University of Nevada, Reno

Created Ponds as Indicators of Restored Sierra Nevada Meadow Hydrology

A thesis submitted in partial fulfillment

of the requirements for the degree of Master of Science in Hydrology

by

Adam M. McMahon

Dr. Sherman Swanson, Thesis Advisor

August, 2013

University of Nevada, Reno
Statewide • Worldwide

THE GRADUATE SCHOOL

We recommend that the thesis
prepared under our supervision by

ADAM McMAHON

entitled

Created Ponds as Indicators of Restored Sierra Nevada Meadow Hydrology

be accepted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

Sherman Swanson, Ph. D., Advisor

David Prudic, Ph. D., Committee Member

Scott Tyler, Ph. D., Graduate School Representative

Marsha H. Read, Ph. D., Dean, Graduate School

August, 2013

Abstract

Stream degradation has led to extensive restoration of wet-meadow systems in the Sierra Nevada. Pond-and-plug restoration reconnects the stream with its historic floodplain and dams eroded gullies, which then fill with water, creating a series of ponds. Elevated groundwater tables and stream flooding return natural function and wet-meadow vegetation. Little research has examined the impacts of these anthropogenic ponds on the hydrology of meadows, and ponds may represent a potential loss in the water budget via evaporation. In addition, ponds provide an opportunity to study proposed hydrologic models of groundwater flow in meadows. Meadows may act as a "sponge, valve, or drain" by absorbing and then releasing groundwater through the season, by recharging the meadow with groundwater through springs, or by allowing percolation of groundwater to deep aquifers. We measured groundwater and pond surface elevations and ponds' areas along with above and below meadow stream flow through a summer following a winter with 30% less snowpack than average. While total meadow pond evaporation was significant, it accounted for less than 10% of total meadow ET. Individual pond evaporation accounted for 40-70% of measured pond declines with the remaining decline attributed to seepage to meadow groundwater, as no surface outflow occurred in selected study ponds. Pond and piezometer decline were highly correlated, with R-squared values generally > 0.9. Spatial and temporal variations in pond elevations indicate possible areas with and without groundwater inflow into meadows. Groundwater storage, inflow, and outflow was evident, but most meadows exhibit heterogeneity in groundwater flow. Prior to historic incision, some meadows may have

had only seasonal outflow. The periods and amounts of augmented base flow from restored meadows vary among project areas.

Acknowledgements

I would like to thank Sherman Swanson and the Hydrology Program at the University of Nevada, Reno for the opportunity of higher education and research in the field of hydrology. In addition, I would like to thank Dr. David Prudic and Dr. Scott Tyler for participating in my thesis committee. This project never would've happened without Jim Wilcox (Feather River Coordinated Research Management) and Rick Poore (StreamWise) practitioners in meadow restoration. They provided invaluable background data and access to study areas, not to mention overall wisdom. Joe Hoffman and Randy Westmoreland (United States Forest Service) also provided background information, and coordinated access to Forest Lands. U.C. Merced kindly shared data on meadows concurrently being studied. Lastly, I would like to sincerely thank Don Lindsey, Herb Jasper, and Tim Lakey for arranging access to private lands, and sharing their knowledge and history. I would also like to thank Barry Hill (United States Forest Service), for providing funding through California Department of Water Resources and the National Fish and Wildlife Foundation, in addition to knowledge and drive for this research. Lastly, I would like to thank the Sierra Nevada Conservancy for funding.

Table of Contents

List of Tables

List of Figures

1. Introduction

Historical land use practices have caused degradation in many meadow ecosystems in the Sierra Nevada. These practices often result in gully formation that initiates a sequence of events resulting in the loss of hydrologic and ecologic function. Gullies lower the groundwater table and confine stream flows, causing increased peak flows and stream bank erosion, decreased groundwater storage and the demise of wet-meadow vegetation (Heede 1979; Swanson et al. 1987; Loheide et al. 2009; Loheide and Booth 2011). This widespread degradation has led to a legacy of environmental impacts affecting local and regional watersheds in the Sierra Nevada. Restoring these ecosystems is a major effort by Federal, State, and local organizations. Feather River Coordinated Resource Management (FRCRM) pioneered the widely applied restoration technique known as pond-and-plug. Using construction techniques and natural channel design (Rosgen 1996; Lindquist and Wilcox 2000), many degraded meadows in the Sierra Nevada have been returned to a historical functioning condition.

