# Effects of the Tioga Road on Hydrologic Processes and Lodgepole Pine Invasion into Tuolumne Meadows, Yosemite National Park

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# Executive Summary

The Tuolumne River drainage of Yosemite National Park is classified as a wild and scenic river, and the park is currently developing a River Management Plan to protect this outstanding natural resource. Tuolumne Meadows serves as the major access point to the Yosemite high country, and has significant density of roads, infrastructure, and other development. This project analyzed the surface and ground water levels and flows, soils and vegetation to produce a preliminary summary of impacts to the meadow. The entire meadow was studied with particular emphasis on anthropogenic impacts due to: 1) the Tioga Pass Road, 2) culverts, 3) the old road through the middle of the meadow, and 4) water diversions from the Dana Fork. Other impacts were identified, including: 1) climate change, 2) historic grazing, 3) fire frequency, 4) burrowing pocket gophers and voles, and 5) grazing deer.

The overall effect of the Tioga Road on Tuolumne Meadows groundwater and vegetation is limited. Groundwater level along our monitoring well transects showed no obvious effects of the Tioga Road to block, intercept or alter the natural flow paths or ground water elevations. Results from the calibrated 2D-model more closely matched the flow paths for simulations with no road than with an impermeable road, suggesting that the road's influence on subsurface transport is small. The Road blocked the surface water flow paths of small streams in 12 locations, and signs of ponding water occurred in 23 locations. Several culverts forced previously dispersed runoff into localized channels, and downcutting was evident downstream of many of the culverts. Downcutting was most notable along Unicorn Creek and Budd Creek and may decrease meadow ground water recharge.

Tree-ring records indicate that episodes of lodgepole pine recruitment occurred in 1905-1940, 1945-1976, and 1996-2000. The timing of these episodes does not coincide with the 1933-1937 construction of Tioga Road. Trees had established in Tuolumne Meadows prior to road construction, and continued to establish after the road was built. Lodgepole pine invasion at Tuolumne Meadows is linked to periods of low precipitation and low year-to-year variability in moisture conditions. Because tree removal activities have occurred in Tuolumne Meadows since ~1933, it is unknown if earlier tree establishment episodes would have survived in the absence of

managed tree removal. Since the mid 1800s, fires appear to have been largely absent, and historical fire effects on trees and meadow vegetation composition are unknown.

Meadow vegetation appears to be influenced by unregulated historic grazing by sheep, current grazing by deer on willows, and pocket gophers and voles churning up the soil. Vegetation has a discontinuous cover of perennial plants in most areas, with broken sods and tussocks, an absence of grasses and sedges in some locations, and high cover of bare ground. Several communities have high soil organic matter that accumulated over millennia from vegetation with high below ground biomass production, and high water tables. While the high water tables still occur in wet years, as measured during 2006, these communities do not support vegetation with high below ground biomass or dense root and rhizome systems that could have produced the high-organic soils. The incomplete vegetation in these stands may be perpetuated by intense levels of pocket gopher and vole activity which produces the bare ground. The abundance of bare and relatively moist soil may be important to lodgepole pine establishment and survival. Little direct or indirect impact to meadow vegetation from the Tioga Road was identified.

Climate change has a strong influence on meadow hydrology and vegetation. Studies in meadows across the Sierra (with and without roads, and with different grazing histories) indicate a large synchronous pulse of tree invasion during the 20th century, correlated with regional climate. Current and future climate shifts leading to earlier snowmelt could cause earlier declines in stream flow and meadow groundwater tables during the summer, creating dryer meadow conditions.

# Table of Contents

# Chapter 1: **Introduction**

Tuolumne Meadows is one of the largest sub-alpine meadows in the Sierra Nevada and a significant tourist destination within Yosemite National Park. A major highway crosses the southern edge of the meadow and provides views of the landscape and access to the area's numerous trails, campgrounds, lodge, store, visitor center and other attractions. The level of human use and development in and around the meadow has potential impacts on the vegetation and the distribution and movement of water that produced and maintained the meadow. A number of ongoing human activities impact the meadow, including possible historic fire suppression in the meadow and surrounding forest for protection of human life and structures, trampling of meadow vegetation and stream banks by hikers and fishermen, and redistribution of surface and ground water via (a) water delivery and sewage systems, (b) roads and trails that intercept rainfall and near surface water flow, and (c) river channel changes due to culverting, bridges, and direct channel modification.

Current human use and development in and around the meadow is high, but is not novel to the area. Native Americans traveled, traded, and lived in Tuolumne Meadows episodically for millennia. People of European origin first entered the area in approximately 1850, and many more soldiers and shepherds soon followed, attending to the mining boom of the 1850s. Perhaps one of the largest historical anthropogenic impacts to Tuolumne Meadows may have been intensive sheep grazing. In 1870 Joseph Le Conte observed that "The Tuolumne Meadows are celebrated for their fine pasturage. Some twelve to fifteen thousand sheep are now pastured here. They are divided into flocks of about twenty-five hundred to three thousand" (Le Conte 1875). Photos from around the 1800's century illustrate the density of sheep present in the meadow (Figs 1-1 and 1-2).

**Figure 1-1.** A shepherd and his flock in Tuolumne Meadows. Negative No. YM-12, 757. The date is unknown, but judging by his clothing and quality of the print, it is likely from the late 1800's. Source: Yosemite Research Library.

**Figure 1-2.** Shepherds and their sheep (in the right background) on the banks of the Tuolumne River in Tuolumne Meadows in 1898. Negative No. RL-17, 087. Source: Yosemite Research Library.

Disentangling the impacts of historic from on-going or recent human activities on Tuolumne meadow is critical to provide the National Park Service with information and an understanding of meadow condition, and the processes that likely have caused its degradation. This information can then be used to manage Tuolumne Meadow. In this report we focused on determining the influence of the Tioga Pass Road on the hydrologic and vegetation patterns of the meadow. Of particular concern is the noted pattern of lodgepole pine invasion that has been occurring for decades, perhaps more than a century (Fig 1-3). Previous researchers and managers have suggested that the highway, which was completed in 1915 and realigned and paved in 1937 (Fig 1-4), has dried parts of the meadow and produced bare ground on which lodgepole could invade. For decades the National Park Service has conducted extensive clearing of young lodgepole pines along the road and meadow to mitigate this perceived invasion and preserve views of the meadow (Fig 1-5).

**Figure 1-3.** Tuolumne Meadows in 1896. Note what appear to be numerous small lodgepole pine seedlings in the left foreground. Negative number 2758. Source: Yosemite Research Library.

**Figure 1-4.** The realigned Tioga Pass Road through Tuolumne Meadows, under construction in 1935. Note small lodgepole pines near the road, but not significant numbers of seedlings in bare areas along the shoulder. Negative number ECW1311. Source: Yosemite Research Library.

**Figure 1-5.** A CCC crew clearing lodgepole pine seedlings from Tuolumne Meadows in the 1930s (National Park Service 1933).

Cunha (1992) examined the invasion of Tuolumne Meadows by lodgepole pine and found a massive invasion of pines along the southern margin of Tuolumne Meadows following the paving of the Tioga Road in 1937. He also found that 85% of tree invasion occurred on the south side of the meadow and not in the east and northwest, which have a more stable forest-meadow ecotone. Cunha hypothesized that human disturbance was the primary factor responsible for the pine encroachment, and his thesis is often cited as proof of the cause of meadow invasion by lodgepole pine, and been used to justified regular removal of lodgepole seedlings.

However, other researchers have highlighted this pattern of lodgepole pine invasion as a regional, not localized, pattern that was not occurring solely in Tuolumne Meadows or along the Tioga Pass Road, but widely across the Sierra Nevada. For example, Vale (1987) found that 23 meadows in the Yosemite high country were being invaded by lodgepole pine. Many different processes may influence lodgepole pine seedling establishment in meadows including shading, snow pack, moisture, temperature, soil type, livestock and rodent disturbance, and fire (Ratliff 1985).

This report provides an analysis of the potential hydrologic impacts to the meadow based on one summer's research during 2006. We analyzed surface and ground water levels and flows, soils and vegetation, tree rings, and developed a conceptual groundwater model for a part of the meadow. The study examined possible impacts due to: (1) the Tioga Pass Road, (2) the old road through the middle of the meadow and other dirt roads, such as that out to Parson's Lodge, (3) the bridge and culverts, and (4) water diversions from the Dana Fork. Surface water (Chapter 2) was examined by measuring stage and discharge at four locations providing water to the meadow (Figure 1-6), by estimating future surface water supplies, and by mapping surface water flows through culverts under the Tioga Road. Seventy-two groundwater monitoring wells (Chapter 3) were installed by hand-augering and monitored weekly during 2006 to analyze groundwater elevation across the meadow. These wells were organized into five main transects as well as smaller transects in areas of heavy tree encroachment (Figure 1-6). Each transect consisted of multiple wells and a stream gage where the transect crossed the Tuolumne River. Detailed surveys of soils and vegetation were conducted at each well location and related to past and present groundwater regimes (Chapter 3). Cores and/or cross-sections were collected from 146 trees in the meadow and along the road (Figure 1-6), and these were analyzed for growth patterns through time and possible human influences (Chapter 4). A 2-dimensional groundwater model was constructed and calibrated based on the summer's surface and ground water level data to conceptualize water flow paths to and through the meadows, particularly near the highway, and as influenced by bedrock characteristics, and long-term precipitation patterns (Chapter 5). Lastly, we summarize our study results, provide an interpretation for management, identify remaining research questions, and recommend future work in Chapter 6.

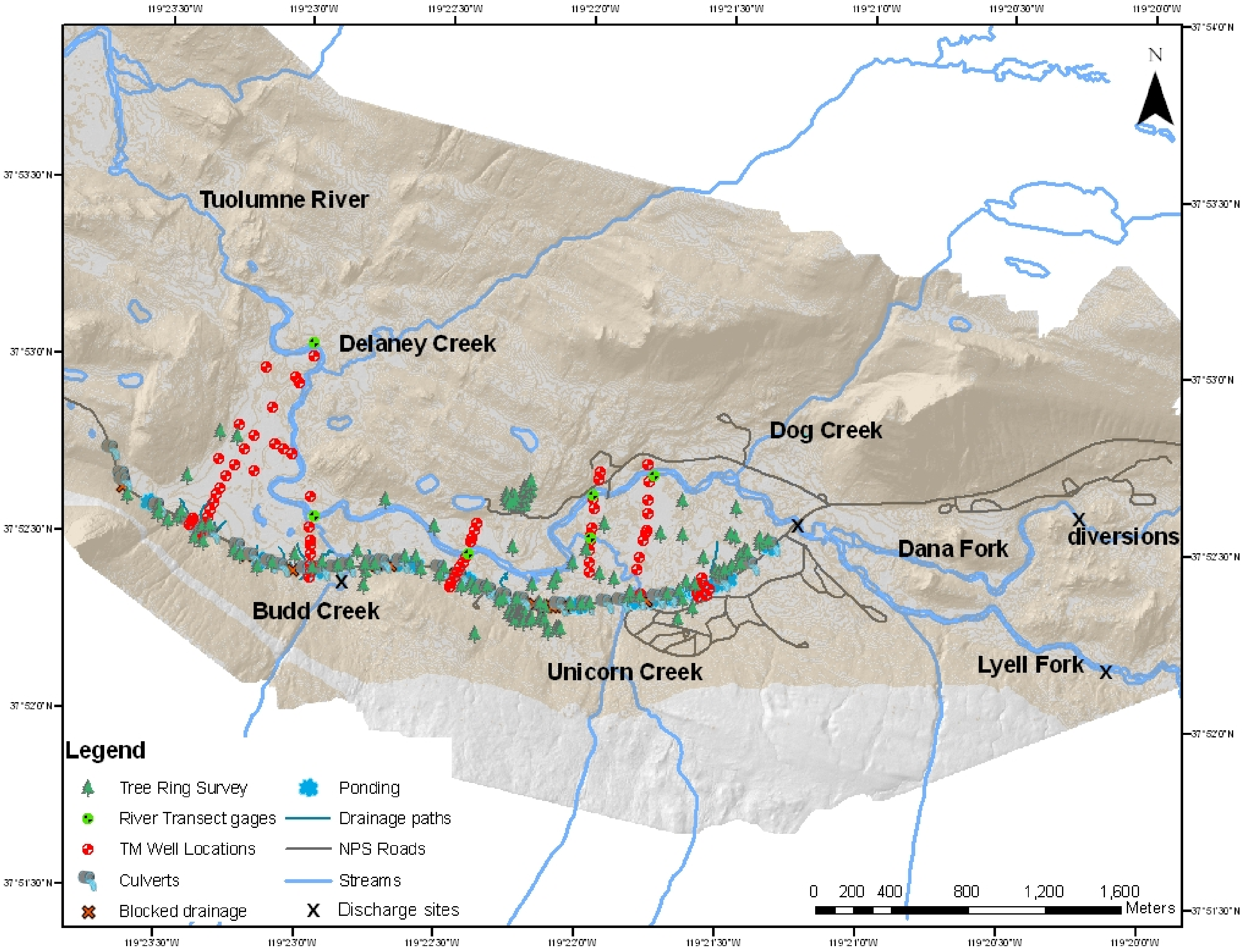

**Figure 1-6**. Map of study area.

# **Chapter 2:** Surface Water

By

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# *Introduction*

In order to understand how human impacts relate to the hydrology of Tuolumne Meadows, we first examine the basin, including basin geology, surface water contributions, surface water delivery to the meadows, and human water use and water supplies. This section focuses on summer 2006 but also uses surface discharge measurements from the Yosemite Hydroclimate Study (Lundquist et al. 2003), which has been operational since summer 2001, to place 2006 in context. Specifically, we address four questions:

1) What are the surface water contributions to Tuolumne Meadows and how did flow volumes change through the 2006 study period?
2) How do surface water fluctuations influence subsurface water tables?
3) How is surface drainage affect by the road, specifically related to culvert locations and functionality?
4) What effects do Dana Fork water diversions (for the local water supply) have on flows downstream?

Finally, we present a section on considerations for the future.

## *Surface water contributions to Tuolumne Meadows: Focus on 2006*

### Overview

The Tuolumne River drainage of Yosemite National Park is fairly typical of the central to southern Sierra Nevada, with its high and cold drainages, Mediterranean (winter-precipitation dominated) climate, rapid snowmelt seasons, and relatively thin soils. Over 90% of the drainage is underlain by intrusive rocks (chiefly granodiorite), which erode slowly, allow less infiltration than other rock types, and interact little with the streamflow. Other types of bedrock may have significant impacts on the drainage's hydrology. Metamorphic rocks are found beneath the headwaters of the Dana Fork of the Tuolumne River. A substantial part of the basin is mantled to varying degrees by glacially derived sediments from the Late Pleistocene glaciation and smaller cirque glaciers present throughout the Holocene. These unconsolidated deposits consist of lateral and recessional moraines and outwash deposits that have a significant effect on current stream morphology and sediment input.

The most populous area of the Tuolumne River drainage, and the most studied, is Tuolumne Meadows, at an elevation of 2600 m (Figure 2-1). Contributing areas were determined using a 30-m DEM of the area and Rivertools software, which calculated all areas draining to a selected point. The area contributing to the Tuolumne River as it flows under the bridge at Highway 120 is about 186 km$^2$, with about 111 km$^2$ draining through the Lyell Fork and 75 km$^2$ through the Dana Fork. The highest point in the drainage is Mt. Lyell at 4000 m, and over 50% of the drainage area lies between 2800 and 3300 m elevation. Precipitation falls primarily as snow, with peak discharge typically occurring in May or June.

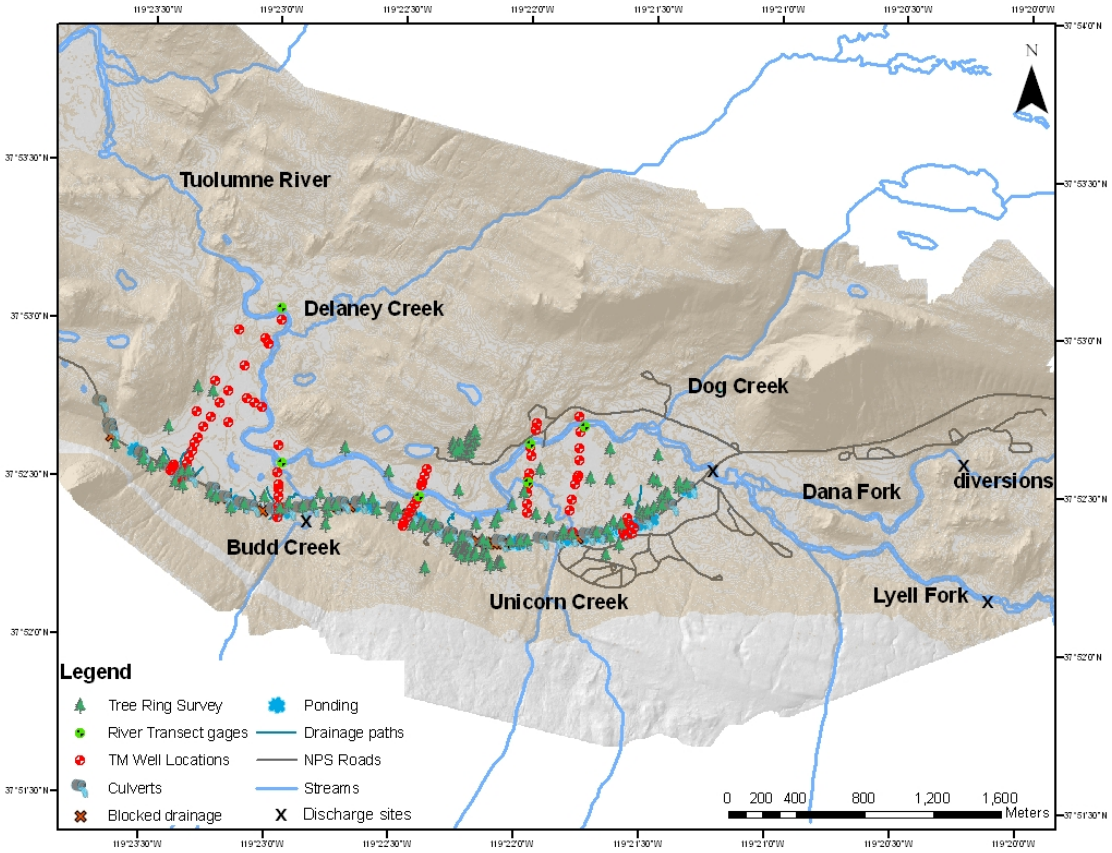

**Figure 2-1.** Surface water contributions to Tuolumne Meadows, in reference to other study components.

Discharges from the Lyell and Dana Forks join each other and intermingle several hundred yards above the Highway 120 bridge in Tuolumne Meadows. Below the bridge is the bulk of Tuolumne Meadows. The river is fed first by Dog Creek (7 km$^2$) just past Lembert

Dome, and then by Unicorn Creek (9 $km^2$) and Budd Creek (6 $km^2$), from the south, about 1/3$^{rd}$ and 2/3$^{rds}$ of the way through the meadow, and by Delaney Creek (14 $km^2$), from the north, just before the river exits the meadow. All of these tributaries dry before the end of the summer.

Budd Creek (Figure 2-2, at bank full flow) maintains discharge the longest of these tributaries and has been gauged since summer 2001. Its discharge is representative of the snow melt contribution from the peaks south of the meadow. The Budd Creek basin is primarily exposed granite. The stream flows through fissures in the rock (Figure 2-3) and has the lowest electrical conductivities recorded in Yosemite (2-4 $\mu S\ cm^{-1}$ throughout the melt season). The low conductivities indicate that meltwater has very little contact with soils and subsurface flow and is primarily surface runoff directly from snowmelt.

**Figure 2-2.** Budd Creek (bank full or fuller) on 6/28/2006. Q=74 cfs.

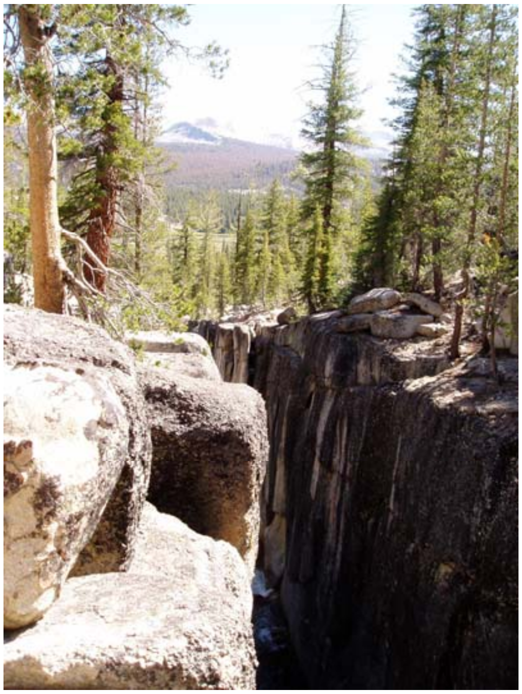

**Figure 2-3.** Granite fissure in Budd Creek basin, with Budd Creek at the bottom.

At the lower end of the meadows, flows are forced together and upwards by granite sills at the northwestern end of the meadow. The drainage area above the meadow outlet is about 237 km$^2$. Of this, 222 km$^2$ are drained by the channels described above and about 15 km$^2$ (6%) drain directly from hillslopes and the meadow itself.

## Methods

### *Surface water level*

Water levels at the Tuolumne River at Highway 120, at Budd Creek, and at the Lyell and Dana Forks of the Tuolumne River (X's in Figure 2-1) have been recorded since August 2001 as part of the Yosemite Hydroclimate Monitoring Project (Lundquist et al. 2003 and Lundquist et al. 2004). These sites were selected to monitor the major contributions to Tuolumne River discharge from different elevations and aspects throughout the summer. Budd Creek is the only monitored subbasin contributing directly to the meadow because it is typically the only one of the four streams contributing to the meadow that has discharge in August.

In order to determine whether hydraulic gradients tended towards or away from the river (*i.e.*, groundwater feeding river, or river recharging groundwater) at different times and locations, water levels in the river were collected by Solinst Leveloggers in vertical stilling tubes where each groundwater transect crossed the Tuolumne river (marked ‘River transect gages’ in Figure 2-1). Data from these stream gages were corrected using manual readings of stream height and data from a barometric station. After the variations from air pressure were removed from the data record, it was referenced to water depth readings taken in the field. The average offset between the instrument record and field readings was used to correct the instrument readings to actual water depth. The offset values all had standard deviations of less than 2 cm.

The tops of the stream gage tubes were surveyed and referenced to a benchmark. Based on the dimensions of each tube setup measured in the field, the elevation (above MSL) of the instrument was calculated. It was assumed that the instrument was located at the same elevation as the bottom of the tube or the river bed at that point. With this elevation as a datum, the true water surface elevation was found.

The gage located below Parsons Bridge (on transect 4) was moved on 22 August 2006. Water depth readings were taken at the old and new locations. Only the new location was surveyed, so the data (both water depths and water elevations) were adjusted to the datum of the new location. Because the instrument remained in the same pool (the newer location was deeper), these offsets provide a continuous record of water level above sea level at this location.

The loggers in transects 1 (near Pothole Dome) and 3 (near the Visitor Center) both broke during installation, but were replaced in late August. The logger in Transect 2 (near Budd Creek) was no longer submerged after mid-August. The logger in Transect 5 was in an oxbow separate from the main river, and began monitoring water evaporation in a pool separated from the main river channel in late August.

To estimate the water elevation at each transect throughout the summer, even when direct gage measurements were not available, water heights at transects 2, 4, and 5 were compared with simultaneous stage data at the Highway 120 bridge, and a linear relationship was established, using least squares analysis. This equation was then used to estimate transect water elevation from 1 January 2006 to 8 August 2006 (the day the Highway 120 datalogger was removed and downloaded). RMSEs between the predicted water levels and actual water levels were 1.1 cm, 0.4 cm and 0.4 cm, or 6%, 3% and 5% of the standard deviation during the period examined, at transects 2, 4, and 5, respectively. Transects 1 and 3 did not have data overlapping with the Highway 120 data, so they were linearly related to the late-season water level heights at Transect

4 (because 2 and 5 were no longer in the main channel at this time). The resulting estimated heights of transects 1 and 3 both had RMSEs of 0.4 cm, which were 8% and 26%, respectively, of the standard deviation during the period examined. The estimated height at Transect 4 for 1 January to 8 August 2006 was then used to estimate height at transects 1 and 3 for the same period. This procedure propagates the errors of estimating transect 4 and of estimating transects 1 and 3, such that the total error for these sites is, on average, $\varepsilon_{total} = a_{1,3}\varepsilon_4 + \varepsilon_{1,3}$, where $a_i$ is the coefficient multiplied with the transect 4 height in the linear regression (close to 1 for both cases) and $\varepsilon_i$ is the error for the the $i^{th}$ transect. These RMSEs are 0.8 cm (11%) and 0.7 cm (29%) for transects 1 and 3, respectively. The percentages are included because the validation period had very little variation, and thus, the errors were very small. During periods of greater variation (e.g., higher flows earlier in the summer) errors will be larger. The standard deviation for the entire spring-summer record at Highway 120 was 34 cm, so 29% of that is 10 cm. Additional errors arise where tributary streams contribute to the river, raising water levels downstream. All four meadow tributaries were dry during most of the calibration period. During peak flow, however, the tributaries have a notable effect. The contributing area of the Tuolumne River grows 27% from the inflow at Highway 120 to the outflow at the Tuolumne Cascades. Assuming that at peak flow, all areas contribute snowmelt volumes proportional to their areas, this would introduce a 27% error in discharge estimated at Transect 1 (the closest to the meadow outflow near Pothole Dome) when using only Highway 120 data. Presuming a standard-shaped stage-discharge relationship (see below), this would correspond to an error in estimating stage of about 18 cm at a Highway 120 flow volume of 1500 $ft^3 s^{-1}$, and 15 cm at a flow volume of 1000 $ft^3 s^{-1}$. Therefore, estimates of river transect water heights during peak flows should be interpreted with caution until more data are available. Measurements at all sites throughout the summer, combined with stage-discharge modeling, could be used to better estimate these values in the future. Estimated stage information has been provided to the park and is presented in conjunction with groundwater level information in Chapter 2.

### ***Groundwater well level loggers***

The groundwater well data were adjusted using a similar process as for the surface water data and were referenced to an actual elevation above MSL. The groundwater well instruments

(Hobo loggers) measured pressure in kPa, which were converted to centimeters of water. A conversion factor of 10.2 was used, which is valid for the range of temperatures encountered.

This pressure record was then adjusted for barometric variations. Diurnal fluctuations in air temperature caused a bias in the pressure readings of the barologger. This effect was determined by plotting the "corrected" elevation in Well 19, which was dry and should have been constant, versus the temperature measured by the barometric sensor (Figure 2-4). This results in apparent pressure changes of about 2 mm °C$^{-1}$ for temperatures less than 7°C and about 0.6 mm °C$^{-1}$ for temperatures greater than 7°C. Large diurnal fluctuations in temperature thus result in erroneous fluctuations in pressure. The temperature in the wells is relatively constant and does not fluctuate diurnally (Figure 2-5). Thus, we used the pressure record in a dry well, Well 19, to subtract atmospheric pressure from water pressure in all of the other wells and eliminated spurious diurnal cycles. For future studies, we recommend insulating the above-ground atmospheric pressure sensor as best possible.

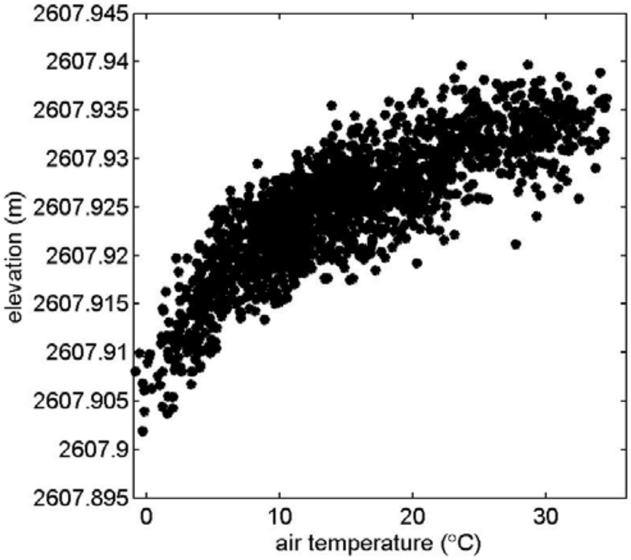

**Figure 2-4.** "Corrected" elevation in a dry well as a function of the air temperature measured by the barologger.

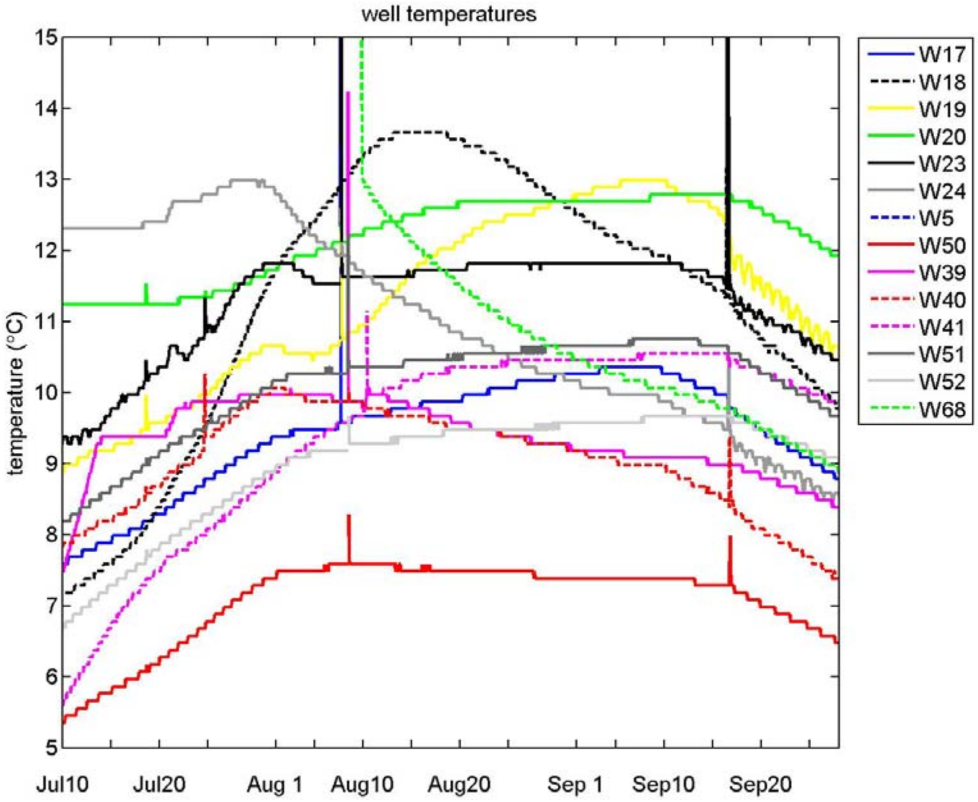

**Figure 2-5.** Temperatures in all of the wells with loggers. Most are relatively constant near 10°C for most of the summer, with cooler temperatures in the spring, early-summer, and fall.

To adjust the instrument record to reflect water table elevations, survey measurements of the ground surface at the wells and manual depth-to-water measurements were used. Depth-to-water readings were taken from the casing and were adjusted to reflect the depth from the ground surface using the measured height of the casing about the ground. The depth-to-water readings were referenced to the ground surface elevations from the topographic survey and converted to an elevation above MSL. A few of the wells were re-dug in mid-summer to remove sediment and ensure that the instrument was below water level. The dataset was adjusted and offset to create a continuous record since the datum for adjustment was the ground surface, not the well bottom. The water surface elevations were referenced to the instrument record to calculate the offset needed to adjust the instrument record to an actual elevation. Due to complications involved with the manual measurement of the depth to water, there was greater variation in the offset values than in the stream gage data. The standard deviation of the offset values for each well was less than 10 cm for 13 out of 14 wells.

### *Measuring discharge and developing rating curves*

Manual measurements of discharge were made at the Tuolumne River at Highway 120 and at Budd Creek for summers 2002 to 2006, using an acoustic Doppler river boat (RDI Instruments) and standard USGS wading techniques (Rantz et al. 1982),. After converting the pressure readings to water depth, as described above, water depth was compared with discharge to develop rating curves of the form: $Q = a(h - h_0)^b$, where $Q$ is discharge, $h$ is the water depth and $h_0$ is the water depth at which flow stops. Least-squares analysis was used to determine the coefficients $a$ and $b$. Figure 2-6 illustrates the rating curve at Tuolumne River at Highway 120, and Figure 2-7 shows the calculated discharge for the past 5 years. The greatest uncertainty exists for the highest and lowest flows.

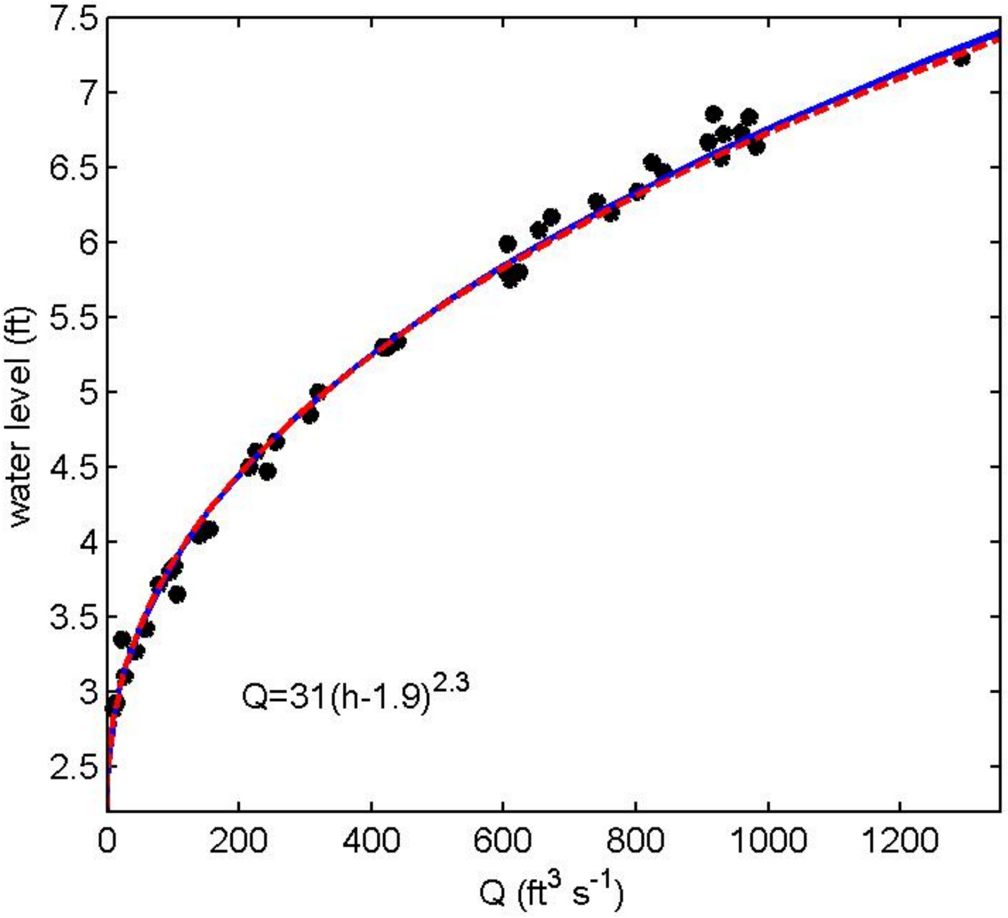

**Figure 2-6.** Rating curve for Tuolumne River at Highway 120, which provides the bulk of the surface runoff to Tuolumne Meadows. Dashed and solid lines indicate results from least squares fit alternating which of stage and discharge is the predictor and predictand. Both yield the same equation: $Q$=31($h$-1.9)$^{2.3}$, where $h$ is the staff gage reading in feet.

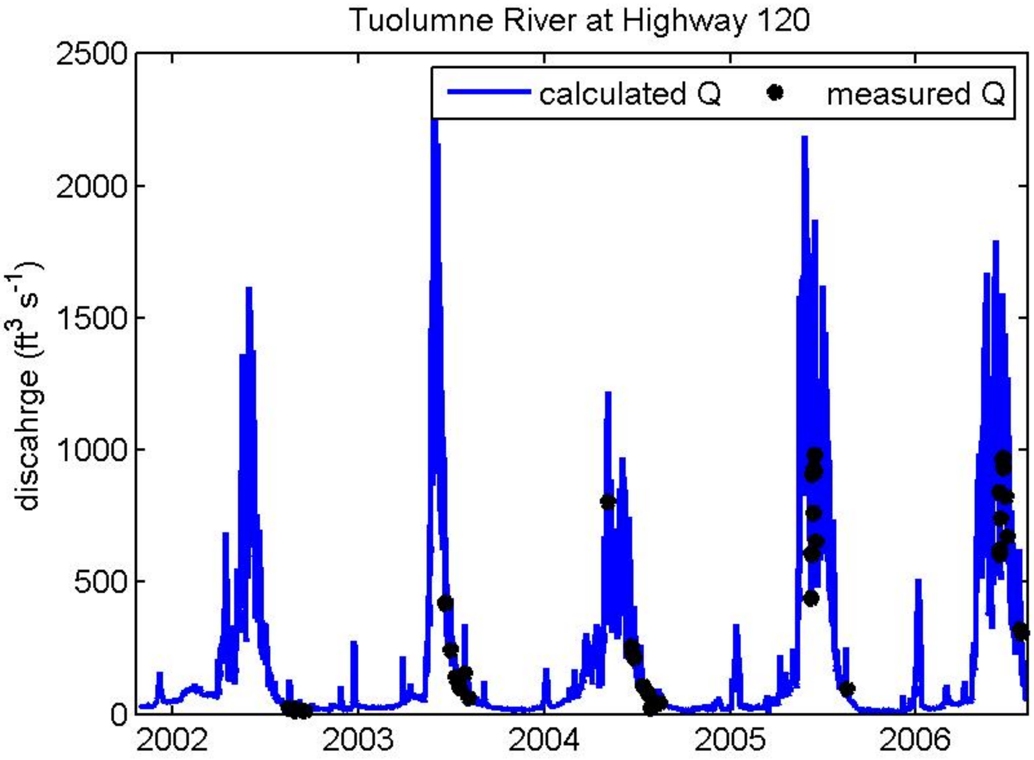

**Figure 2-7.** Calculated discharge at the Tuolumne River at Highway 120 for the past 5 years, based on the rating curve shown in Figure 4.

