on the lower Stehekin River (Mason and Koon, 1985). Large wood storage and transport zones in the lower valley generally correspond to sediment storage and transport zones. While most of the lower Stehekin River is within sediment and wood storage zones, three kilometer-long (1/2 mile) reaches adjacent to the alluvial fans of Company, Boulder and Rainbow creeks are generally free of large wood accumulations.

Log jams form in two primary locations along the Stehekin River in the storage zones, including at the entrances to side channels and on gravel bars (Figures 12 and 13). There are currently 166 logjams consisting of 10 or more pieces on the lower 10 miles of the Stehekin River. These logjams contain a total volume of 309,000 cubic meters of large wood. Some of the logjams are massive, such as the jam the head of Noname Creek in McGregor Meadows, which contains nearly 2,000 logs (Figures 13 and 14). Other massive logjams include four at the mouth of the Stehekin River; the largest of these contains 861 pieces. Another logjam near kilometer 6 below Harelquin Bridge contains more than 1250 logs, many of which are rotting. Some of the largest logjams on the Stehekin River have been stable features on the floodplain since 1985, including the large logjams at the mouth of Stehekin River and below Harlequin Bridge.

The increase of large wood on the Stehekin River in the decades following wood removal in the early 1970s is impressive. For example, the 166 logjams counted in 2007 represent a significant increase compared to the 101 logjams in the 2000 survey. Further, wood volume has increase substantially at every river kilometer since 1984 (Figure 13). In 1984 the total volume of large wood on the lower river was 17,000m^3, increased to 103,000m^3 by 2000, and is now 309,000 m$^{3.}$ Since 2000, a particularly large increase occurred above Lower Field at river kilometer 12. There were very few logjams in this area before passage of the 2003 flood. This record event appears responsible for at least 2/3 of the wood along the river in the lower valley.

Overall, the effect of the log jams is generally to increase hydraulic roughness (resistance to flow) and width to depth ratio of the channel, while reducing flood flow velocity (Barnes, 1967; Arcement and Schneider, 1987). Thus, the Stehekin is a shallower stream than typically found on the east slope of the North Cascades (Southerland, 2003). The effect of large scale energy dissipation from large wood accumulations is also to increase channel stability. Removal of wood tends to remobilize channel gravels, resulting in sedimentation, channel instability, and bank erosion downstream. At the local, or site scale log jams can redirect flow by blocking side channels, and can cause scouring, deposition, and bank erosion.

Floodplain
The floodplain of the Stehekin River is known to be a dynamic feature of the landscape, changing with the erosion of banks, filling of the channel with gravel, and the passage of large flood events. The NPS mapped the floodplain as part of a surficial geology inventory designed to identify geologic hazards and landform age (Figure 4). The boundaries depicted in Figure 4 generally coincide with the channel migration zone of the river, but they are not necessarily the same as the floodplain boundaries determined using hydraulic modeling and shown in Figure 11 (NPS 1993).

The 100 year floodplain of the Stehekin River below McGregor Meadows was mapped by FEMA contractor CH2MHill in the late 1970s. A final Chelan County flood insurance study was published in 1981. The U.S. Geological Survey extended the floodplain map upvalley through McGregor Meadows in the mid 1980s (Nelson, 1986). In 1993 the NPS surveyed the area above the USGS study, corrected areas surveyed by FEMA and USGS, and completed a floodplain map that extended from the Lake upvalley past Stehekin Valley Ranch. Neither the USGS or NPS data have been incorporated into the Chelan County flood insurance program.

Erosion Management Structures
The NPS has monitored the number and effective shoreline length of erosion control structures on the Stehekin River since the early 1990s (Table 6). The most recent inventory lists more than 40 sites along the lower river where attempts have been made to control bank erosion (Figure 15). Most of the erosion control efforts have been focused on the McGregor Meadows and river mouth areas.

Most of these sites have rip rap bank protection, but use of rock barbs in the past 15 years has grown to 30 structures at eight sites. Ten of the 30 barbs were built to protect private property, with the remaining 20 barbs were built to protect public roads from river bank erosion. The NPS constructed two-dimensional hydraulic models to assess the impact of barbs before they were installed at two sites. The NPS followed up with surveys of the effects of barbs at mile 2.5 along the main Stehekin Valley Road. Based on the modeling studies and observations, the effect of the barbs is generally confined to the same bank. In addition to stopping bank erosion, the primary effect observed was development of scour holes on the channel bed within 200 feet downstream of the barbs. The effect of the rock barbs is also limited in time in parts of the channel prone to gravel deposition. Five of the rock barbs previously placed on the Stehekin River are submerged in sand and gravel, leaving them hydraulically ineffective less than 15 years after they were installed.

Another effect of the bank hardening is to delay channel migration. The majority of erosion control structures in the valley do not raise the water surface elevation of floods since they were built at grade (i.e. are not associated with levees or dikes).

Flood Control
Only one extensive flood control project is in place in the lower Stehekin valley. The site is located along upper Company Creek Road at km 9.5, and consists of a 400 ft long, 4-5 ft tall levee constructed by the NPS in the early 1980s. This feature limits flood water

from entering portions of the right bank floodplain, and locally raises the water surface elevation. Water at flood stage does flow around the downstream end of the levee, down the Company Creek road, and reaches a series of old river channels and wetlands above Company Creek fan (Figure 10).

In summer 2007, a 720 piece logjam was moved from an entrance to a river side channel known as the '1948' river channel. Almost all of the logs were repositioned downstream of the channel mouth below the ordinary high water mark. The jam was removed to lower the surface elevation of the 100 year flood. Previous hydraulic modeling indicated that this blocked channel raised the 100 year flood elevation approximately 0.5 ft in the lower valley (Christman, 2001). This project represents the first large scale manipulation of wood on the Stehekin River in more than 35 years. It was completed entirely on private land within the Lake Chelan backwater influence zone, and is unlikely to impact other property downstream. Due to these site-specific conditions, this approach may not work at other sites in the valley, such as those where logjams are not across side channels.

Important Reach Scale Locations

Two sites in the lower Stehekin valley with difficult flooding problems stand out when examining the information summarized above. These sites are both areas of sediment and large wood storage that have extensive development in the floodplain and along the river. However, there are different reasons why these sites are experiencing enhanced flooding after passage of the 1995, 2003, and 2006 floods.

McGregor Meadows

At McGregor Meadows, the width of the Stehekin valley increases 3-fold, and as a result the gradient drops, sediment is deposited. Through the process of lateral replacement, the channel has become particularly unstable. The positions of the Stehekin River's channel have been plotted at various times since 1905. In the McGregor Meadows reach, channel sinuosity has increased as floods of the past half-century have filled the main channel with gravel, which causes erosion of stream banks and deposition of large woody debris.

The NPS has observed a 3-4 foot increase in the elevation of the bed of the Stehekin River adjacent to kilometer 10 in the past 15 years. Following the 1995 flood, a private consultant and NPS river managers agreed that the loss of channel conveyance due to gravel accumulation on the river bed would ultimately result in a channel shift to the left bank, through McGregor Meadows along NoName Creek. However, growth of a 1900 piece log jam has blocked the entrance to this route, and the river appears to be seeking a new path a few hundred meters upstream. It is also possible that continued deposition of wood and gravel in the channel will result in the river breaking out of its channel further upstream and following the Stehekin valley road through McGregor Meadows.

In response to the formation of pilot channels in McGregor Meadows, about 10 grade control structures were installed on the left (north) bank floodplain in the late 1990s. Grade control structures are essentially trenches filled with large rocks and gravel that are built perpendicular to flow. They are designed to keep water spread-out across a floodplain to prevent flood channels from enlarging. Since the tops of these structures are at grade, they are not visible do not raise the water surface elevation of floods. In response to overbank flooding and scour of roads upstream and on the opposite bank, four additional grade control measures were installed by the NPS in 2007.

At McGregor Meadows, channel deposition has led to rapid bank erosion on the right bank and an increase in width to depth ratio. The NPS has installed 10 rock barbs in a half-mile long reach to slow erosion, while private landowners have placed another three barbs. Plugging of the channel with gravel, and alter wood, is forcing a large amount of water overbank between river kilometers 10 and 11.

Just downstream of McGregor meadows, channel deposition led to a shift in the channel to the opposite side of a gravel bar in two locations. Above Wilson Creek, the channel has jumped to the left bank, causing increased bank erosion at the toe of a steep glacial moraine. Downstream, the channel has moved into the right bank, resulting in greater overbank flooding on the Scutt and Winkel properties. The net result of all of these changes is an increase in sinuosity in the reach at and below McGregor Meadows (Figure 10).

River Mouth and Lake Chelan
Deposition of gravel and large wood, and channel instability, also occur where Stehekin River enters Lake Chelan. In a 2001 study, Christman found that the level of Lake Chelan has a strong influence on hydraulic conditions on the lower river. When the lake is at full pool and river discharge approaches 20,000 cfs (i.e. a 100 year flood), the backwater effect of the lake extends about ¼ mile upstream. The backwater effect extends several hundred feet further upstream for smaller floods that occur at full pool. No effect from Lake Chelan was observed when lake level is below 1094 ft (Figure 16).

The effect of the lake backwater is to raise the 100 year flood elevation about 0.5 ft, and to cause sediment deposition and accumulation of large woody debris. Further PUD modeling of the effect of large wood on flood water surface elevations near the river mouth indicated that logjams blocking side channels on the right bank raise the water surface elevation another 0.5-1 ft. In summer 2007, one of these logjams was removed from the head of a side channel near river kilometer 1 on the right bank. This channel was occupied by the river prior to the 1948 flood, and is know as the 1948 flood channel.

Data Gaps

<u>Relative influences of Agnes Cr., upper Stehekin River, and Bridge Creek on Flooding.</u>
Draining the drier east slope of the North Cascades, Bridge Creek is dominated mainly by spring snow melt floods. In contrast, upper Stehekin River and Agnes Cr. head much farther west on the Pacific Crest and have both fall-winter rain-on-snow and spring snow melt floods. There is a need for at least one and possibly two gages on the upper river to understand the contribution of each major Stehekin tributary to flooding in the lower valley.

Up-to-Date Floodplain Maps

With passage of the record floods in 1995, 2003, and 2006, the river has undergone several changes that have produced new information gaps. For example, the FEMA floodplain map adopted by Chelan County in 1982 and updated in 1989 was found to be inaccurate in several locations in an NPS study completed in 1993. Channel filling, bank erosion, and river realignment have rendered the FEMA (1981) and NPS (1993) floodplain maps obsolete in many parts of the valley. As a basis for planning and future county floodplain management, the NPS and Chelan County are joining forces with Chelan PUD to create a new floodplain map. This effort will include surveying of 50 or more river cross sections, development of a one-dimensional hydraulic model, and creation of a computer-based map. The model will also produce supporting data such as flood depth and velocity for the lower valley that will be the basis for development of a floodplain hazards map.