In pond-and-plug restoration, surface water flows at the head of a degraded reach are diverted into a remnant or constructed channel, returning the stream to a natural flooding regime. A higher water table elevation is established and combined with frequent floodplain inundation the groundwater table rises to near historic levels (Hammersmark et al. 2008). This higher groundwater table fills the adjacent gully, which is plugged using local soil and alluvium to prevent drainage and further erosion, transforming the gully into a series of ponds. Reconnecting the stream to its floodplain and elevated groundwater leads to reduced sediment loads and flood attenuation, increased groundwater storage, and recruitment of wet-meadow vegetation

(Hammersmark et al. 2008; Loheide and Gorelick 2005; Tague et al. 2008; Hoffman et al. 2009).

In addition to environmental benefits, pond-and-plug restoration provides many watershed services beneficial to humans, such as flood attenuation and decreased sediment loads, and possibly increased stream base flows. Base flows result from groundwater released from aquifers or riparian sediments (Lowry et al. 2010; Winter 2007). These base flows coincide with hot, dry conditions when water is most needed for irrigation and plant and animal use, making it the most valuable water of the year (Loheide and Gorelick 2006). To increase base flows, managers have used a variety of methods to augment stream flows via increased riparian storage (Swanson et al. 1987; Ponce and Lindquist 1990). Studies specific to pond-and-plug have found similar benefits using a variety of measurement methods, such as temperature and stream gauging (Tague et al. 2008). These findings have led to proposals to restore meadows as opposed to building reservoirs to supplement water supplies (NFWF 2010).

However, contradictory research and personal observations have indicated that pond-and-plug restoration can have either no effect, or even worse, a detrimental effect on late summer persistence of base flows (Hammersmark et al. 2008; Tague et al. 2008; Hoffman et al. 2009). Reasons include: a new raised channel bed that no longer drains groundwater to the same extent, modified groundwater flow paths, and evapotranspiration losses (Hammersmark et al. 2008). A significant part of wet-meadow water budgets, evapotranspiration, doubled from 1.5-4 mm/day to 5-6.5 mm/day after restoration (Loheide and Gorelick 2005) and increased in duration through the dry season (Hammersmark et al. 2008). This increase in evapotranspiration is attributed to increased transpiration from returning wet-meadow vegetation and evaporation from pond water surfaces. While pond-and-plug restoration has successfully reached many of its objectives, one anticipated benefit, increased base flows, may not always persist into late summer because of the elevated channel, increased evapotranspiration (ET), and altered flow paths (Hammersmark et al. 2008).

One important hydrologic process is surface and groundwater interactions. Surface water and groundwater interactions are well established (Baxter et al. 2003; McCallum et al. 2012; Ferone and Devito 2004; Prudic et al. 2005) and any modification in the hydrologic regime of either system can modify these interactions (Sophocleous 2002). Pond complexes, an artificial feature created during restoration, are likely interacting with meadow groundwater and streams. However, little study has focused on the hydrology of these created ponds, and how they interact with ground or surface waters. Thus, constructed ponds represent an enduring feature of the meadow landscape that may influence the hydrologic regime of these restored meadow systems.

Ponds may interact with meadows in a variety of ways. Water from ponds may seep into underlying groundwater, groundwater may discharge into ponds, or groundwater may discharge into one pond edge and seep back into the groundwater on another pond edge (Ferone and Devito 2004; Prudic et al. 2005; Hill and Neary 2007; Turner and Townley 2006; Westbrook et al. 2006). These interactions may change with season, pond to pond, meadow to meadow, and even as the ponds age and fill with finer sediments (Ferone and Devito 2004; Prudic et al. 2005). Regardless of the interaction, ponds and ET may capture water prior to it being discharged to a stream, thus reducing the quantity of base flow in a stream.