### *2006 Discharge and water levels*

Water year 2005-2006 was wet, with above average precipitation, a phenomenally warm and wet December and early January, and a cool and snowy spring. During the five years of Tuolumne record (August 2001 to 2006), Merced River runoff at Happy Isles correlated well with runoff at the Tuolumne River above the Meadows ($R^2$=0.89). Discharge normalized by basin area was very similar for the two streams (illustrated for 2005 in Figure 2-8), with higher values in the Merced during the early snowmelt season and higher values in the Tuolumne during the late snowmelt season, reflecting the different altitudes contributing to each gage (from 8,600 ft to 14,000 ft for Tuolumne, and 4,000 ft to 14,000 ft for Merced). The two matched best during peak snowmelt runoff, and 2006 was the 10th highest snowmelt discharge in the 90-year record at Happy Isles (Figure 2-9). Discharge at the Tuolumne River at Highway 120 and at Budd Creek peaked in early June, fell with a cold spell, and then rose again in late June when temperatures warmed and thundershowers added to runoff (Figure 2-10). Daily peak flows at

Budd Creek were approximately 1/10th as large as daily peak flows at the Tuolumne River, but the range of diurnal variations was much larger at Budd Creek, reflecting the smaller basin size and larger fraction of surface runoff to discharge.  Figure 2-11 shows discharge fluctuations for just the summer study period.

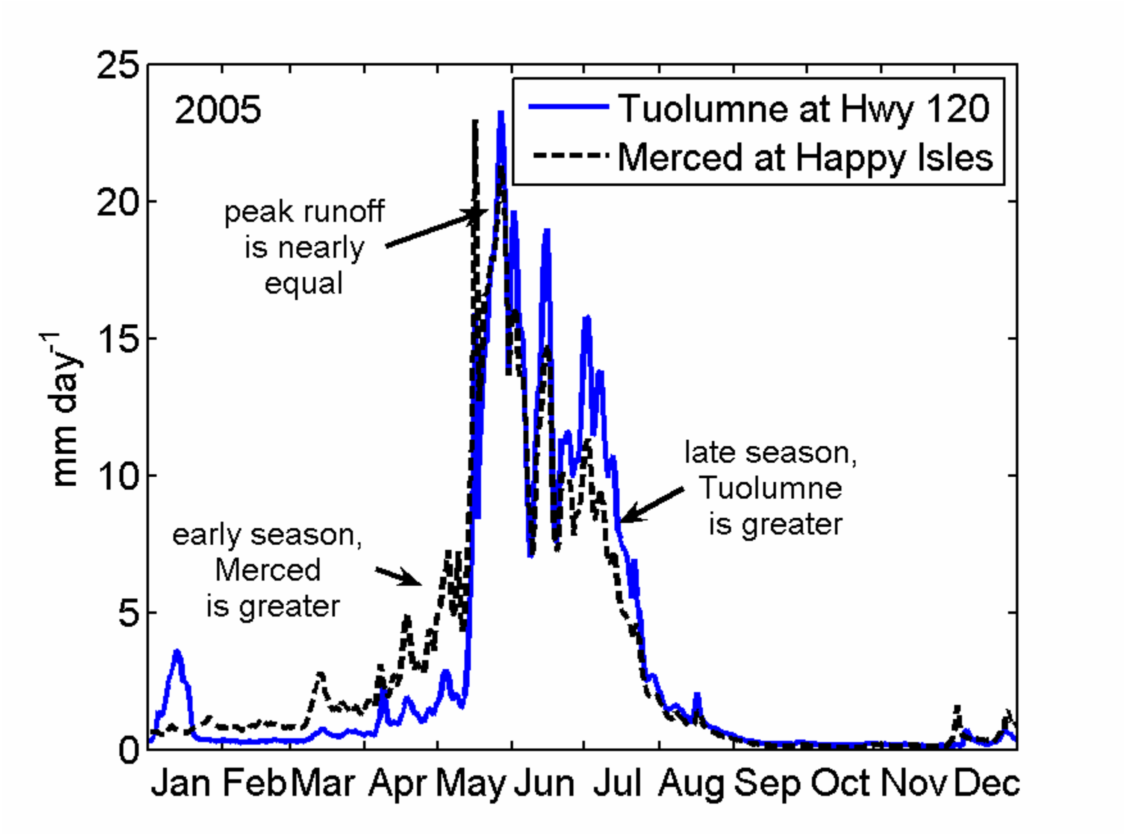

**Figure 2-8.** Basin-area-normalized flows for the Tuolumne River at Highway 120 and the Merced River at Happy Isles for 2005, illustrating the correlation between them, with best correspondence near the seasonal peak flow.

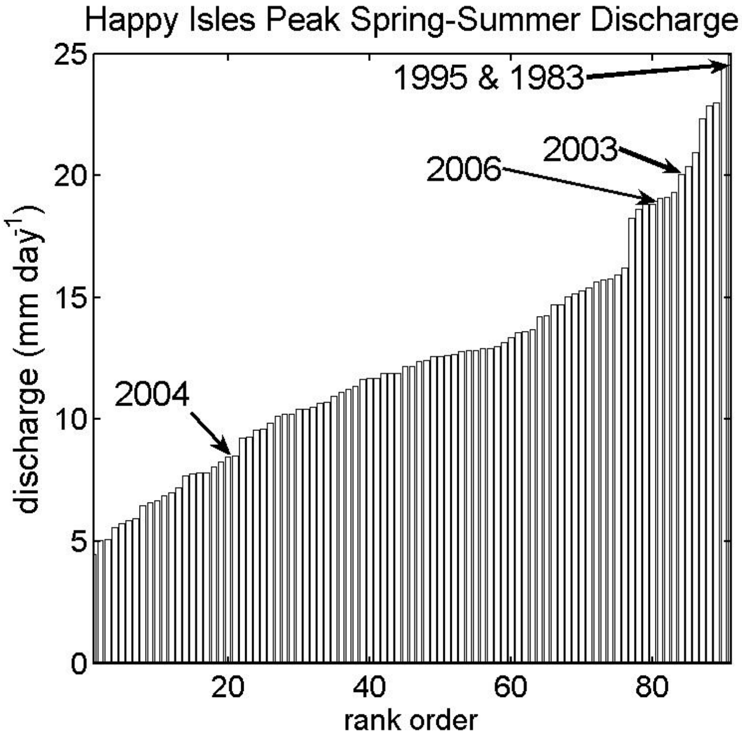

**Figure 2-9.** Peak summer discharge at Happy Isles, arranged in rank order from lowest to highest, where 1 corresponds to the lowest summer peak, and 90 corresponding to the highest summer peak. Assuming that spring/summer peaks at Tuolumne are comparable those at Happy Isles, the 2006 study summer had the 10th highest peak on record.

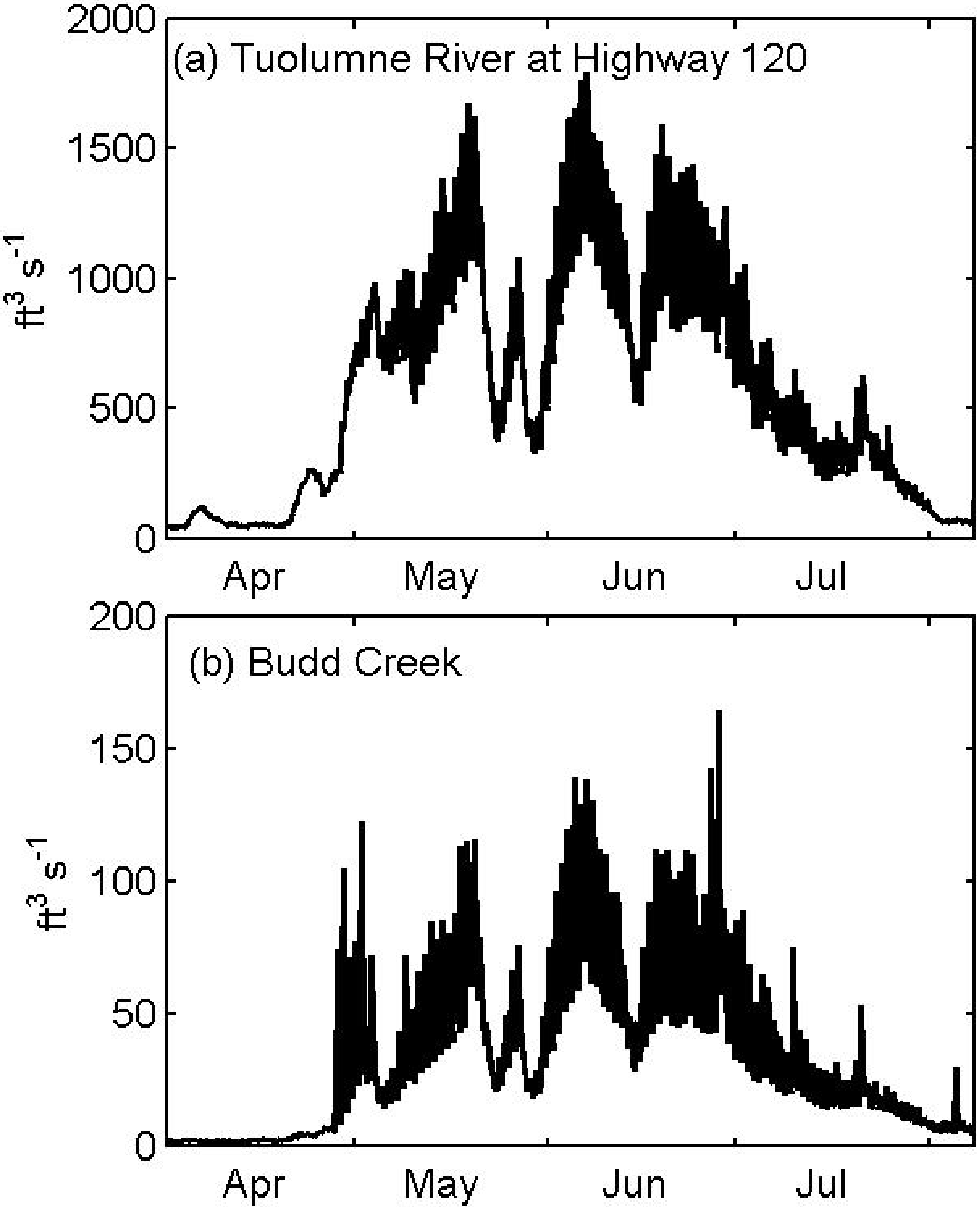

**Figure 2-10.** Calculated discharge at (a) the Tuolumne River at Highway 120 and (b) Budd Creek. Streamflow peaked in early June, followed by a cold-spell and then returned high flow in late June, which was punctuated by afternoon thundershowers. Note that the scale for Budd Creek is one-tenth that of the scale for the Tuolumne River.

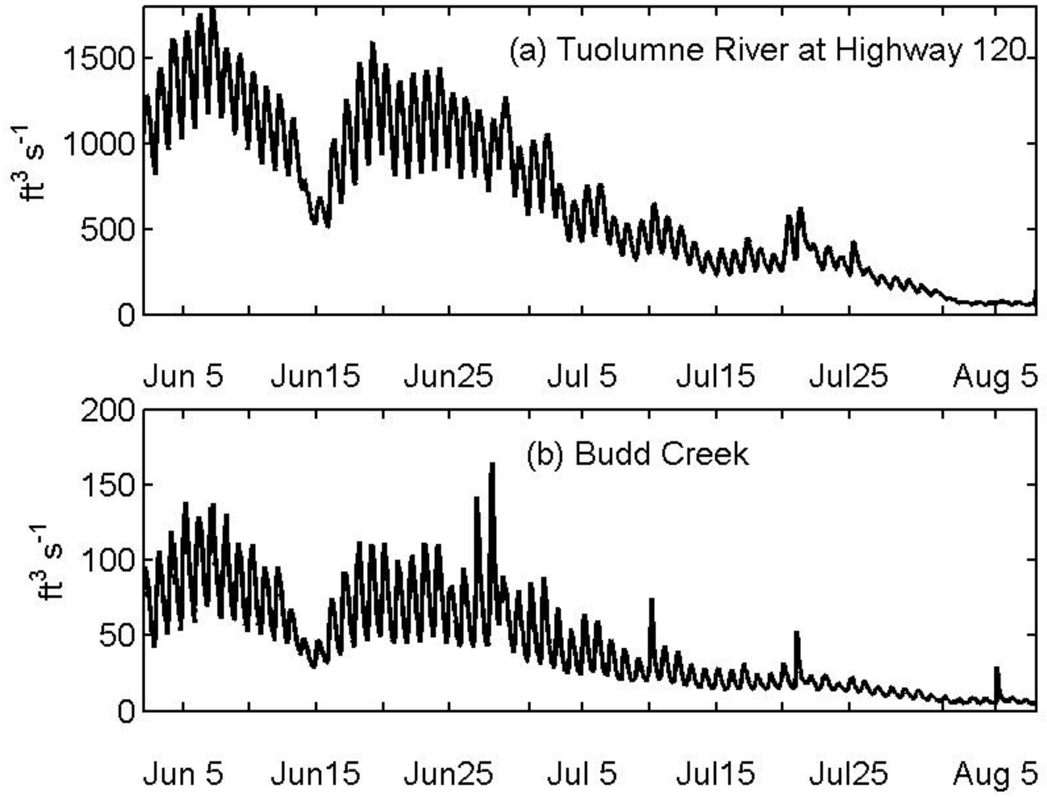

**Figure 2-11.** Discharge as in Figure 10, except zoomed to the summer study period.

Multiple discharge measurements at various meadow locations (Table 2-1) in late August and September demonstrated that during the low-flow season, surface water quantities remained approximately equal while entering and exiting the meadow, suggesting that any net loss to or net gain from the meadow's groundwater tables was within the range of error of the discharge measurements at these times.

**Table 2-1:** 2006 Discharge measurements ($ft^3 s^{-1}$) along Meadow Transects

| | **22 Aug 2006** | **11 Sept 2006** | **20 Sept 2006** |
|---|---|---|---|
| Tuolumne @ 120 | 48.91 | 28.05 | 14.74 |
| Dana Fork | | 7.84 | |
| Lyell Fork | | 13.79 | |
| Visitor Center (T3) | | | 11.5 |
| Pothole Dome (T1) | 51.77 | 21.93 | 11.86 |
| Budd Creek | 2 | Negligible | 0 |
| Comments: | Surface streams can account for increase | Likely overestimate at 120, since sum of | Possible repeat overestimate at 120 |

| | | | |
|---|---|---|---|
| | | Lyell and Dana is about 22 | |

## *Surface-subsurface flow interactions and Diurnal cycles in groundwater levels*

All of the gauged wells along Transect 4 (mapped in Figure 2-12) exhibited diurnal fluctuations during the first half of the summer (Figure 2-13). These appear to be primarily caused by diurnal fluctuations in streamflow in Unicorn Creek and in the main Tuolumne River, since timing is similar between the various locations. Water elevation is about 30 cm higher in Well 17, just south of old Highway 120 than in Wells 18 or 19, just north of the old Highway 120, during the early season, suggesting that the old highway, now a trail to Parson's Lodge, may be blocking groundwater drainage. Well 23, right next to the Tuolumne River, is well-correlated with Tuolumne River fluctuations. Well 17, 18 and 20 fluctuations match fluctuations in Unicorn Creek in mid-July but not later in the summer when discharge levels in Unicorn Creek become very low. In Transect 2 (Figure 2-14), diurnal fluctuations at Well 41 are nearly synchronous with diurnal fluctuations in the Tuolumne River (Figure 2-15). However, fluctuations at Wells 39 and 40 are out of phase with fluctuations at both Budd Creek and the Tuolumne River (Figure 2-15). The phase shift and change in shape may be due to water transport times in the subsurface or to additional effects of evaporation, but further study combining modeling work with the observations is needed to determine what the dominant factors are.

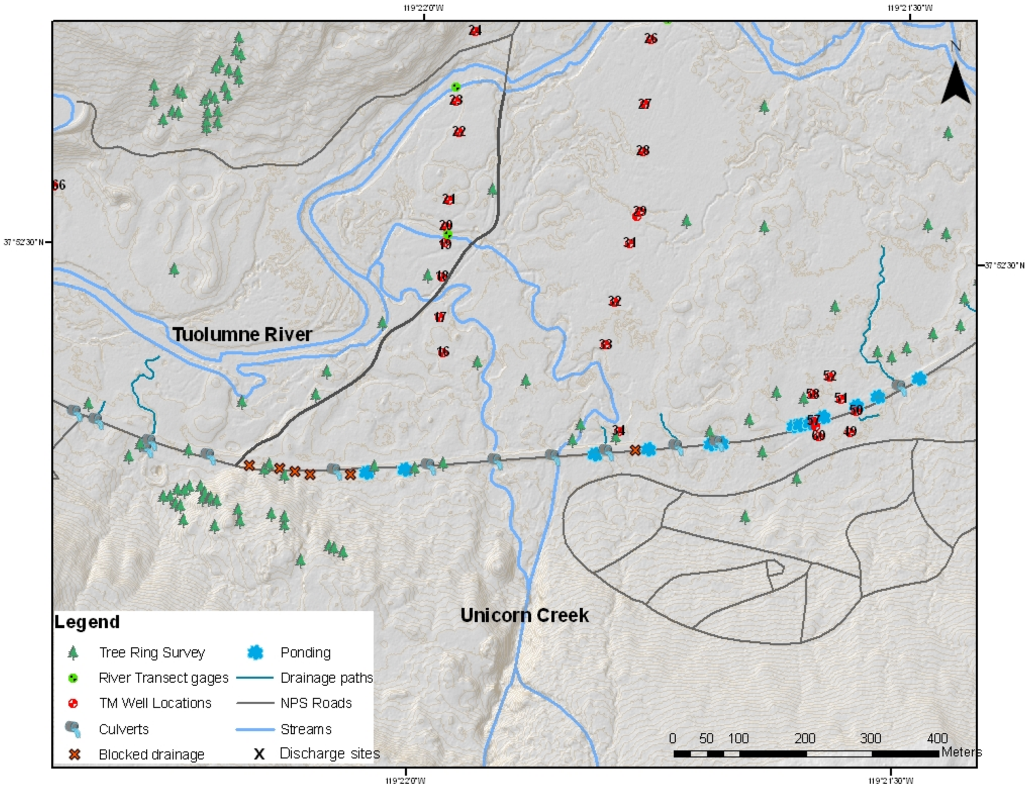

**Figure 2-12.** Map zoomed to Transect 4 (16-24), Transect 5 (26-34), and Enchanted Forest cluster (49-60).

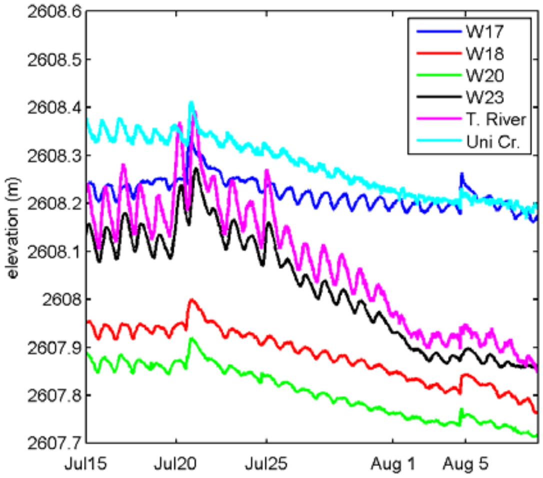

**Figure 2-13.** Diurnal fluctuations in wells along Transect 4. All monitored locations appear very influenced by fluctuations in the river and Unicorn Creek. In contrast, no fluctuations were observed in the Enchanted Forest.

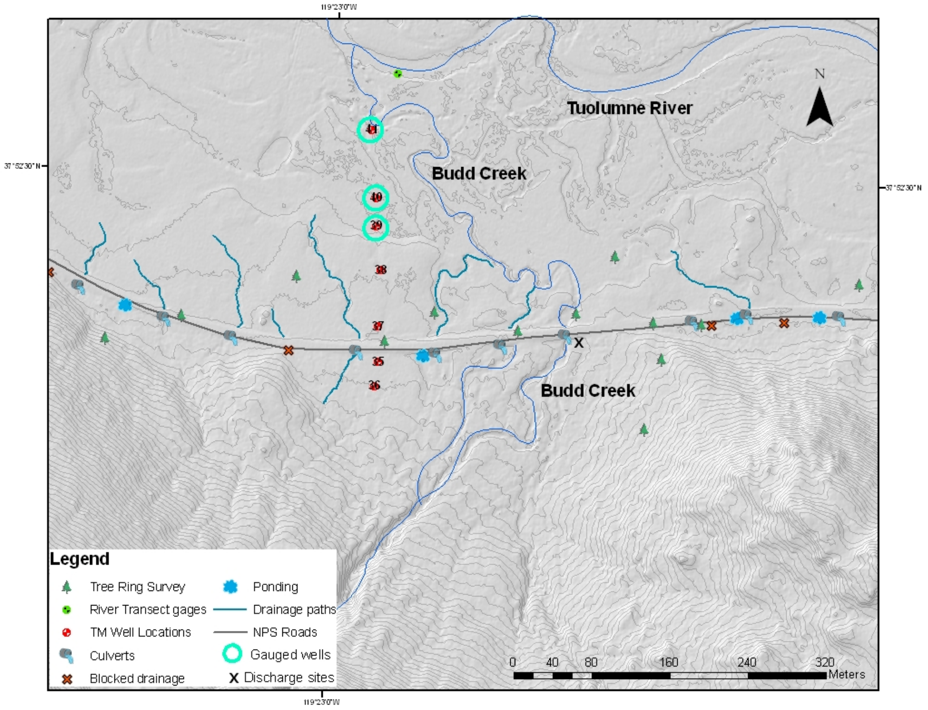

**Figure 2-14.** Zoomed in map of transect 2.

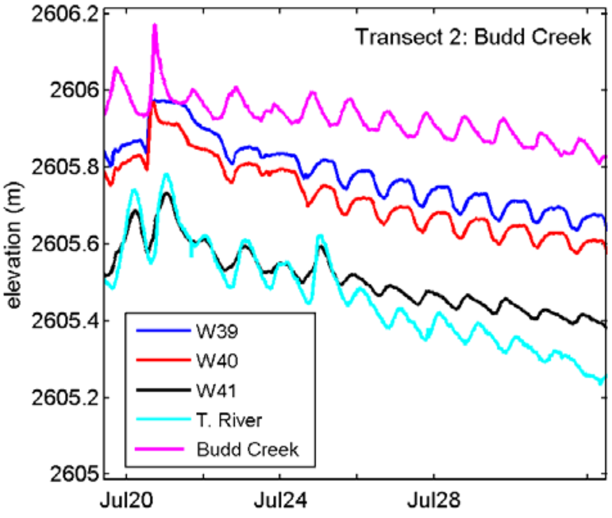

**Figure 2-15.** Stream height of water table fluctuations in 3 gauged wells and streams along transect 2. Absolute height of Budd Creek water level is estimated, with height fluctuations measured at the discharge site near the culvert.

During the late summer (September), both Unicorn Creek and Budd Creek went dry (Figure 2-16). The corresponding change in groundwater levels in the nearby meadow wells suggests that both creeks were recharging the meadow groundwater. After the creeks went dry, diurnal fluctuations in groundwater stopped, and groundwater levels dropped at much faster rates (Figure 2-16). This transition suggests that meadow groundwater levels in areas near Transects 2, 4, and 5 (near these creeks) are very sensitive to climatic shifts that would cause the tributary creeks to dry out earlier in the season.

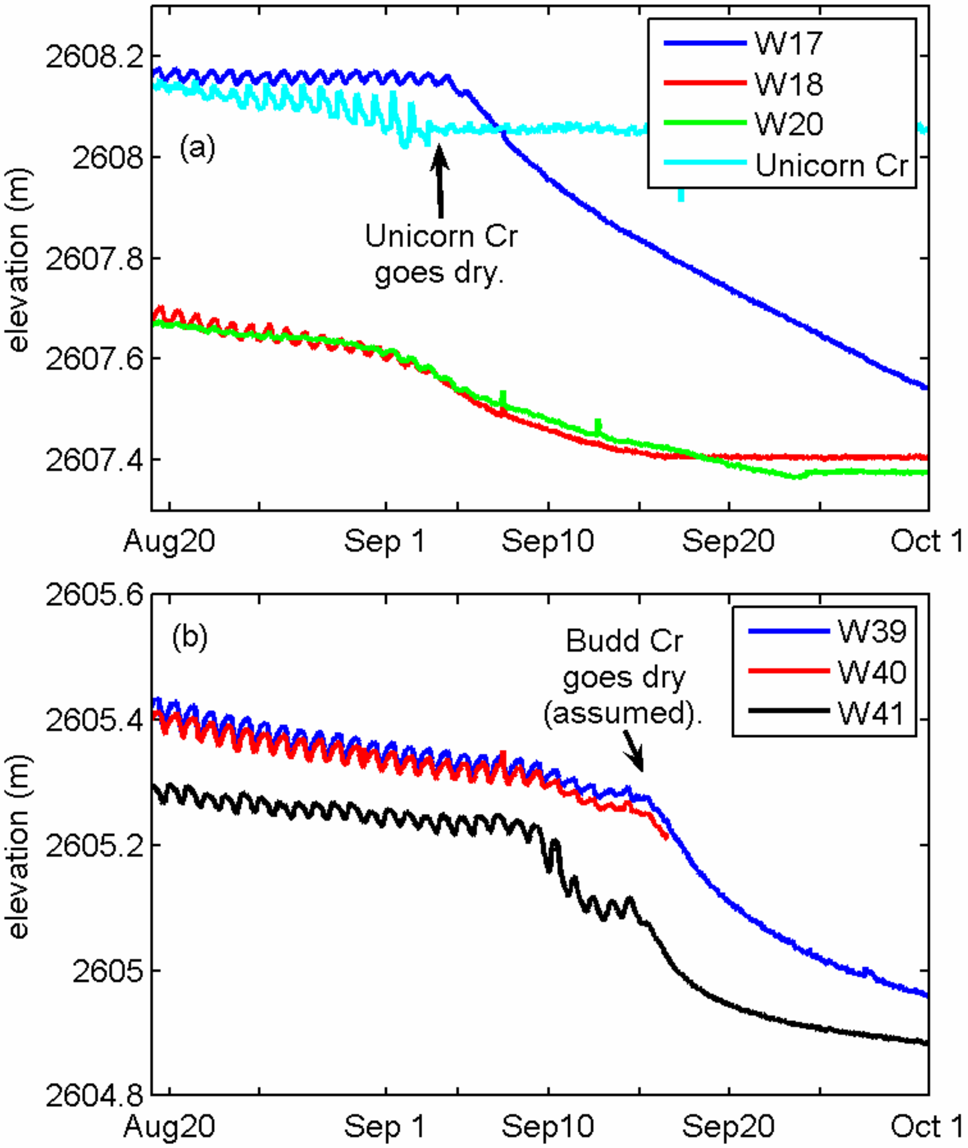

**Figure 2-16.** Groundwater levels along (a) transect 4, near Unicorn Creek and (b) transect 2, near Budd Creek. Water tables drop much more rapidly after nearby tributary streams go dry. Budd Creek is not plotted because the data for August and September will be downloaded in summer 2007 and is not yet available.

## *Road influences on surface runoff: culverts and blocked drainages*

Highway 120 through Tuolumne Meadows has 35 culverts (Figure 2-1), which allow surface water flowing from the slopes south of the meadow to drain into the meadow. A number of culverts were blocked with debris and sediment and should be periodically cleaned for optimal functionality (Figure 2-17). Blocked drainage paths were observed in 12 locations, and signs of ponding water were observed in 23 locations south of the road (Figure 2-1 and 2-18), but generally the water was diverted laterally a distance less than 10 meters before a culvert allowed water transmission. Ponding was much more frequent near the east end of the meadow, where the campground, gas station, store, and other infrastructure, coupled with lower surface slopes, interrupted water flow. Culverts were spaced further apart along the eastern sections of the road.

**Figure 2-17.** Example of culvert filled in with sediment, which obstructs water flow. Filled culverts are more common on the east end on the meadow.

**Figure 2-18.** Ponding observed upstream of road, near Transect 2 and Budd Creek.

Because the culverts forced previously disperse runoff into localized channels, downcutting was evident downstream of many of the culverts (Figure 2-19), particularly in the west end of the meadow. These channels result in levee formation and soils with greater permeability than surrounding meadow soils in certain areas and prolonged wetness in the areas where the downcut channels are located. Cunha (1992) identified the levees along these culvert-produced channels as good sites for lodgepole pine establishment.

**Figure 2-19.** Example of downcutting observed in meadow directly downstream of culvert.

## *Dana Fork diversions and water supply*

The Dana Fork (Figure 2-20, 424 $ft^3\ s^{-1}$ on 28 June 2006) currently provides the water supply for Park activities and structures in Tuolumne Meadows, via a surface water diversion just upstream of the Tuolumne Lodge. Approximately 200 $m^3$ (50,000 gallons) are pumped each day during peak summer occupancy (mid June to the end of August). One groundwater production well in the vicinity of Ranger camp serves the needs of winter rangers. Otherwise groundwater exploration in the area has proven unsuccessful. Well tests in 1993 identified that groundwater was not an option for the Tuolumne water supply (HRS Water Consultants, Inc., 1994). Thus, future water supply for the area most likely will depend on some sort of surface water diversion.

**Figure 2-20.** Bank full flow on Dana Fork of Tuolumne River near Bug Camp, 6/28/2006. Q=424 cfs.

Tuolumne Meadows water use has been similar each summer for the past 5 years. Approximately 200 $m^3$ $day^{-1}$ is consumed throughout the peak summer season (mid-June to the end of August), with lower consumption during the shoulder seasons (Figure 2-21). In contrast, the water supply varies dramatically, from over 4 million $m^3$ $day^{-1}$ during peak runoff to less than 7500 $m^3$ $day^{-1}$ during the fall. During the early summer, water withdrawals are less than 1% of discharge. During late August, September, and October, discharge is much lower. The lowest measured discharges on record for the Dana Fork are 3 $ft^3$ $s^{-1}$ (7300 $m^3$ $day^{-1}$) on 17 September 2002, and 4.6 $ft^3$ $s^{-1}$ (11,000 $m^3$ $day^{-1}$) on 27 September 2006. We estimate that during a dry year, the lower limit of flow would be about 1 $ft^3$ $s^{-1}$ (2400 $m^3$ $day^{-1}$). At this very low flow, August water withdrawals would be approximately 10% of the Dana Fork discharge, and about 5% of discharge to Tuolumne Meadows (based on observations that late-season flows of the Lyell and Dana Forks are approximately equal and that all other tributaries are dry at this time). During the late season, the river provides a source of water to the meadows, and lower discharge would lead to lower water heights and less meadow recharge. Thus, during the end of a dry year, we recommend monitoring river discharge and water withdrawals carefully and potentially implementing conservation measures.

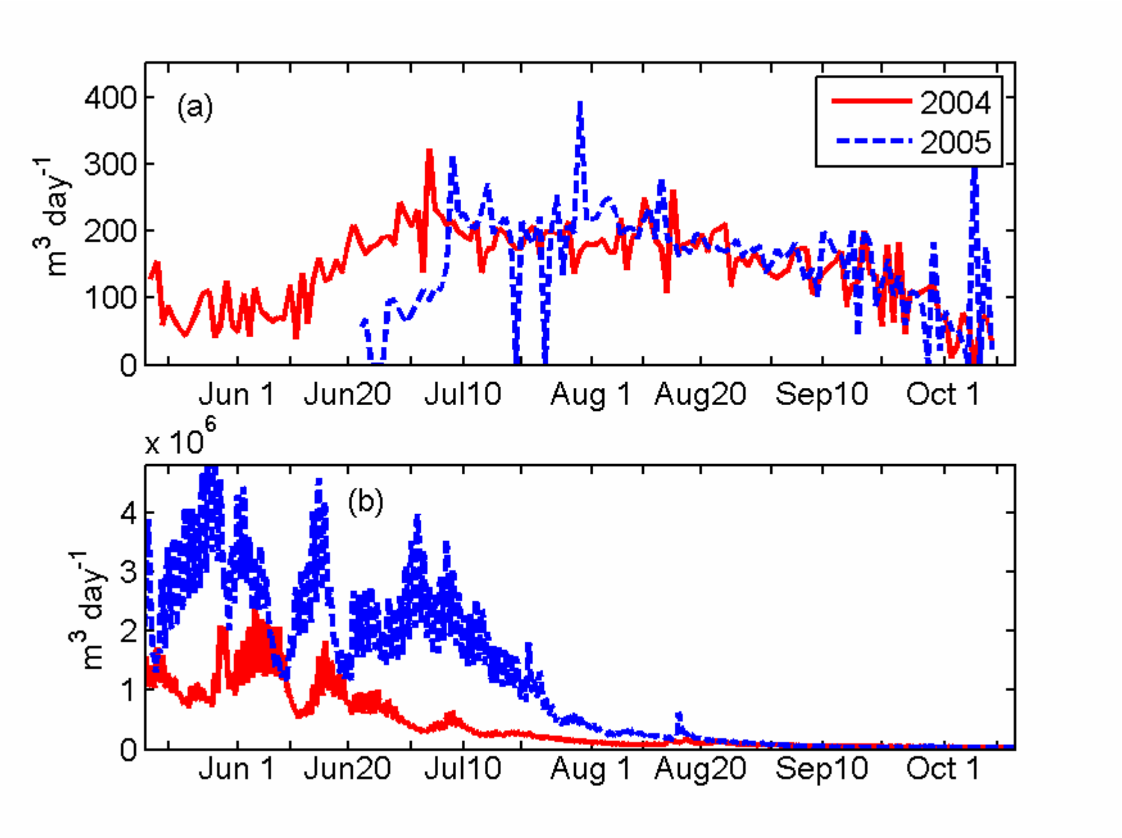

**Figure 2-21.** Daily water withdrawals (a) and approximate daily discharge in the Tuolumne River at Highway 120 (b) for 2004 (a year with very early melt onset) and 2005 (a year with late melt onset). The y-axis in (b) is 10,000 times as large as the y-axis in (a).

Because of the Dana Fork's contribution to the water supply, more discussion regarding its contributing areas is warranted. In contrast to other drainages above Tuolumne Meadows, which are underlain by granodiorite, about 30 to 40% of the Dana Fork is underlain by metamorphic rocks, which erode more easily than granodiorite and thus have formed thicker soils since the last glaciation. Metamorphic soils also have a greater water holding capacity than soils of granitic origin and form subsurface reservoirs that drain slowly and provide baseflow throughout the late summer and fall. All of the streams draining subbasins in the Dana Fork have higher temperatures and higher conductivities than subbasins of similar size in the Lyell Fork drainage, due to the greater contributions of subsurface flow to the Dana Fork. The Dana

Fork also contains several rock glaciers, which may provide late-season discharge (Millar and Westfall, submitted). As a consequence, Dana Fork discharge per unit area during the late season is greater than that of any other subbasin feeding into Tuolumne Meadows. The Dana Fork originates between Mt. Dana and Mt. Gibbs, with headwaters draining 15 $km^2$, and is fed by Gaylor Creek (16 $km^2$) and Parker Pass Creek (24 $km^2$) before reaching Tuolumne Meadows. Usually by August, the headwaters from Mt. Dana and Mt. Gibbs are barely a trickle, Gaylor Creek is completely dry, and Parker Pass Creek, which drains the north slopes of the Kuna Crest, provides most of the Dana Fork discharge. In addition to contributions from north-facing cirques and rock glaciers, the Parker Pass drainage has many meadows with thick soils and areas with peat where soils are probably saturated all year.

During the 5 years monitored, low flows were sufficient to support the current Dana Fork diversions for water to the park without detectable consequences downstream. However, climate projections concur that average regional temperatures will be about 2.5°C warmer by the end of the 21st Century, which will result in earlier snowmelt and earlier streamflow in mountain streams (Dettinger et al., 2004). While average regional precipitation is not anticipated to change, the April to July fraction of annual streamflow in the Merced River at Happy Isles is anticipated to drop from 60% to 40% by 2100, and August, September, and October low flows are projected to be lower still (Dettinger et al., 2004). All of the years monitored (2002 to 2006) had average snowpacks or above, so late season flow during a drought year could be less than 1 $ft^3$ $s^{-1}$ in a future drought year with both a small snowpack and early melt. Increased fractions of rain, rather than snow, over the next century (Knowles et al., 2006) will also reduce the late summer water supply. Future limits to late season runoff must be considered before making any management decision on future water demand in Tuolumne Meadows.

## *Recommendations for future work*

The Summer 2006 study provided a first step towards understanding surface and subsurface water contributions to Tuolumne Meadows. However, because installations and measurements began in late June and July, we were unable to fully characterize the first half of the melt season. In mid to late summer, surface water appears to recharge groundwater in the meadows, but the opposite may be true earlier in the melt season. The Tuolumne River appears to be widening (discussed more in Chapter 3), and this change in channel geometry results in a lower river water level, which may influence surface-subsurface flow interactions. By more fully characterizing both surface and subsurface water flows in upcoming years, the park will be able to better assess how changing snowpacks, surface runoff, and channel geometry will impact meadow groundwater levels and ecosystems. One method of characterizing these flows could be to monitor discharge and conductivity at all tributaries to the meadow system throughout the summer to 1) quantify how much surface runoff contributes to the meadow and any given time and 2) to qualitatively, based on conductivity, determine how the mix of surface to subsurface water compares between tributaries and over time.

Potential ponding at well 17 suggests that old Highway 120 may impact water flow through the meadow. Thus the influence of this old road should be investigated more thoroughly. This may be accomplished by installing additional wells on either side of the old road.

Many culverts need to be cleaned out, and local vegetation communities downstream of culverts should be examined for potential changes due to channel downcutting and concentrated groundwater recharge.

The greatest threat to Tuolumne Meadow's water supply is a loss of late-season streamflow in the Dana Fork due to climatic warming. Because Parker Pass is the primary contributor to the Dana Fork during the late summer and fall, the Parker Pass drainage, including the rock glaciers and permanent snowfields on the Kuna Crest should be carefully studied to better anticipate how they will respond to warmer temperatures. Topographic shading may provide some relief in select locations (Lundquist and Flint, 2006), and rock glaciers have to date retreated slower than traditional glaciers (Millar and Westfall, submitted). However, further work is needed before future water supply availability can be assured. This may be a sensitive region to highlight as part of the park's inventory and monitoring initiatives.

# Chapter 3: **Effects of the Tioga Road and other Factors on Groundwater and Vegetation in Tuolumne Meadows**

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# *Introduction*

Tuolumne Meadows is a striking landform that allows unobstructed vistas of the high Sierra Nevada as well as views of a broad and diverse meadow complex and the Tuolumne River. Understanding the hydrologic regimes that supports the meadow vegetation and soils, and that preserve the mountain views and meadow integrity is critical to land managers in Yosemite National Park. The current study was initiated to evaluate the effects of the Tioga Road on the meadow hydrologic regime, and its possible influence on lodgepole pine (*Pinus contorta*) invasion into the meadow, and other ecological changes.

The invasion of lodgepole pine threatens to obstruct vistas, and change some meadow herbaceous communities to woody plant dominated communities. The causes of this invasion were investigated by Cunha (1992) who concluded that "the current invasion of Tuolumne Meadows by lodgepole pine is primarily the result of anthropogenic influences" (page 75). In particular, Cunha (1992) identifies the upgrading of the Tioga Road in 1938 as a cause of a massive invasion of lodgepole pine along the southern margin of Tuolumne Meadows. He concluded that the road environment created suitable habitat for lodgepole pine seedlings. Road construction led to changes in the local topography and soils, and probably influenced hydrology. He also cites concern about small mammals triggering tree invasion, but felt that the role of mammals was too difficult to quantify. He concluded that "past anthropogenic practices of burning and grazing have not influenced the invasion of lodgepole pine in Tuolumne Meadows" … and … "these activities have had no lasting effects on the ecological integrity of Tuolumne Meadows".