Sediment Yield

Measuring sediment discharge is a very difficult problem, and we have only ball-park estimates about total sediment load and gravel load on the Stehekin River. Areas of valley width and slope change are generally areas of rapid sediment deposition and storage in the floodplain. Our understanding of sediment transport and storage in these zones could be improved by looking at existing data. We are comparing the 2007 channel topographic survey with historic FEMA, USGS, PUD, and NPS surveys to estimate the volume of sediment deposition or erosion in various reaches. Chelan PUD surveys of the river mouth in 2001 will be particularly useful in this comparison because they will give us an estimate of change induced by the big floods of 2003 and 2006 at the river mouth.

Another option to improve our understanding of sediment yield includes monitoring sediment transport at a few select sites. Further, an inventory of all major sediment sources in upper Stehekin valley would help improve sediment yield estimates. However, introduction of sediment by landslides, debris torrents, and other localized events add a random and unpredictable nature to sediment transport.

Potential for Channel Instability to Migrate from McGregor Meadows Downstream

Observation of the Stehekin River during the past 20 years has led to development of the idea that a major channel shift at McGregor Meadows will lead to a chain-reaction downstream over the next few decades (or more). This process has been observed on other rivers, and works as follows. First, a channel shift cuts off a large river meander, or series of meanders, and results in a straightening and shortening of the river. This reconfiguration leads to a steeper river gradient and more stream energy to transport channel gravels. The movement of gravel downstream results in instability at a new location and another meander cut-off, and the process proceeds downstream to Lake Chelan.

We do not know is if this process has occurred in the past, or how fast it might take for a channel shift at McGregor Meadows to lead to channel instability at the lake. It was thought that a channel shift at McGregor Meadows was inevitable after the 1995 flood. However, even after the record floods of 2003 and 2006, this process is still proceeding.

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TABLES

Table 1. Stehekin River inventory, monitoring, and research. See bibliography for full references.

Monitoring	agency	length record
discharge	USGS	1911-present
channel pattern	NPS	1906-2007

Inventory	agency	date
surficial geology (landforms)	NPS	2005
soils	NPS-NRCS	1988 + new project
vegetation	NPS	1988 + new project
main stream and side channel habitats	NPS	1998
wetlands	NPS	1988
floodplain	FEMA	1981
floodplain	NPS	1992
large wood accumulation	NPS	1985, 2000, 2007

Research	author	date
sediment transport	Nelson	1974
effect of erosion control structures	Nelson	1986
hydraulic effect of bank barbs	West Eng.	1997
maximum flooding	Jarrett	1998
sedimentation	Riedel	2000
lake backwater effect	Christman	2000
channel hydraulic geometry	Southerland	2003

Table 2. Comparison of Stehekin River sediment yield with other rivers.

River System	Load Type *	Sediment Load (m^3/km^2yr)
Stehekin	Total	28
Skagit [1]	Bed	12
Columbia-N. Pacific[2]	Total	66
Rocky Mtn. region[3]	Total	84
Sierra Nevada[3]	Total	410
Coast Range, Oregon[3]	Total	38
Amazon[4]	Total	58
Mississippi[4]	Total	38

*load types include dissolved, suspended, bed, and total

1= Stewart and Bodhaine, 1961.

2=US Water Resources Council, 1968; average sediment yield for drainage areas <100 miles^2

3=Geiger, 1958; sediment yield from studies of reservoir deposits in small watersheds.

4=Sundborg, 1983

Table 3. Chronology and features of the ten largest floods on the Stehekin River.

Date	Flood type	Discharge cfs	Recurrence Inverval
October 20, 2003	Intense rainfall	25,900*	>100 years
November 29, 1995	Rain on snow	20,900	100 years
November 7, 2006	Rain on snow	19,100	100 years
May 29, 1948	Snow melt	18,900	100 years
November 7, 1948	Rain on snow	18,400	50-100 years
December 26, 1980	Rain on snow	17,300	50 years
June 16, 1974	Snow melt	16,600	25 years
November 24, 1990	Rain on Snow	14,700	10 years
June 2, 1968	Snow melt	14,400	10 years
June 10, 1972	Snow melt	14,400	10 years
June 21, 1967	Snow melt	13,900	10 years

* flood discharge an estimate due to gage malfunction

Table 4. Peak discharge for 50, 100, and larger than 100 year floods on the Stehekin River gage 12451000. Inclusion of the 2003 and 2006 flood data (A) results in a significant increase in base flood discharge. Based on USGS Water Resources Division bulletin 17-B analyses.

site	river mile	drainage area (miles^2)	PEAK DISCHARGE (cfs)		
			50 yr.	100 yr.	100-500 yr.*
(A) 1927-2007	**1**	**344**	**19,490**	**21,400**	**25,850**
(B) 1927-1996	1	344	17,900	19,200	22,100
Orchard	2	308	16,500	17,700	20,300
Company Cr.	4.5	277	15,200	16,300	18,800
Lower Field	6.7	256	13,920	14,928	17,217

*The estimate for the return interval for this sized flood is well beyond the observed record for Stehekin River (i.e a 500 year return interval for the 2003 flood is likely inaccurate due to climate change, the Sthekin's flood-prone nature, and the potential for debris dams to form).

Table 5. Hydraulic geometry and flow conditions of the lower Stehekin River as measured by Southerland (2000) near the lower field (river kilometer 12) and the NPS (2007).

	Lower Field (km 12)	River Mouth (km 1)
Entrenchment Ratio	2.59	n/a
Width-Depth ratio	54	119
Sinuosity	1.26	2.5
Slope	0.9%	0.6%
D50	17 cm	6 cm
Width at bank-full flow	209 ft	800 ft
Average depth at bkfl. flow	3.95 ft	5 ft
Q100 Channel Velocity	13-14 fps	7 fps
Q100 Channel Depth	10 ft	10.3 ft

Table 6. Erosion control structures on the Lower Stehekin River as of December 2007. These data are based upon a 2000 shoreline inventory from Lake Chelan to High Bridge (97,152 feet of shoreline). Locations shown on Figure 15.

Bank Protection Technique	**Number of Locations**	**Affected Streambank (ft)**	**% of Total Shoreline**
Bank armoring with rip-rap	15 (1 site also has rock barbs)	2632	2.71
Cabled logs	14 (2 sites also have rip-rap)	1156	1.19
Rock barbs	8 (30 barbs)	2900	2.06
Log cribbing/jam	4	640	0.66
Concrete bags	1	33	0.03
Cumulative length of shoreline *currently* affected by erosion control structures:		6761	6.65
Length of shoreline that would be affected by this bank barb proposal, if implemented:		600	0.62
Cumulative length of shoreline that would be affected by all erosion control structures, including this proposal:		**7361**	**7.6**

*in 1993 there was a total of 4,664 ft of erosion control on the lower Stehekin River

FIGURES

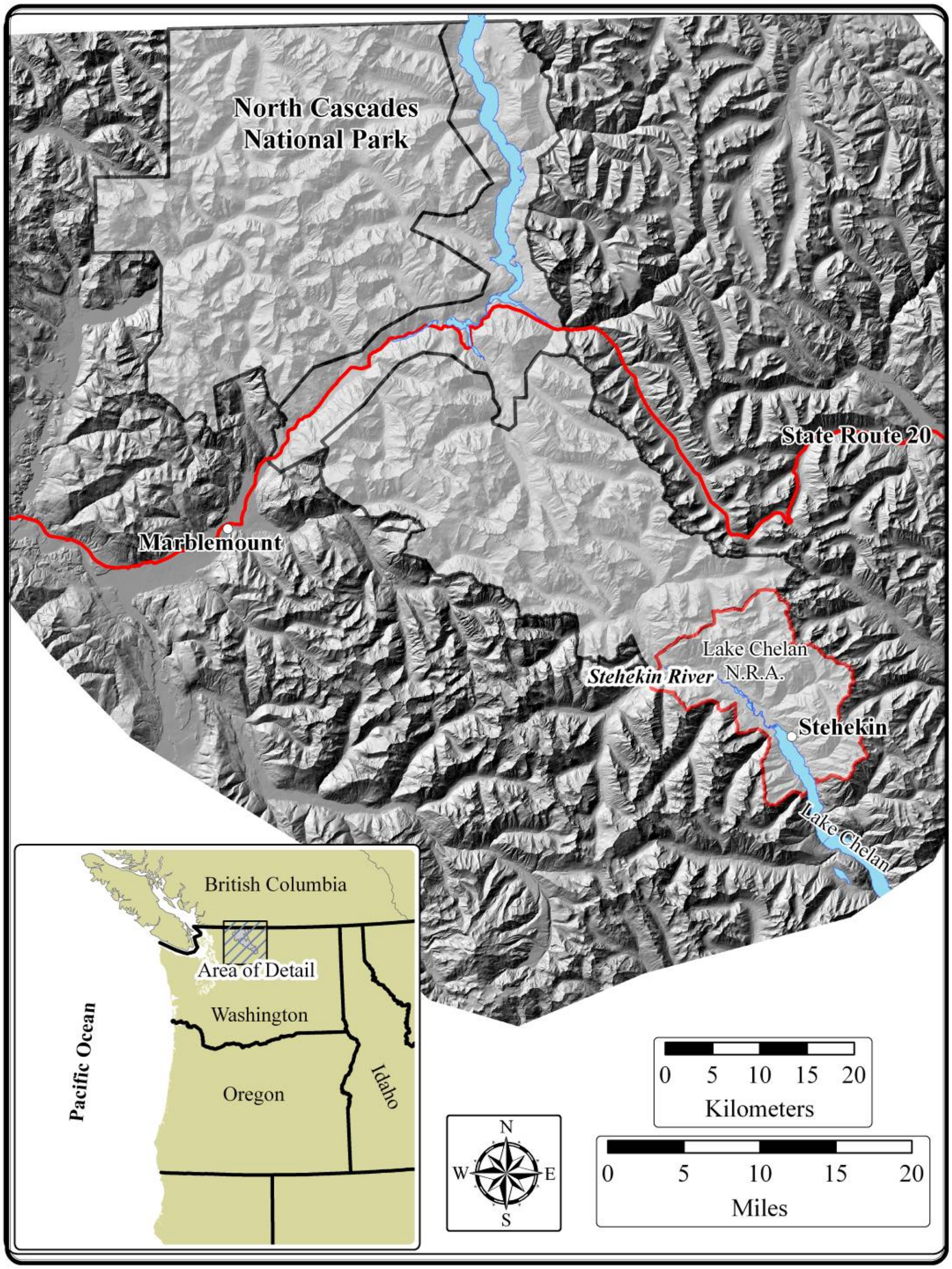


Figure 1. Location of the Stehekin River in north-central Washington (inset) and within North Cascades National Park and Lake Chelan National Recreation Area.