Tree invasion into subalpine meadows has been observed and researched for nearly a century in the mountains of western North America. Reports of tree invasion in Sierra Nevada meadows date from 1911 (Bradley 1911), and have been researched by many including Boche (1974), Vale (1981a), Vankat and Major (1978), and Millar et al. (1999) in addition to Cunha (1992) and Vale and Vale (1994). Conifer trees have invaded high mountain meadows not only in the Sierra Nevada, but also in the Cascade Range (Franklin and Mitchell 1967, Vale 1981b), and the Rocky Mountains (Patten 1963, Vale 1978). The causes of meadow deterioration, vegetation changes and tree invasion have been linked to natural climate change that has produced warmer and wetter growing seasons since the end of the Little Ice Age (ca. 1870) (Jacobus and Romme 1993), historic and modern livestock grazing that reduced plant cover and created bare soil that trees could establish on (Sharsmith 1959, Dunwiddie 1977, Vale 1978, Vankat and Major 1978, Vale 1981a, Ratliff 1985, Miller and Halpern 1998, Dull 1999), and fire suppression which reduced tree mortality (DeBenedetti and Parsons 1979). It is likely that all of these factors influence tree invasion in some mountain regions, but the question remains: what has triggered tree invasion into Tuolumne Meadows?

Other large scale vegetation changes may also have occurred in Tuolumne Meadows over the past 150 years. As illustrated in Chapter 1 of this report, very heavy sheep grazing occurred in the 1800's. Prior to 1890, when Yosemite National Park was formed, an "era of tacit consent" occurred because the Federal Government made no attempt to control grazing on public lands and these lands were wide open to unlimited exploitation (Ernst 1949). Even after 1890 sheep regularly entered Yosemite National Park, and in 1898 alone 215,050 sheep and over 1,000 cattle illegally entered and were ejected from the park (Ernst 1949). These large numbers only make one wonder what number of sheep occurred in the 1860's through 1880's. Ernst (1949) also indicated that in the 1940's there were "areas in the park where the character of the ground and nature of the vegetation able to survive or re-invade are slow in showing signs of ultimate recovery from the excessive impacts they sustained." He reported this nearly 60 years after the cessation of sheep grazing. The effects of this unprecedented and high intensity grazing on Tuolumne Meadows is unknown, however in the southern Sierra Nevada Dull (1999) showed that significant vegetation changes occurred in the middle to late 1800's likely driven by overgrazing.

This report investigates patterns and processes of ground water flow in Tuolumne Meadows to determine whether the Tioga Road affects ground water flow from south to north. We also analyze water table depth and soil saturation in the meadow that could increase opportunities for lodgepole invasion. We investigated the composition of meadow vegetation in relation to ground water depth and percent soil organic matter, and provide interpretations of the characteristics and condition of meadow vegetation.

# *Methods*

## Hydrology

Ground water monitoring wells were installed in lines across the meadow. Five transects extended across the meadow from south to north, and six shorter transects were also established in the vicinity of the road and in the far western portion of the meadow. Monitoring wells were either (1) hand augered bore holes, which were fitted with perforated PVC pipe and backfilled with native soil, or (2) steel drive points that were pounded into the ground until large rocks or bedrock were encountered. A total of 73 wells were installed. Because most wells were installed in June 2006, during a period of very high water, many did not reach sufficiently deep to intersect the mid or late summer water table, and were deepened in late summer. Wells were topographically surveyed to determine their elevation.

Staff gauges were installed in the Tuolumne River along each major transect. Using hand read well data we construct ground water profiles, hydrographs, and water table maps. Electronic water level loggers were installed at five Tuolumne River staff gauges and the Unicorn Creek staff gauge, and in wells 5, 17, 18, 19, 20, 23, 24, 39, 40, 41, 51, 52, and 68. The loggers measured the water level every hour and the data are presented as ground water elevation, and depth to water table below the ground.

## Vegetation

Vegetation composition was analyzed in a circular 3 m radius plot centered on monitoring wells 1-72. A list of all plant species was made, and the canopy coverage of each species, as well as bare ground was estimated on 7 August 2006. Plant nomenclature follows Botti (2001). Plants were classified as annual, short lived perennial, and long-lived perennial for analysis.

## Soil

Soil was collected from 10-20 cm depth in a soil pit in each plot as suggested by Ratliff (1985). The air dried soil was oven dried at 105 °C for 24 hours, weighted, and burned in a muffle furnace at 550 °C for 10 hours, allowed to cool and reweighted. Percent organic matter is the difference between dry and ash weight.

## Statistical Analyses

A vegetation classification was developed using the divisive cluster analysis technique Two Way Indicator Species Analysis (Gauch 1982), using the computer program PCOrd (McCune and Mefford 1999). One way Analysis of Variance (ANOVA) was used to identify differences between plant communities in organic matter content, bare soil, and total vegetation cover. Pair wise differences were analyzed using Tukey’s HSD procedure with the family wise type I error rate controlled at $\alpha = 0.05$. ANOVA were performed with SAS (SAS 2002). Detrended Correspondence Analysis (DCA) an indirect ordination technique was performed using the computer program PCOrd (McCune and Mefford 1999). The input to DCA is the list of species present, and their canopy coverage for each plots. The analysis compares the floristic composition of stands to each other, and plots with the most similar composition are plotted closer to each other in the resulting ordination space. The axes are in standard deviation (SD) units, and stands plotted more than ~3 SD units apart (300 on the DCA figure in this report) have little floristic overlap.

# *RESULTS*

## Ground water levels and flow paths in Tuolumne Meadow

### *Water Table Profiles*

Five north-south transects (T1-T5) each instrumented with at least eight ground water monitoring wells, and staff gauges, are used to characterize the patterns of ground water elevation in the study area (Figure 3-1). Four additional shorter transects (1a-d) were added to Transect 1, and transects 6 and 7 were installed, to provide details about the hydrologic effects of the Tioga Pass highway on the meadow water table.

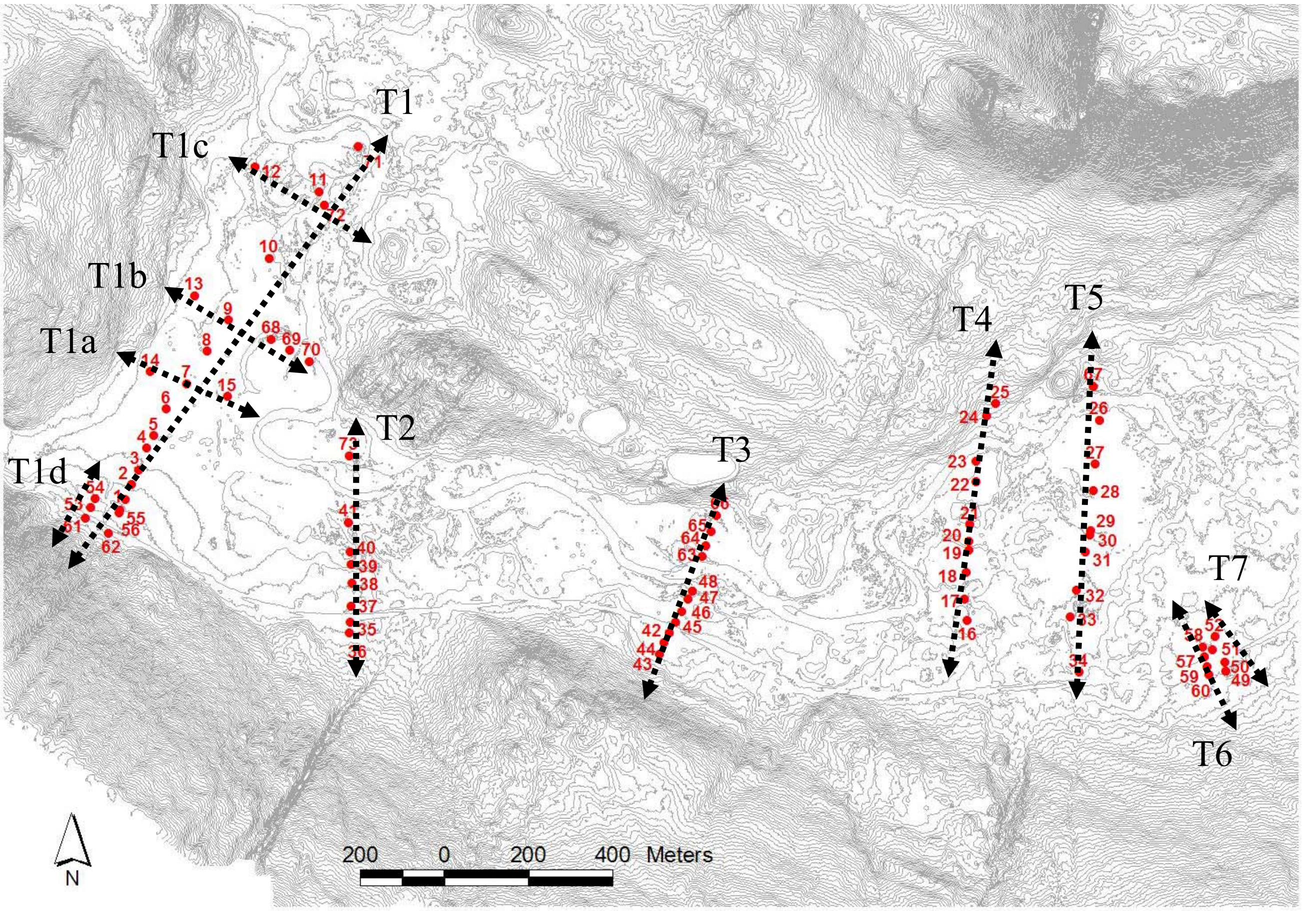

**Figure 3-1.** Map showing the location and number of monitoring wells and the 11 transects.

Transect 1: Transect 1 spans the western portion of Tuolumne Meadows. Well 62 is in the forest south of the highway and well 71 is near the river margin. There is more than 6 m of water table elevation drop from south to north along this transect (Figure 3-2). Ground water flows from the uplands to the south through the moraine and alluvial fan south of and near the Tioga Road where wells 62, 56, 55, 1, 2, and 3 occur. The landscape and water table flattens from well 4-9, forming a broad floodplain that was inundated during June 2006 by Tuolumne River overbank flows and high ground water levels. The water table at wells 4-9 is nearly 1 m above the Tuolumne River staff gauge located just north of well 71. Wells 10, 11 and 71 have nearly identical ground water levels as the river at the staff gauge (SG). Ground water flow from well 62 to well 9 is always toward the north although the gradient decreases from June through September. Ground water flow at wells 10-71 may be from southeast to northwest.

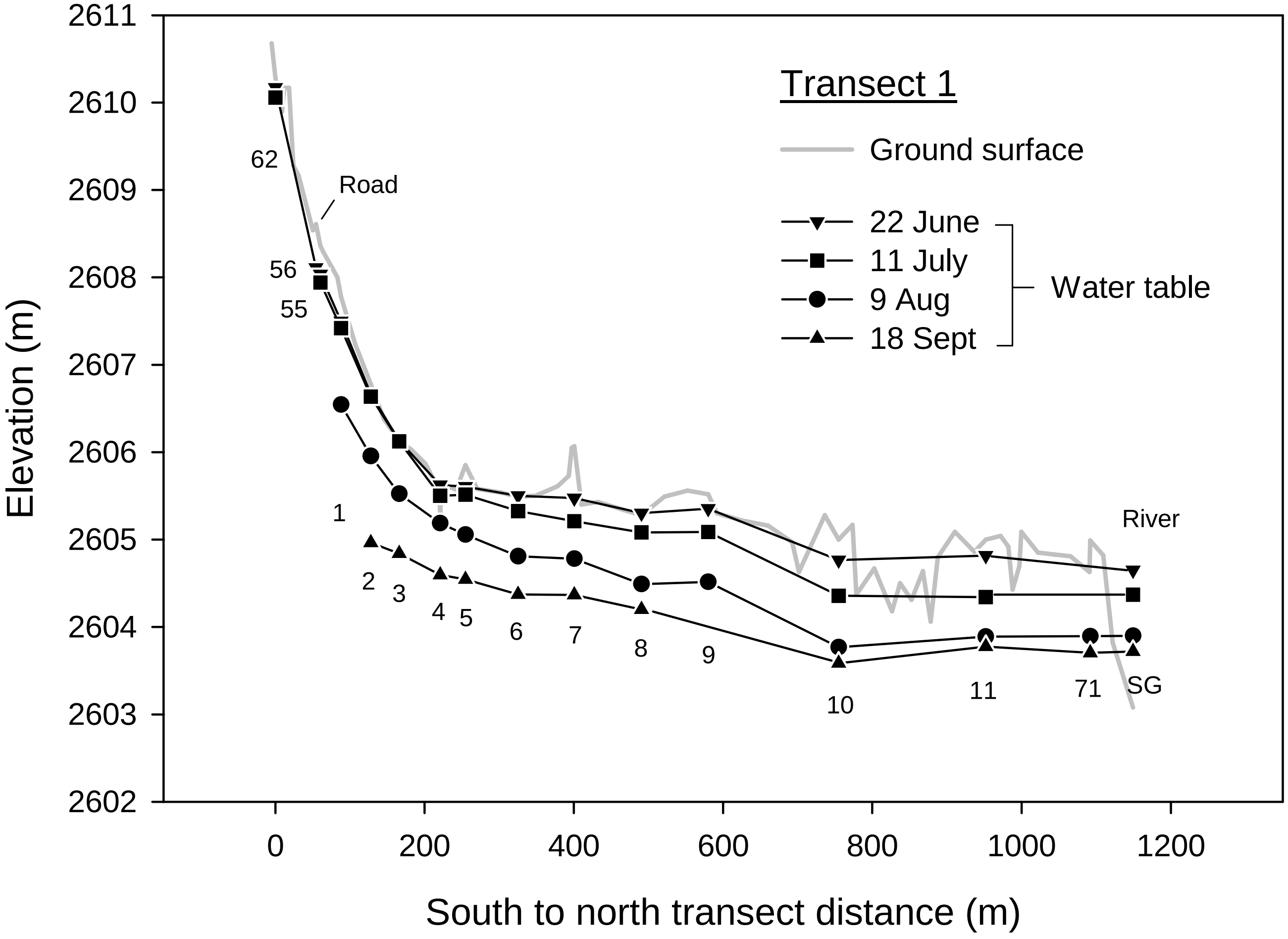

**Figure 3-2.** Ground water and surface water elevations for Transect 1 on 22 June, 11 July, 9 August and 18 September 2006.

<u>Transects 1a, 1b, 1c</u>. Transect 1a crosses the middle of the meadow from west to east, and has a relatively flat ground water profile on all dates, and when compared with T1, it indicates that the overall ground water flow is perpendicular to this transect, to the north (Figure 3-3). Transect 1b crosses T1 at well 9. The overall ground water level is relatively flat on 9 August, the only date with data for all wells. However, ground water levels are lower in wells 68, 69, and 70, suggesting that ground water flows both to the north toward well 10, and east toward wells 68-70. Transect 1c crosses the very northern portion of T1. On the two dates with data for all wells, the river likely is recharging ground water through well 72 and toward wells 11 and 12, producing a westerly flow through the floodplain.

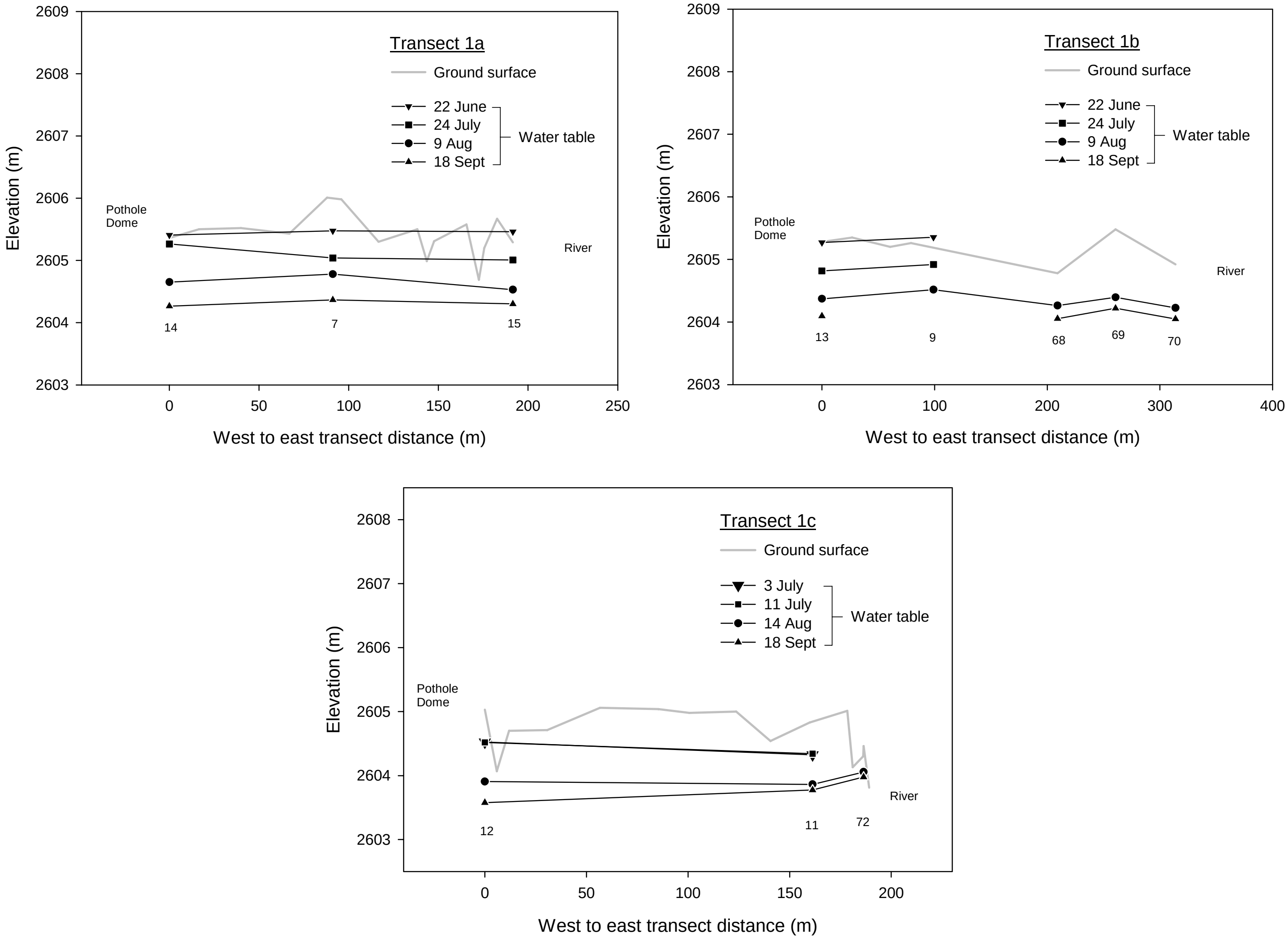

**Figure 3-3**. Ground water levels and stream stage along transects 1a, 1b, and 1c on 3 July, 11 July, 14 August and 18 September 2006.

Transect 1d. Transect 1d includes three wells, 61, 53, and 54, which were installed across, and perpendicular to the road to identify possible road effects on ground water flow from south to north (Figure 3-4). The water in well 61, south and upslope of the highway, is always higher than wells 53 and 54 north of the highway. The slope of the water table as it passes under the road is similar to, or a little flatter than the ground water gradient below the road. This suggests that there is little effect of the road on ground water flow patterns in the area of Transect 1. This is affirmed by ground water flow patterns from well 62 toward wells 56 and 55 along Transect 1, which again appears unimpeded.

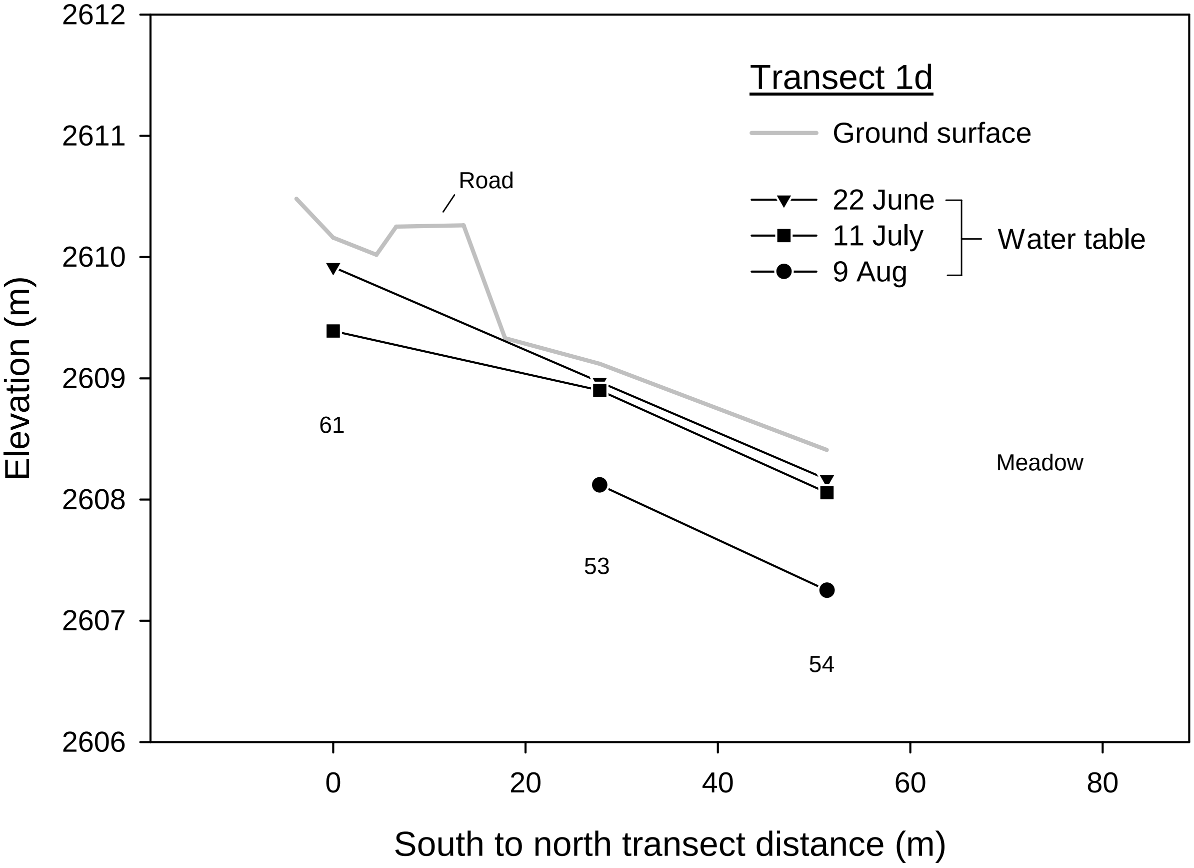

**Figure 3-4**. Ground surface and ground water levels along transect 1d for 22 June, 11 July and 14 August 2006. The location of the Tioga Road is identified by "road".

Transect 2. Transect 2 crosses the floodplain just west of the Budd Creek inflow. There is a steep ground water gradient from well 36 south of the highway to well 39 on the Tuolumne

River floodplain (Figure 3-5). The water table dropped below the casings for wells 35, 36, and 37 in the summer. We did not have a functioning staff gauge on 22 June, however the river was at bankfull stage and this elevation has been estimated. A ground water gradient from south to north persisted to 11 July, however the water table in all wells south of well 39 dropped below the bottom of our casing and we have no data on water table depth in mid to late summer. It is likely that ground water continues to flow from south to north all summer, as the water elevation in wells 39 and 40 remains higher than the Tuolumne River on 14 August and 18 September, but the ground water gradient is flatter. On 18 September, the ground water level in well 73, on the north side of the river, was lower than the river. This suggests that the river was recharging ground water through the gravel bar complex on the north side of the river, and ground water flow was northwest. Ground water flow from wells 36 and 35 appears uninterrupted by the Tioga Road as it moves to wells 37 and 38. Thus, little or no effect of the road on ground water flow can be detected at this transect.

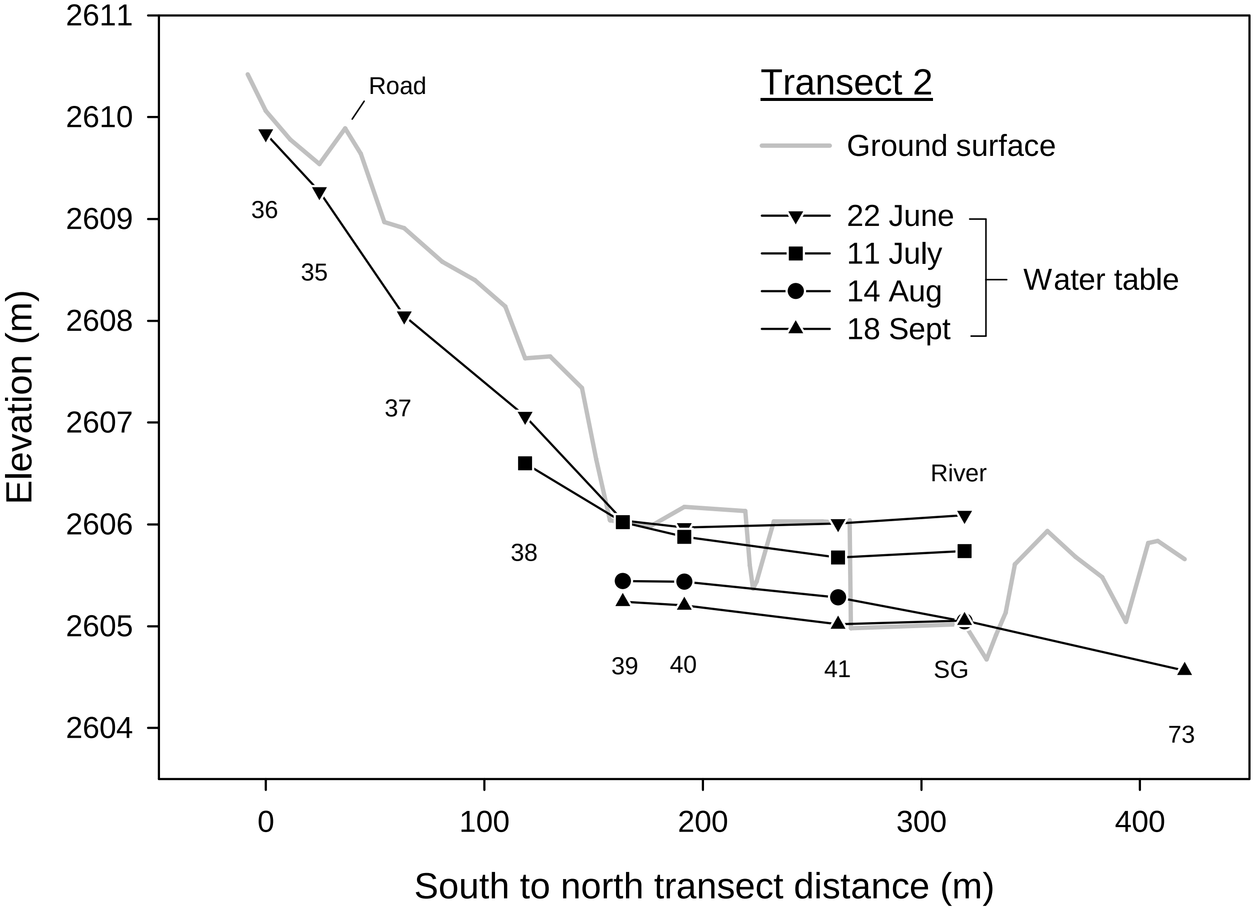

**Figure 3-5**. Ground surface and ground water levels along transect 2 for 22 June, 11 July, 14 August and 18 September 2006. The location of the Tioga Road is identified by "Road".

<u>Transect 3</u>. Similar to transect 2, the ground water flow at transect 3 is from south to north toward the Tuolumne River in early to middle summer as seen on 22 June and 11 July (Figure 3-6). River staff gauge information is incomplete but it appears that ground water on the north side of the river is recharged by the Tuolumne River, and water levels are considerably lower than the river. This produces deeper ground water levels on the north than the south side of the river at similar land surface elevation, and the vegetation bears this out. The vegetation at well 47 is dominated by *Calamagrostis breweri* while that at well 65 is dominated by *Carex filifolia* indicating much drier soil conditions. The water table intersects the ground surface in early summer at well 66, that appears to be an abandoned channel, and a marsh dominated by *Carex vesicaria* occurs. Ground water flow from wells 43, 44 and 42 toward the north to wells 45 through 48 appears uninterrupted by the highway, indicating that the highway had little or no effect on ground water flow in this portion of the Meadow.

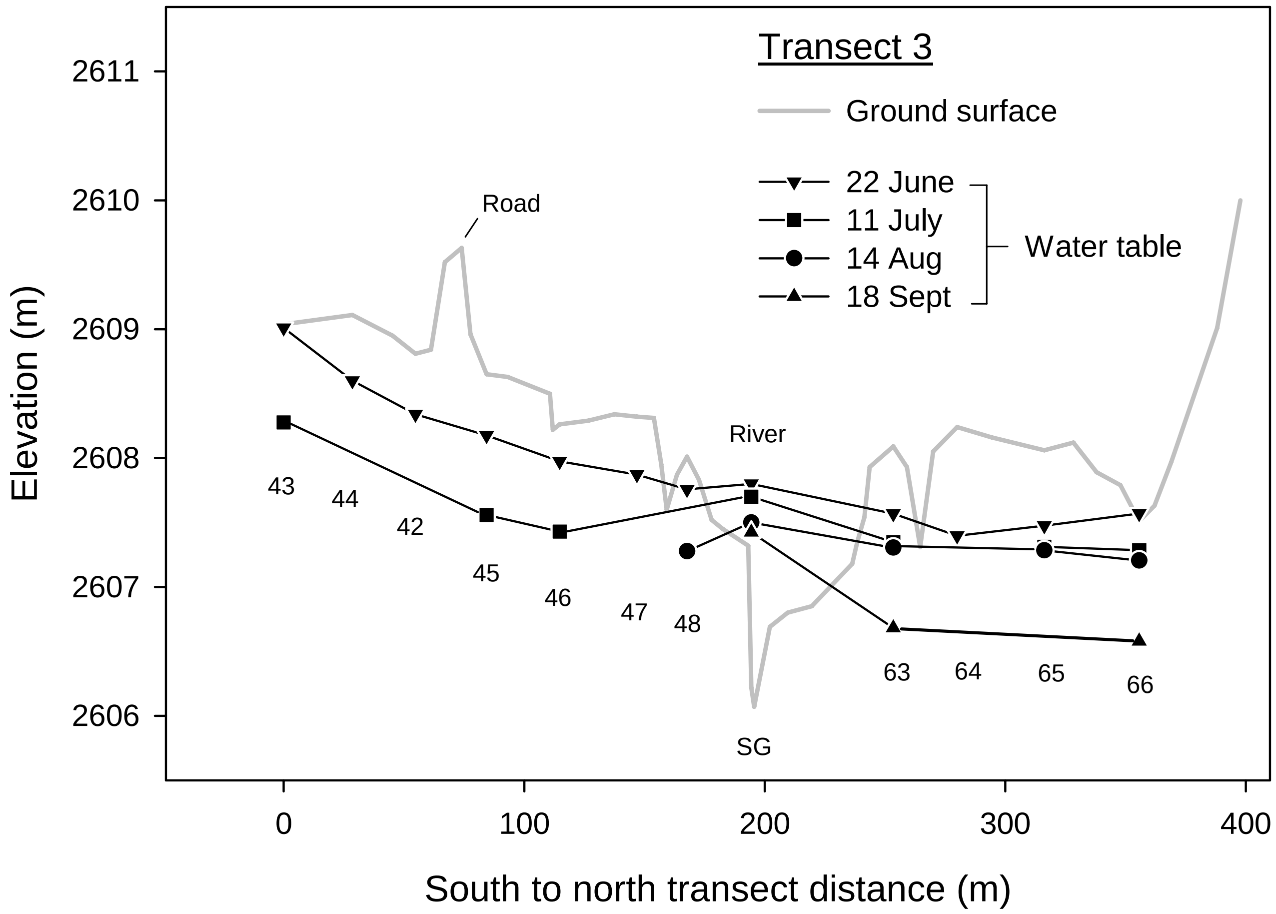

**Figure 3-6**. Ground surface and ground water levels along transect 3 for 22 June, 11 July, 14 August and 18 September 2006. The location of the Tioga Road is identified by "road".

<u>Transect 4</u>. This transect cross the meadow along the path to Parson's Lodge and Soda Springs. Wells 24 and 25 are in the Soda Spring wetland, which is a distinct ground water source, and is tributary to the River. Across most of this transect the ground water level is relatively flat, and well 23 being close to the river, likely reflects river stage (Figure 3-7). A topographic gradient occurs with the south river margin being nearly 1 m higher than the ground at well 18. A ground water gradient from the Tuolumne River into the meadow south of the river occurs at all times. The channel of Unicorn Creek flows through this transect, and supports surface water that is considerably higher than the surrounding ground water levels at all times. Unicorn Creek appears to be losing water to the surrounding meadow both to the north (well 20) and to the south (well 18 and 19).

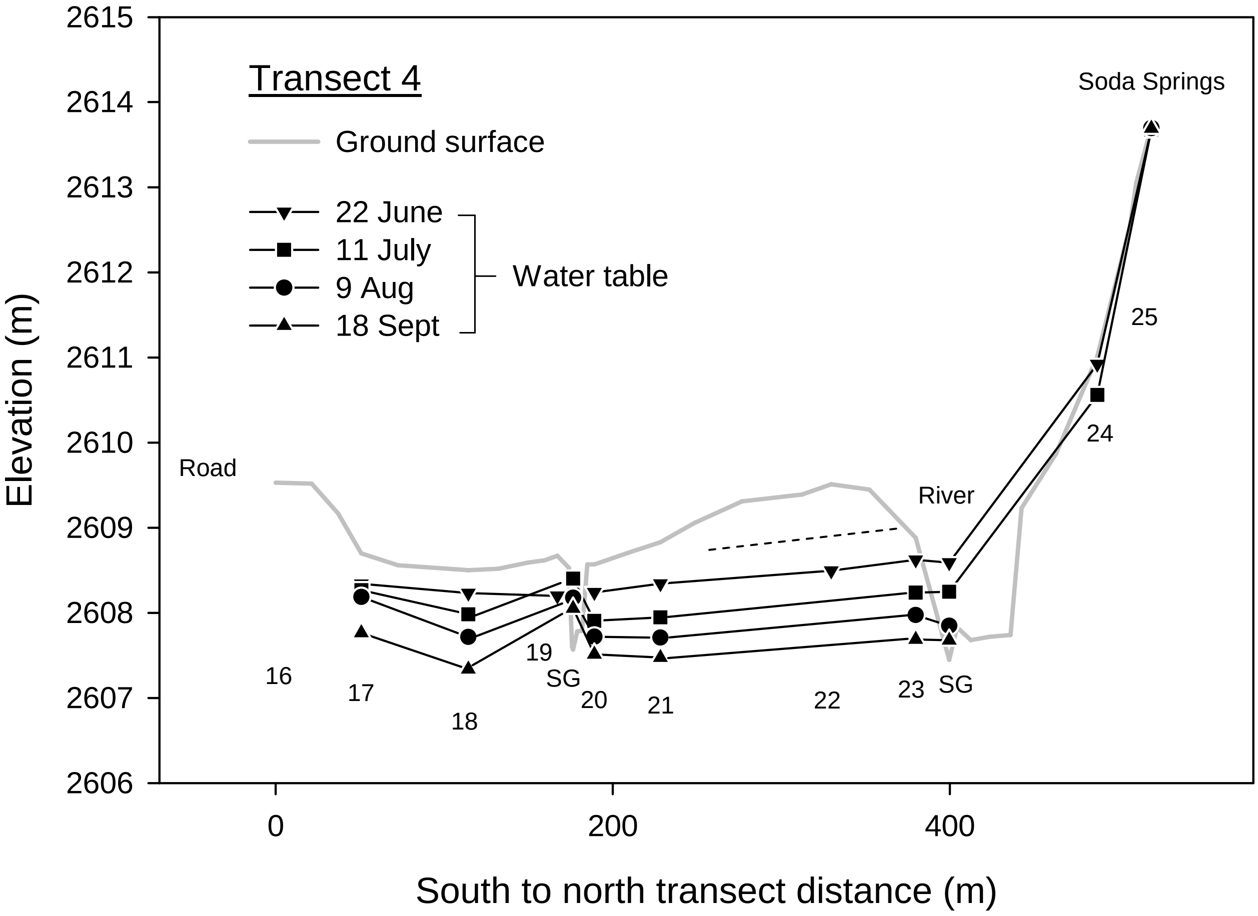

**Figure 3-7**. Ground surface and ground water levels along transect 4 for 22 June, 11 July, 14 August and 18 September 2006. The location of the Tioga Road is identified by "road".

Transect 5. Transect 5 spans the eastern portion of the meadow and begins at well 34 just below the highway on the Unicorn Creek alluvial fan (Figure 3-8). Unicorn Creek likely recharges ground water on this fan, and creates a ground water gradient from south to north through wells 34, 33, 32 and 31. However, a ground water low appears at wells 29 and 30 early in the summer and throughout the area from wells 26-30 later in the summer. Flow south from the Tuolumne River toward well 29 appears to occur at several times during the summer, such as on 22 June and 18 September.

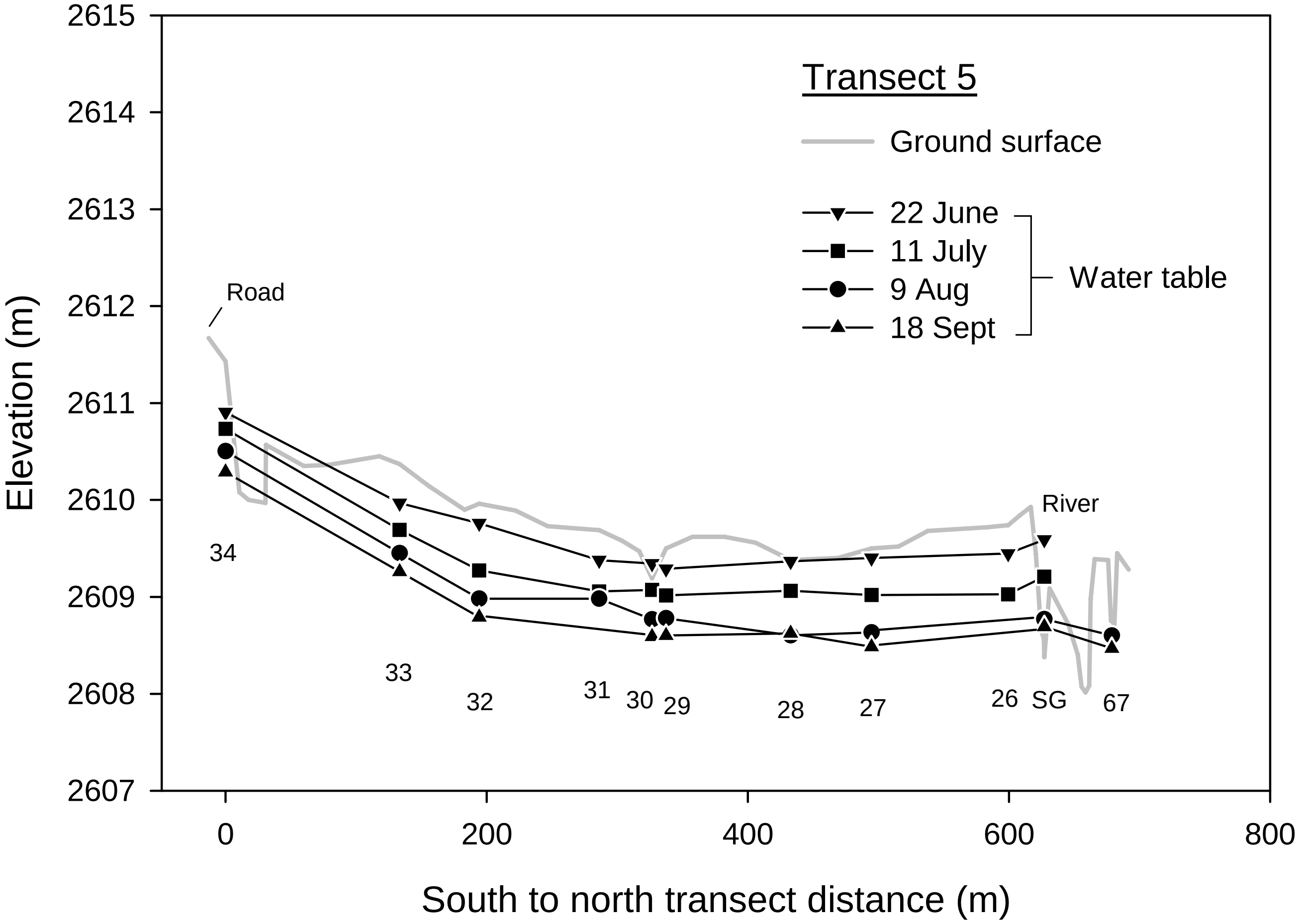

**Figure 3-8**. Ground surface and ground water levels along transect 5 for 22 June, 11 July, 14 August and 18 September 2006. The location of the Tioga Road is identified by "road".

Transects 6 and 7. Transects 6 and 7 are known collectively as the “Enchanted Forest”. Each transect has four wells, two north and two south of the highway and were installed to determine whether the Tioga Road intercepts ground water flow from south to north (Figure 3-9). Along transect 6 the Road does pond water behind the road prism at well 59. However, by early July this effect has disappeared. Along transect 7 ground water flow is relatively continuous from south to north. The only distinctive feature of ground water along transect 7 is that wells 49 and 50 have a slightly larger water table decline than wells 51 and 52, but that could be caused by a flatter topographic gradient on the north side of the highway. This transect indicates that the road does pond water in early summer, but this water drains under the road, and by summer’s end little or no influence on ground water flow is apparent.

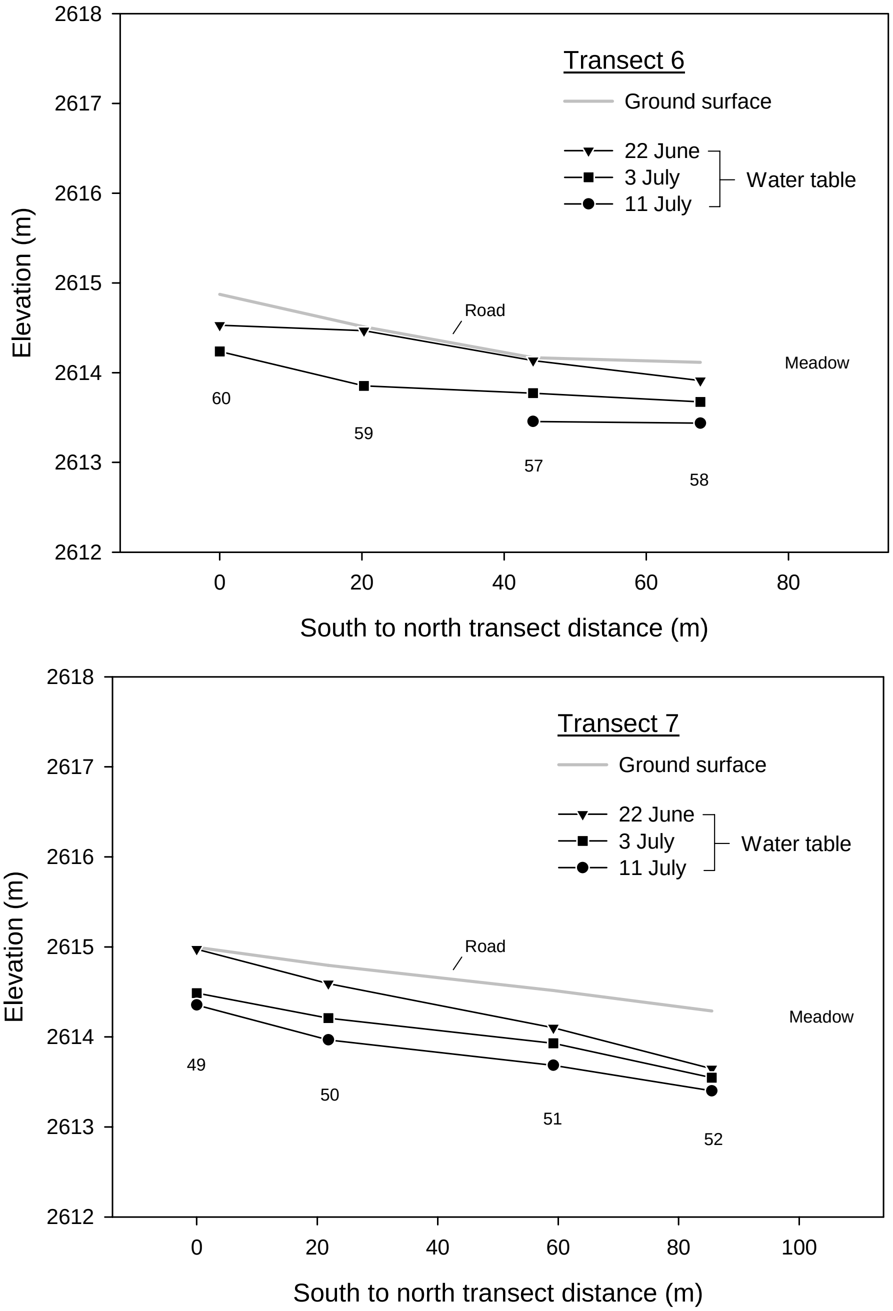

**Figure 3-9**. Ground surface and ground water levels along transects 6 (top) and 7 (bottom) for 22 June, 3 July and 11 July 2006. The location of the Tioga Road is identified by “road”.

### *Continuous Surface Water and Ground Water Levels*

Continuous ground and surface water level records for wells 5 and 68, and SG1 along transect 1 indicate a relatively continuous and slow rate of water level decline. Well 5 water levels were always higher than well 68 and SG1 (Figure 3-10). Along transect 2, wells 39, 40 and 41 had similar water level variation as SG2 during July. The staff gauge was moved in late July and went dry in early August. The wells continued their gradual decline through the summer. Water level increases resulted from rain showers. Along transect 4 SG4 had a very similar pattern to well 23, near the stream bank. These water levels are higher in elevation than wells 18 and 20, which have flatter and nearly identical water level declines. Unicorn Creek stage is higher than ground water in wells 18 and 20. Transect 6-7 wells (Enchanted Forest) had rapid water level decline rates in July and August, with more than one m drop in a month.

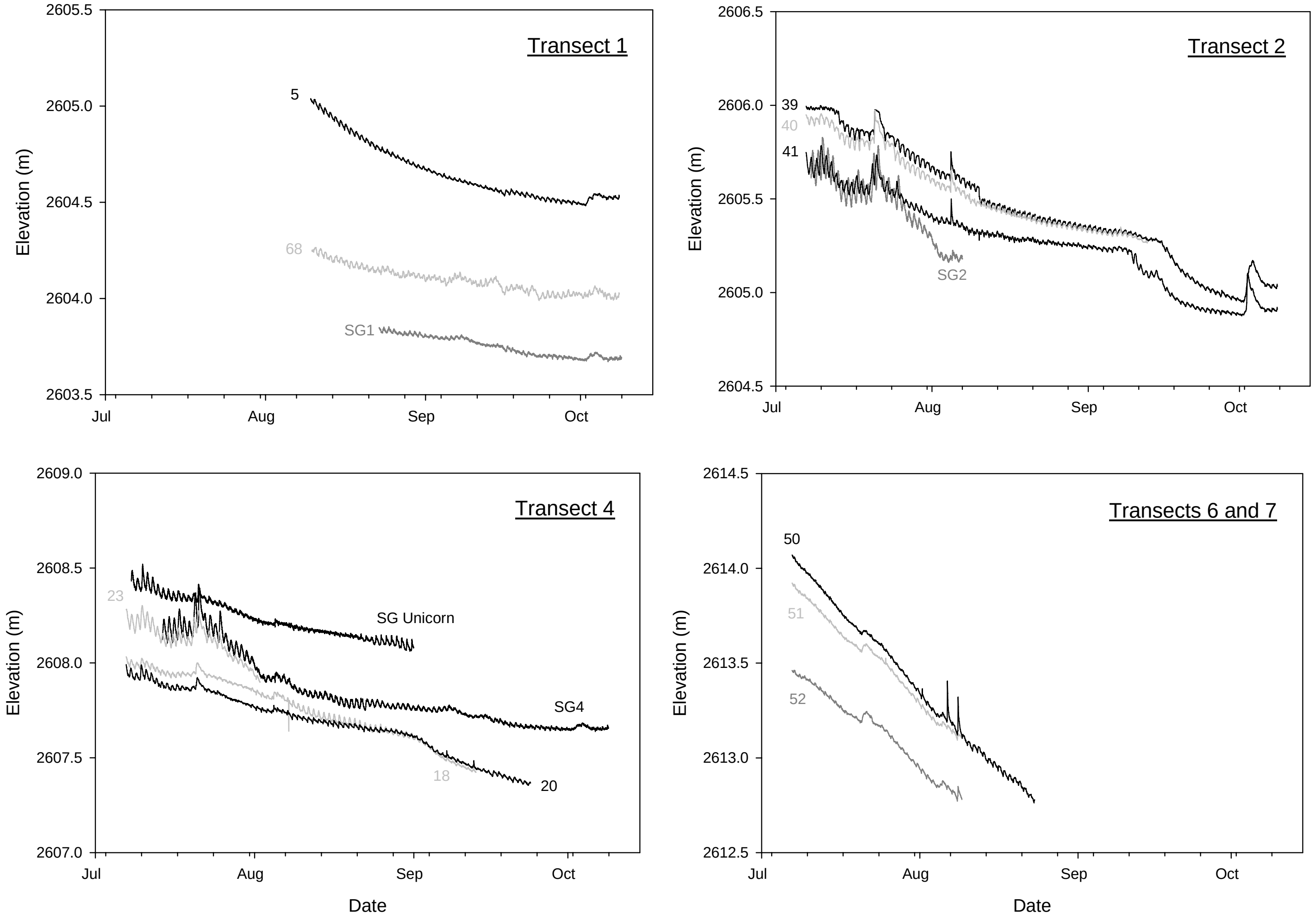

Figure 3-10. Logger data for wells and staff gauges along transects 1, 2, 4, and transects 6 & 7 together.

## *Water Table Maps*

Water table maps of Tuolumne Meadows for 22 June, 24 July and 18 September reveal a strong east to west flow at all times in the eastern portion of Tuolumne Meadows (Figures 3-11, 3-12, 3-13). This is the principal gradient through transects 5 and 4. There is also a strong gradient from the south, particularly at the Enchanted Forest, where Unicorn Creek enters the meadow and at transects 1, 2 and 3. At transects 1, 2, and 3 a very steep gradient occurs near the southern meadow-forest interface, and on alluvial fans on the southern meadow edge.

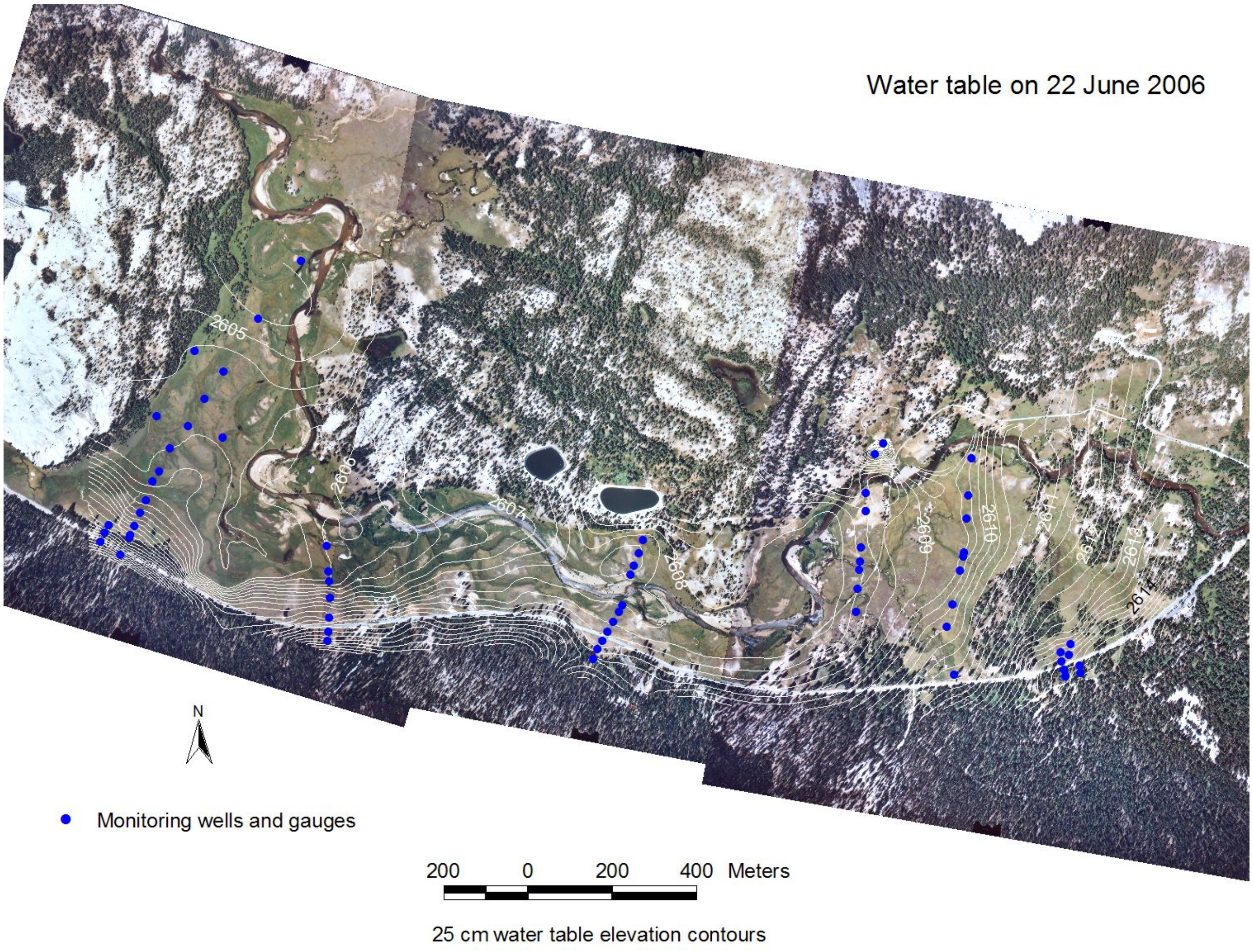

**Figure 3-11**. Ground water table map for Tuolumne Meadows on 22 June 2006, 25 cm contour intervals.

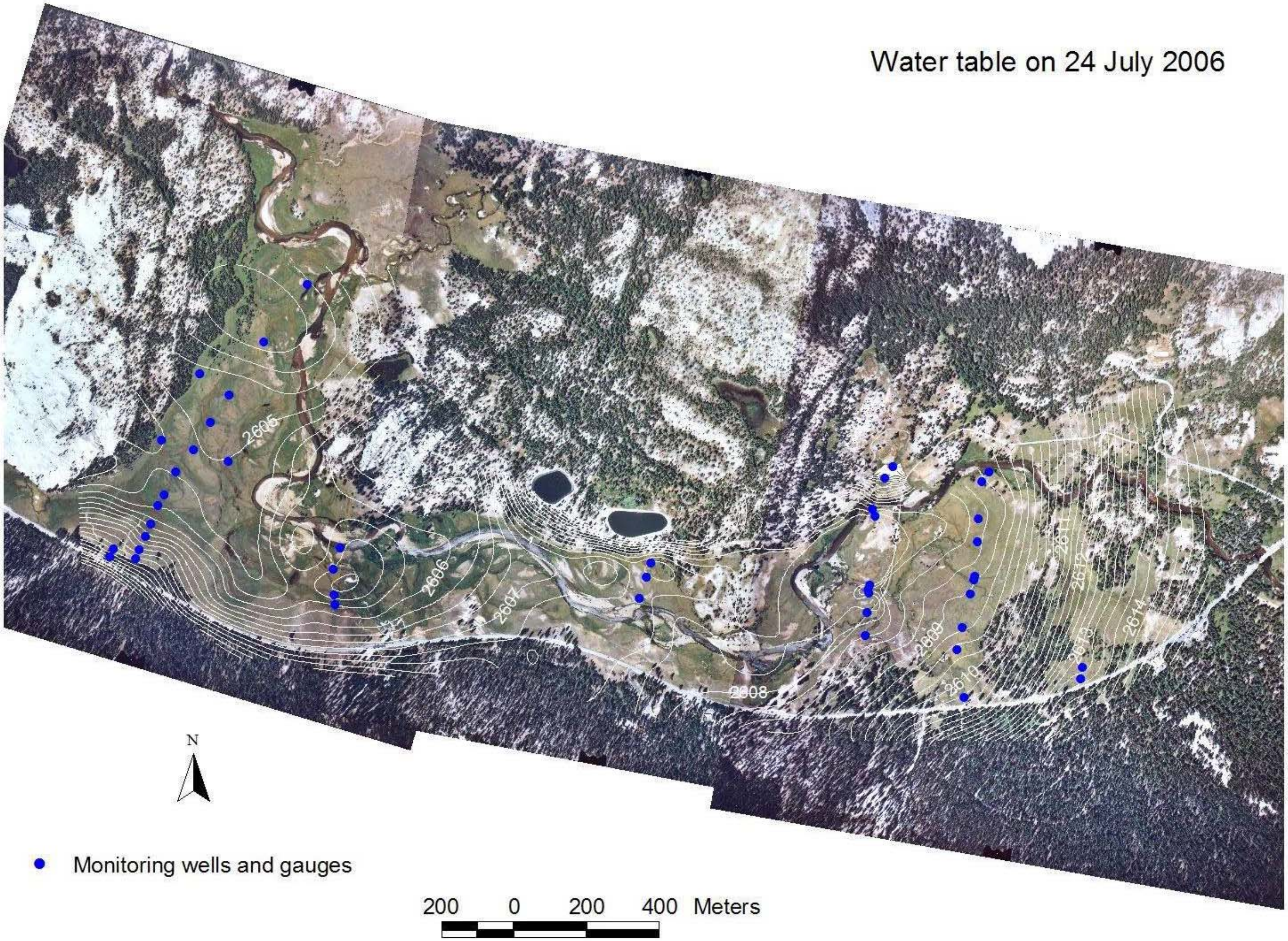

**Figure 3-12**. Ground water table map for Tuolumne Meadows on 24 July 2006, 25 cm contour intervals.

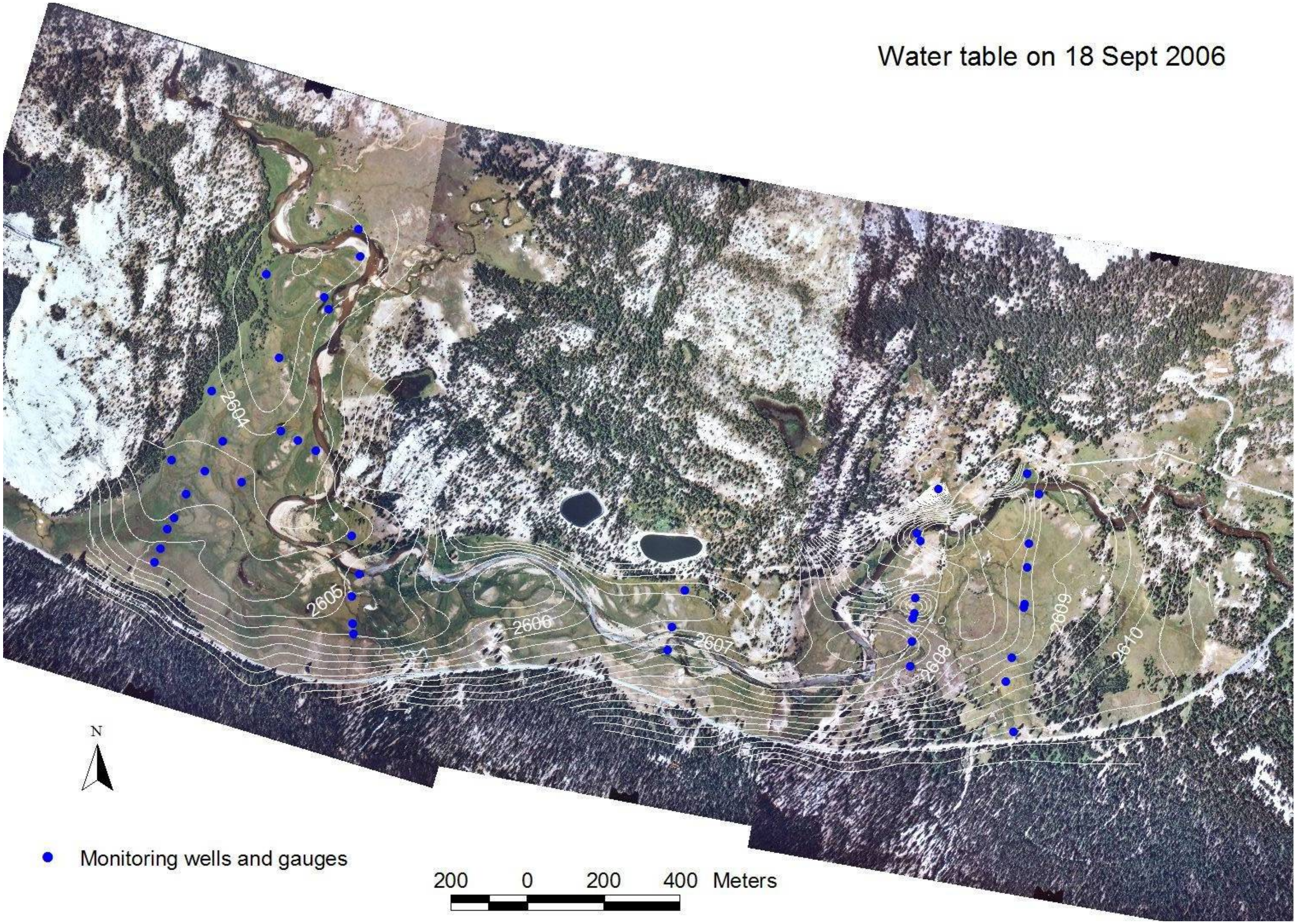

**Figure 3-13**. Ground water table map, 18 September 2006, 25 cm contour intervals.

## Vegetation

### *Plant Community Characterization*

Six plant communities were identified in Tuolumne Meadows using TWINSPAN. The plant species composition, hydrologic regime and soils of each community type are described and analyzed below.

***Carex vesicaria – Salix eastwoodiae*** (Plots 4, 14, 15, 66, 67, 68, 70, 72). This community type occupies depressions that likely are abandoned Tuolumne River channels. It is most common in the western portion of the study area. All stands had more than 0.5 m of standing water in June, and many stands remained inundated through July (Figure 3-14). All stands have high plant production with of *Carex vesicaria* and many also have thickets of the clonal willow *Salix eastwoodiae* in and on the edge of the stands. The willows are intensely browsed by deer, with nearly every stem being utilized during the summer of 2006. Some stands support tall willow species as well. The soils contains an average of nearly 17% organic matter the highest of the six communities described, and two stands have >20% organic matter. The organic content of these soils is lower than that present in fens, which typically would be at least 24-36%. This community type is not reported by Ratliff (1982, 1985), but is included in the Yosemite vegetation classification as *Carex vesicaria* seasonally flooded herbaceous alliance, and the *Salix eastwoodiae* seasonally flooded shrubland alliance.

***Aster alpigenus – Carex subnigricans*** (Plots 3, 6, 8, 9, 13, 24, 25, 30, 39). This community dominates the western portion of Tuolumne Meadow on the large low lying flats that were flooded in June and had a high water table through most of the summer. The taprooted, short lived perennial *Aster alpigenus* is abundant, and *Muhlenbergia filiformis* and *Dodecatheon alpinum* are common. *Muhlenbergia* is an annual, with very little below ground biomass, and little ability to stabilize or contribute organic matter to soils. The taprooted *Aster alpigenus* also appears to provide little soil stability. *Carex subnigricans* and *Juncus balticus* occur as scattered culms and low canopy coverage, and are the only two long-lived perennial rhizomatous species present. This community is highly disturbed by pocket gophers and meadow voles and in early summer the ground is almost entirely bare soil having been churned up by their activity under the winter snowpack. Large areas of bare soil persist through the summer. The water table was near the soil surface through the main part of the summer indicating persistent soil saturation. Soils had an average of 12% organic matter, which may be typical of montane wet meadows in the Sierra Nevada (Ratliff 1985). Although the organic content of the soil is high, the modern vegetation produces very little below ground biomass, and likely could not have produced these organic rich soils. The turnover of soils by small mammals, and the low below ground biomass suggests that stands of this community may be losing soil organic matter on an annual basis. The *Oreostemma alpingenum* var. *andersonii* herbaceous alliance in the Yosemite vegetation classification may include this community.

***Ptilagrostis kingii – Polygonum bistortoides*** (Plots 7, 10, 11, 12, 21, 27, 28, 29, 33, 34, 40). This grassland community has high canopy coverage of *Ptilagrostis kingii, Danthonia intermedia, Antennaria corymbosa,* and lower cover but high constancy of *Horkelia fusca, Trisetum spicatum, Stellaria longipes, Aster alpigenus* and *Polygonum bistortoides*. This is the most abundant community in the eastern and northwestern portions of Tuolumne Meadows, in low lying, relatively level sites. This community had a water table near the soil surface in June and July and the soil contains an average of >11% organic matter. Intensive and widespread disturbance by small mammals occurs in all stands. The relatively dense cover of the grasses *Ptilagrostis, Danthonia* and *Trisetum* contribute considerable stability to the soil and inputs of below ground biomass. The *Ptilagrostis kingii* seasonally flooded herbaceous alliance is reported in the Yosemite vegetation classification.

***Calamagrostis breweri – Vaccinium caespitosum*** (Plots 1, 2, 5, 17, 18, 19, 20, 31, 32, 41, 47, 48, 49, 51, 52, 53, 54, 55, 57, 58, 69). This is the most widespread community type in Tuolumne Meadows, and dominates alluvial fans around the meadow margin, as well as the top of high terrace remnants on the Tuolumne River floodplain. *Calamagrostis breweri* is the most abundant taxon, but the prostrate *Vaccinium cespitosum* and *Antennaria corymbosa* are also characteristic and their bluish gray, and red leaves color the land surface. *Aster alpigenus, Danthonia intermedia, Solidago multiradiata, Muhlenbergia filiformis* and *Castilleja lemonii* are constantly present and may have high canopy cover in some stands. *Pinus contorta* seedlings, saplings and adult trees are present in most stands and trees may form an open overstory. The water table was near the soil surface in early summer, but dropped to more than 1 m deep by summer's end. Stands contain 5-10% organic matter, with an average of 7.7%. Stands of this community have high plant canopy coverage (Figure 3-17) but nearly 30% bare ground (Figure 3-18). This is a characteristic community of Sierra Nevada meadows (Ratliff 1982), and would be included in the *Calamagrostis breweri* herbaceous alliance of the Yosemite vegetation classification.

***Carex filifolia – Antennaria corymbosa*** (Plots 16, 22, 23, 26, 37, 38, 42, 43, 44, 45, 46, 63, 64, 65, 71). This community occupies high, upland areas on alluvial fans and bedrock outcrops within and on the meadow edge. Canopy cover is low, soil organic matter averages 6.6% and soil is exposed over much of the stand. Along with *Carex filifolia, Antennaria corymbosa, Muhlenbergia filiformis* and *Solidago multiradiata* are common. Some stands have high cover of *Artemisia tridentata* particularly the very dry surfaces in the eastern valley along transect 4. *Pinus contorta* seedlings, saplings and adults are present in most stands. The water table is always more than 0.5 m below the soil surface and soils are dry by summer's end. This is a characteristic dry meadow community in the Sierra Nevada (Ratliff 1982), and is in the *Carex filifolia* herbaceous alliance of the Yosemite vegetation classification.

***Pinus contorta – Carex rossii*** (Plots 35, 36, 50, 56, 59, 60, 61, 62). This community type occurs on bedrock, glacial till and other upland sites on the valley margin. The water table may be near the soil surface in June, but by July the water table is deep, or has dropped below the large rocky substrate that we were unable to penetrate with our auger or steel drive points. The soil is largely bare of plants, live canopy cover is the lowest of the six community types identified, and seedlings, saplings and adults of *Pinus contorta* are present. In a few stands, *Tsuga mertensiana* are present. The soils contain an average of ~6% organic matter.

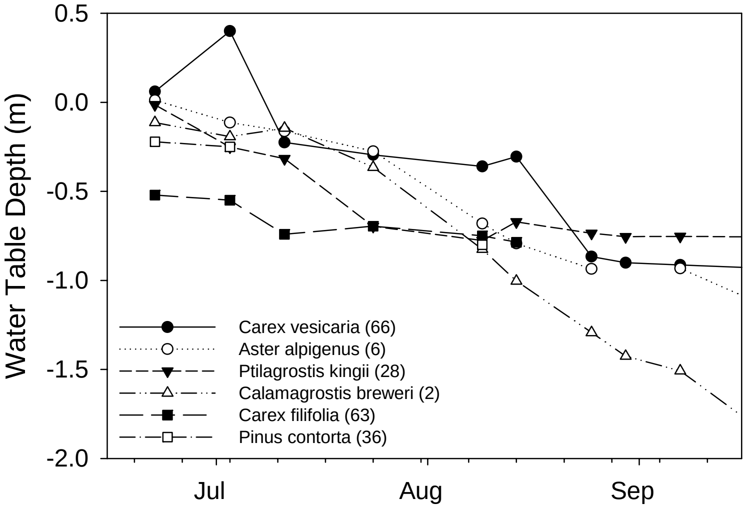

**Figure 3-14.** Depth to the water table below the ground surface (0.0) for one representative well in each of the six community types.

### *Soil Organic Matter in Communities*

There are statistically significant differences in the mean soil organic matter content among the six community types ($p < 0.0001$) (Table 3-1). The highest organic content was in the *Carex vesicaria – Salix eastwoodiae* community. The *Aster alpigenus – Carex subnigricans* and *Ptilagrostis kingii – Polygonum bistortoides* communities had similar organic matter contents, but are different from the other four communities (Figure 3-15). The soil organic matter differences suggest that the *Carex vesicaria – Salix eastwoodiae* community has high organic matter production and storage. The *Aster alpigenus – Carex subnigricans* and *Ptilagrostis kingii – Polygonum bistortoides* communities have soils with high organic matter content typical of wet meadows, while the *Calamagrostis breweri – Vaccinium caespitosum, Carex filifolia – Antennaria corymbosa* and *Pinus contorta – Carex rossii* communities are found in uplands or meadow margins and higher landscape positions within meadows, and have much lower organic matter content. Soils with the highest organic content occur closest to the Tuolumne River, and in the flat central portions of the meadows along transects 1, 2 and 5 (Figure 3-16).

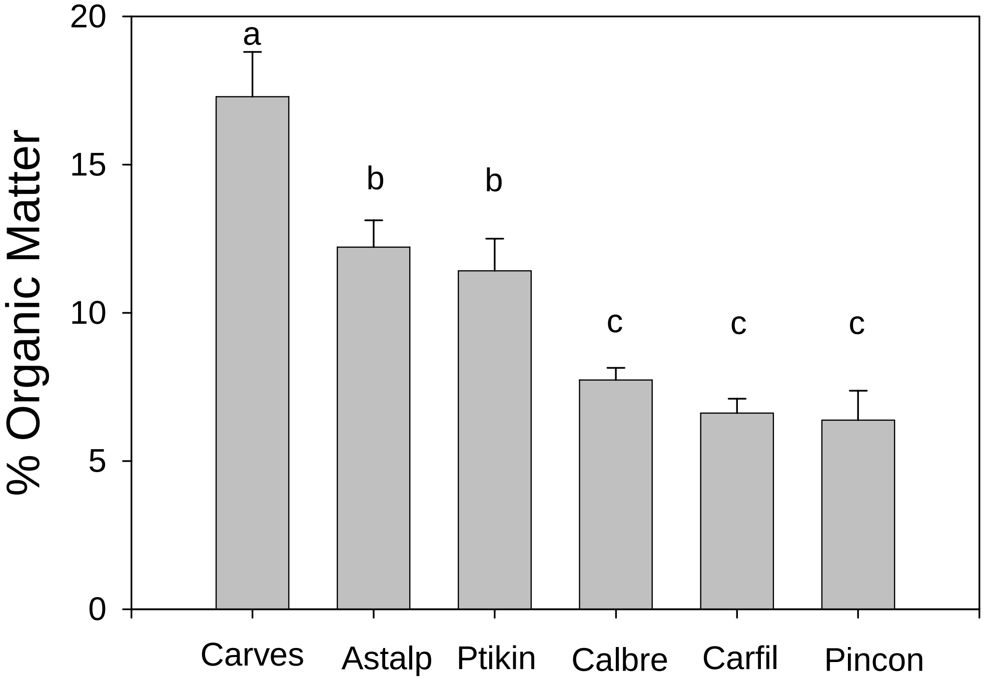

**Figure 3-15.** Mean % organic matter (+1se) for all soils for the six community types. Communities with similar letters have means that are not statistically significantly different.

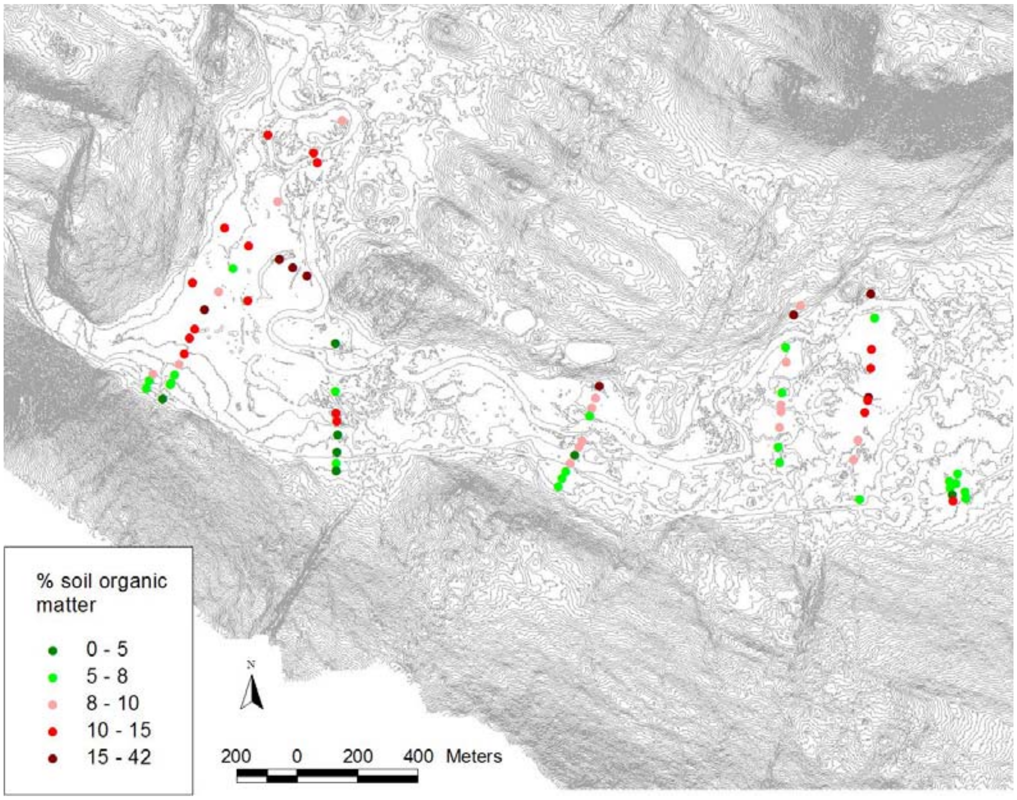

**Figure 3-16.** Map of the percent soil orgamic matter at the vegetation plots.

**Table 3-1**. Results of one-way ANOVA for % organic matter in the six communities.

| Source of variation | Sum Squares | DF | Mean Sq | F | p |
|---|---|---|---|---|---|
| Community | 804.28 | 5 | 160.86 | 22.40 | <0.0001 |
| Within cells | 466.82 | 65 | 7.18 | | |
| Total | 1271.10 | 70 | | | |

## *Total Plant Cover of Tuolumne Meadows Vegetation Types*

Late summer total plant cover is relatively high for all communities other than *Carex filifolia – Antennaria corymbosa* (Figure 3-17). There are statistically significant differences among community types (p < 0.0001) (Table 3-2), but most of the difference is due to the low plant cover in the *Carex filifolia – Antennaria corymbosa* community. This community has significantly different total cover than the *Aster alpigenus – Carex subnigricans*, *Ptilagrostis kingii – Polygonum bistortoides* and the *Calamagrostis breweri – Vaccinium caespitosum* communities, suggesting that high plant production, and cover occurs in most communities.

However, the vegetation of several communities is composed in large part of weakly rooted, and fine stemmed, or prostrate species, for example in the *Aster alpigenus – Carex subnigricans* and *Ptilagrostis kingii – Polygonum bistortoides* communities.