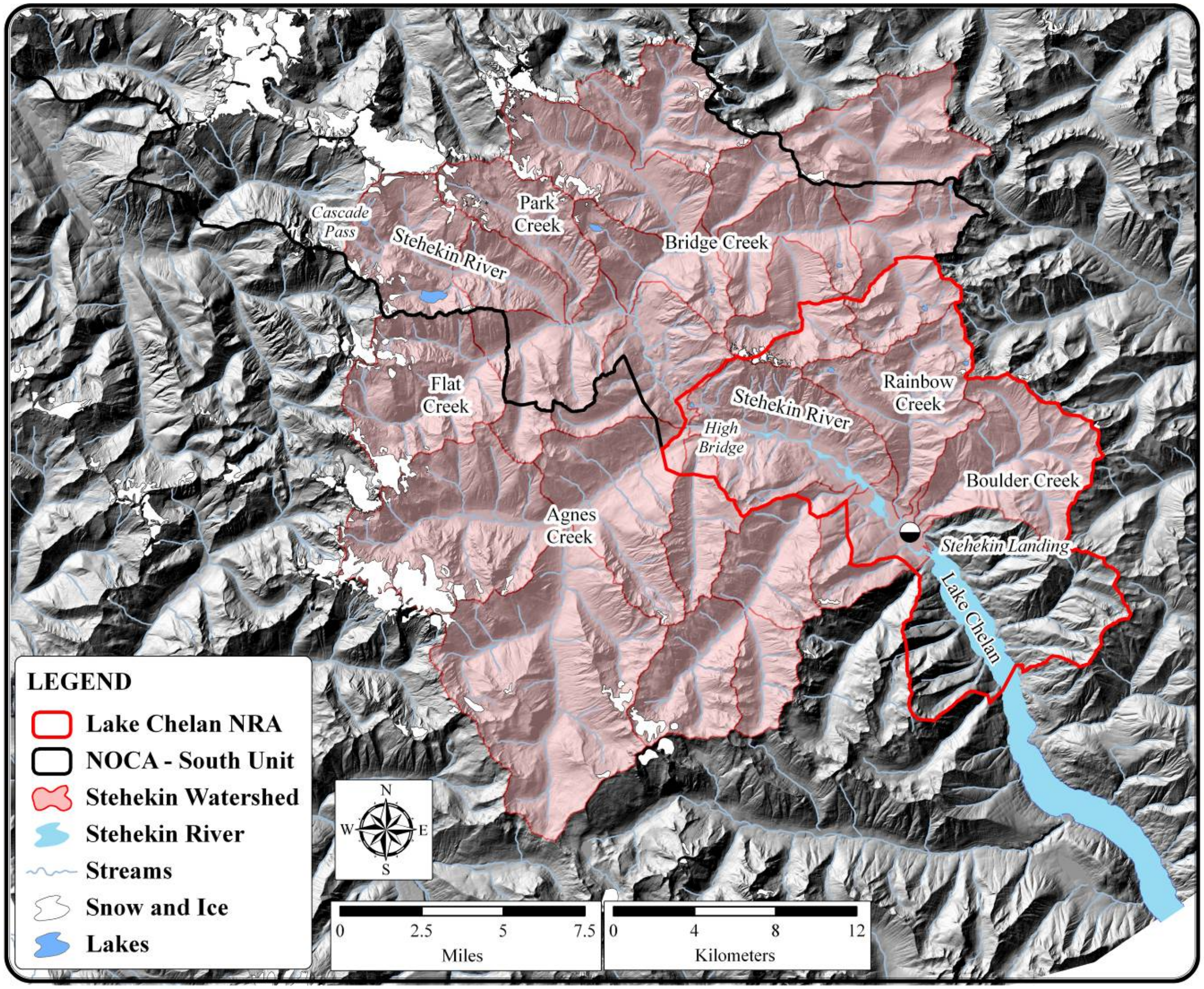


Figure 2. Stehekin River watershed. Note location of stream gage above Lake Chelan.

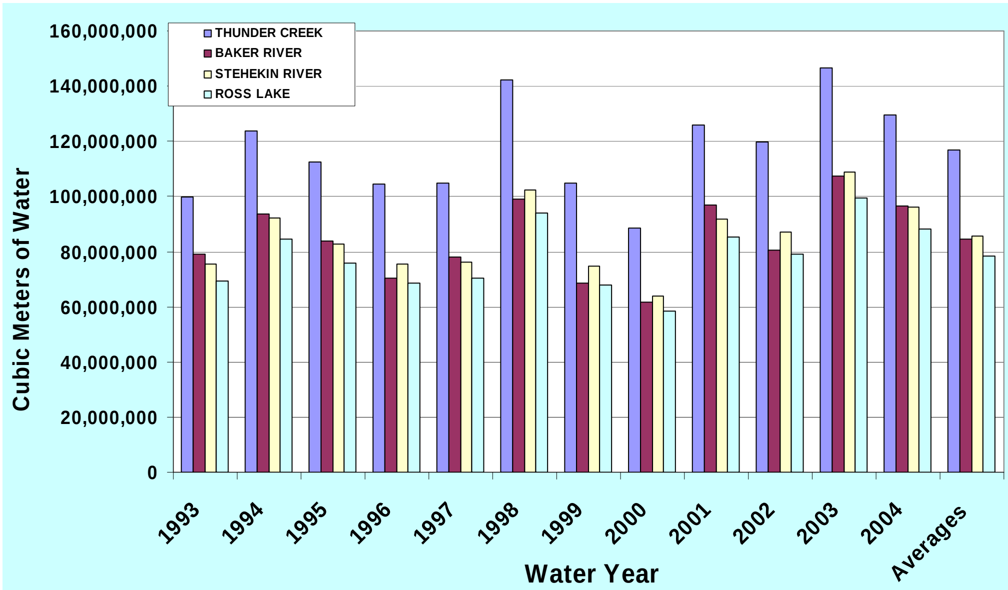


Figure 3. Glacial contribution to summer runoff on the Stehekin River and three other North Cascades watersheds. One cubic meter of water equals 264 gallons.

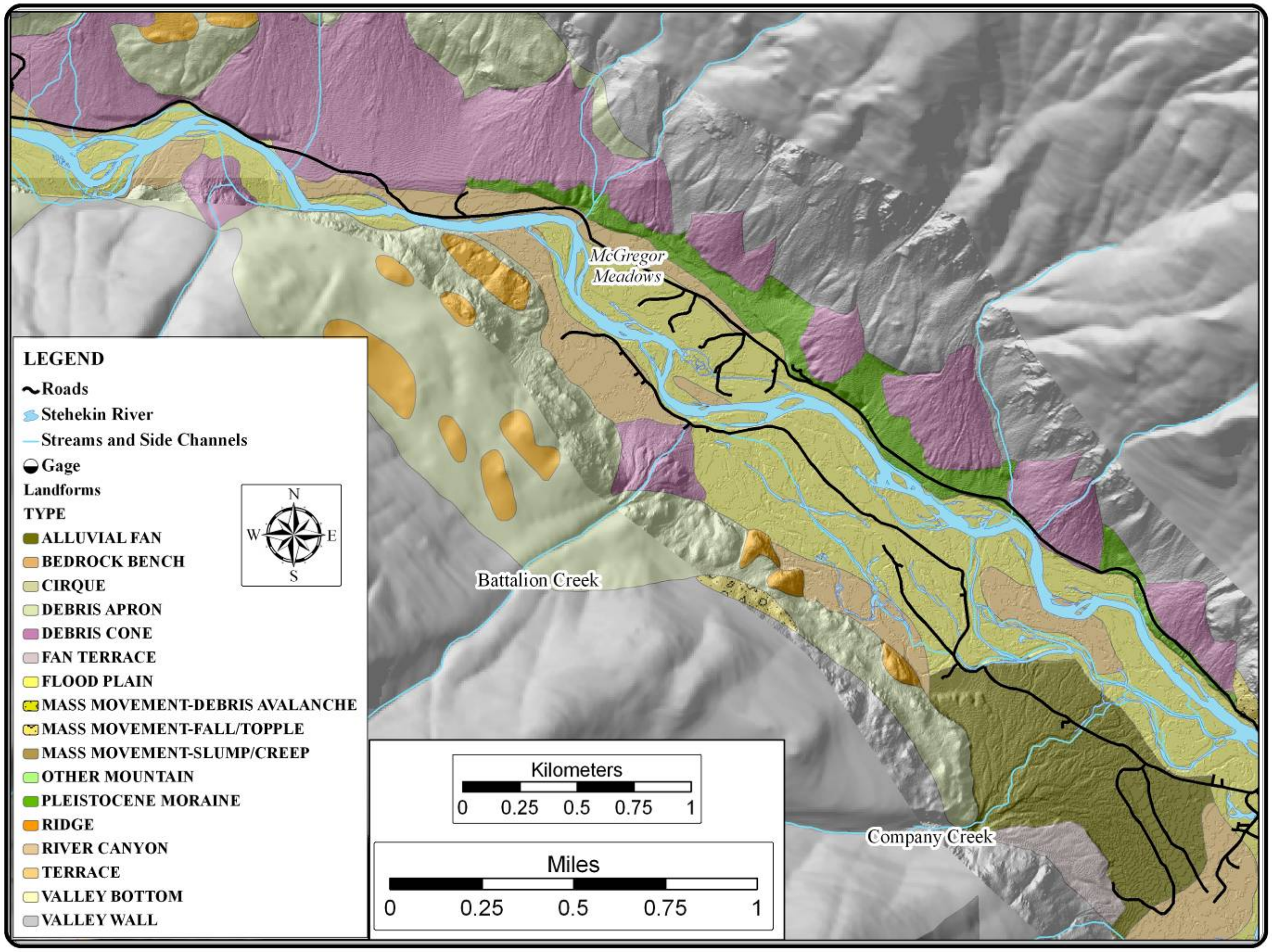


Figure 4A. Landforms and road network of lower Stehekin valley above Harlequin Bridge. Note the olive-green colored alluvial fans built by tributary streams and orange colored terraces above the floodplain.