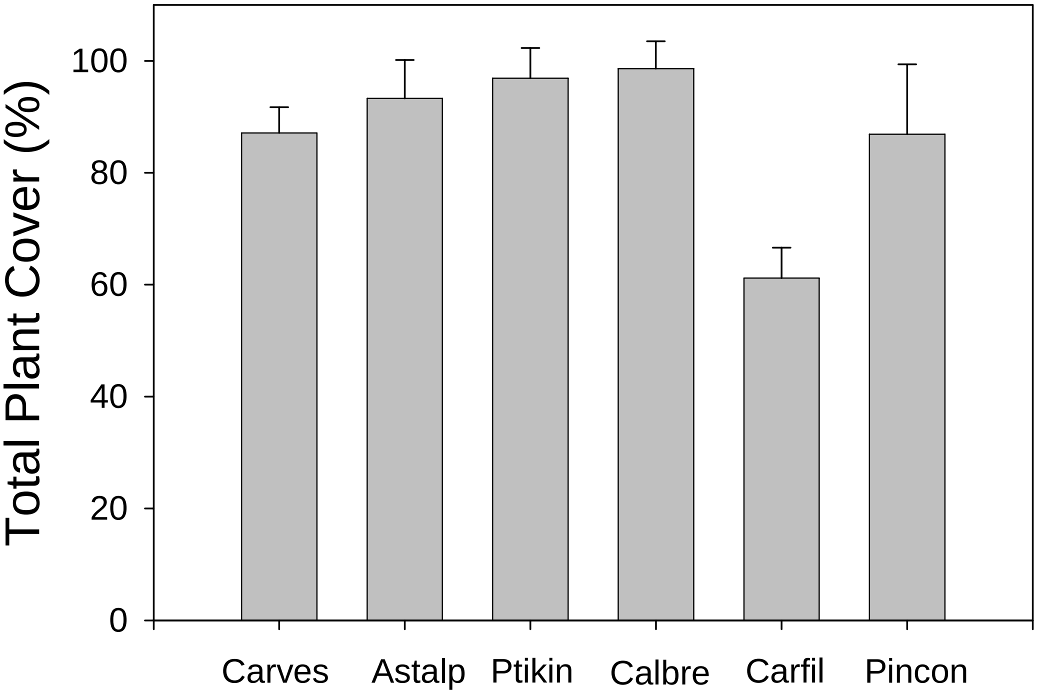

**Figure 3-17.** Mean % plant cover (+1se) for the six community types. The *Carex filifolia* (Carfil) community is statistically significantly different from all other communities.

**Table 3-2.** Results of one-way ANOVA for % plant cover in the six communities.

| Source of variation | Sum Squares | DF | Mean Sq | F | p |
|---|---|---|---|---|---|
| Community | 14289.708 | 5 | 2857.942 | 5.65 | 0.0002 |
| Within cells | 33374.670 | 66 | 505.677 | | |
| Total | 47664.378 | 71 | | | |

## *Bare Ground in Tuolumne Meadows Community Types*

There are large and statistically significant differences in mean bare ground among communities (p = 0.0003) (Table 3-3). The *Carex filifolia – Antennaria corymbosa* and *Pinus contorta – Carex rossii* have very high ground with nearly ½ of the soil being bare (Figure 3-18). The *Carex vesicaria – Salix eastwoodiae* community had the lowest bare ground, ~5%, due to the high cover of *Carex vesicaria* and the dense *Salix* stands. The remaining three communities have an average of 20-30% bare ground in late summer, a very high proportion considering the high water table and high soil organic matter present in stands of these communities.

The large area of bare soil suggests three ecologically important processes are likely occurring. First, abundant sites for *Pinus contorta* seedling establishment occur on these bare mineral soils that are relatively free of competition from other plants in all but the *Carex vesicaria – Salix eastwoodiae* community. Second, the bare areas are susceptible to rapid loss of soil organic matter due to low above and below ground organic matter inputs as well as accelerated decomposition and erosion rates. The lack of plant cover exposes the soil to insolation. Elevated soil temperature coupled with the moist conditions that occur at these sites can produce very high organic matter decomposition rates. The *Aster alpigenus – Carex subnigricans* community in particular may be experiencing unprecedented rates of organic matter loss. Third, the species present are mostly tufted, tap-rooted or annual plants, and no long-lived rhizomatous and clonal plants that could reduce the area of bare ground are present. Thus, processes that could cover the bare soil are operating very slowly, or not at all.

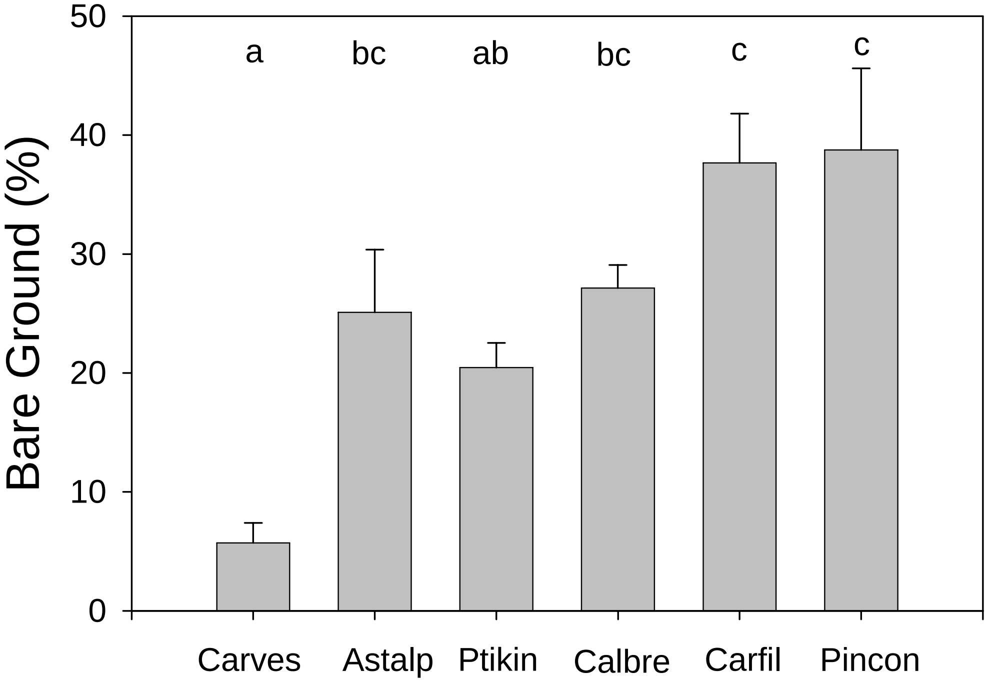

**Figure 3-18.** Mean % bare ground (+1se) for the six community types. Communities with similar letters have means that are not statistically significantly different.

**Table 3-3.** Results of one-way ANOVA for % bare ground in the six communities.

| Source of variation | Sum Squares | DF | Mean Sq | F | p |
|---|---|---|---|---|---|
| Community | 6486.526 | 5 | 1297.305 | 7.86 | <0.0001 |
| Within cells | 10892.461 | 66 | 165.037 | | |
| Total | 17378.986 | 71 | | | |

## *Influence of the Water Table Depth Gradient on Vegetation*

Depth of the water table below the ground surface varies by nearly 2 m across the study area on 3 July 2006. Water table depth is positively correlated (r = 0.551) with plot % soil organic matter as shown in Figure 3-19A. However, the water table depth gradient is not correlated with either the % cover of perennial grasses and sedges (Figure 3-19B) or the percent cover of dicotyledonous plants (Figure 3-19C). A water table 0 to 0.4 m below soil surface in early July should produce moist to wet soils, and support high cover of perennial grasses and sedges. However, in our plots the cover of these taxa varies from almost 0 to very high cover in this water table range, and long-lived sedges, rushes, and grasses are all but absent from most stands. *Carex subnigricans, Juncus balticus, Carex aquatilis* and *Eleocharis pauciflora* are present as widely scattered individual culms in many stands of the *Aster alpigenus – Carex subnigricans* and *Ptilagrostis kingii – Polygonum bistortoides* communities, and less so in the *Calamagrostis breweri – Vaccinium caespitosum* community. These species are all turf formers, that can create dense sods with thick rhizome mats and highly productive root systems that stabilize soils, limit pocket gopher and vole disturbance, and cover the soil with live foliage and litter.

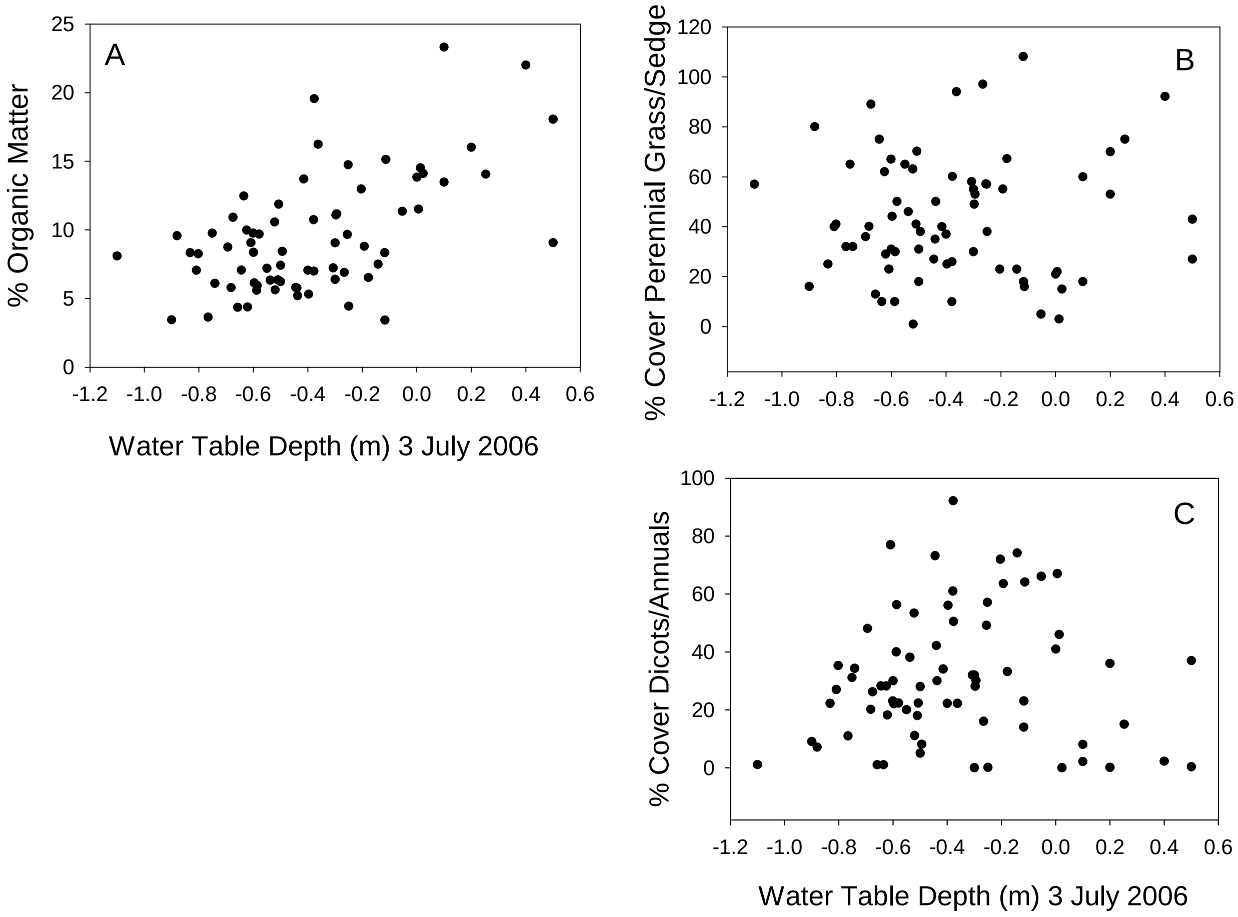

**Figure 3-19**. Scatterplots of 3 July 2006 water table depth vs. % soil organic matter, % cover of perennial grasses and sedges, and % cover of herbaceous and woody dicotyledons and annuals for all Tuolumne Meadows plots.

### *Influence of the Water Table Depth Gradient on Plant Species Distribution*

Most plant species occupy a distinct water table range along the 3 July 2006 water table gradient. *Muhlenbergia filiformis* has a peak in plots where the water table is from 0.2 to 0.6 m below the soil surface (Figure 3-20A). *Aster alpigenus* occurs mainly where the water table is close to the soil surface in early summer (Figure 3-20B). *Calamagrostis breweri* (Figure 3-20C) and *Ptilagrostis kingii* (Figure 3-20E) both occur where the water table is more than ~0.2 m below the soil surface in early summer, similar to *Muhlenbergia filiformis*. *Juncus balticus* and *Carex subnigricans* occupy broad niches where the water table is 0.8 to 0 m below the soil (Figure 3-20D). *Salix eastwoodiae* occurs in flooded sites, while *Pinus contorta* occupies a very broad range occurring in sites that are flooded and those with a water table -0.8 m below the ground (Figure 3-20F).

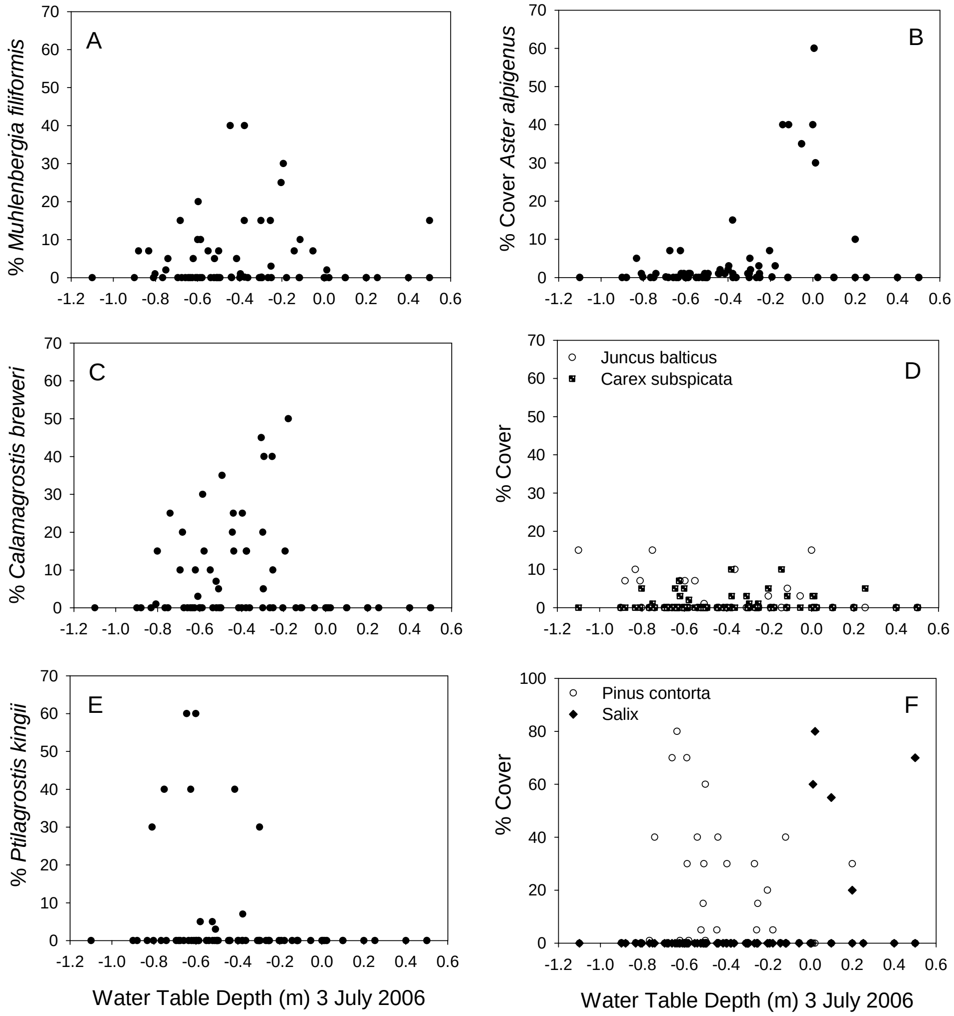

**Figure 3-20.** Water table depth on 3 July 2006 vs. (A) cover of *Muhlenbergia filiformis*, (B) *Aster alpigenus*, (C) *Calamagrostis breweri*, (D) *Juncus balticus* and *Carex subnigricans*, (E) *Ptilagrostis kingii*, (F) *Pinus contorta* and *Salix eastwoodiae*.

## *Tuolumne Meadows Vegetation Patterns*

Indirect ordination using DCA illustrates the overall structure of the vegetation data set. The ordination axes are in standard deviation (sd) units, and plots that are more than 3 sd (300 units on the ordination axes) apart have little or no species in common (Figure 3-21). Plots on the right side of the ordination space have little floristic similarity with plots in the center or left side of the ordination space. The x axis in ordination analyses typically represents a hydrologic gradient, with stands in the wettest locations plotted on one side (the right in our case), and those in drier sites plotted on the other side (the left). Plots from Soda Springs are at the top of the ordination diagram, distinct from all other plots with their high cover of wetland *Juncus* and *Carex* species. Plots dominated by *Ptilagrostis kingii* and *Calamagrostis breweri* are plotted near the center of the ordination diagram. Species which are quite rare in Tuolumne Meadows, including *Carex subnigricans* and *Carex aquatilis* are plotted in the largely empty section of the diagram between *Carex vesicaria* and *Muhlenbergia filiformis*. Meadows throughout the Sierra Nevada are dominated by these taxa, but such communities are not present in Tuolumne Meadows.

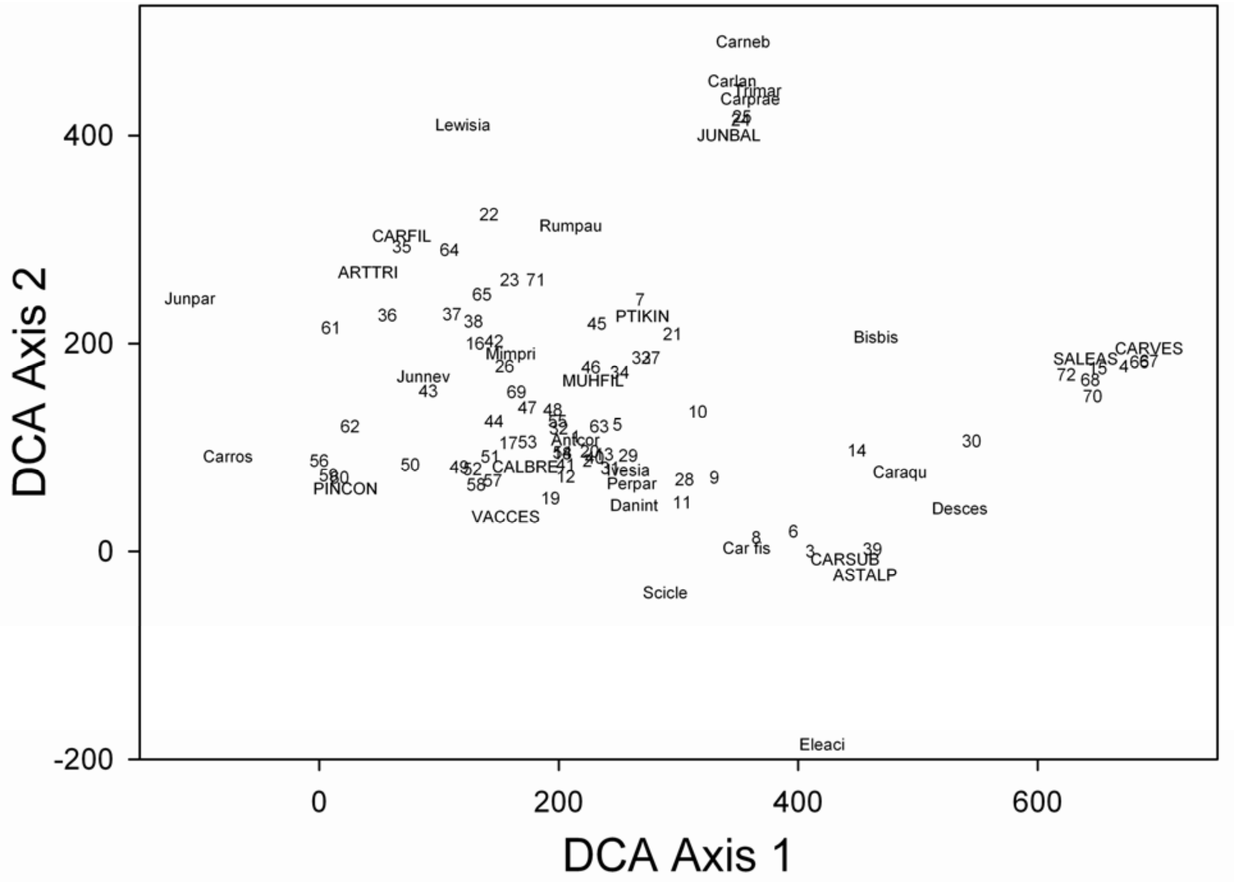

Figure 3-21. Detrended correspondence analysis of plots shown as numbers. Centroids of prominent species are also shown. Carneb=*Carex nebraskensis*, Carlan=*Carex lanuginosa*, Trimar=*Triglochin maritimum*, Carpra=*Carex praegracilis*, JUNBAL=*Juncus balticus*, CARVES=*Carex vesicaria,* SALEAS=*Salix eastwoodiae*, Desces=*Deschampsia cespitosa*, Caraqu=*Carex aquatilis*, Bisbib=*Polygonum bistortoides*, CARSUB=*Carex subnigricans*, ASTALP=*Aster alpigenus*, Eleaci=*Eleocharis acicularis*, Carfis=*Cares fissuricola*, Scicle=*Scirpus clementis*, Danint=*Danthonia intermedia*, Perpar=*Perideridia parishii*, VACCES=*Vaccinium caespitosum*, Ivesia=*Horkelia fusca*, Antcor=*Antennaria corymbosa*, CALBRE=*Calamagrostis breweri*, PINCON=*Pinus contorta*, Carros=*Carex rossii,* Junnev=*Juncus nevadensis*, Mimpri=*Mimulus primuloides*, PITKIN=*Ptilagrostis kingii*, ARTTRI=*Artemisia tridentata,* CARFIL=*Carex filifolia*, Junpar=*Juncus parryi*, Lewisia=cf. *L. nevadensis*, Rumpau=*Rumex pauciflora*.

# *Discussion*

## Vegetation Characteristics

The vegetation of Tuolumne Meadows and adjacent hillslopes supports six major plant communities, with distinctive dominant species, soils and hydrologic regimes. The meadow edge is forested with lodgepole pine, and most stands are classified into our *Pinus contorta – Carex rossii* community with an understory of upland plants such as *Carex rossii, Juncus parryi, Deschampsia elongata,* and *Ribes montigenum*. The water table in early summer can be close to, or even at the ground surface, as occurred along Transect 3 at well 43, but quickly dropped during the summer and soils dried. Organic matter content was low.

The *Carex filifolia – Antennaria corymbosa* community also occurred where the water table was well below the soil surface in summer, and bare ground and soil organic matter are both low. *Carex filifolia* is a strongly tufted plant that forms dense, organic rich sods and tussocks. However, in Tuolumne Meadows most *Carex filifolia* tussocks are degraded, and have eroding edges, and tussocks are separated from adjacent tussocks by gravel soils (Figure 3-22). This community is widespread in the Sierra Nevada on dry meadow edges, and it is reported that once the sod if broken much time is necessary to rebuild the turf (Ratliff 1982). The most likely cause of this degradation is historic livestock grazing. Ernst (1949) also reported heavy historical livestock grazing damage, from which there was very slow vegetation recovery.

**Figure 3-22.** Eroded tussocks of *Carex filifolia*, and bare gravel, in plot 22 along transect 4.

The *Calamagrostis breweri – Vaccinium caespitosum* community is the most widespread vegetation type on the meadow margins. It is highly disturbed by pocket gophers during the winter and summer, has large areas of bare soil, low soil organic matter content and most stands have abundant lodgepole pine seedlings. This community is characteristic and widespread in Sierra Nevada wet meadows, and this community type is described by Klikoff (1965) and Ratliff (1973, 1982, 1985) who called it the "shorthair" community. The high percent cover of *Muhlenbergia filiformis,* shown in Figure 3-23, indicates that little below ground root mass is present in this community, and low organic matter input to soils. This community is potentially losing organic matter.

**Figure 3-23.** *Calamagrostis breweri – Vaccinium caespitosum* community at plot 2. Note the scattered tufts of *Calamagrostis breweri*, and the very short stature *Muhlenbergia filiformis* filling the space between the tufts (right photo), and patches of *Antennaria corymbosum* (whitish ground cover).

The *Ptilagrostis kingii – Polygonum bistortoides* community type is considered by Ratliff (1982) to be a variant of the *Calamagrostis breweri – Vaccinium caespitosum* community, however it is worth distinguishing in Tuolumne Meadow at this time. It appears to occur more in the central portions of the meadow, for example in the middle of Transect 5 at wells 27-29. It is similar to the *Calamagrostis breweri – Vaccinium caespitosum* community in the abundance of *Muhlenbergia filiformis*, and large areas of bare soil however it has much higher soil organic matter, similar to the *Aster alpigenus – Carex subnigricans* community.

The *Aster alpigenus – Carex subnigricans* community is abundant in the wetter western portion of the study area. Ratliff (1982) described the *Gentian-Aster* community characterized by *Aster alpigenus* as a disturbance community created by excess grazing in the "shorthair" community. While this is one possibility for the origin of this community type, it may also have formed from the degradation of a community type that no longer exists in Tuolumne Meadow. For example, Ratliff (1982) described meadow communities dominated by *Carex nebraskensis, Eleocharis pauciflora,* and *Deschampsia cespitosa* as being common in the Sierra Nevada, but these communities are not present in Tuolumne Meadows. The stands investigated in Tuolumne Meadows had scattered culms of *Carex subnigricans* (Figure 3-24) and *Juncus balticus* and communities dominated by these species may have occurred in the past. The *Aster alpigenus – Carex subnigricans* community contains no long-lived plant species, and all litter is completely decomposed or consumed during the winter as can be seen in the bright green aspect of this community in spring and summer. In spring nearly 100% bare soil is present as shown in Figure 3-25.

**Figure 3-24.** *Aster alpigenus – Carex subnigricans* community at plot 3. Note the lack of litter on the ground in the upper left photo, as well as remnant pocket gopher and vole disturbance patches, and the homogenous single species dominance by *Aster alpigenus*. *Carex subnigricans* is shown in the top right photo. The bottom photo is the boundary between the *Aster alpigenus – Carex subnigricans* (lower) and *Ptilagrostis kingii – Polygonum bistortoides* (upper) communities along transect 1.

**Figure 3-25.** Early summer aspect in an *Aster alpigenus – Carex subnigricans* stand. Note the meadow vole nest at top, the numerous runways, and the large area of bare soil.

The *Carex vesicaria – Salix eastwoodiae* community occupies the wettest sites on the floodplain, typically seasonally flooded oxbows, and other basins. The two species for which the community is named may both be abundant. This community has very high plant production, high soil organic matter, and low bare soil. These species are highly resilient to annual flood disturbance and may recover quickly from other types of disturbance as well, due to favorable soil conditions and perennial below ground root stocks. Because they are flooded for long duration each year, they likely have very low small mammal populations.

## Historical and Modern Influences on the Vegetation

### *Mammal grazing/browsing*

Three mammals appear to be the principal herbivores of meadow vegetation in recent decades, pocket gophers (*Thomomys* cf. *monticola*), voles (*Microtus montanus*) and mule deer (*Odocoileus hemionus*). Voles likely inhabit the meadow all year, particularly in communities dominated by *Calamagrostis breweri* and *Ptilagrostis kingii*. However, during the winter, they live under the snow, making runways, nests, and consuming above and below ground vegetation in all communities (Figure 3-26). Pocket gophers live below the soil surface and move large amounts of soil to the ground surface (Figure 3-27). These two animals turn over a large proportion of the ground as seen in Figures 3-26 and 3-27. Most areas with vole and pocket gopher populations were flooded during the spring of 2006, and animals in the meadows likely drowned. However, refugia are present on high remnant terraces in the western meadow, and on the meadow edges, and enough animals would have survived to re-colonize the meadow during winter.

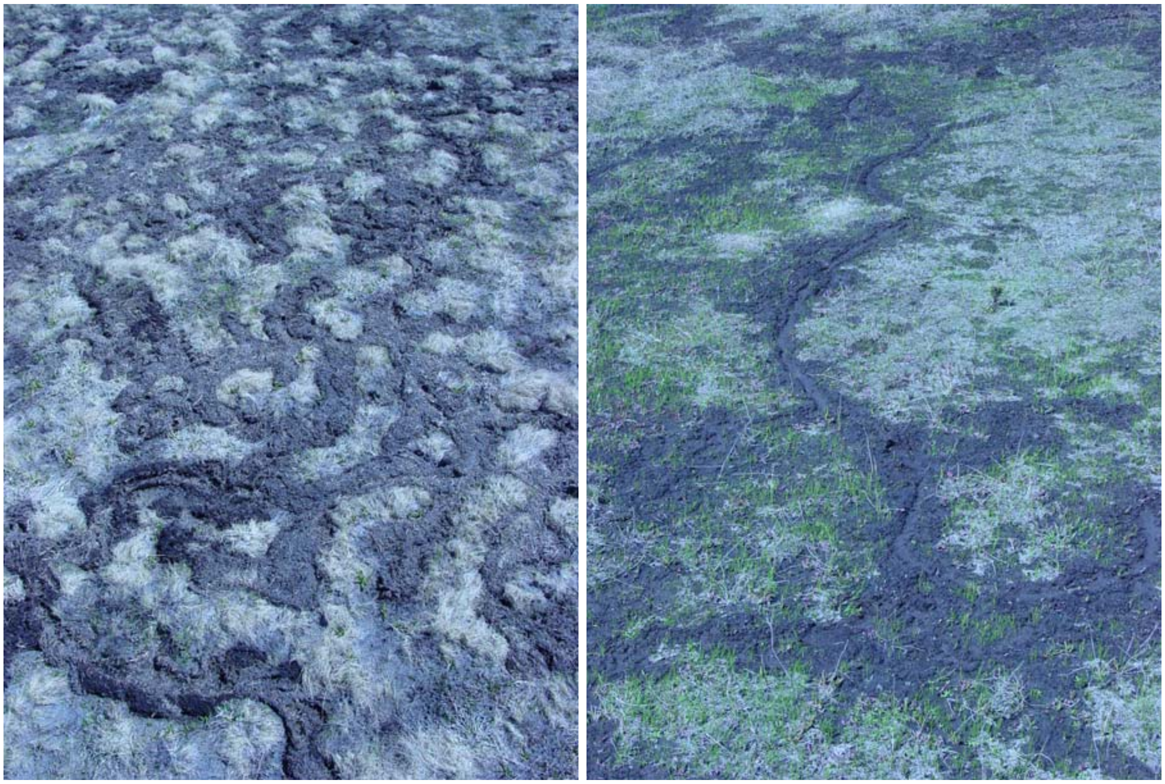

**Figure 3-26.** Vole runways and litter piles and pocket gopher diggings in early summer.

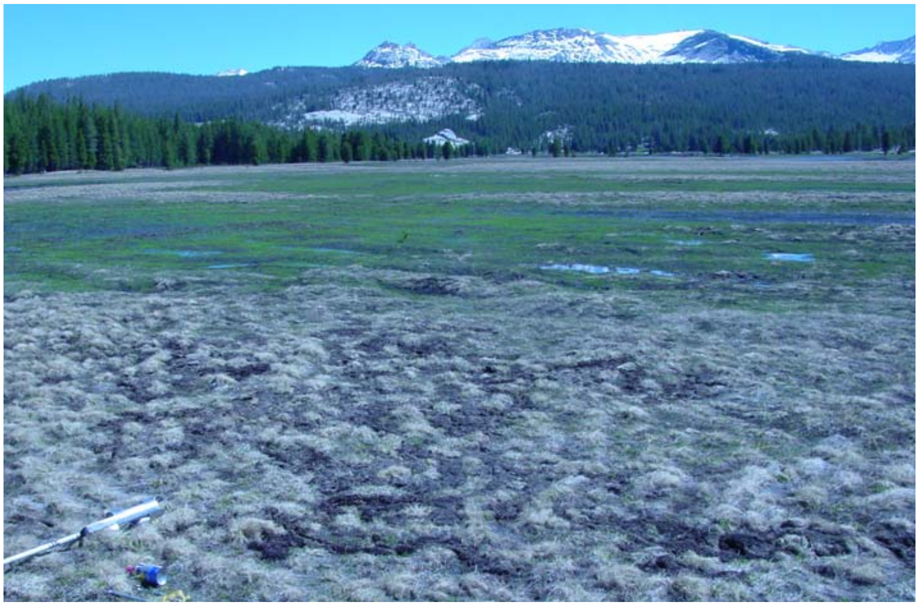

**Figure 3-27.** Pocket gopher excavated soil (foreground) in early summer 2006.

Deer are summer residents in Tuolumne Meadows and can be spotted at almost any time. Although a diet study was not performed, the deer feed heavily on *Salix eastwoodiae*, which are heavily browsed (Figures 3-28, 3-29). Browsing suppresses the plant height to ~0.5 m, when it should reach 1-2 m tall, and limits the presence of willow stands which would be important nesting habitat for passerine birds. It is possible that heavy browsing of seedlings also limits willow recruitment on river bars, which presently are bare, moist sand and gravel, a normally ideal establishment environment for willow.

**Figure 3-28**. Heavily cropped *Salix eastwoodiae* in former river channel, height ~0.5 m.

**Figure 3-29.** Close up of willows illustrating that every stem is browsed.

The historic photo of the Tuolumne River shown in Figure 3-30 indicates that abundant willow stands were present along the river in 1867.

**Figure 3-30.** Ground photo looking southwest from the area near Soda Springs showing *Salix* dominated vegetation along the Tuolumne River, negative 2447 in Yosemite archives, 1867.

Tuolumne River banks are eroding on outside meanders, and the channel likely is widening. Channel widening will produce a shallower channel with a lower river stage for any given flow volume. The two photos in Figure 3-31 contrast a typical river bank lacking willows (left panel) with one of the few areas with willows (right panel). Point bars support few willow seedlings (Figure 3-32), and are largely bare. Thus, as banks erode and the channel widens the lack of willow establishment on bars will contribute to the net river channel widening. This will result in a drop in river stage and a concurrent drop in the water table associated with the river.

**Figure 3-31**. Eroding (left) vs. stable (right) river banks. Left photo is east of well 15, while the right photo is near well 48.

**Figure 3-32**. Point bar east of well 15, illustrating the near lack of willow recruitment, and the rapidly eroding outside bank.

### *Influence of Historic Grazing*

Several lines of evidence indicate that livestock grazing in the late 1800s has had lasting impacts on the vegetation of Tuolumne Meadow. First, and most broadly, the main vegetation types in Tuolumne Meadows, including the *Aster alpigenus – Carex subnigricans, Calamagrostis breweri – Vaccinium caespitosum,* and *Carex filifolia – Antennaria corymbosa* communities all have much higher percent bare soil, and lower cover of long-lived clonal and densely tufted plants than would be expected for an areas with an intact wet meadow hydrologic regime and stands with high soil organic matter. In the drier parts of the meadow historic trampling impacts are evidenced by *Carex filifolia* tussocks that are severely degraded and continue to erode. In low lying, flat meadow expanses that we would expect to support a dense cover of rhizomatous monocotyledonous species the vegetation is typically dominated by *Aster alpigenus*, a tap-rooted plant that doesn't form sods. Intense grazing and hoof punching can destroy the underground network of rhizomes that supports sod forming plants, and their reestablishment is an extremely slow process. This was previously noted by Ernst (1949).

Once a rhizomatous sod layer is broken apart, the loose, bare ground is susceptible to erosion, bioturbation by rodents, and invasion by non-meadow plants. Percent bare soil in all four communities is very high in early summer, due to intense pocket gopher and vole activity during the winter and even with high soil water availability during the summer, bare soil remains high. Shallow rooted annuals such as *Muhlenbergia filiformis*, *Mimulus primuloides* and *Eleocharis acicularis* dominate these disturbance patches, and lodgepole pine seedlings are common.

The high organic content of these soils and the low below ground plant production suggests that the existing vegetation could not have formed these soils. Thus, the modern vegetation is likely the product of intensive historic disturbances from which it has not recovered. The only recent large scale disturbance was grazing by cattle and sheep from 1860's to 1891. Numerous reports, including those of John Muir (1911), and Ernst (1949) indicate that high intensity grazing occurred for many years and Yosemite meadow vegetation was highly impacted. At this time there was no limit to the size of sheep herds that entered the Sierra Nevada, or the length of time that they could utilize a specific area. Likely millions of sheep grazed Sierran meadows (Beesley 1996). Some observers indicated that during this period many native perennial plants were replaced by annual plants due to this unregulated grazing, and turfs were turned to gravel and little forage was available to packstock (Beesley 1996, Kinney 1996).

Because many clonal sedges, rushes and grasses live for hundreds, or even thousands of years, with infrequent establishment of new genets (individual plants), massive disturbance may have produced conditions from which the vegetation has not recovered. The low density of belowground roots and rhizomes allow pocket gophers and voles to maintain these communities in a perpetual state of disturbance, and may have created an alternative stable state (Suding et al. 2004). Lodgepole pines easily invade the large areas of bare and moist mineral soil on which there is little or no biotic competition.

The most quantitative study to address the impacts of historic grazing was Dull (1999), who analyzed pollen in soil cores collected from meadows on the Kern Plateau in the southern Sierra Nevada. He dated soil layers using $^{210}$Pb and found that in the middle 19th century there was a rather abrupt reduction in *Salix* and increase in *Artemisia* and *Cyperaceae* pollen. The decrease in *Salix* likely was due to the loss of willow stands along streams and wetlands. The increase in *Artemisia* may indicate the denudation of soils, and an increase in sagebrush. There was also a near complete loss of *Riccia* a genus of thalloid liverworts that are common in ponds, and seasonally saturated to flooded sites. The liverworts are easily damaged by trampling.

It is possible that many of the issues discussed in this report resulted from this relatively brief but intensive period of livestock grazing from which meadow vegetation and soils have not recovered. Intact perennial sods of meadow vegetation are resilient to minor disturbances such as fire and light grazing, as long as the structure of the rhizome network remains intact. Once that network is destroyed, erosion will occur, upland plants can become established, and the natural reestablishment of perennial meadow vegetation may take centuries. The damage may be perpetuated by constant vole and pocket gopher activity, willow browsing by deer which limits seedling establishment, and intensive needle ice formation in the bare soils which uproots slow growing plants that are establishing (Figure 3-33). The meadow may be locked in an alternative state of vegetation composition, and soil forming processes. Climate change also is producing warmer and longer summers, with drier meadow soils, and it may be less likely that meadow plants could reestablish naturally. It is possible that the only potential approach to restore the natural vegetation of Tuolumne Meadow will be human aided restoration approaches, including seeding and planting of native sedge, grass and rushes, deer exclusion, and possibly experimental removal of small mammals from study plots.

**Figure 3-33**. Needle ice formation in bare soil in Tuolumne Meadows, September 2006. Needles are ~5 cm in length.

## *Recommendations for Future Research*

Field and laboratory experiments are needed to determine the germination and establish niche of lodgepole pine on soils with different hydrologic regimes, meaning differing flood frequencies, and summer water table depth. The role of bare soil on tree establishment must also be determined. These results will help clarify whether wet conditions preclude the invasion of lodgepole pine into the meadow, and can be used to identify portions of the meadow where this species could and could not establish under modern vegetation, soil and hydrologic conditions.

Field and laboratory analyses of soils to analyze not only pollen, but soil seedbank, macrofossils and phytoliths, can be used to determine which species were most common when the highly organic meadow soils were formed. The work of Dull (1999) includes techniques that can help provide information on the history of Tuolumne Meadows vegetation. If it is determined that vegetation changes occurred in the middle to late 1800’s, then restoration techniques could be developed to restore the vegetation composition, below ground biomass, soil forming processes, and stability of the pre-historic meadow vegetation.

The condition of Tuolumne River banks is another huge concern as the river appears to be widening. Banks are eroding as they have little or no woody vegetation, and although point bars are forming, they are not covered by willows, and where willows occur they are largely cropped and short. Most of the willows present in the study area are precocious, meaning that flowers appear on last years stems, in the spring before leaf and twig growth occurs. However, if last years stems are browsed by deer, seed production may be severely limited. A detailed study of willows is necessary to understand what factors limit willow establishment and persistence in the study area.

# Chapter 4: **Tree-Ring Analyses**

By

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# *INTRODUCTION*

The placement of Tioga Road along the south margin of Tuolumne Meadows may have altered environmental conditions and subsequently changed lodgepole pine (*Pinus contorta* var. *murrayana* (Grev. & Balf.) Engelm.) dynamics. Possible changes in lodgepole pine recruitment at Tuolumne Meadows following the 1937 completion of Tioga Road (HAER) are of particular interest because trees encroaching into the meadow have been subject to managed removal since at least 1933 (National Park Service, 1933; Cunha 1992, and references therein). Managed tree removal can be used to change or maintain the visual appearance of the meadow and may potentially serve to offset tree encroachment that would not have occurred in the absence of Tioga Road. It is also possible that Tioga Road factors are not related to tree encroachment, and that managed tree removal has acted to disrupt natural processes that promote episodic tree establishment in the meadow. While tree encroachment in Tuolumne Meadows is an obvious expression of changing stand conditions, less obvious changes in stand structure or tree growth may also have occurred in response to road construction or other anthropogenic disturbances.

Young trees that encroach into a meadow are commonly referred to as meadow invasion trees because they extend into the meadow beyond the limit of a relatively distinct and apparently older forest edge (see Fig. 4-4). Meadow invasion patterns in the western U.S. have been linked to climate variability (Franklin et al., 1971; Helms, 1987; Jakubos and Romme, 1993; Woodward et al., 1995; Rochefort and Peterson, 1996; Dyer and Moffett, 1999; Millar et al., 2004) as well as to fire frequency and domestic grazing disturbance (Vale, 1981a; Vale, 1981b; Butler, 1986; Magee and Antos, 1992; Miller and Halpern, 1998; Hadley, 1999; Norman, 2002). In Yosemite National Park, both climate (Helms, 1987; Millar et al., 2004) and climate-disturbance interactions (Vale, 1981a) have been proposed to explain lodgepole pine meadow invasion patterns. Repeat photo evidence at Tuolumne Meadows (Vale, 1987; Vale and Vale, 1994) indicates changes in meadow invasion and forest patterns during the 20th century. Notably, a relationship between Tioga Road construction and lodgepole pine meadow invasion at Tuolumne Meadows has been proposed (Cunha, 1992). This finding is based largely on the proximity of meadow invasion trees to anthropogenic disturbance features, and on the large number of meadow invasion trees that post-date the construction of Tioga Road.

The construction of a road or other linear opening in a forest results in an edge effect where trees growing adjacent to the road are impacted by changes in light availability, soil moisture, and other environmental factors (Luken et al., 1991; Chen et al., 1992; Chen et al., 1995; Chen et al., 1996; Chen and Franklin, 1990; Burke and Nol, 1998). Increases in radial growth (Kramer, 1958; Landbeck, 1965; Pfister, 1969), basal area (Bucht, 1977; Bucht and Elfving, 1977; McCreary and Perry, 1983; Isomaki and Niemisto, 1990; Chen et al., 1992; Bowering et al., 2006), crown size (Oliver and Larsen, 1996), and root growth (Urban et al., 1994) have been reported for trees growing immediately along roadways and linear openings. An investigation of lodgepole pine growth response to road construction (Bowering et al., 2006) indicates that increases in basal area occur within 5 m of roadway edges, and that this growth response is greatest during the 6- to 10-year period following road construction.

Dendrochronological techniques can be used to reconstruct the timing of tree recruitment episodes, the timing and location of disturbance events, and the relationships between climate and tree growth (Fritts, 1976). These themes were used to organize the analysis of lodgepole pine tree-ring patterns at Tuolumne Meadows. Specifically, tree-ring samples were collected at Tuolumne Meadows and examined for evidence of anthropogenic disturbance impacts on tree recruitment and growth. Particular attention was given to the potential impact of Tioga Road construction on tree growth and meadow invasion.

## *METHODS*

### Field Sampling

Field reconnaissance and tree-ring sampling were conducted at Tuolumne Meadows during July 3-27, 2006. Five research components were selected to evaluate the response of lodgepole pine trees to anthropogenic disturbance factors and climate: 1) roadside trees, 2) meadow seedlings, 3) tree thickets, 4) fire history, and 5) climate-growth relationships.

For the roadside tree research component, 29 mature lodgepole pine trees were sampled along the shoulders of Tioga Road between Pothole Dome and Tuolumne Meadows

Campground (Fig. 4-1). The oldest possible trees were selected based on old age characteristics (Fritts, 1976), particularly the presence and condition of crown deadwood and the size of secondary branches in relation to the main stem (Fig. 4-2). A single increment core was extracted from each tree between 0.9 m and 1.2 m above the ground surface. Fourteen of the 29 trees were arranged in seven tree pairs, with each pair representing trees directly across from each other on opposite shoulders of Tioga Road. Topographic measurements were made at the tree pair locations using a line level. The roadside tree collection consists of 29 increment core samples from 29 live trees.

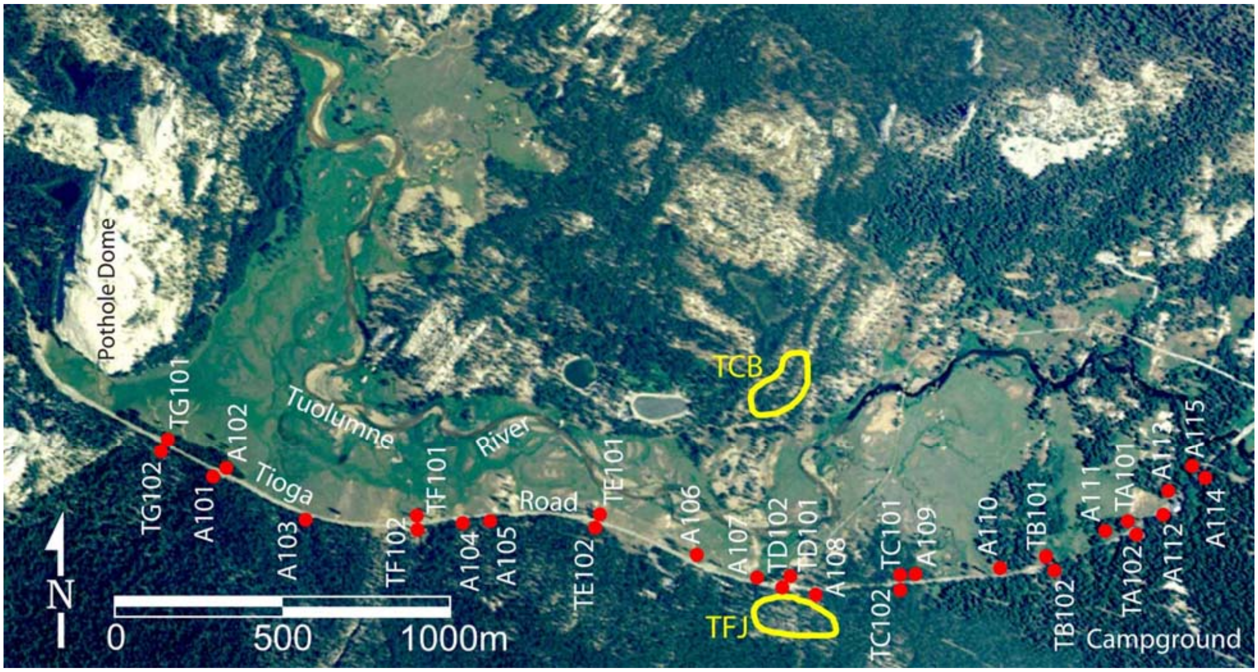


**Figure 4-1.** Roadside tree sampling points. TFJ and TCB are the location of tree-ring chronology sites (described below).

**Figure 4-2.** Roadside tree A104. This lodgepole pine is over 400 years old and has a DBH of 118 cm.

For the meadow seedling research component, 32 sampling points were established in Tuolumne Meadows between Pothole Dome and Tuolumne Meadows Campground (Fig. 4-3; Fig. 4-4). Lodgepole pine trees at these locations range from approximately 0.1 m to 3.0 m in height, with an accompanying diameter range of 0.5 cm to 13 cm. Trees greater than 15 cm in diameter were used to define the meadow-forest edge. The majority of the meadow seedling sampling points were sited away from the meadow-forest edge and toward the open meadow. At each sampling point a plot center was established, and whorl counts, height and diameter measurements, and subsurface stem examinations were conducted on ten randomly selected trees within 10m of plot center. Five of the trees were used to make initial inspections of root crown locations and tree age, the other five tree were used to collect a formal set of tree-ring samples. Because the meadow was slated for managed tree removal during summer 2006, destructive sampling techniques were employed. For trees greater than approximately 1.3 cm in diameter, an excavation measuring 2 cm to 10 cm wide by 10 cm to 25 cm deep was needed to examine subsurface stem features. Trees less than approximately 1.3 cm in diameter could often be pulled directly from the ground; this technique was most successful in wet soil conditions. Excavated soil and duff were replaced following sampling activities.

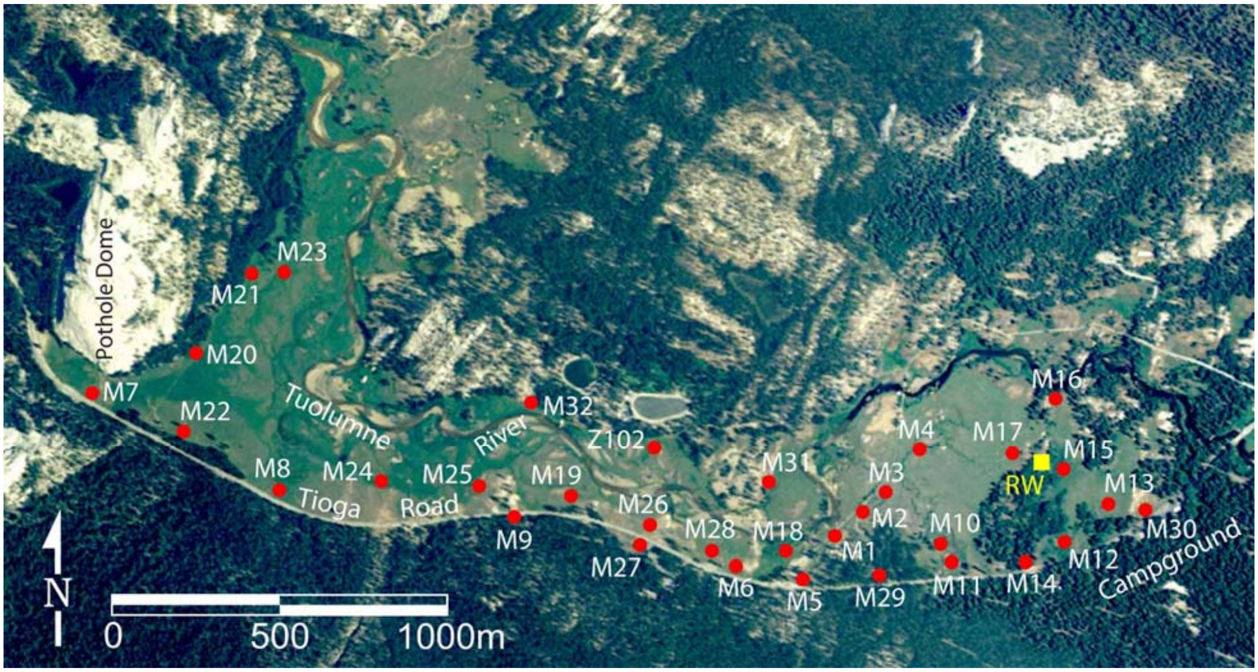


**Figure 4-3.** Meadow seedling sampling points. RW indicates the location of trees analyzed by Millar et al. (2004).

**Figure 4-4.** Meadow seedlings at sampling point M20. The standing flag is 1 m tall.

For the five initial inspection trees, root and whorl positions were noted in relation to the ground surface and transverse saw cuts were made on the main stem at apparent root crown position, ground surface, and 15.25 cm above ground surface. The transverse stem surfaces were sliced with a razor blade to facilitate preliminary ring counts. Root crowns on the inspection trees were most often located between 1.3 cm and 5.1 cm below the existing level of duff or herbaceous vegetation. In some cases one or more live or dead branch whorls were concealed within the duff or herbaceous vegetation. Some dead whorls were only evidenced by small stem protrusions or a stem thickening. Preliminary information from the five inspection trees was used to help assess root crown locations on five additional trees at each sampling point. Three cross-section samples were cut from each of the five additional trees: at apparent root crown, 15.25 cm above root crown, and 30.50 cm above root crown. Root crown positions were identified by direct examination of roots, branch whorls, and whorl remnants. The meadow seedling tree-ring collection consists of 480 small cross-sections from 160 live trees at 32 sampling points. Six of the sampling points (M5, M9, M14, M27, M29, M30; Fig. 4-3) are located along the immediate edge of Tioga Road pavement where narrow lines of seedlings grow parallel to the roadway (Fig. 4-5).

**Figure 4-5.** Narrow line of lodgepole pine seedlings at sampling point M5. The standing flag is 1 m tall.

Due to the possibility of tree recruitment episodes associated with flood disturbances, meadow seedlings were not collected in close proximity to Tuolumne River. To the north of Tuolumne River few lodgepole pine seedlings were found in the meadow except for several clusters of small or stunted trees growing in well-defined gravel accumulations (Fig. 4-6). Because the process of formation of these accumulations is unknown, only a single deadwood sample from a small tree (sample Z102, Fig. 4-3) was collected at this type environment.

**Figure 4-6.** Lodgepole pine seedlings at sampling point Z102. The seedlings are growing in zones of gravel accumulation.

For the tree thicket research component, four sampling points were established along the south shoulder of Tioga Road (Fig. 4-7). Lodgepole pine trees grow at these locations in dense thickets that extend parallel to Tioga Road (Fig. 4-8). The thicket trees range in diameter from 1.0 cm to 29.5 cm and are relatively small compared to trees growing upslope of Tuolumne Meadows. The four tree thicket sampling points appear to be located in areas of seasonal ponding associated with Tioga Road grading. As with the meadow seedling research component, five trees were initially examined at each tree thicket sampling point. Following this examination, individual tree-ring samples were collected at the apparent root crowns of 12 additional trees. Root crown positions were identified by direct examination of roots, branch whorls, and whorl remnants. Cross-section samples were collected from trees less than approximately 10 cm in diameter; increment core samples were collected from trees greater than approximately 10 cm in diameter. The tree thicket tree-ring collection consists 32 small cross-sections and 16 increment core samples from 48 live trees.

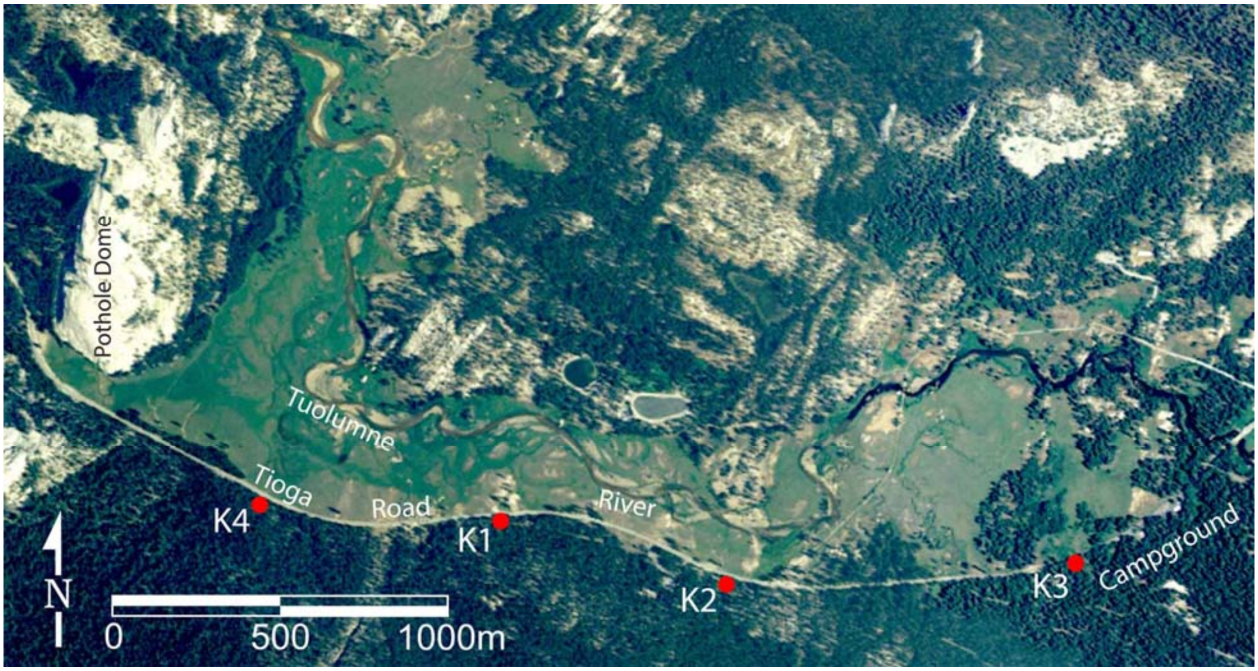


**Figure 4-7.** Tree thicket sampling points.

**Figure 4-8.** Lodgepole pine thicket at sampling point K1. The north-south width of the thicket is 23 m. The south shoulder of Tioga Road can be seen in the foreground.

Eighty-nine fire-scarred trees were identified during preliminary field reconnaissance in the forested region upslope of the south edge of Tuolumne Meadows; some of these trees are located at the immediate edge of the open meadow (Fig. 4-9). Few fire-scarred trees were identified along or upslope of the north edge of Tuolumne Meadows. For the fire history research component, 12 fire-scarred lodgepole pine trees were sampled in the vicinity of the south edge of Tuolumne Meadows between Pothole Dome and Tuolumne Meadows Campground (Fig. 4-10). Only trees with charcoal evidence and obvious fire-scar margins were sampled (McBride, 1983). Three fire-scarred trees were accessible sampling because they had been previously cut down (Fig. 4-11); five fallen snags containing fire-scars were also sampled. Cross-section samples were extracted from the cut stumps and dead trees using a set of hand saws and chisels. Additional fire-scar samples were collected from three live trees and one dead standing snag. These four trees were sampled by extracting multiple increment cores at suspected fire-scar margins. The fire history tree-ring collection consists of eight cross-section samples and 12 increment core samples from 12 trees.

**Figure 4-9.** Fire-scarred tree at edge of Tuolumne Meadows. Note the multiple fire-scar margins. This tree is located near sampling point M22 (Figure 4-3).

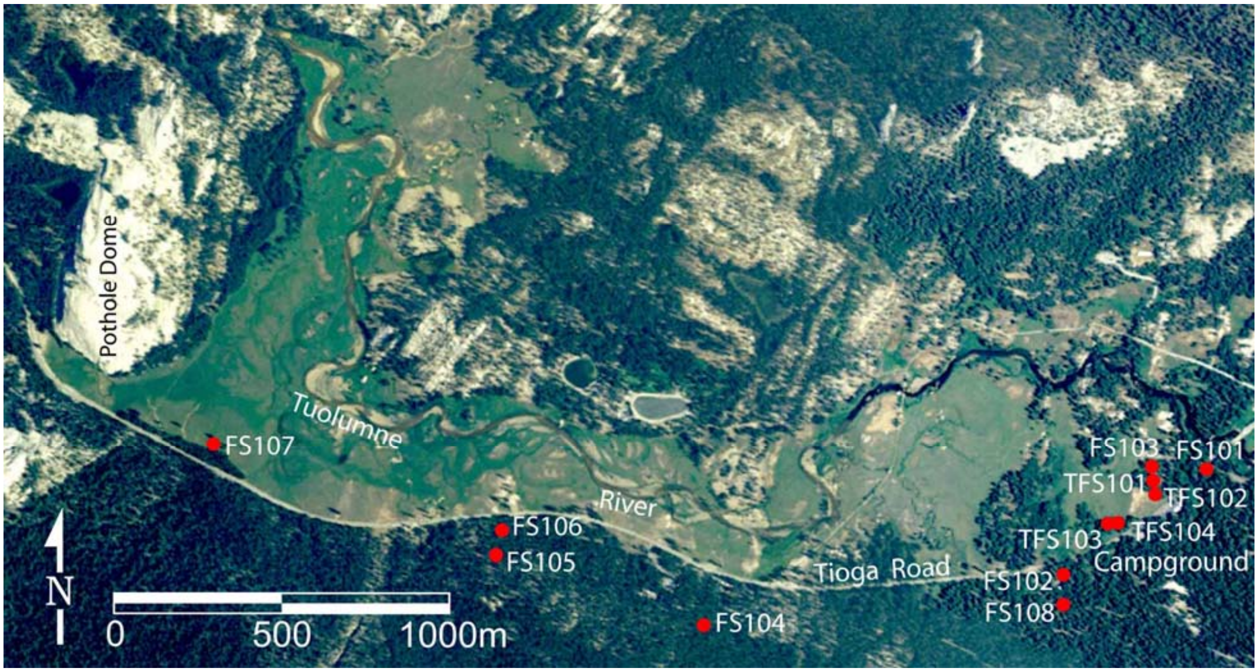


**Figure 4-10.** Lodgepole pine fire-scar sampling points.

**Figure 4-11.** Fire-scar tree FS102 at Tuolumne Meadows Campground. The stump diameter is 104 cm.

For the climate-growth research component, lodgepole pine tree-ring samples were collected from 25 trees on the south side of Tuolumne Meadows and 25 trees on the north side of Tuolumne Meadows. These collection sites are referred to as Fourth of July Hill (TFJ) and Climbing Bear (TCB), respectively (Fig. 4-1). The TFJ site (Fig. 4-12) is located approximately 29 m to 84 m south of, and 7 m to 15 m above Tioga Road. The TCB site is located approximately 53 m to 198 m north of, and 6 m to 19 m above the unpaved utility road along the north edge of Tuolumne Meadows. The two sites were selected for their close proximity to Tuolumne Meadows and their lack of obvious human disturbance. At each site, the oldest possible trees were sampled to facilitate the assembly of long reference chronologies. A single increment core was extracted from each tree between 0.9 m and 1.2 m above the ground surface. The climate-growth tree-ring collection consists of 50 increment core samples from 50 live trees.

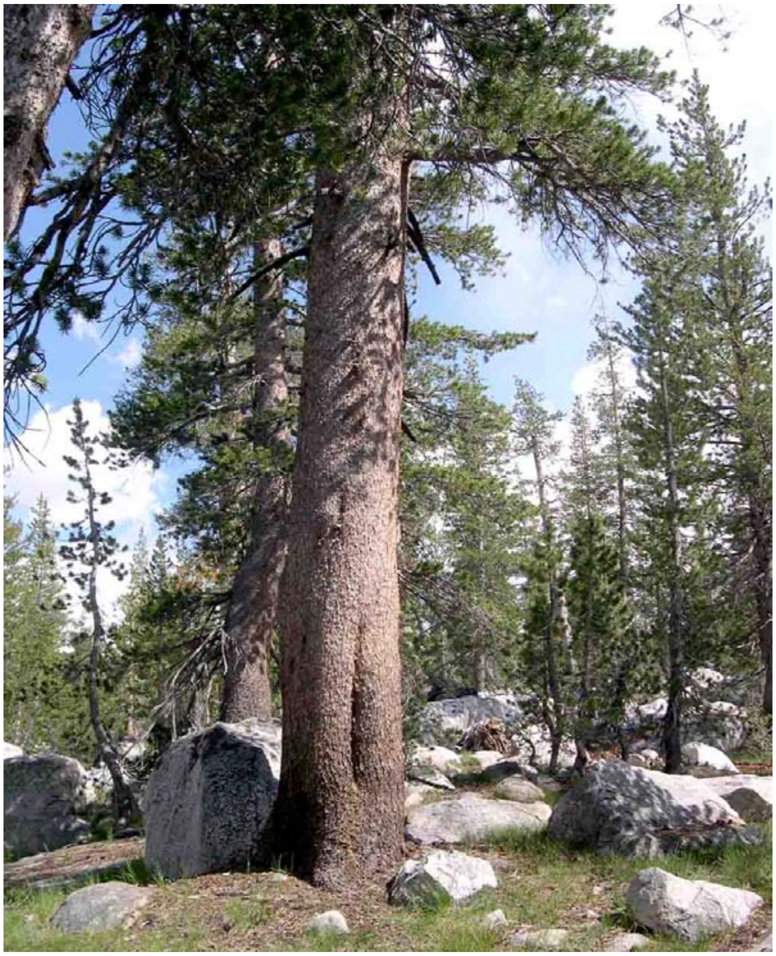


**Figure 4-12.** Reference chronology tree TFJ116. The DBH of this lodgepole pine is 72 cm.

## Cross-Dating and Chronology Development

Tree-ring samples were processed using standard techniques (Stokes and Smiley, 1968) and finely surfaced to clarify cell and ring structure. The meadow seedling and tree thicket samples required 45 days of air-drying to allow for resin hardening prior to surfacing. For the TFJ and TCB collection sites, and for the roadside tree and fire-scar samples, exact calendar year dating was established by measuring each tree-ring series to the nearest 0.001 mm and subjecting the samples and measurement series to a set of dendrochronological techniques. Direct sample comparisons, skeleton plot matching (Stokes and Smiley, 1968; Millar et al., 2006), and correlation patterns (Holmes et al., 1986; Yamaguchi and Allen, 1992; Yamaguchi 1994) were used to assess cross-dating quality. Samples having ambiguous cross-dating features or unresolved locally absent rings were excluded from chronology development. Tree-ring chronologies were compiled by removing age-related trend from the data by fitting a negative exponential curve or straight line of zero or negative slope to the measurement series. Dimensionless indices resulting from the ratio of actual to modeled growth were combined into standard chronologies as a mean value function of bi-weight robust means (Holmes et al., 1986). Regional curve standardization techniques (Briffa et al., 1992) were considered but not employed because the majority of the tree-ring samples lack accurate pith date estimates. Tree-ring samples having the highest cross-dating correlations in the TFJ and TCB collections were combined into a composite record that was subsequently used to resolve cross-dating in samples with marginal cross-dating patterns.

Precise cross-dating of a tree-ring sample requires an adequate number of annual rings in order to establish a pattern match with a reference chronology. For lodgepole pine in Yosemite National Park, a minimum of approximately 50-70 rings are required for successful cross-dating (ITRDB, 2006). Because the meadow seedling and tree thicket samples typically contain fewer than approximately 15 rings and 60 rings respectively, conventional cross-dating techniques could not be applied. Instead, these samples were dated by simple ring counts that were tentatively verified using low-growth marker rings, light-latewood rings and frost-rings (King and Graumlich, 1998; Millar et al., 2004). The use of ring count techniques may result in dating errors when false or locally absent rings are present. In the TFJ and TCB tree-ring collections, cross-dating results indicate that there are no false rings, and that 1-2 locally absent rings occur in approximately 12% of trees during the period 1940-2006. Because of this, ring counts of the meadow seedling and tree thicket samples may underestimate tree age by 1-2 years in some samples.

## Meadow Seedling and Tree Thicket Growth Patterns

The recruitment patterns of the meadow seedlings and tree thickets were compared to the timing of meadow invasion at sites in and adjacent to Yosemite National Park (Vale, 1981a; Helms, 1987; Cunha, 1992; Millar et al., 2004). The recruitment patterns were also compared to temperature and precipitation records at Yosemite Valley, PRISM climate records at Tuolumne Meadows, and records of the Pacific Decadal Oscillation and the Palmer Drought Severity Index. The Pacific Decadal Oscillation (PDO) is an El-Nino-like pattern of sea surface temperature variation that impacts climate on decadal time scales. The Palmer Drought Severity Index (PDSI) is a measure of long-term soil moisture conditions. Temperature and precipitation records for Yosemite Park Headquarters were obtained from the United States Historical Climatology Network (http://cdiac.ornl.gov/epubs/ndp/ushcn/newushcn.html) and the California Climate Data Archive (http://www.calclim.dri.edu/). Pacific Decadal Oscillation Indices (Mantua et al., 1997) were downloaded from http://jisao.washington.edu/pdo/PDO.latest. Palmer Drought Severity Indices (Palmer, 1965) for California Division 7 were obtained from the NOAA Earth System Research Laboratory (http://www.cdc.noaa.gov/PublicData/). PRISM data were generated using the Parameter-Elevation Regressions on Independent Slopes Model (Daly et al., 1994). Monthly data for the PRISM analysis were downloaded (http://www.ocs.orst.edu/prism/) and spatially averaged for the Tuolumne Basin for each month. The Tuolumne Basin was defined as the upstream area of the Tuolumne River from its junction with Conness Creek, just downstream of Tuolumne Falls. Significant differences in mean growth rate between the thicket trees and meadow invasion and mature tree set (roadside and TFJ collections) were evaluated with a *t* test.

## Climate-Growth Relationships

The TFJ standard chronology was selected to examine climate-growth relationships because this tree-ring site is located closer to Tioga Road than the TCB site (Fig. 4-1). Relationships between monthly climate variables and the TFJ standard chronology were explored using correlation functions (Fritts, 1976; Blasing et al., 1984). This approach generates correlation coefficients based on a comparison of tree-ring growth in the current year to a set of monthly climate variables extending from the previous year to the current year. Correlation functions provide for a preliminary examination of climate-growth relationships, although they may contain patterns associated with climate variable intercorrelations. Correlation functions were calculated for temperature and precipitation records at Yosemite Valley and Tuolumne Meadows.

## *RESULTS and DISCUSSION*

### Roadside Tree Growth

Tree-ring chronologies assembled for the TFJ collection site and for trees growing immediately along the shoulders of Tioga Road demonstrate a close correspondence (Fig. 4-13). The most pronounced difference in these records occurred during the ten year period from 1939 to 1948 when roadside tree growth increased relative to TFJ growth. The 1939-1948 growth difference began at least one full growing season following the 1937 completion of Tioga Road construction at Tuolumne Meadows [HAER). Construction of the current alignment of Tioga Road included clearing, grading, and culvert placement during 1933-1934; seal coating and a layer of granite screenings were added during 1935-1937. The 1961 repaving of Tioga Road at Tuolumne Meadows (Babalis et al., 2006) was not accompanied by a similar change in roadside tree growth. The 1939-1948 pattern of growth increase in the Tioga Road trees is similar to the response of lodgepole pine trees at other road sites. Bowering et al. (2006) found that lodgepole pine basal area increases are greatest within 5 m of road edges and within 6 to 10 years following road construction. This type of growth response is apparently related to changes in light availability, soil moisture, and other environmental factors associated with road construction and the sudden creation of forest edges along the roadway alignment. The 1939-1948 growth increase in the Tioga Road trees is not seen in other trees at Tuolumne Meadows and appears to be due to environmental changes brought about by tree clearing and construction of Tioga Road. Following 1948, growth in the roadside trees has closely matched growth in the TFJ trees.

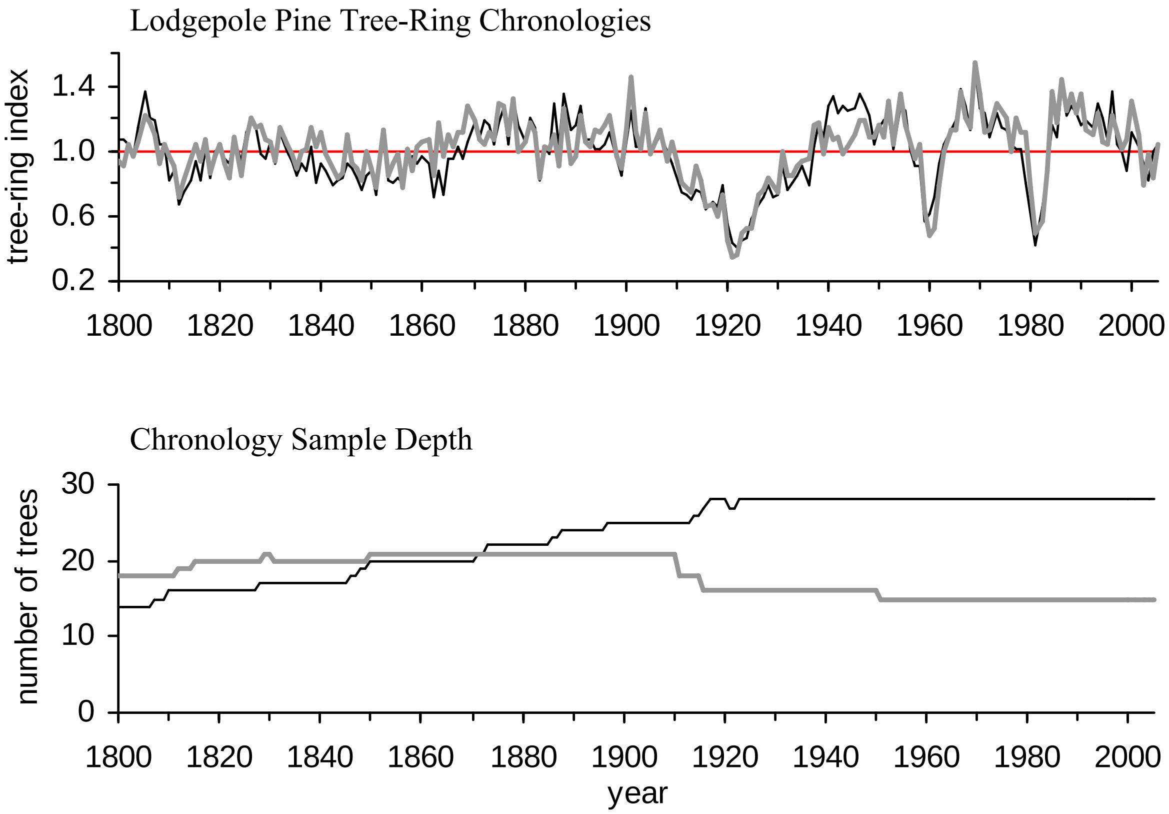
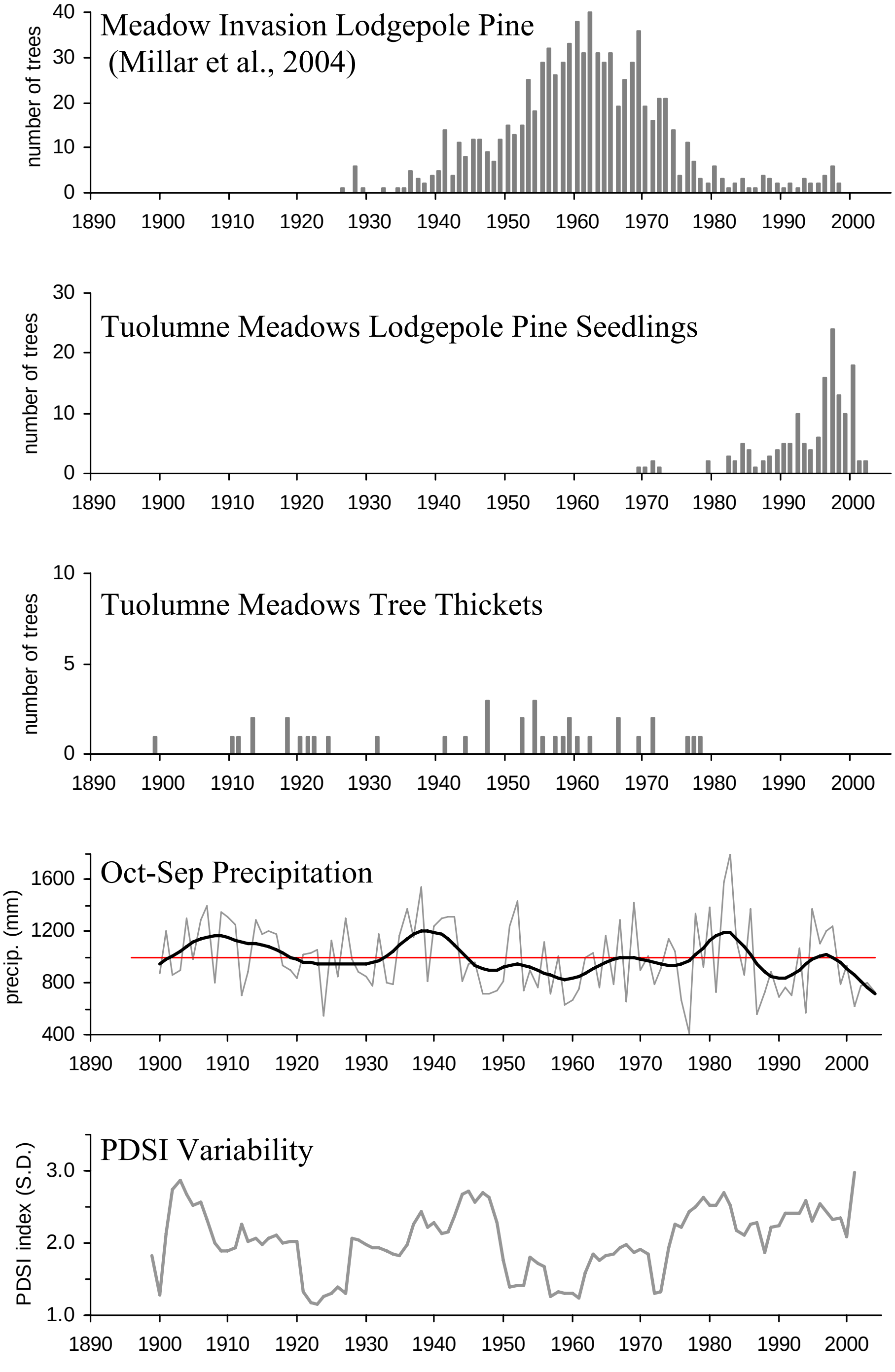


**Figure 4-13.** Standard tree-ring chronologies and chronology sample depth for Tioga Road trees (thin line) and TFJ trees (thick line). Sample depth reflects the number of trees incorporated into the chronology for each year of record.

## Meadow Invasion and Thicket Trees

An investigation of meadow invasion, snowfield invasion, annual branch growth, and vertical branch growth, conducted in and near Yosemite National Park (Millar et al., 2004), identified four multidecadal periods associated with ecological response. These periods are: <1925, 1925-1944, 1945-1976, and >1976. The 1945-1976 period corresponds with the timing of lodgepole pine meadow invasion at ten sites (including Tuolumne Meadows and Dana Meadows) examined in the study. The combined meadow invasion record for these ten sites is shown in Figure 4-14. Differences in environmental conditions and anthropogenic disturbance (including domestic grazing) among these sites implicates regional climate in the synchronous timing of meadow invasion. Low interannual variability in available moisture combined with warm temperatures and low-moisture conditions were proposed as the primary set of climate-related factors associated with meadow invasion.