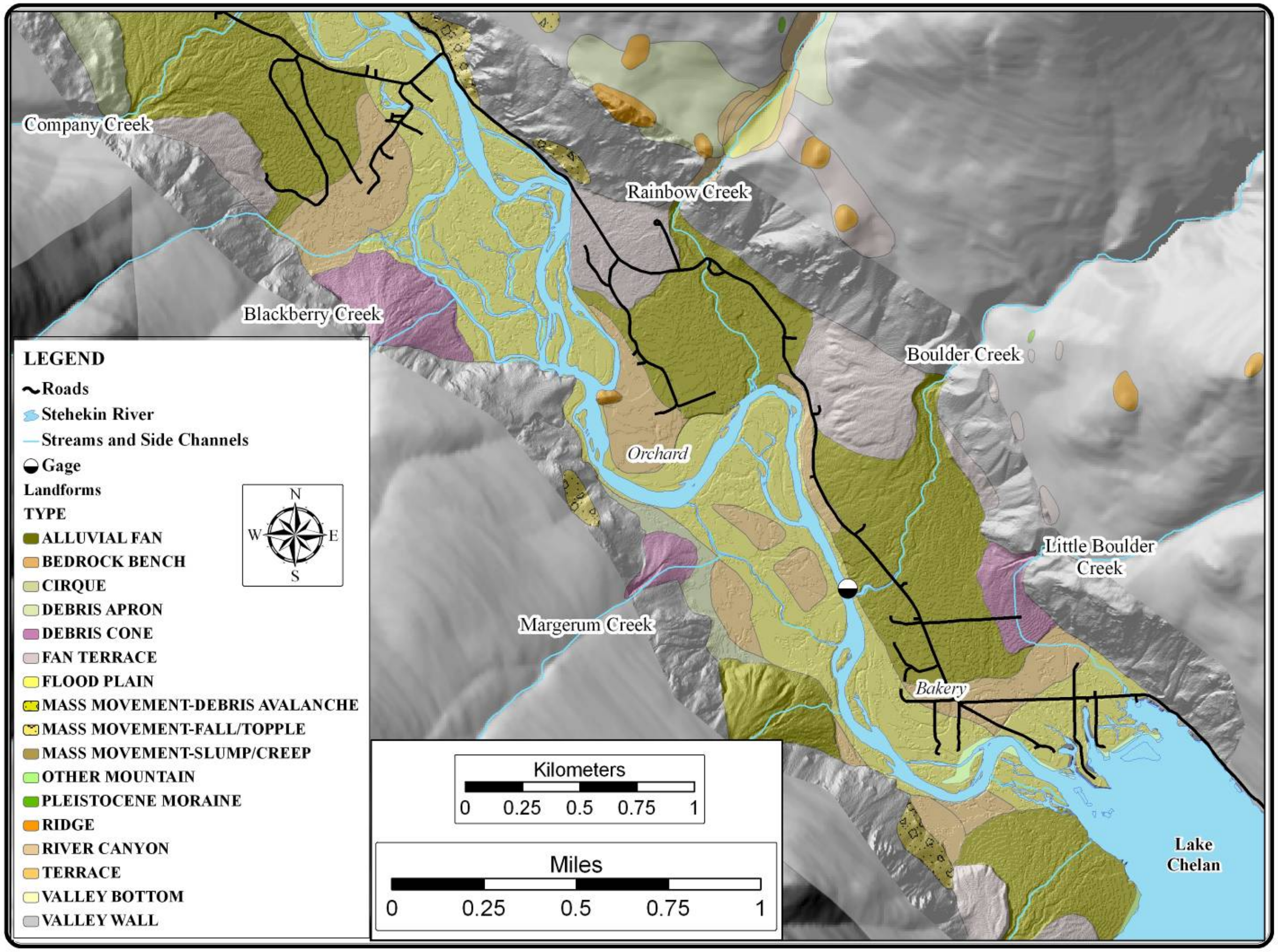


Figure 4B. Landforms and road network of lower Stehekin valley near Lake Chelan. Note the olive-green colored alluvial fans built by tributary streams and orange-colored terraces above the river.

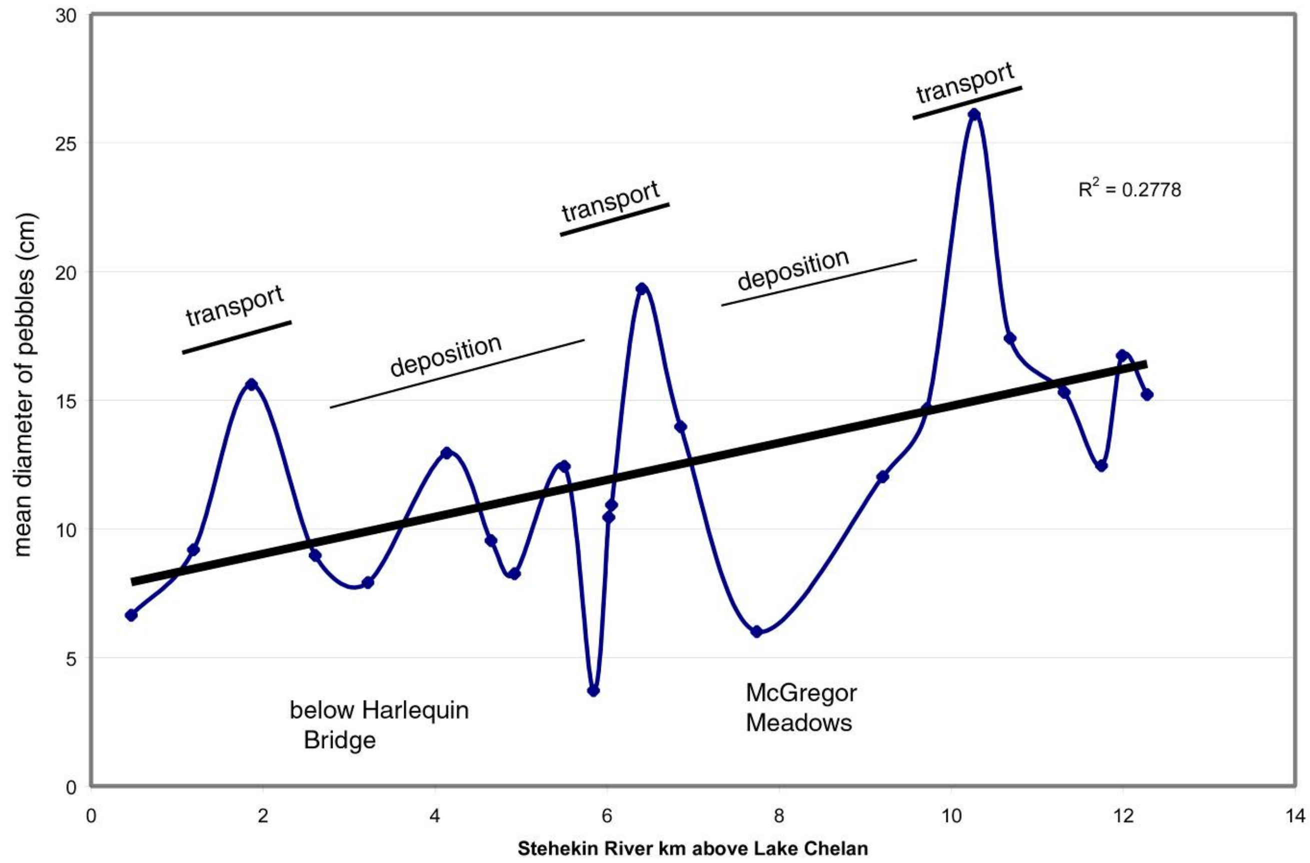


Figure 5. Longitudinal change in mean diameter of channel gravels along the lower Stehekin River.

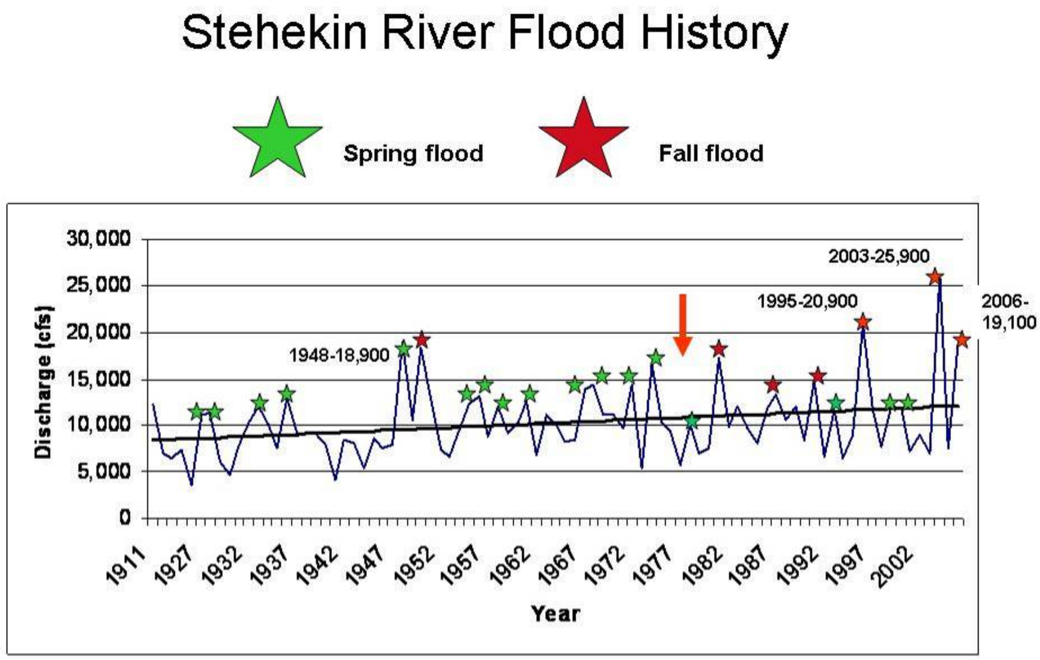


Figure 6. Peak annual discharge for the Stehekin River 1911-2006 with linear trend indicating 3,000-4,000 cubic feet per second (cfs) increase in the peak annual event.