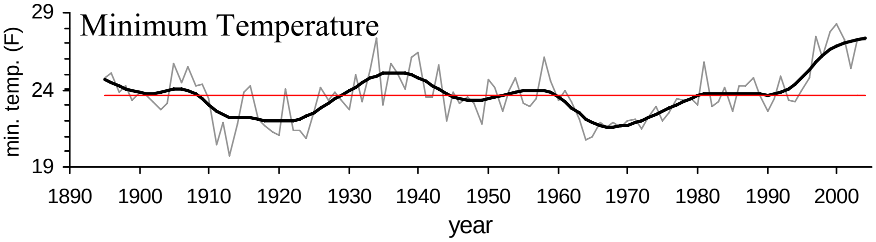


**Figure 4-14.** Lodgepole pine recruitment patterns and climate records. The October-September precipitation record is based on monthly PRISM data at Tuolumne Meadows. Nine year running standard deviations are computed for California Division 7 PDSI data. The annually averaged minimum temperature record is based on monthly PRISM data at Tuolumne Meadows. Precipitation and temperature data have been fitted with a 15 year cubic smoothing spline.

Studies conducted at Dana Meadows (Vale, 1981a) and along the trail to Lost Bear Meadows (Helms, 1987) in Yosemite National Park broadly define two periods of lodgepole pine meadow invasion: 1905-1940 and 1948-1973. The 1948-1973 invasion period corresponds closely with the 1945-1976 regional meadow pattern described above (Figure 4-14; Meadow Invasion Lodgepole Pine). This timing is synchronous with trends of low interannual variability in PDSI and low precipitation (Fig. 4-14). The 1905-1940 invasion period does not match the 1945-1976 regional pattern, but does correspond with episodes of low interannual variability in PDSI and low precipitation. A 1973-1977 pulse of lodgepole pine recruitment at Tuolumne Meadows (Cunha, 1992) does not match the timing of either the 1905-1940 or 1948-1973 Yosemite invasion episodes or the 1945-1976 regional pattern. The 1973-1977 pulse occurred in a period of increasing interannual variability in PDSI and below average precipitation. A 1996-2000 recruitment pulse in tree-ring samples collected in 2006 at Tuolumne Meadows (Fig. 4-14; Tuolumne Meadows Lodgepole Pine Seedlings) does correspond with a small recruitment pulse in the most recent portion of the regional record, but does not match the timing of the 1905-1940 or 1948-1973 Yosemite invasion episodes, the 1945-1976 regional pattern, or the 1973-1977 Tuolumne Meadows recruitment pulse. The 1996-2000 recruitment pulse corresponds with increased interannual variability in PDSI and average to below average precipitation.

Recruitment at tree thickets along Tioga Road spans the period from 1899 to 1978 (Fig. 4-14; Tuolumne Meadows Tree Thickets). The longest interval with no tree thicket recruitment in this record is 1932-1940. The timing of this nine year recruitment gap closely matches the 1933-1937 timing of Tioga Road construction and also falls in a time period of relatively low regional meadow recruitment. The portion of the tree thicket distribution that occurs before 1932 (prior to the gap) spans the period from 1899 to 1931; the portion of the distribution that occurs after 1940 (following the gap) spans the period from 1941 to 1978. Except for one tree with a recruitment date of 1899, the 1899-1931 portion of the tree thicket distribution falls within the timing of the 1905-1940 episode of Yosemite meadow invasion described above. The 1941-1978 portion of the distribution closely matches both the 1945-1976 regional pattern, and the 1948-1973 Yosemite invasion episode.

Apparent differences in the reported timing of meadow invasion in the vicinity of Yosemite National Park may be due to: 1) the timing of research activities, 2) the timing of managed tree removal activities in Tuolumne Meadows, and 3) the definition of the meadow-forest border. Earlier research projects (Vale, 1981a; Helms, 1987; Cunha 1992) were conducted prior to the 1990s, and so can not reflect the 1996-2000 recruitment pulse. The 1973-1977 recruitment pulse in Tuolumne Meadows (Cunha, 1992) occurred following at least 40 years of managed tree removal activities (National Park Service, 1933; Cunha, 1992, and references therein). Because of this, meadow invasion trees representing the majority of the 1945-1976 regional recruitment pattern may have been largely removed. If this is the case, then the 1973-1977 pulse may only reflect the most recent portion of the 1945-1976 regional recruitment distribution. Similarly, the current Tuolumne Meadows invasion distribution, which is characterized by a 1996-2000 recruitment pulse, may lack evidence of earlier recruitment episodes due to ongoing tree removal practices. The definition of the meadow-forest border, as it has been used to differentiate meadow invasion trees from trees in the forest proper, may have influenced meadow invasion research results, particularly the resolution of earlier recruitment episodes. Forest border trees have greater mean age and greater age variability than trees extending toward open meadow (Millar et al., 2004). Meadow invasion sampling transects that extend further into the apparent forest border may yield trees in older age classes than transects that end closer to the open meadow. Meadow invasion sampling point M32 (Fig. 4-3) and the tree thicket sampling points (Fig. 4-7) are examples of older trees being found further into the meadow-forest border. The 1969-1972 recruitment dates of the five trees at sampling point M32 are in the earliest portion of the current meadow invasion distribution and within the timing of the 1945-1976 regional recruitment distribution. Sampling point M32 is the only meadow invasion sampling point located in the immediate vicinity of trees greater than 15 cm in diameter. In addition, the recruitment dates of tree-ring samples collected at a forested lobe of Tuolumne Meadows (Millar et al., 2004; Point RW in Figure 4-3) fall in the time period of the 1945-1976 regional recruitment distribution. The tree thickets are also located in the immediate vicinity of trees greater than 15 cm in diameter and have recruitment dates extending back to 1899. The recruitment dates of the tree thickets fall within the timing of the 1905-1940 and 1948-1973 Yosemite invasion episodes and the 1945-1976 regional pattern.

Mean growth rate in the thicket trees is less than mean growth rate in the meadow invasion trees ($P < 0.001$) or in the set of mature trees ($P < 0.001$) (Table 4-1). Northward movement of surface water or ground water appears to result in seasonal ponding at the tree thickets due to the barrier of Tioga Road. It is not known if tree growth in the thickets was similarly suppressed prior to the 1933-1937 construction of Tioga Road because there is not enough tree-ring record in the early time period for testing. It is possible that the thicket locations were limiting to tree growth prior to the construction of Tioga Road; it is also possible that seasonal ponding conditions or other factors associated with Tioga Road have limited tree growth. High stem density conditions, together with the distinct parallel alignment of the thickets with the roadway, strongly suggest a Tioga Road impact on thicket development. This impact does not appear to be expressed in the timing of recruitment, because tree thicket recruitment corresponds with regional recruitment episodes. Rather, Tioga Road factors appear to increase tree density and possibly decrease tree growth rates at the four tree thicket locations. Lodgepole pine thickets can be found at other locations along the south shoulder of Tioga Road, particularly in the area between roadside trees A102 and A106 (Fig. 4-1).

**Table 4-1.** Lodgepole pine growth rates. Growth rates in the thicket trees and meadow invasion trees are based on the full time period of each tree-ring sample. Growth rates in the mature trees are based on the outermost 2.5 cm of tree growth.

| **Collection Site** | **# of Trees** | **Mean Growth (rings/cm)** | **SD (rings/cm)** |
|---|---|---|---|
| **Thicket trees** | **37** | **33.69** | **22.78** |
| **Meadow invasion trees** | **151** | **14.61** | **9.63** |
| **Mature trees (roadside and TFJ trees)** | **41** | **10.28** | **4.06** |

The recruitment of small trees in narrow lines along the immediate edges of Tioga Road pavement (meadow invasion sites M5, M9, M14, M27, M29, M30; Fig. 4-3; Fig. 4-5), falls within the timing of the 1945-1976 and 1996-2000 regional recruitment episodes. As with the tree thickets, the distinct linear configuration of these narrow lines of trees suggests a Tioga Road impact on the location of tree establishment. The narrow lines of trees are typically located within 2 m of the paved edge of Tioga Road.

The timing of meadow invasion and tree thicket recruitment at Tuolumne Meadows appears to be associated with regional climate trends rather than anthropogenic disturbances. While the location, density, or growth rate of trees may be influenced by anthropogenic disturbances, the timing of lodgepole pine recruitment at Tuolumne Meadows falls within the timing of recruitment at other meadow sites in the Yosemite region. Based on these findings, previously described (Cunha, 1992) patterns of lodgepole pine invasion at disturbed sites (e.g., roadway shoulders, ditches, culverts, trail ruts) in Tuolumne Meadows probably also fall within the timing of regional meadow invasion episodes. Three episodes of meadow invasion appear to have occurred in Tuolumne Meadows and vicinity: 1905-1940, 1945-1976, and 1996-2000. The 1905-1940 episode may represent trees growing close to or into the forest margin. The recent pulse of recruitment during 1996-2000 may expand or die-back in the future depending on changing environmental conditions. While warm temperatures have been associated with the timing of meadow invasion (Millar et al., 2004), the relationship between temperature and meadow invasion in Yosemite National Park is unclear (Fig. 4-14). The 1905-1940 and 1945-

1976 recruitment periods coincide with below average temperature trends, while the 1996-2000 recruitment period coincides with elevated temperatures. The timing of meadow invasion in Yosemite National Park is most closely associated with low interannual variability in PDSI and low precipitation.

Because the timing and location of managed tree removal activities at Tuolumne Meadows since approximately 1933 is largely unknown, the current findings do not provide a complete picture of lodgepole pine dynamics in the meadow. It is not known if earlier recruitment episodes in Tuolumne Meadows would have persisted to the present in the absence of managed tree removal activities.

## Fire History

Both natural and anthropogenic factors appear to have influenced fire history at Tuolumne Meadows. Lightning-ignited fires are documented in Yosemite National Park (van Wagtendonk, 1994), however, the spatial and temporal patterns of this type fire at Tuolumne Meadows during the last 500 years is largely unknown. Prior to the 1850s, Native Americans may have set fires in Yosemite National Park and at Tuolumne Meadows in order to modify vegetation patterns (Reynolds, 1959; Gassaway, 2005). Sheep grazing occurred in Tuolumne Meadows from the mid 1860s until approximately 1905; in the early part of this period, sheepherders may have set fires in forested areas around Tuolumne Meadows in order to expand grasslands (Babalis et al., 2006). Fire suppression efforts at Tuolumne Meadows began after 1891 under the direction of the U.S. Army (Babalis et al., 2006). Natural fires have not occurred at Tuolumne Meadows since at least 1921 (Cunha, 1992, and references therein). It is not known if natural or anthropogenic fires burned across Tuolumne Meadows or stopped at the forest-meadow margin.

The set of fire-scar dates for tree-ring samples collected at Tuolumne Meadows is shown in Table 4-2. Based on the near-completion of the growth ring preceding each fire-scar, all of the fires appear to have occurred during the late growing season.

**Table 4-2.** Fire-Scar Dates at Tuolumne Meadows.

| **Tree ID** | **Fire-Scar Dates** | **Sample Type** | **Notes** |
|---|---|---|---|
| **FS101** | **1795** | **dead tree cross-section** | |
| **FS102** | **1739, 1756, 1788** | **dead tree cross-section** | |
| **FS103** | **1778, 1833** | **dead tree cross-section** | |
| **FS104** | **n/a** | **dead tree cross-section** | **sample does not cross-date (254 yr)** |
| **FS105** | **1773** | **dead tree cross-section** | |
| **FS106** | **1703** | **dead tree cross-section** | |
| **FS107** | **1810** | **dead tree cross-section** | |
| **FS108** | **n/a** | **dead tree cross-section** | **sample does not cross-date (185yr)** |
| **TFS101** | **1829** | **live tree cores** | |
| **TFS102** | **n/a** | **live tree cores** | **samples not viable** |
| **TFS103** | **n/a** | **live tree cores** | **samples not viable** |
| **TFS104** | **1829** | **dead tree cores** | |

Except for the 1829 fire date in samples TFS101 and TFS104, the set of fire dates is not synchronous. This may be due to low sample depth, or it may suggest that fires during this period were relatively small in size or low in intensity. The most recent fire occurred in 1833, nineteen years prior to the first Anglo-American exploration of Tuolumne Meadows (Babalis et al., 2006). Based on sample quality and the length of time-series in undated samples FS104 and FS108, the fire-scar dates in these trees probably predate the year 1600 (i.e., predate the existing lodgepole pine tree-ring record at Tuolumne Meadows). Fire disturbance has been absent from Tuolumne Meadows since at least the early 1900s but may have been relatively frequent prior to the mid 1800s. If earlier fires modified the meadow environment or led to the mortality of meadow seedlings, then lodgepole pine dynamics at Tuolumne Meadows may have changed substantially over the last 100 years in the absence of fire disturbance.

## Climate-Growth Relationships

For the period 1907 to 2005, monthly records of temperature and precipitation from Yosemite Valley were found to have the strongest relationship with lodgepole pine growth at Tuolumne Meadows. Correlation function analysis (Fig. 4-15) of the TFJ lodgepole pine standard chronology suggests that minimum temperature is the dominant climate factor associated with tree growth. The most extreme low growth years (1922, 1960, 1981) and high grow years (1969, 1986) in the 313 year TFJ tree-ring record (sample depth >10) occurred during the 20th century (Fig. 4-13). These growth extremes are not explained by the minimum temperature relationship. More sophisticated techniques may be required to develop a model that accurately relates climate to tree growth.

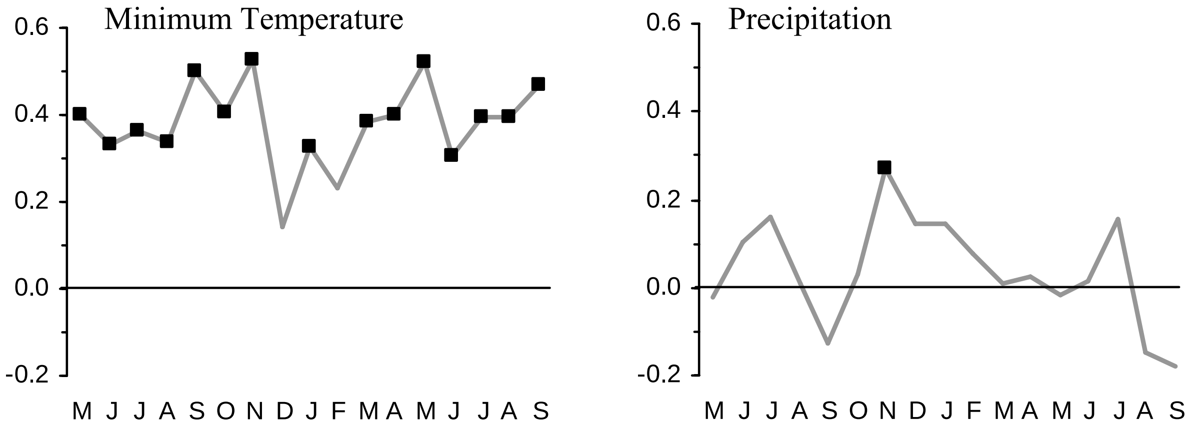


**Figure 4-15.** Correlation functions for the TFJ lodgepole pine standard tree-ring chronology. Black squares indicate significant correlations (99% confidence interval). The correlation functions examine monthly climate variables extending from May of the prior year to September of the current tree growth year.

## Forest Margin Patterns

During reconnaissance and field collection activities, a difference was noted in the appearance of the forest-meadow margin between the west end and east end of Tuolumne Meadows. This observation was based on preliminary ring counts of tree-ring samples, photographs, and visual assessments of tree age. The forest margin at the west end of Tuolumne Meadows in the vicinity of Tioga Road is characterized by a relatively well-defined line of 250-400 year old lodgepole pine trees growing at the immediate edge of the open meadow (Fig. 4-16 and Fig. 4-18). This age class represents the oldest lodgepole pine trees identified at Tuolumne Meadows. While dense seedling growth can currently be found in the meadow beyond the limit of the mature tree line, the old age of the tree line suggests an aspect of long-term stability.

Episodic meadow invasion and retreat may have occurred many times in the last 250-400 years, but the current forest edge has not retreated during this interval.

**Figure 4-16.** Forest margin at the west end of Tuolumne Meadows.

The forest margin at the east end of Tuolumne Meadows in the vicinity of Tioga Road has some locations where trees greater than 200 years old can be found growing at the edge of the open meadow. At other locations, 200-300 year old trees are set back between approximately 5 m and 50 m from the open meadow, with younger trees extending toward the open meadow (Fig. 4-17 and Fig. 4-18). The recruitment dates of 54 trees at one point in this type of forest margin range from 1937 to 1973 (Millar et al., 2004; see point RW in Figure 4-3). The age structure at this type of forest edge may reflect a different set of environmental conditions than those associated with the distinct old age tree line at the west end of the meadow. The impact of managed seedling removal and historic tree cutting practices on forest edge age structure is unknown.

**Figure 4-17.** Forest margin at the east end of Tuolumne Meadows. The open meadow can be seen in the background.

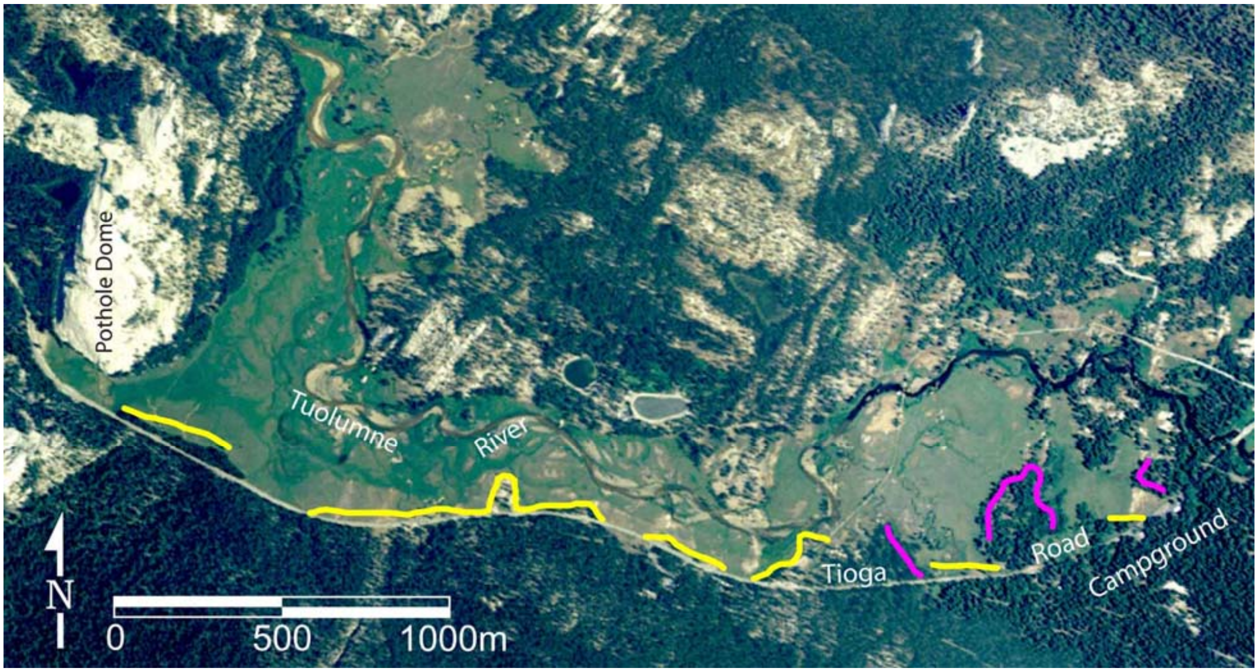


**Figure 4-18.** Forest margin patterns at Tuolumne Meadows. Yellow lines indicate regions where 250-400 year old trees are growing at the immediate edge of open meadow. Violet lines indicate regions where 200-300 year old trees are set back from the edge of the open meadow with younger trees extending to the open meadow.

## *CONCLUSIONS*

The construction of Tioga Road during 1933-1937 appears to have impacted the growth of mature lodgepole pine trees during 1939-1948. Compared to trees at a control site, trees along the shoulders of Tioga Road experienced a relative growth increase during 1939-1948. This growth increase appears to be due to edge effect environmental changes associated with the construction of Tioga Road. Roadway impact on mature tree growth does not appear to extend beyond the shoulders of Tioga Road. Following 1948, growth in the roadside trees has closely matched growth in the control trees.

Current and previous lodgepole pine meadow invasion research findings at Tuolumne Meadows and vicinity appear to differ due to the timing of research activities, the timing of managed tree removal activities in Tuolumne Meadows, and the use of different definitions of the meadow-forest border. If these factors are taken into account, then the timing of meadow invasion and tree thicket recruitment at Tuolumne Meadows does seem to correspond with the timing of meadow invasion episodes at other sites in the region. Because meadow invasion is synchronous across the landscape, regional climate is implicated as the driving factor. The periods of meadow invasion at Tuolumne Meadows are: 1905-1940, 1945-1976, and 1996-2000. These periods are most closely associated with low interannual variability in PDSI and low precipitation. While the timing of meadow invasion and tree thicket recruitment at Tuolumne Meadows appears to be driven by regional climate, anthropogenic disturbances may alter tree density, growth rate, or location of tree recruitment. Examples of this include the linear tree thickets adjacent to the south shoulder of Tioga Road and the narrow lines of trees growing along the immediate edges of Tioga Road pavement. Because the timing and location of managed tree removal activities at Tuolumne Meadows since approximately 1933 is largely unknown, the current findings do not provide a complete picture of lodgepole pine dynamics in the meadow. The tree-ring growth pattern in mature lodgepole pine trees at Tuolumne Meadows is most strongly correlated with minimum temperatures.

Relatively frequent fires occurred along the south edge of Tuolumne Meadows between the early 1700s and the mid 1800s. Since at least the early 1900s, fire disturbance has been largely absent. If earlier fires modified the meadow environment or resulted in the mortality of meadow seedlings, then lodgepole pine dynamics at Tuolumne Meadows may have changed substantially during the last 100 years.

The forest margin at the west end of Tuolumne Meadows is characterized by a relatively well-defined line of 250-400 year old lodgepole pine trees growing at the immediate edge of the open meadow. At the east end of the meadow, 200-300 year old trees are set back between 5 m and 50 m from the open meadow, with younger trees extending toward the open meadow. The environmental conditions associated with these forest margin differences are unknown.

# Chapter 5: **Impacts of Tioga Road on Groundwater Flow in Tuolumne Meadows: Preliminary Conceptual Model and Numerical Analysis**

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## *Introduction*

In support of investigations to ascertain the impact of historical land management, park development, or climatic cycles on the encroachment of lodgepole pines into Tuolumne Meadows, an evaluation of the hydrologic processes in the meadows was undertaken. In specific, the development of a conceptual model of water flow into the meadow and the subsequent 2-dimensional flow through the meadow to the river was needed as a framework for overlying other processes. Using 2-D numerical modeling, the impact of Tioga Road was considered specifically on the transmission of water under snowmelt conditions from April – May, and throughout the growing season from May through July for 2006.

### Development of a Conceptual Model of Groundwater Flow for Tuolumne Meadows

Following principles of groundwater flow there are several initial premises that can be assumed in the development of a conceptual model of groundwater flow in the Tuolumne Meadows area. First of all, groundwater always flows from areas of higher hydraulic head to an area of lower hydraulic head, and therefore, groundwater can flow downward, laterally, or upward. Secondly, when considering the topography of the region (Figure 5-1), we can assume that watershed elevation and surface contours control the direction of water flow, and that surface water flows at right angles to surface contour lines. Subsurface flow incorporates unsaturated flow along with saturated flow, and our conceptual model of subsurface flow needs several simplifying assumptions: (1) unsaturated flow can only move vertically, (2) lateral subsurface flow is saturated flow, and (3) lateral subsurface flow is also at right angles to the bedrock contour lines, which mimic surface contour lines (although subsurface heterogeneity can have a great influence).

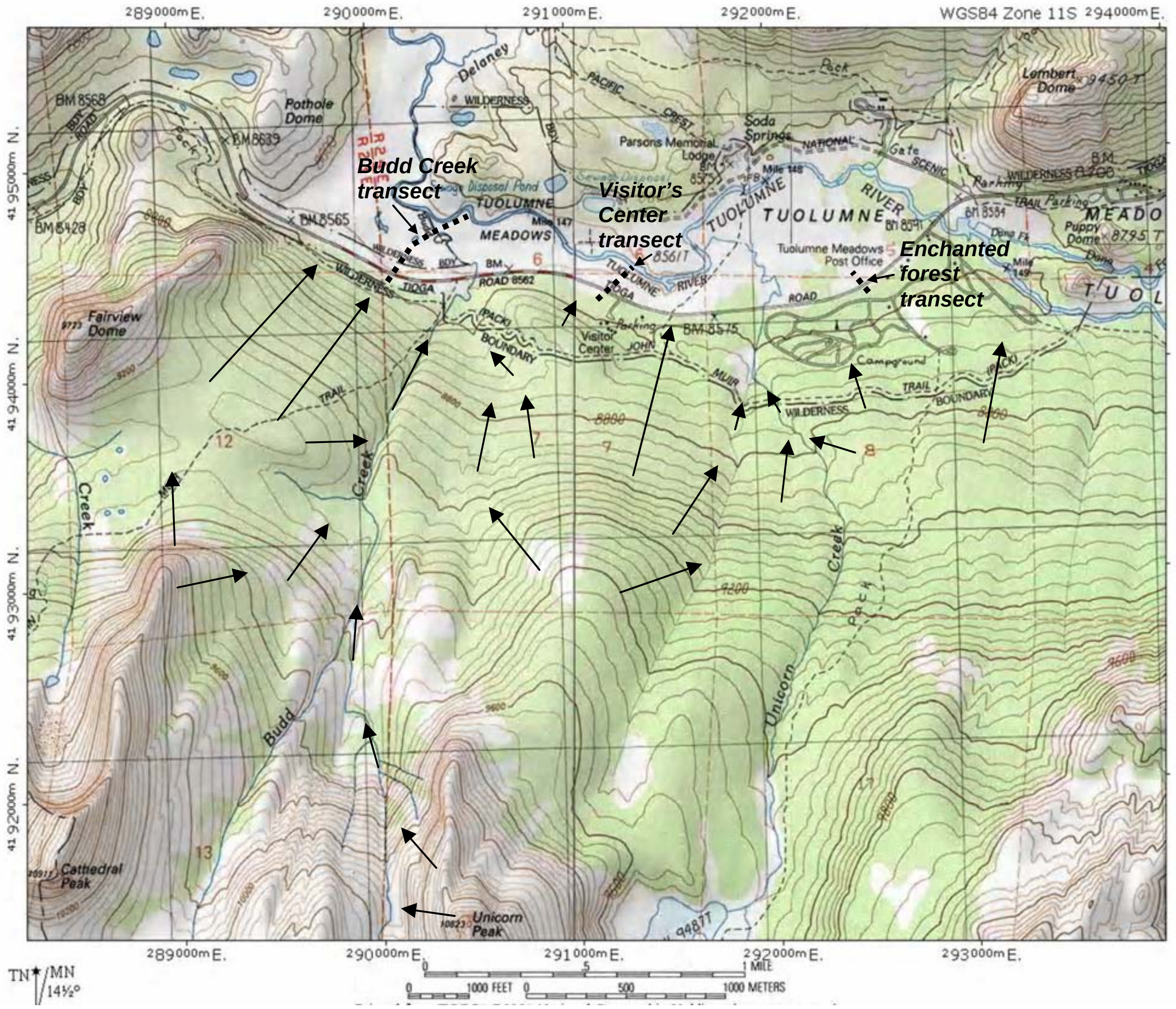

Figure 5-1. Topographic map, flow direction, and ground penetrating radar transects in Tuolumne Meadows.

On a basin-wide basis, spring snowmelt and rain vertically infiltrate, except when snowmelt or rainfall rates exceed the infiltration capacity of the soil (i.e., Hortonian or saturated overland flow occur), or the bulk permeability rate of the bedrock.

With regard to the geometry of the basin, field observations and measurements using ground penetrating radar support the assumption that the bedrock surface is fairly uniform but dips toward the valley centerline, the soil thickness is thin and fairly uniform in the upland source area, but varies over the valley floor, and is controlled by flood plain processes and human intervention (i.e., roads, trails, construction).

Assumptions regarding the bedrock are less certain but still supported by field observations and measurements to some degree. Fractures in the granite extend to a finite but undefined depth, and the variation of that depth in space can be used to construct and test different conceptual models. One extreme suggests that, along a transect from the ridge top to the valley bottom, fractures extend several meters in depth for the entire transect and transmit water downward and laterally within the bedrock. An alternate model includes concepts of geomorphological processes whereby fractures extend several meters in hilltops and side slopes, and transmit water accordingly, but in the depositional regions the fractures are likely more closed or filled with deposits and are less permeable.

Evaluation of the surrounding topography as illustrated in the topographic map in Figure 5-1, while considering the underlying assumptions discussed above, provides an assessment of the paths and contributing area for available water to the various locations in the meadows during the snowmelt and runoff period. Consider first that all the slopes to the south of the road generally face north and have approximately the same energy loading for snow melt. Noting that the arrows indicate likely paths following perpendicular to the contours, it can be seen that the largest contributing area directly next to the southern edge of Tioga Road is located on the west end of the meadows between Budd Creek and Pothole Dome. The uphill area to the west of the visitor center has water diverted to Budd Creek resulting in a small contributing area at that location. Further east at the location of the old trail that extends across the meadows to Parson's Memorial Lodge, there is a narrow slope that extends the entire distance to the top of Unicorn Peak, although the road is a bit farther from the slope at this location, and the concavity of the slope tends to divert water to drainages on both the west and east. The eastern third of the meadow from Unicorn Creek to the Tuolumne Bridge is broad from the base of the slope to the road with surface obstructions and imperviousness, and much of the water from the slopes is directed toward the Tuolumne River above the bridge or to Unicorn Creek.

This analysis suggests that excess water during and following spring snowmelt provides the most water directly to the south side of Tioga Road at the west end of the meadow, and less so as one traverses east. Sustained drainage from the slopes should therefore influence the drainage on the south side of the western portion of the road more than other areas, without regard to management practices such as plowing roads or clearing parking lots.

# *Methods*

Domain geometry, upper atmospheric boundary conditions, lateral and lower flow boundary conditions, and hydrologic properties of subsurface materials are necessary for the development of numerical models. There is existing information for the Tuolumne Meadows area, and additional data was collected for this project.

## Model geometry and material properties

To establish the physical geometry of the area, three transects (Figure 5-1) were taken using ground penetrating radar to estimate the depth to bedrock. Given the capability of the available instrumentation and the lack of resolution in the detections of subsurface contrasts in properties at depths of less than 1 meter, the interpretation of the data is uncertain, as the depth to bedrock for most of the measured transects ranges from 0.3 m to approximately 2 m. Surface observations helped to constrain the interpretations. In addition, estimates of bedrock depth obtained from the installation of wells along or very near each transect helped to constrain the final estimates of bedrock depth. An example of an interpretation of ground penetrating radar data is shown in Figure 5-2 with the interpreted bedrock depth indicated. Surface elevation data was collected for each of the well transects and was used to develop cross sections for model domains. Soil observations were made during the auguring of wells and were used to designate soil layers for the 3 transects (Figure 5-3).

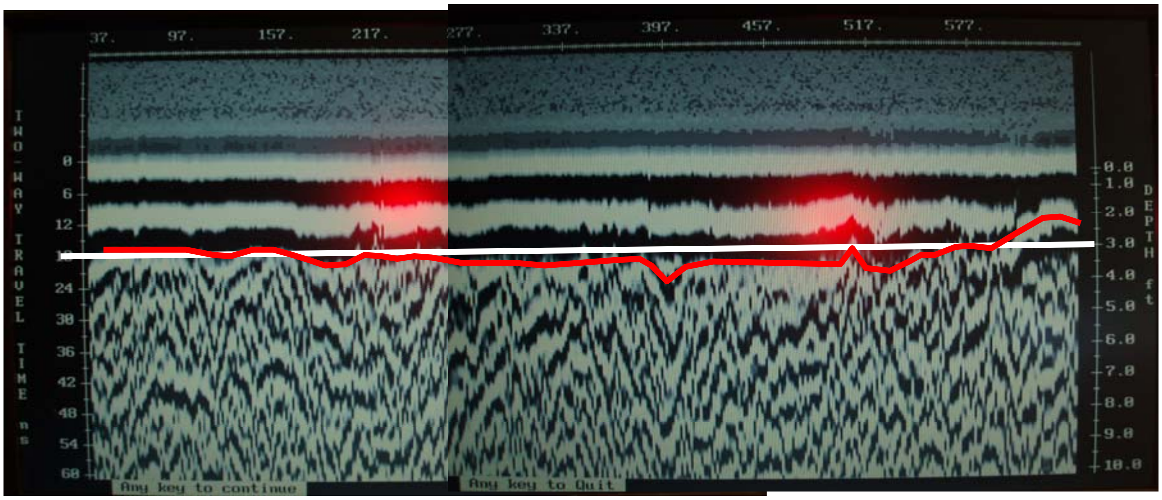

Figure 5-2. Screen capture of ground penetrating radar result for Visitor’s Center transect with 1 meter depth shown as white line, and interpreted bedrock depth illustrated in red line.

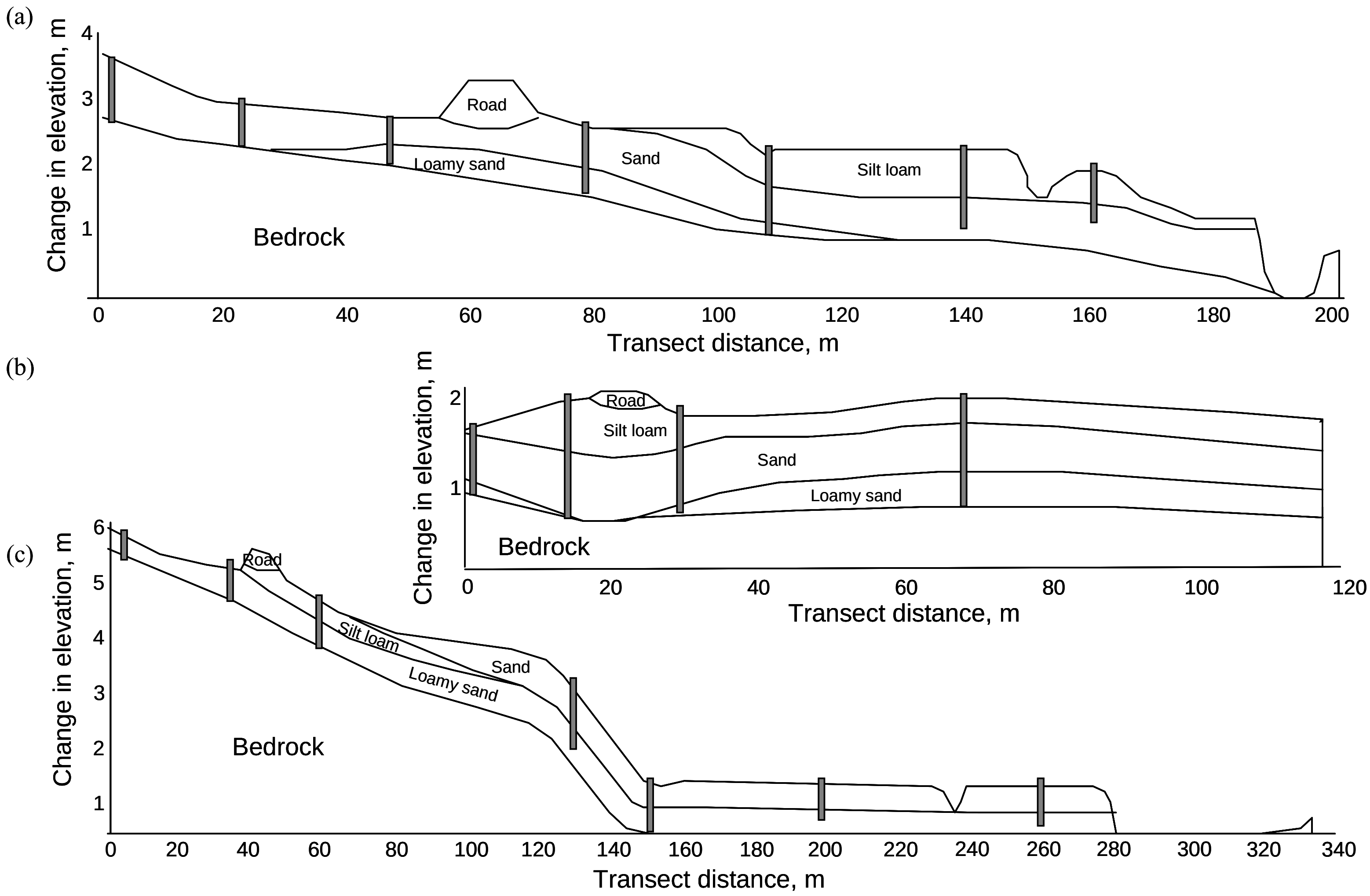

Figure 5-3. Elevation, geometry, and soils of three ground penetrating radar transects at (a) Visitor's Center, (b) Enchanted Forest, and (c) Budd Creek, all vertically exaggerated. Wells are indicated.

The numerical code used in the development of the Tuolumne Meadows models is HYDRUS-2D (Simunek et al., 1999). HYDRUS-2D is a two-dimensional finite element code for simulating movement of water, heat, and multiple solutes in variably saturated media. The program numerically solves the Richards' equation for saturated-unsaturated water flow using a Galerkin-type linear finite element method applied to a network of triangular elements. The unsaturated soil hydraulic properties follow the van Genuchten (1980) formulation. HYDRUS-2D implements a Marquardt-Levenberg-type parameter estimation technique for inverse estimation of selected soil hydraulic and/or solute transport and reaction parameters from measured transient or steady-state flow and/or transport data. The procedure permits several unknown parameters to be estimated from observed water contents, pressure heads, concentrations, and/or instantaneous or cumulative boundary fluxes (e.g., infiltration or outflow data). Additional retention or hydraulic conductivity data, as well as a penalty function for constraining the optimized parameters to remain in some feasible region (Bayesian estimation), can be optionally included in the parameter estimation procedure.

The Visitor’s Center transect was developed in HYDRUS-2D using cross section (a) in Figure 5-3 (Figure 5-4a). A mesh was generated and observation points were input at locations representing the bottom of wells in the transect (Figure 5-4b) for which water level data was obtained several times throughout the season June – August. A model was also developed for the Enchanted Forest transect according to the geometry in Figure 5-3b. Initial estimates of material properties were made on the basis of textural observations made of soils during the drilling of the wells and were used to constrain the model inversions which used material property parameters during the calibration to well drainage rates. HYDRUS-2D uses a neural network to estimate hydraulic parameters on the basis of available information, in this case textural class for the soil layers. Initial bedrock properties were estimated on the basis of observations and measurements made at Gin Flat in 2004 (Flint et al., in press).