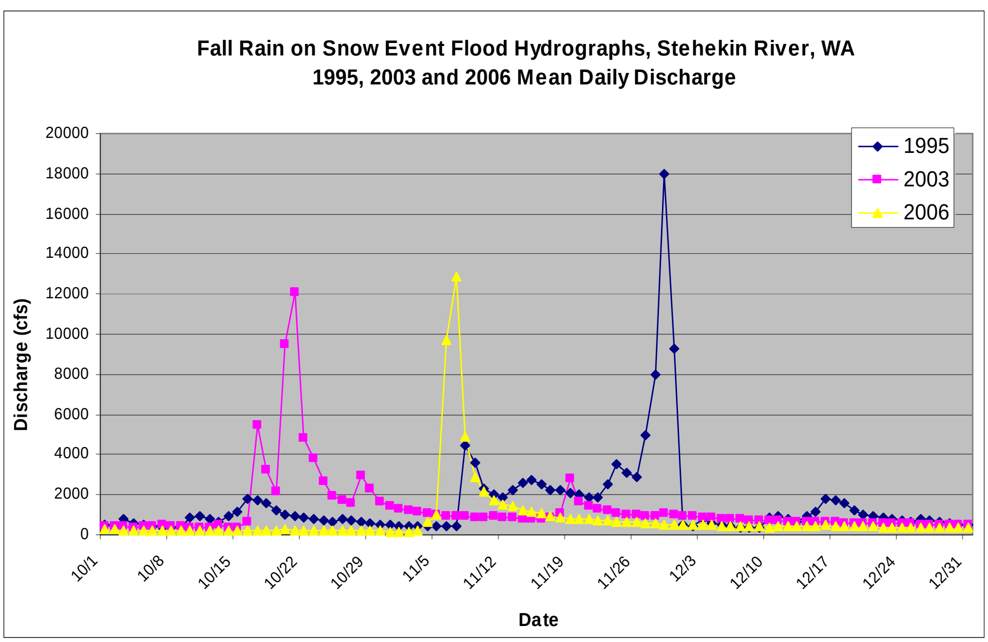
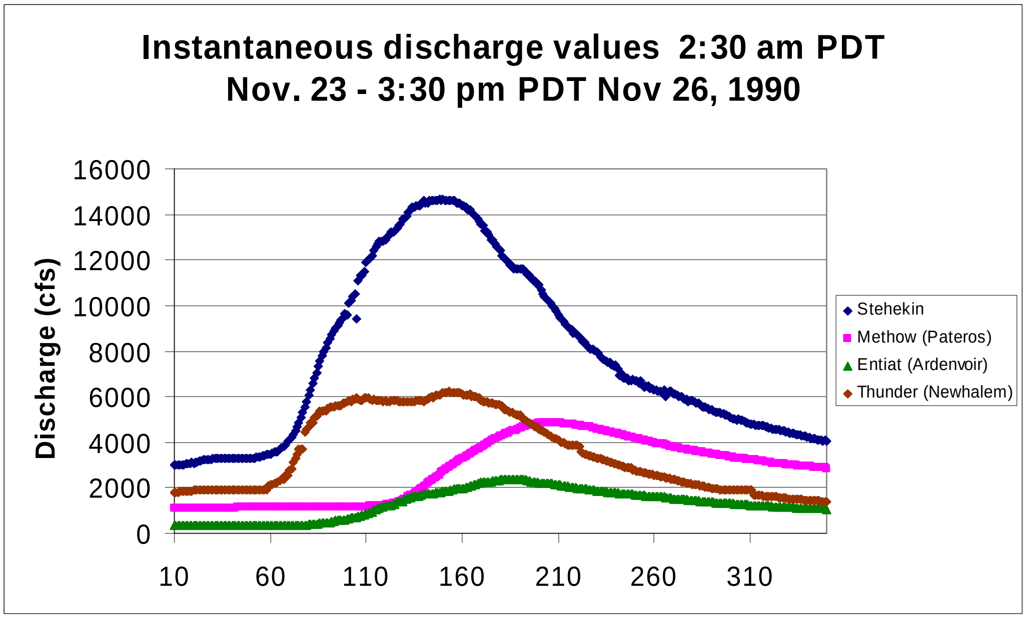


Figure 7. Comparison of the average daily discharge for the three large fall floods of the past 12 years. Note early occurrence of 2003 flood in mid-October, and rapid rise of 2003 and 2006 floods, which rose during a period of less than 10 days.



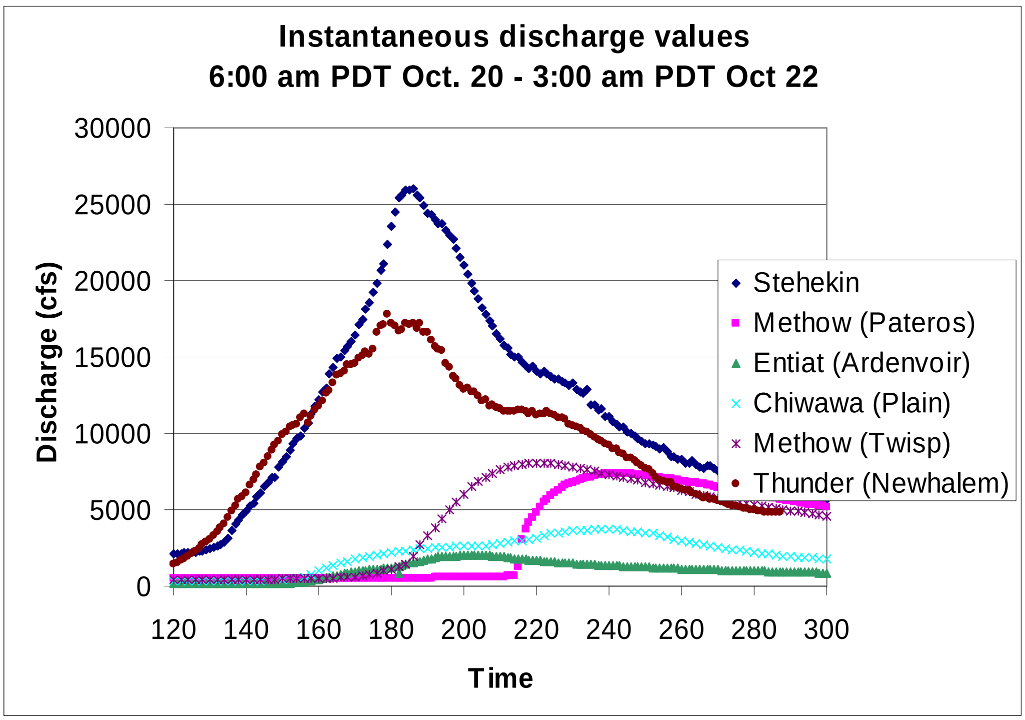


Figure 8. Comparison of the hydrographs for the 1990 (top) and 2003 floods on rivers in north-central Washington. Note that the Thunder Creek gage malfunctioned in the 1990 flood.

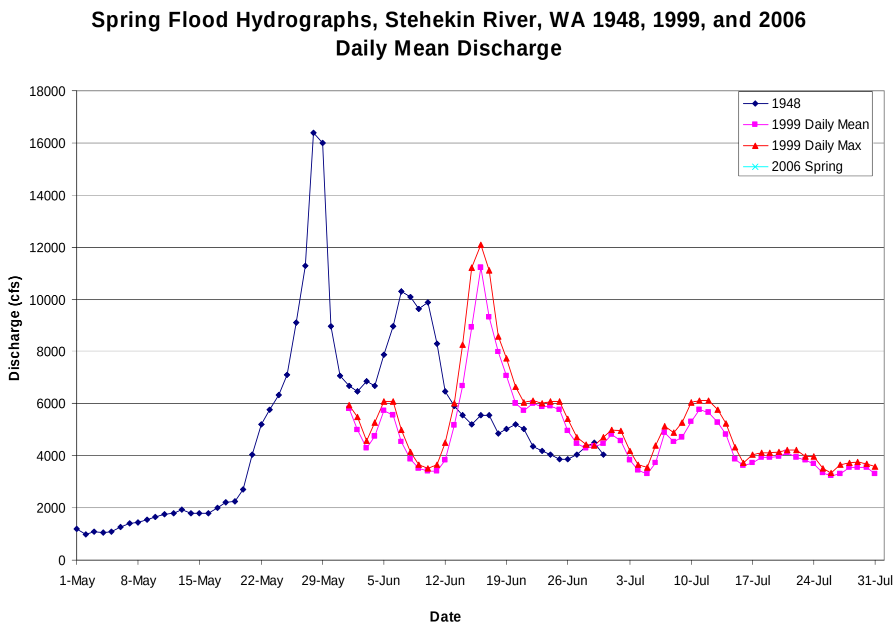


Figure 9. Comparison of two large spring flood events, both of which lasted for weeks and had multiple flood peaks.

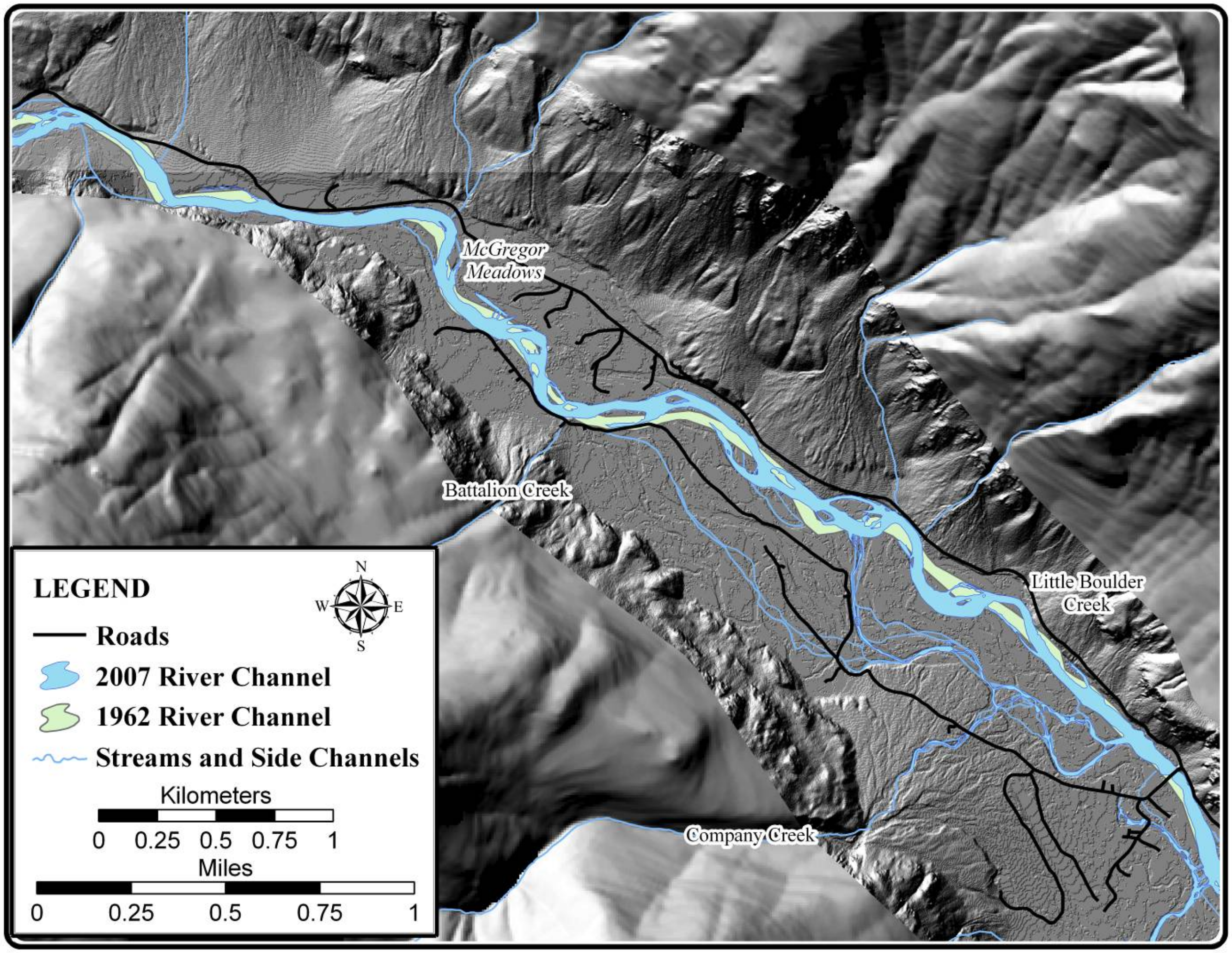


Figure 10A. Stehekin River channel changes above Harlequin Bridge1962-2007.