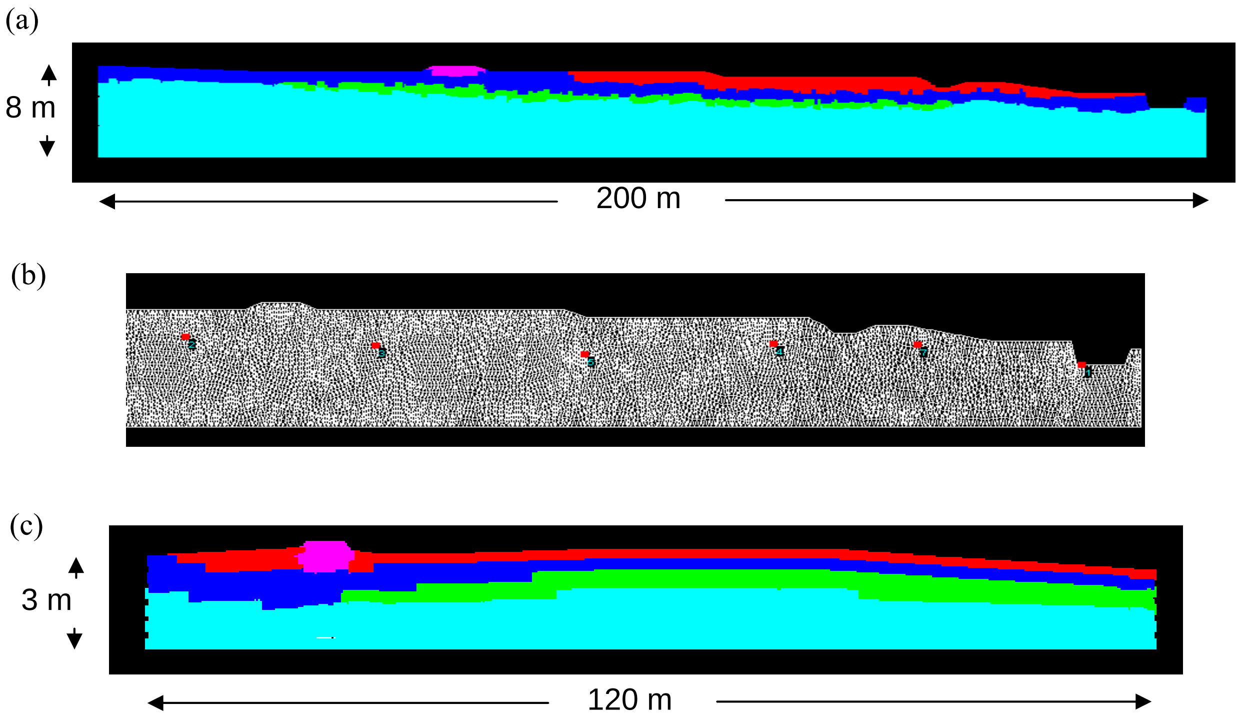

Figure 5-4. Illustrations of (a) geometry for Visitor's Center model showing bedrock and soil layers and (b) finite element grid with observation points representing bottom of wells, and ( c) geometry for Enchanted Forest model showing bedrock and soil layers.

## Boundary conditions

Upper atmospheric boundary conditions included precipitation and evapotranspiration. Daily precipitation data was available from the Department of Water Resources precipitation gage located on the Tuolumne River just upstream of the Tioga Road bridge. Evapotranspiration estimates were modeled using solar radiation modeled with topographic shading and a correction for cloudiness, and the Priestley-Taylor evapotranspiration equation (Flint and Flint, in review). Lateral boundary conditions were represented as a seepage face into the Tuolumne River on the northern boundary. Prior to June 1 snow continued to melt, creating ponded conditions on the south side of Tioga Road, with likely, but unknown subsurface flow into the soil/bedrock profile. Snow was gone by June 1, and on the basis of rapid drainage observed in the wells, no flow conditions at the upper flow boundary were assumed after June 1. Lower flow boundary conditions were unknown and used as a calibration parameter, beginning with a no flow condition.

## Model calibration

Data used for calibration of the two models is shown in Figure 5-5 as water depths measured on 6 dates beginning June 8, 2006. Reasonable bounds on the initial hydraulic parameter estimates were input during model operation in inverse mode, and the model was run for 70 days from June 1 – August 8. Parameters could not be found that allowed the soils to drain until the lower flow boundary condition was changed to allow for flux downward through the bedrock. An estimate of 6 mm day$^{-1}$ flux downward out of the domain for the Visitor's Center model provided optimized final calibrated parameters shown in Table 5-1. The parameters for the road represent a gravelly, sandy loam with an increased bulk density. Bedrock parameters represent a very high air entry value for the matrix, but a saturated hydraulic conductivity that can transmit water relatively quickly via fractures. A comparison of measured and simulated water depth for 5 wells and 6 measurement dates is shown in Figure 5-6, showing an average absolute error of about 6 cm and a total $r^2$ fit of 0.93.

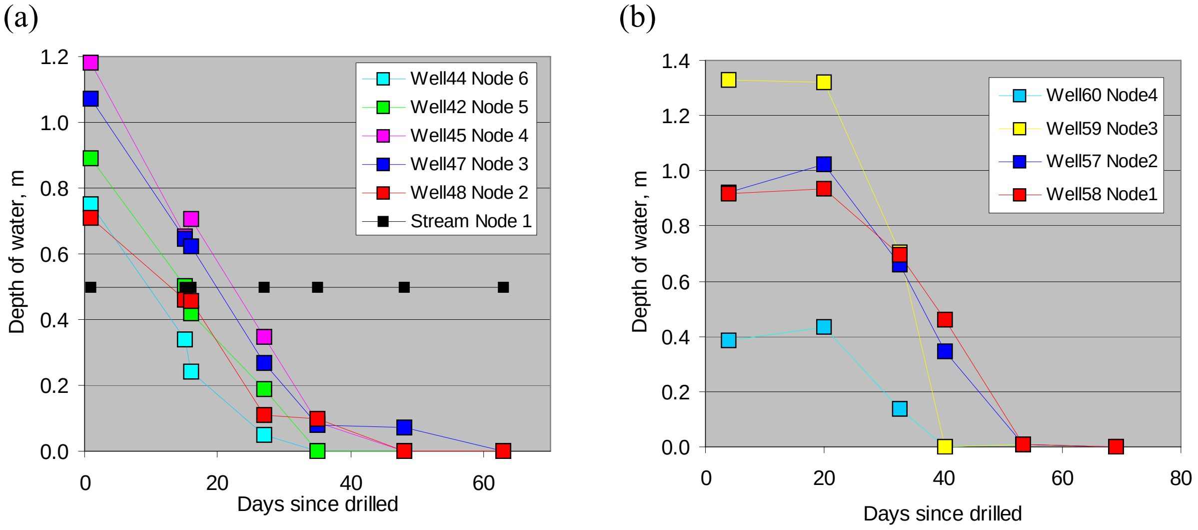

Figure 5-5. Water depth data for wells used in model calibration for (a) Visitor’s Center transect and (b) Enchanted Forest transect. Wells in legend are in order of from south to north, and stream elevation is estimated from field observation.

Table 5-1. Calibrated material properties for 3 soil layers, road, and bedrock for Visitor’s Center model. Moisture retention curve-fit parameters are from van Genuchten (1980).

| Layer | Residual water content (m/m) | Saturated water content (m/m) | Moisture retention parameters alpha (m$^{-1}$) | Moisture retention parameters n | Saturated hydraulic conductivity (m/day) |
|---|---|---|---|---|---|
| Soil 1: Silty sand | 0.065 | 0.414 | 3.19 | 3.35 | 0.740 |
| Soil 2: Sand/gravel | 0.057 | 0.380 | 7.56 | 1.67 | 2.250 |
| Soil 3: Sand | 0.057 | 0.500 | 12.70 | 2.50 | 5.300 |
| Road | 0.100 | 0.350 | 3.00 | 1.41 | 0.610 |
| Bedrock | 0.068 | 0.380 | 0.80 | 1.09 | 0.048 |

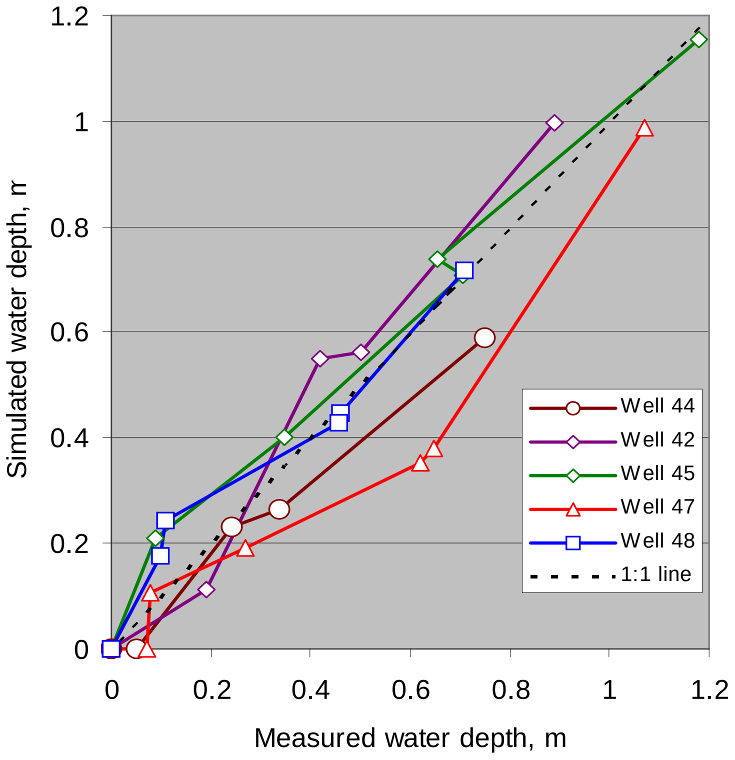

Figure 5-6. Comparison of simulated and measured water depth for 5 wells in the Visitor's Center model for calibrated parameters.

## *Results*

The calibrated model for the Visitor's Center transect began nearly saturated at June 1, with water flowing north downhill primarily through the soil, but also through the bedrock. Seeps are indicated at the swale at 150 m and at the river for day 42 (Figure 5-7a). Following model calibration, the model was run under conditions representing snow melt, with a saturated upper boundary condition and an inflow of 20 cm day$^{-1}$ along the entire southern domain boundary. Water flowed directly through the road under these saturated conditions.

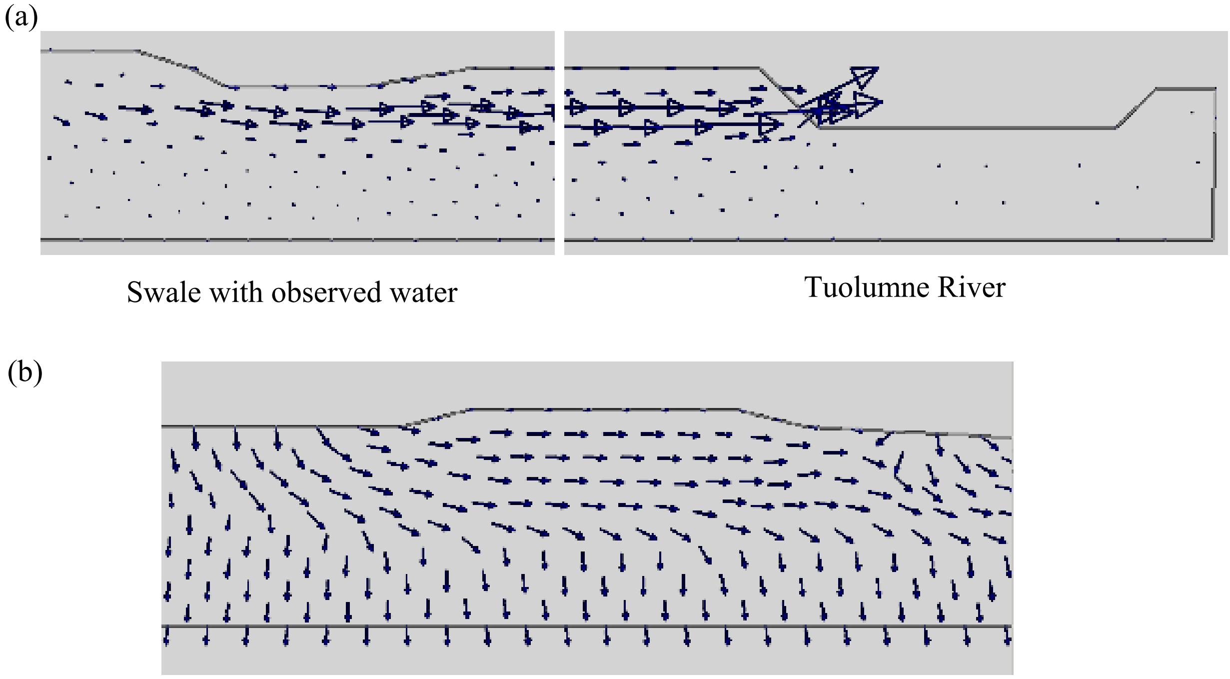

Figure 5-7. Illustration of flow vectors for calibrated model for the Visitor's Center transect indicating (a) flow at 2 seepage faces where surface water was observed on July 19, day 42 of model simulation, and (b) saturated flow through the road materials during snow melt conditions.

To investigate the impact of the presence of Tioga Road on the flow of water from the mountains to the south to the Tuolumne River, several scenarios were tested. Using the calibrated model with the geometry of the road indicated in Figure 5-3a (approximately a meter in thickness into the underlying soil and about 10 meters in length), flow was simulated with parameters that would result in no flow through the road, and with parameters matching that of the surrounding soil, to represent no road. Results are shown in comparison to simulations for the calibrated model for the locations of the wells on either side of the road in Figure 5-8. During the drainage process, flow is unsaturated and follows potential gradients. If the road is treated as a barrier to flow, the drainage appears to be faster in both wells next to the road (Figures 5-8 and 5-9). The gradients become vertical with the water draining into the bedrock under more saturated conditions and therefore higher relative permeabilities. Velocity vectors are shown in Figure 5-10b. The opposite occurs for the scenario with no road, whereby the water does not need to divert to beneath the road, can maintain slower velocities, and can follow gradients down slope throughout the profile (Figure 5-10c), thus maintaining water closer to the surface as it flows down gradient, which is south to north.

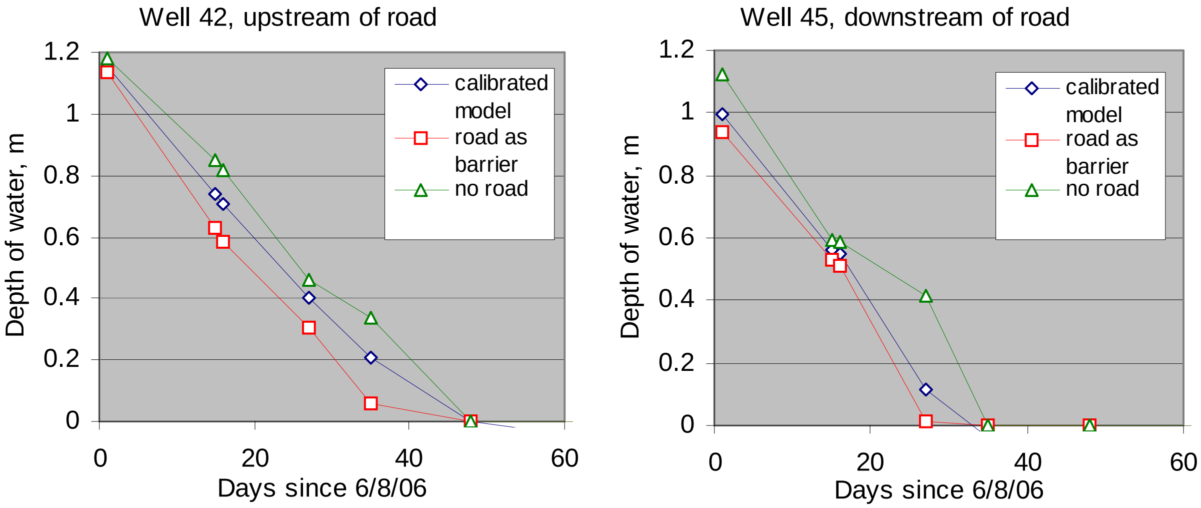

Figure 5-8. Comparison of simulated drainage for 3 conditions for wells (a) upstream and (b) downstream of road in transect 3 model.

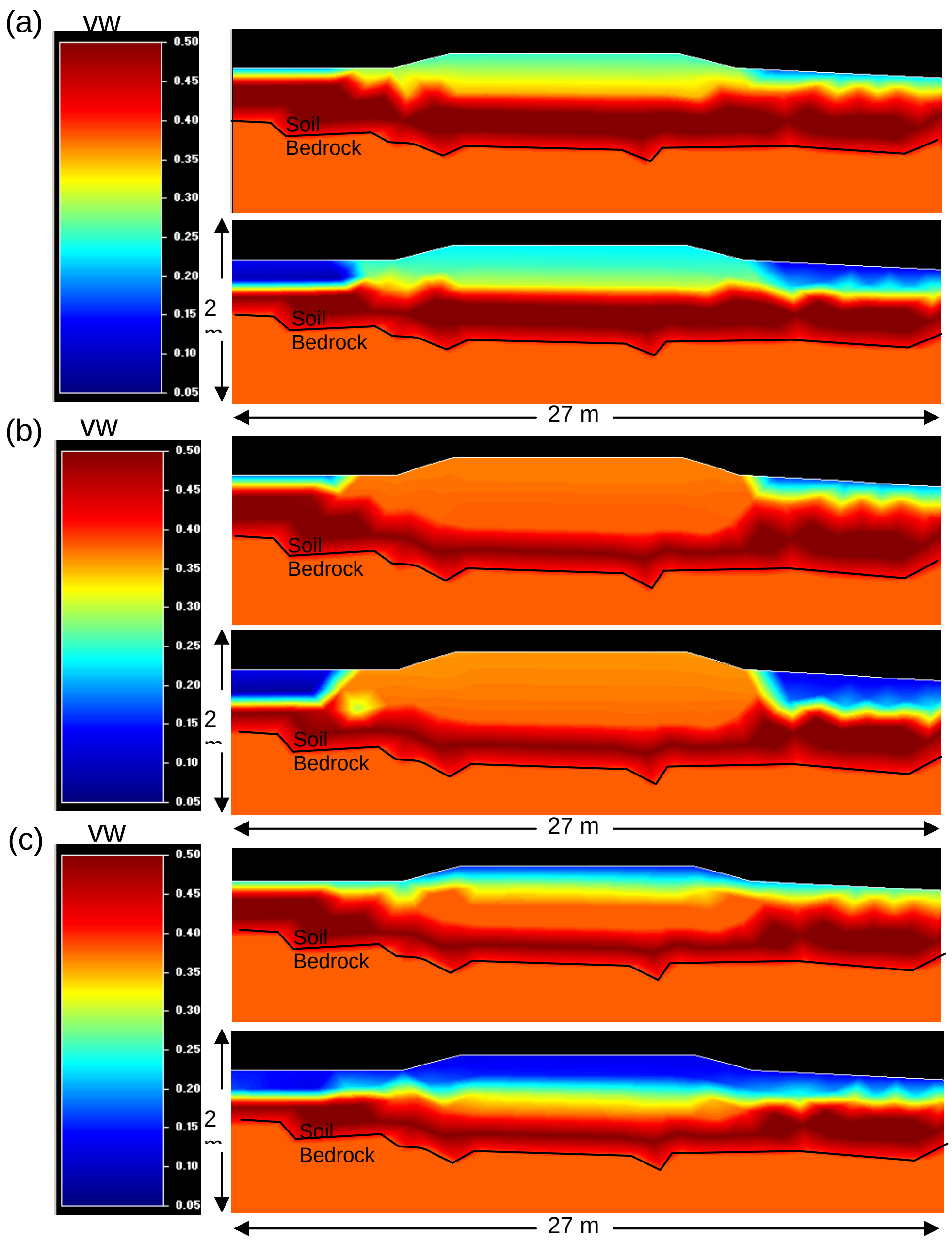

Figure 5-9. Comparison of volumetric water content (VWC) at 3.5 days (top) and 24.5 days (bottom) for (a) calibrated model, (b) model with road as a barrier, and (c) no road.

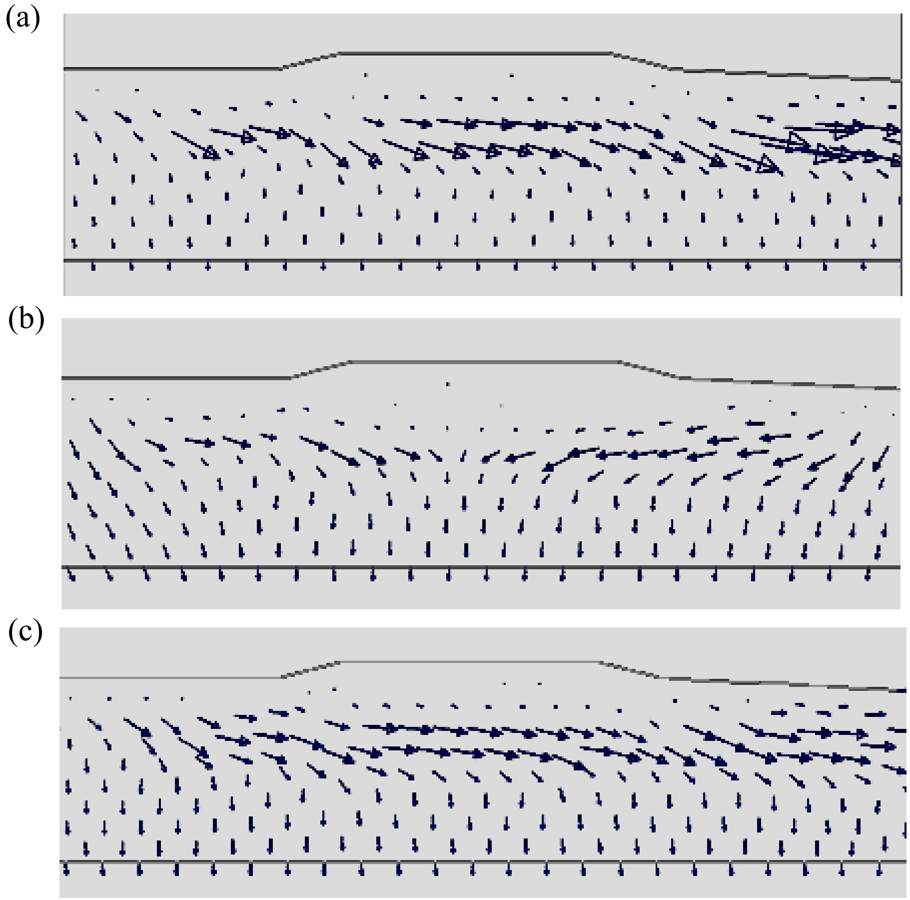

Figure 5-10. Comparison of flow vectors (< 0.5 m/day) on day 42 of transect 3 model simulation for (a) calibrated model, (b) model with road as barrier, and (c) no road.

Inversions to develop calibrated parameters for the Enchanted Forest model resulted in parameters indicating slightly finer grained soils and slower drainage. However, simulations of scenarios with the calibrated parameters are not as definitive because the flow gradients are not as strongly south to north because of the bedrock high to the north of the road. Flow vectors with the calibrated parameters on day 42 show weak flows to the north, but mostly vertical flow (Figure 5-11). This geometry likely requires a 3-dimensional analysis to adequately evaluate the hydrologic processes. The Budd Creek transect was not developed into a numerical model, but the south to north elevational gradients and drainage rates suggest that it would behave in a 2-dimensional manner. The gradient and resulting drainage rates are very similar for the Budd Creek and Visitor's Center transects, with the change in water level with length of transect being 0.008 m/m and 0.014 m/m, respectively. Without constraints on the actual upper flow boundary conditions from the hillslopes, which were assumed to be zero as of June 1 for the Visitor's Center model on the basis of how rapid the wells drained, or differences in the lower boundary conditions, which were determined via inversions on properties, it is not possible to determine if any differences in the flow fields between the two locations are due to material properties or boundary conditions. On the basis of groundwater contours for the meadows, the down-meadow gradient is very small, less than 0.002 m/m. In addition, in the early part of the season, the south-north gradients are fairly perpendicular to the road on the south side of the river, and parallel to the Visitor's Center and Budd Creek transects, suggesting 2-D flows for those locations. Gradients for the Enchanted Forest transect are somewhat perpendicular to the road, but are likely influenced by local perturbations, such as the bedrock high apparent in Figure 5-3b. However, neither larger scale gradients or local perturbations are likely to create dominant 3-D patterns for the other two transects.

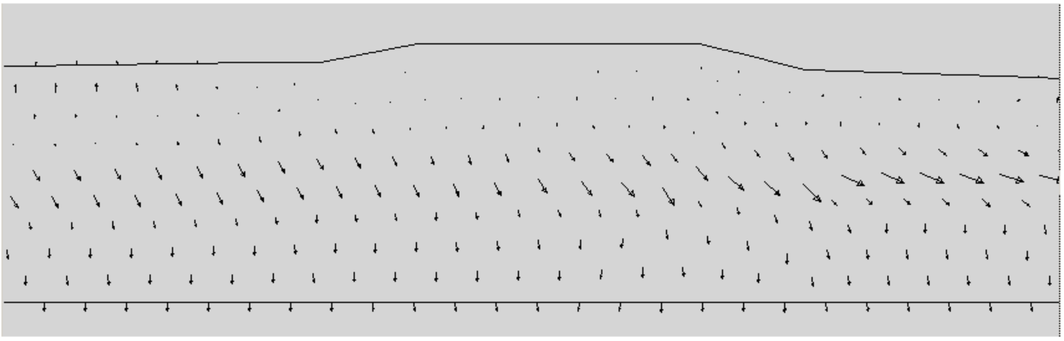

Figure 5-11. Flow vectors for Enchanted Forest model with calibrated parameters.

## *Summary*

A preliminary conceptual model of hydrologic processes in Tuolumne Meadows was formulated and aspects of how water flows north into the meadows were numerically tested to investigate the influence of the presence of Tioga Road on the flow field. Deliverance of snow melt to the meadows can be evaluated on the basis of surrounding topographic features and the up-gradient source area, with more water likely to be delivered to locations on the west end of the meadows than the east end where the source areas are smaller or water is diverted to channels, and the road is also further away from the hillslopes.

Ground penetrating radar data and well information were used to develop cross sections of geometry and materials for 3 transects that began on the south side of Tioga Road and extended northward. Two of the cross sections, one near the Visitor's Center, and one in the Enchanted Forest, were used to develop 2-dimensional numerical models, which were calibrated to changes in water levels in wells. Although the model in the Enchanted Forest was less conclusive due to the inability to represent the 3-dimensional nature of the location in a 2-D model, the Visitor's Center model represented the processes from snowmelt to mid-summer drainage. Parameters could not be calibrated without the inclusion of permeable underlying bedrock. The road, with more dense properties than the surrounding soils and extending to a meter in depth, was also included in the calibrated model. Lateral flow was exhibited through the road bed under saturated conditions and was diverted downward slightly during drainage. With zero permeability properties representing the road as a hydraulic barrier, the gradients became vertical and flow was downward through the bedrock. If road properties were the same as the surrounding soil, representing no road, flow moved laterally and downward through the profile, similar to the calibrated model.

## *Implications and Future Directions*

Many uncertainties exist in a modeling exercise such as this that may result in solutions that are not unique, whereby assumptions are canceling out each other to give the wrong answer. Constraints on this model, however, are relatively good. We do have a high level of certainty on the geometry of the domain and the upper atmospheric boundary conditions, the measured data provide a large range of hydrologic conditions, the resulting calibrated parameters are within reason, and the results are explicable. The assumption that the lower boundary conditions are influenced by the flow of groundwater through bedrock is supported by observations at Gin Flat, and by others' studies in the region. However, the extent and magnitude of this process is relatively uncertain. In Tuolumne Meadows it may be the most critical hydrologic characteristic to understand for the evaluation of the impacts of management practices on the hydrologic flow field, because, given the shallowness of the soil, this process by itself can negate the impacts of roads and other surface structures and features on the transmission of water to and within the meadows.

The characterization of hydrology that represents all the pertinent processes and scales can only realistically be done with rainfall-runoff modeling and subsequent groundwater modeling at that same scale. The pertinent processes and scales include hillslope delivery of snowmelt, and surface flow of water in the rivers, as well as the annual and historical variation in precipitation and air temperature. These processes demand the consideration of 3-dimensional analyses, and at the least, rainfall-runoff modeling, to elucidate the spatial distribution of hydrologic processes occurring in the meadows and the relative contributions of the various locations to the vegetative processes observed. On the basis of topographic analysis, observations of source area and spatial variation along the meadows can be deduced, but the ability to provide the quantification necessary to drive hydraulic gradients and establish environments coinciding with the growth patterns of lodgepole pines is limited.

# Chapter 6: **Summary and Synthesis**

## ***Summary***

The Tuolumne River drainage of Yosemite National Park is classified as a wild and scenic river, and the park is currently developing a River Management Plan to protect this outstanding natural resource. The most populous area of the Tuolumne River drainage is Tuolumne Meadows. Because Tuolumne Meadows serves as the major access point to the Yosemite high country, it has significant density of roads, infrastructure, and other development that have changed the flow of surface water to and through the meadows and appear to have altered meadow hydrologic processes, soils and vegetation. This project analyzed the surface and ground water levels and flows, soils and vegetation to produce a preliminary summary of impacts to the meadow. The entire meadow was studied with particular emphasis on anthropogenic impacts due to: 1) the Tioga Pass Road, 2) culverts, 3) the old road through the middle of the meadow, and 4) water diversions from the Dana Fork. Other impacts were identified, including: 1) climate change, 2) historic grazing, 3) fire frequency, 4) burrowing pocket gophers and voles, and 5) grazing deer. The following synthesis summarizes factors influencing the hydrology and vegetation of these meadows and offers preliminary recommendations for park management.

To carry out the analysis, surface water inflows to Tuolumne Meadow were quantified, and a rating curve was developed for the Tuolumne River at the Tioga Road crossing. Ground water levels were measured in 72 monitoring wells organized in 5 major and 6 minor transects. These data were used to produce ground water profiles in relation to ground surface elevation for each transect, as well as water table maps, and well hydrographs. A two-dimensional numerical model was developed in HYDRUS-2D using information collected from one groundwater transect, and calibrated to water level data. Six plant community types were identified for Tuolumne Meadows based upon an original data set of plant species composition and coverage for 72 plots centered over wells 1-72. Tree ring chronologies and growth rates were established from cores of 29 mature lodgepole pines along the shoulder of Tioga Road, and fire scars, tree thickets, and seedlings were also examined .

## ***Synthesis of Results***

Based on the findings of this study, the overall effect of the Tioga Road on Tuolumne Meadows groundwater and vegetation is limited. No groundwater transect showed obvious effects of the Tioga Road to block, intercept or alter the natural flow paths and elevations of ground water. Results from the calibrated 2D-model more closely matched the flow paths for simulations with no road than with an impermeable road, suggesting that the road's influence on subsurface transport is small. Well 17, just south of the old Tioga Road, appears to experience much higher water levels and a steeper gradient than other wells from June through August, suggesting that the old Tioga Road may be blocking water transport from the south to the north of the meadow in this region.

Tree-ring records from other meadows in the region, together with records developed in and immediately adjacent to Tuolumne Meadows, indicate that episodes of lodgepole pine recruitment occurred in 1905-1940, 1945-1976, and 1996-2000. The timing of these episodes does not coincide with the 1933-1937 construction of Tioga Road. Trees had established in Tuolumne Meadows prior to road construction, and continued to establish after the road was built. Lodgepole pine invasion at Tuolumne Meadows is linked to periods of low precipitation and low year-to-year variability in moisture conditions. Because the timing and location of managed tree removal activities at Tuolumne Meadows since approximately 1933 is largely unknown, the current findings do not provide a complete picture of lodgepole pine dynamics in the meadow. For example, it is not known if earlier tree establishment episodes would have persisted to the present in the absence of managed tree removal activities.

While the timing of tree invasion episodes at Tuolumne Meadows appears to be driven by regional climate, Tioga Road has promoted local impacts on tree growth. Mature lodgepole pine trees that established prior to the construction of Tioga Road, and that currently grow immediately adjacent to both sides of the road, exhibited increased growth rates from 1939 to 1948. This pattern is not seen in trees elsewhere at Tuolumne Meadows. The increased growth rates appear to be due to edge effect environmental changes associated with the construction of Tioga Road.

Tree thickets found approximately 10m to 25m south of the paved edge of Tioga Road are apparent because of their high stem density condition and distinct parallel alignment with the road. In addition, growth rates in the thicket trees are less than those found in meadow invasion trees or other mature trees in the area. Localized ponding conditions or other factors imposed by Tioga Road may be associated with increased stem densities and decreased growth rates at thicket locations. The timing of tree thicket development corresponds with the timing of meadow invasion episodes (i.e., associated with regional climate). Distinct, narrow lines of small lodgepole pine trees growing at locations within 2m of the paved edges of Tioga Road also appear to be associated with roadway disturbance. Similar to the tree thickets, development of these narrow lines of trees corresponds with the timing of meadow invasion episodes.

Numerous small inflows of water from the south are blocked by the Road, producing blocked drainage paths in 12 locations, and signs of ponding water in 23 locations south of the road. The Tioga Road through Tuolumne Meadows has 35 culverts, which allow surface water flowing from the slopes south of the meadow to drain into the meadow. Several culverts forced previously dispersed runoff into localized channels, and downcutting was evident downstream of many of the culverts. Because the slopes south of the meadow supply a large portion of water to the meadow, surface water from culverts, most notably Unicorn Creek and Budd Creek, provide a source of groundwater recharge to the meadows, resulting in locally higher water levels near the streams. Downcutting may decrease recharge from surface water to meadow groundwater since it lowers the water table in the downcut streams.

Aside from the road, many other factors are influencing the meadows. Meadow vegetation appears to be influenced by historic grazing by sheep, current grazing by deer on willows, and pocket gophers and voles churning up the soil Most the communities have a discontinuous cover of perennial plants, with broken sods and tussocks, and high cover of bare ground. Several communities have high soil organic matter that accumulated over long time periods from vegetation with high below ground biomass production, and high water tables. While the high water tables still occur in wet years, as measured during 2006, these communities do not support vegetation with high below ground biomass or dense root and rhizome systems that could have produced the soils. The incomplete vegetation in these stands may be perpetuated by intense levels of pocket gopher and vole activity which produces the bare ground. The abundance of bare and relatively moist soil may be the key to lodgepole pine establishment and survival. The cause of meadow vegetation degradation is likely not the Tioga Road, but either uncontrolled 19th century sheep and cattle grazing, or natural processes of climate change. This meadow degradation provides bare ground that is essential for past and ongoing tree establishment.

Climatic change also has a strong influence on meadow hydrology and vegetation. Studies in meadows across the Sierra (with and without roads, and with different grazing histories) indicate a large synchronous pulse of tree invasion during the 20th century, correlated with regional climate. Current water diversions from the Dana Fork of the Tuolumne River are less than 1% of discharge through most of the summer and a maximum of 10% of discharge at low flows. Warming temperatures could result in earlier snowmelt and lower late-summer streamflows, such that diversions from the Dana Fork could constitute a larger fraction of Tuolumne River discharge over a longer period of time. Given that Unicorn Creek and Budd Creek recharge the meadow groundwater tables, climatic shifts leading to these streams drying out earlier in the season will result in earlier drops in meadow groundwater tables. Because the Tuolumne River recharges the meadow groundwater at many locations, lower late-season flows in the Tuolumne River will also result in less available meadow groundwater.

A preliminary investigation of fire history suggests that relatively frequent fires burned along the south edge of Tuolumne Meadows prior to the mid 1800s. Both natural and anthropogenic fire ignition sources are possible. Since the mid 1800s, fires appear to have been largely absent. It is not known if the meadow burned during these fires or if the change in fire frequency has impacted the structure or composition of vegetation in the meadow.

## Recommendations

Road impacts on the meadow were few and appear localized. A number of culverts were blocked with debris and sediment and should be cleaned for optimal functionality. Well 17, just south of the old Tioga Road (now the trail to Parson’s Lodge), is the only well that appeared to experience blocked subsurface discharge. This was the only well positioned to measure blockages from the old road, so more wells near this road are needed to detect if the entire old road is interrupting flow or if this effect is localized to the vicinity of Well 17.

Overall, results from this study recommend future research that will result in 1) understanding what factors control changes to meadow vegetation, including lodgepole pine establishment, and 2) understanding how changing climate and park management practices will influence these factors. Specific recommendations for further study are detailed below.

To understand meadow invasion by lodgepole pines, field and laboratory experiments are needed to determine the ability of lodgepole pine to germinate and establish on soils with different hydrologic regimes, including differing flood frequencies and summer water table depths, and the role of bare soil on tree establishment. Managed tree removal activities have made it hard to document environmental conditions that result in tree mortality in the meadow. It is recommended that several permanent plots that extend from the forest margin to the meadow center be established, and that these plots be excluded from future managed tree removals. In addition, by specifying the structural characteristics of the forest-meadow edge, and establishing precise survey locations at several locations in Yosemite National Park, forest dynamics and meadow invasion patterns can be more highly resolved. Such an approach could potentially be used to delineate different zones of sensitivity in Tuolumne Meadows with respect to climate change and disturbance events.

Relatively frequent fires occurred along the south edge of Tuolumne Meadows between the early 1700s and the mid 1800s. Since the mid 1800s, fire disturbance has been largely absent. This change in fire frequency may have resulted in large changes in the meadow vegetation community as well as changes in lodgepole pine meadow invasion patterns. Work should be done to establish if and how fires modify the meadow environment or result in the mortality of seedling pines. By identifying spatial and seasonal fire patterns it may also be possible to identify the relative impacts of natural and anthropogenic fires, particularly fires that occurred prior to the 19th century.

More work is needed to understand how all vegetation will respond to changes in hydrology. Work is needed to determine which areas of the meadow and respective vegetative communities are most and least sensitive to changing groundwater levels. Field and laboratory analyses of soils to analyze not only pollen, but macrofossils and phytolith, should be used to determine which species were most common when the highly organic meadowsoils were formed, to test if vegetation community shifts were associated with late 1800's grazing activities. Restoration techniques should be developed that could be used to restore the vegetation composition, below ground biomass, soil forming processes, and stability of the pre-historic meadow vegetation.

The Tuolumne River appears to be widening considerably because its banks have little or no woody vegetation to prevent erosion. Point bars are forming, and while these are prime willow habitat, they are not covered by willows. Existing willow throughout the meadow are largely cropped and short, due to browsing by deer. Most of the willows present in the study area are precocious, meaning that the flowers appear on last years stems. Thus, if last year's stems are eaten by deer, seed production may be severely limited. A detailed study of willows is needed to understand what is limiting their establishment and persistence in the study area. The relation of stream width on groundwater recharge should also be examined.

Climatic warming is a threat to Tuolumne Meadow's late-season water supply and will affect groundwater levels and vegetation across the meadow. Because Parker Pass is the primary contributor to the Dana Fork's water supply during the late summer and fall, the Parker Pass drainage, including the rock glaciers and permanent snowfields on the Kuna Crest should be carefully studied to better anticipate how they will respond to warmer temperatures. The effects of earlier snowmelt, earlier drying out of ephemeral streams, and lower water levels on meadow groundwater levels should also be examined.

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