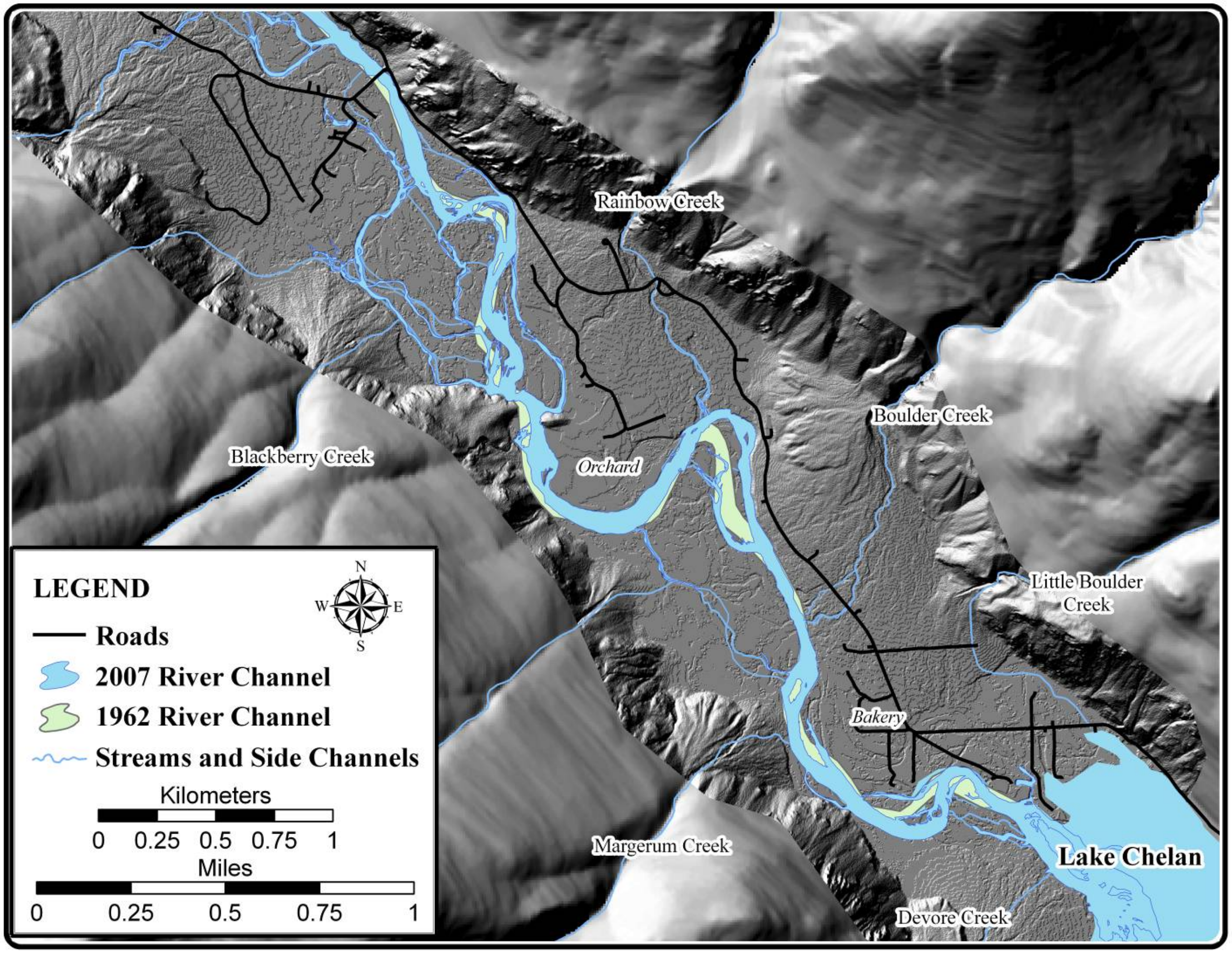


Figure 10B. Stehekin River channel changes below Harlequin Bridge 1962-2007.

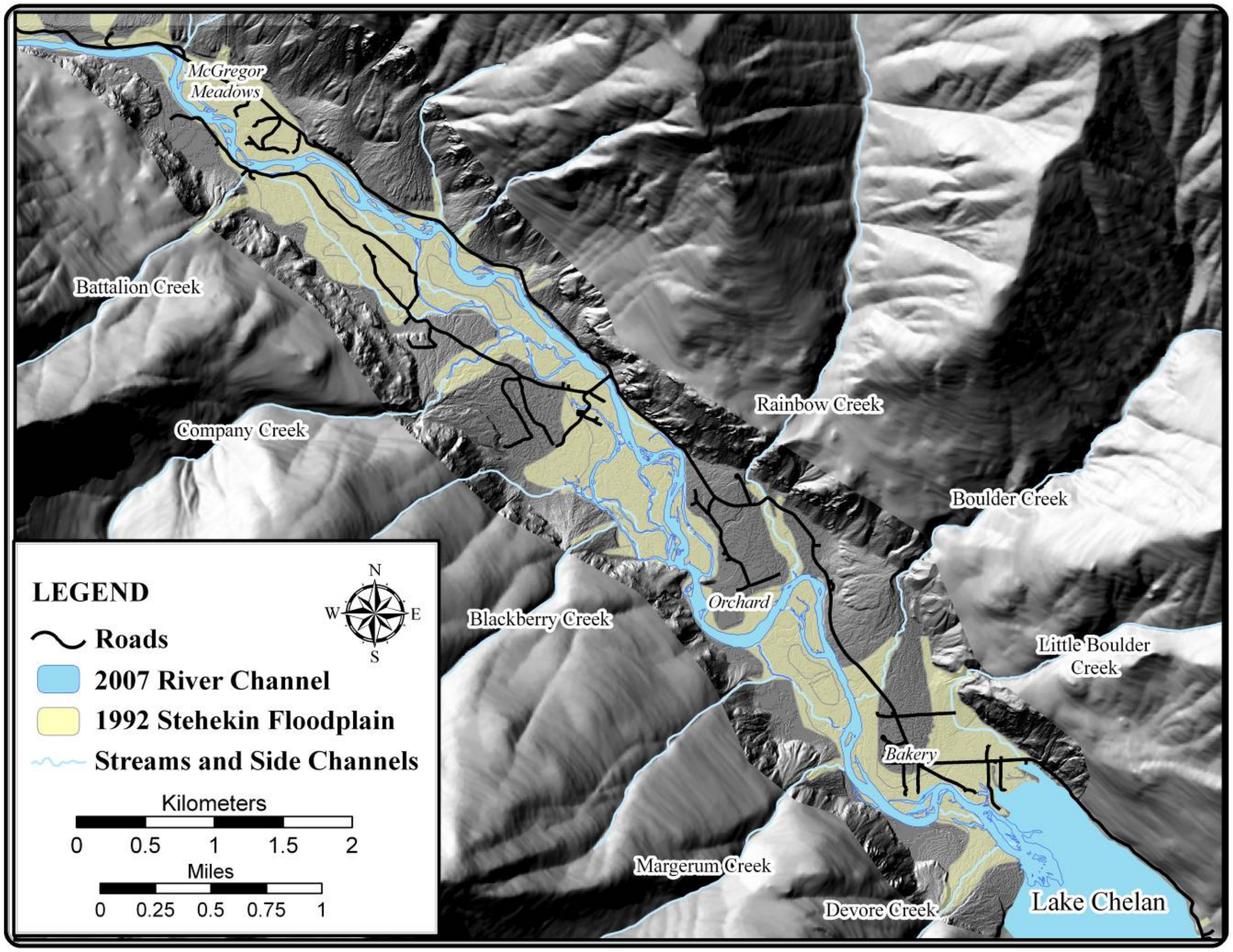


Figure 11. Floodplain (NPS, 1992) and side channels of the lower Stehekin valley.

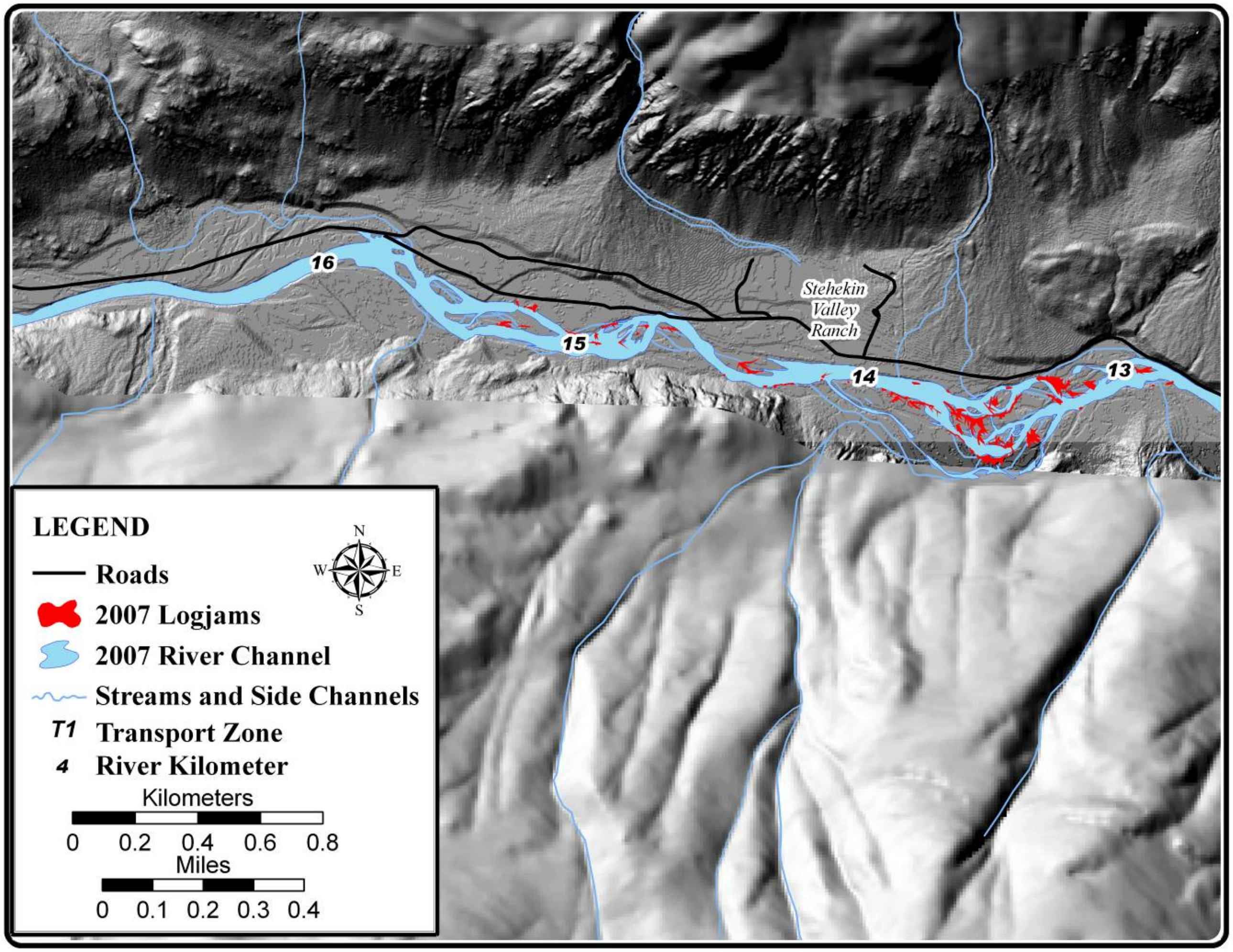


Figure 12A. Locations of logjams on lower Stehekin River with wood and sediment transport zones (T1-T3).

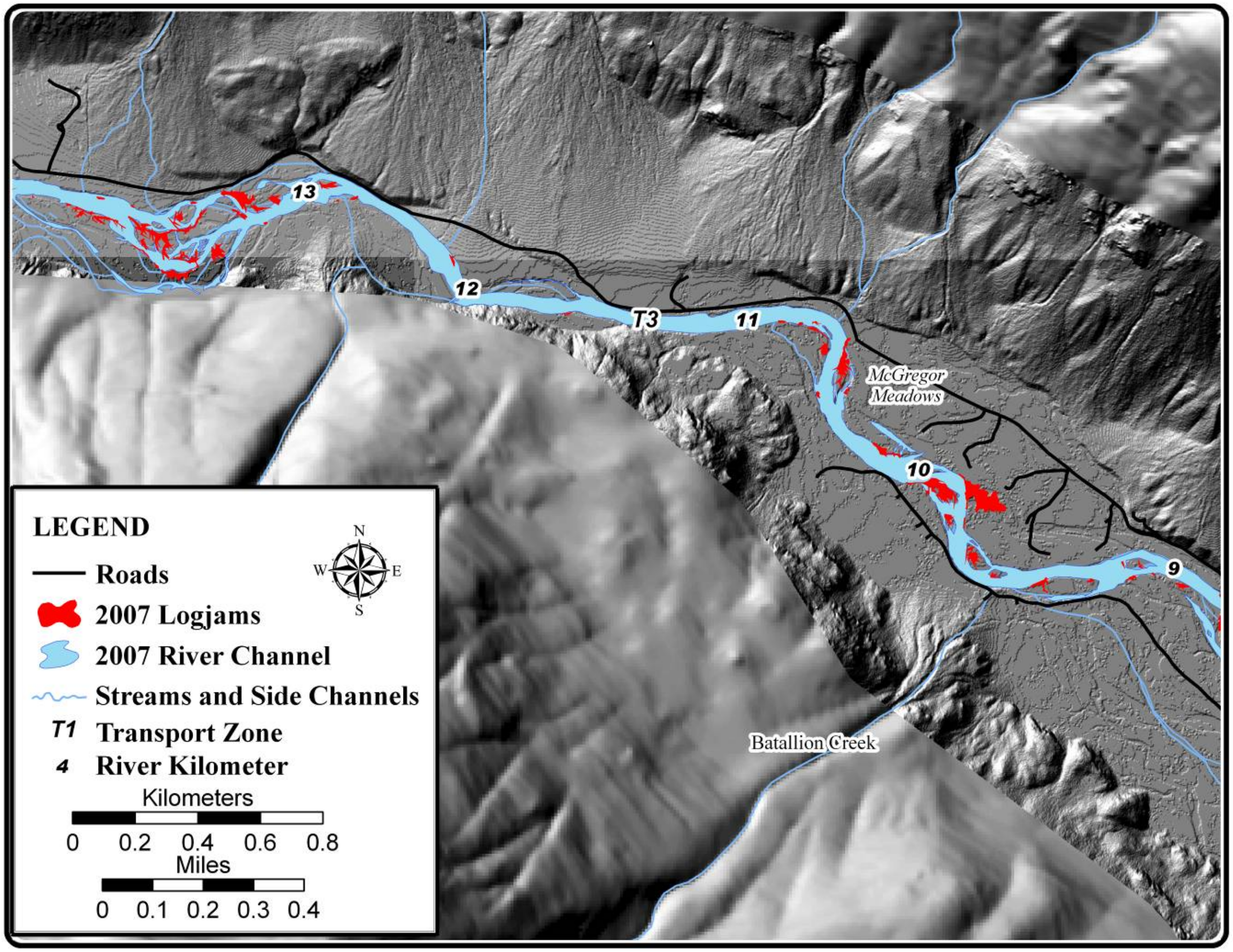


Figure 12B. Locations of logjams on lower Stehekin River with wood and sediment transport zones (T1-T3).

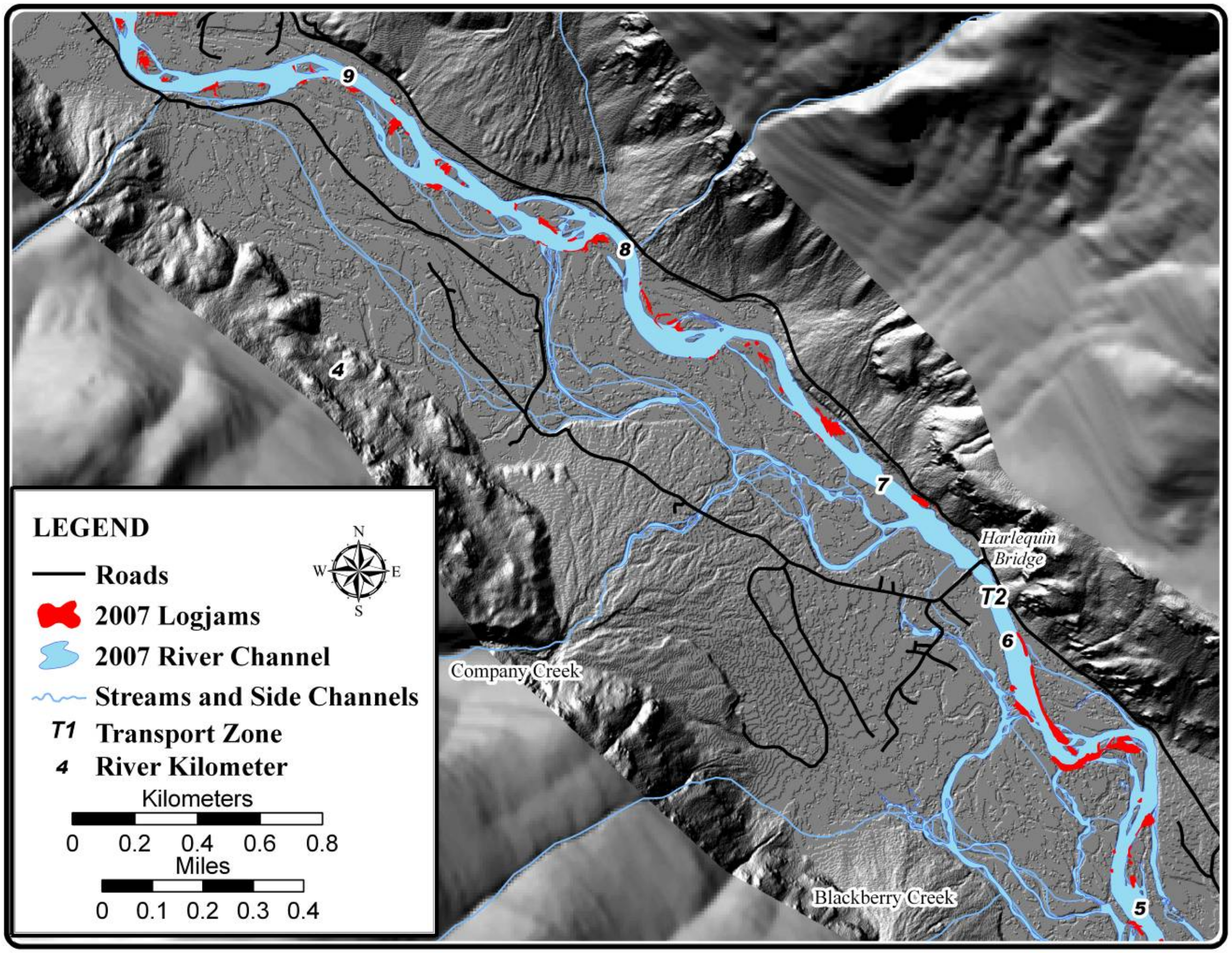


Figure 12C. Locations of logjams on lower Stehekin River with wood and sediment transport zones (T1-T3).

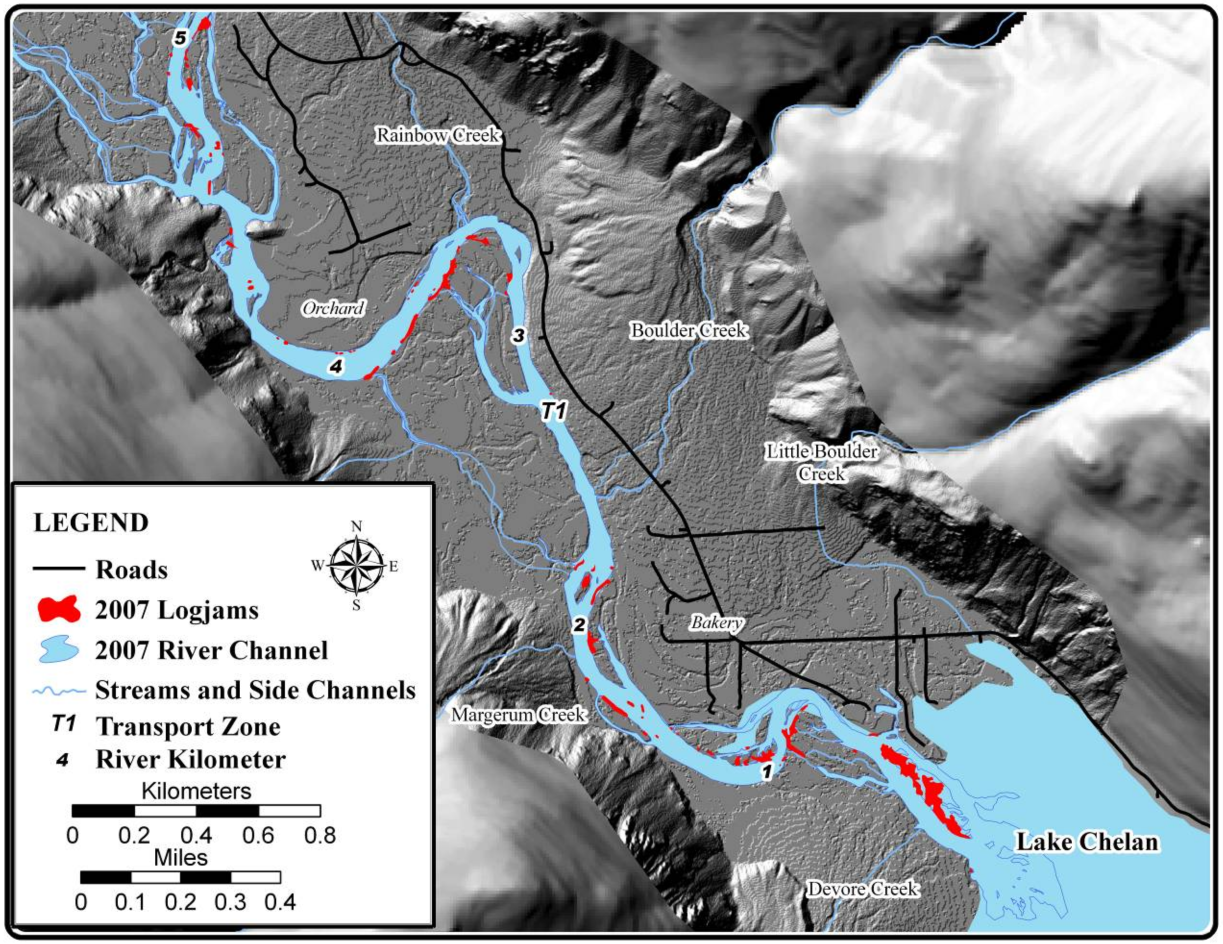


Figure 12D. Locations of logjams on lower Stehekin River with wood and sediment transport zones (T1, T2, T3).

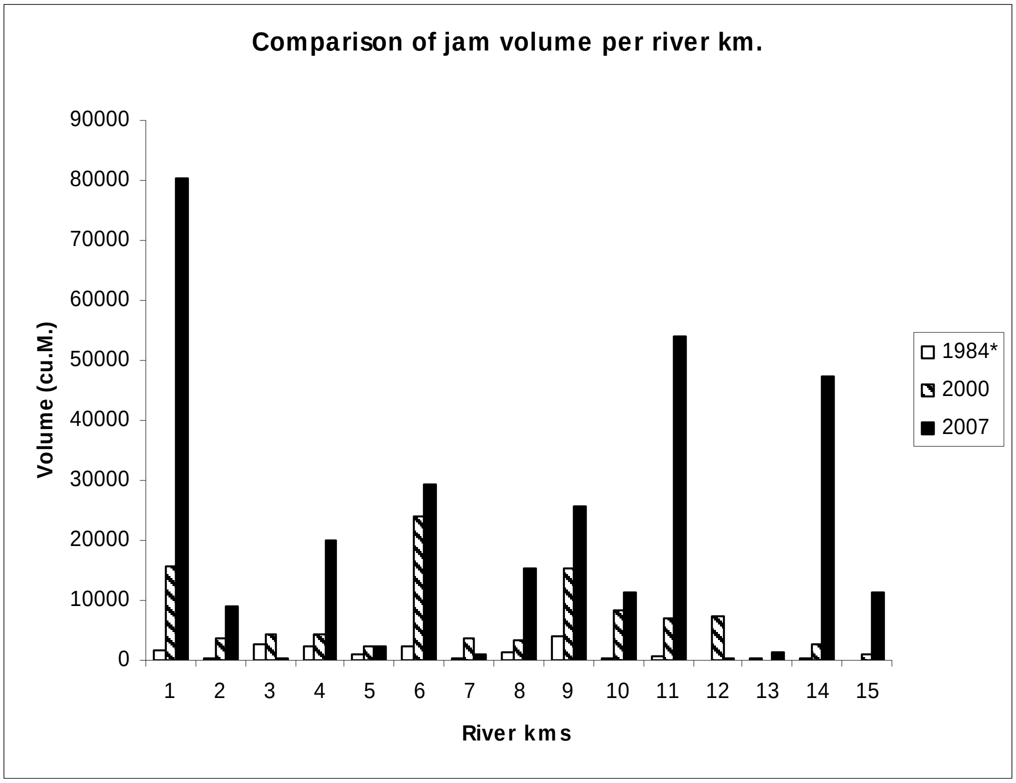


Figure 13. Changes in large woody debris volume between 1984 and 2007 by river kilometer from Lake Chelan.

Figure 14. Photo of the 1900 piece logjam at McGregor Meadows (see Figure 11B).

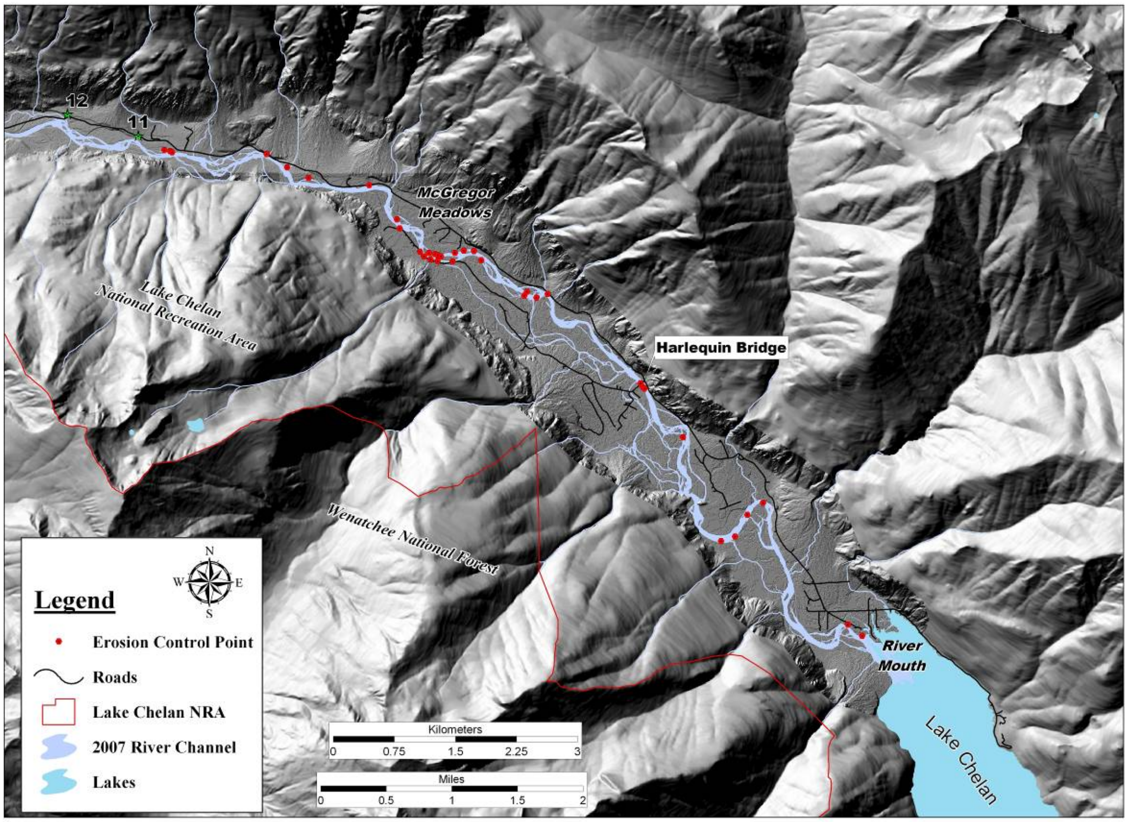


Figure 15. Location of erosion management structures on lower Stehekin River in 2000.

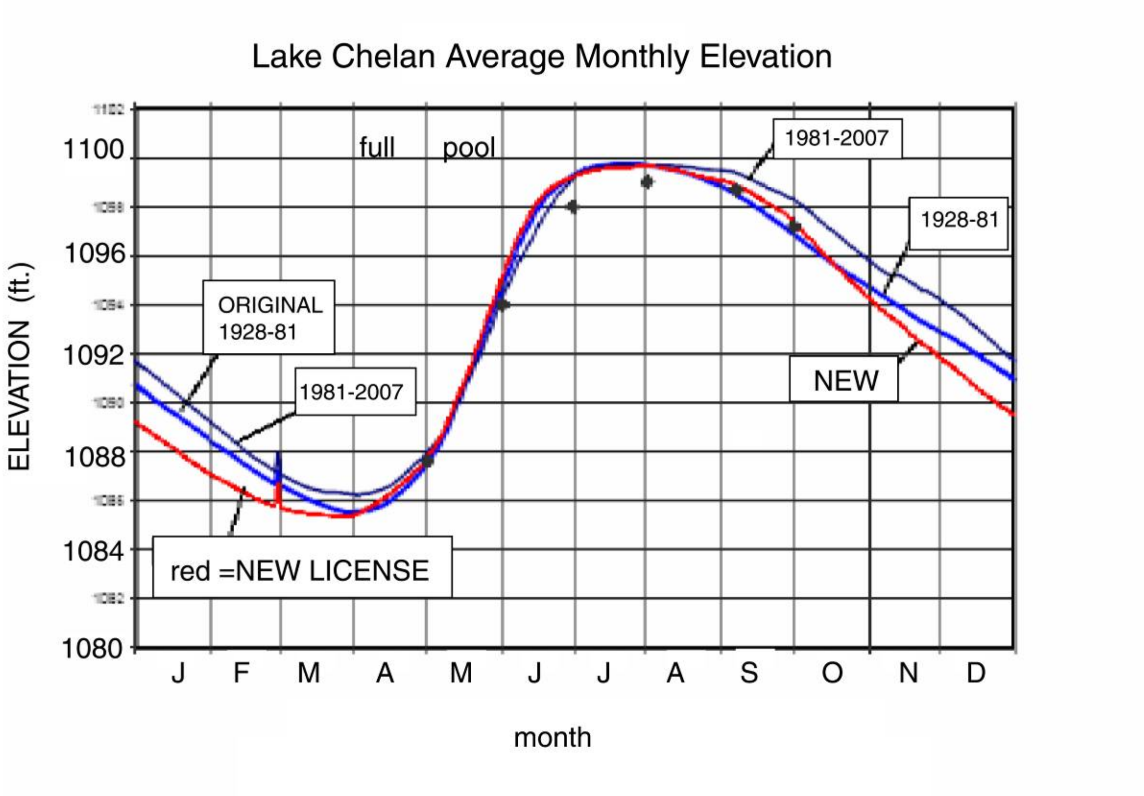


Figure 16. Average monthly Lake Chelan surface elevation for the old (blue) and new (red) Chelan PUD operating license.