Variation in local meadow properties may influence base flows and base flow augmentation (Ponce and Lindquist 1990). Loheide et al. (2009) proposed that the rate and distribution of regional groundwater flow and hydraulic properties of meadows are the major factors influencing groundwater flow beneath meadows. For instance, meadows containing low-permeability materials may influence groundwater flow differently than meadows with high-permeability materials (Hill and Mitchell-Bruker 2010). Three conceptual models, termed “sponge, valve, and drain”, have been proposed to describe groundwater flow in mountain meadows (Fig 1).

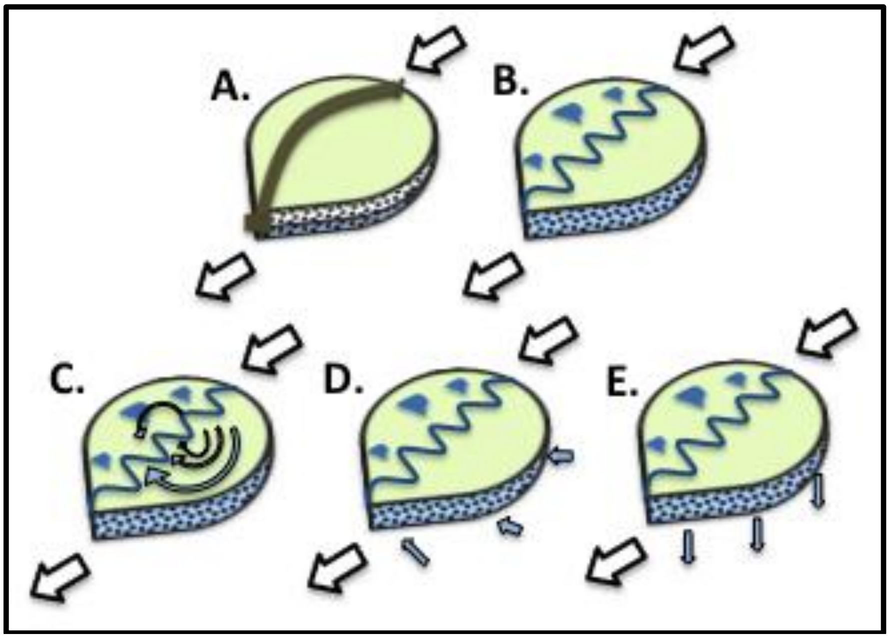


Figure 1. Diagram of Sierra Nevada meadow conceptual models with arrows representing water flow. Meadow A represents an un-restored meadow with a gully, where surface water enters and leaves the meadow with minimal delay. Meadow B represents a restored meadow, with elevated groundwater levels, ponds, and a restored stream channel. Meadow C represents the sponge conceptual model, where incoming stream flow fills the local meadow sediments via flooding and bank storage, and moves down through the meadow, later being released as stream base flow. Meadow D represents the valve conceptual model, where incoming groundwater from outside the meadow is controlled by low hydraulic conductivity sediments and contributes to the meadow water budget. Meadow E represents the drain conceptual model, where the meadow loses water out to surrounding aquifer, reducing the meadow water budget.

Pond-and-plug restoration creates a stream channel that floods annually during peak discharge from snowmelt runoff. Flood water moving down the meadow, also percolates laterally (Pinder and Sauer, 1971) and vertically (Hammersmark et al. 2008) into the stream bank and meadow sediments. Aquifer recharge reduces flood peak and sustains base flows as the flood peak recedes and storage was not thought to occur in unrestored, gullied meadows, or only on a small scale (Hammersmark et al. 2008). Vertical floodplain storage (Hammersmark et al. 2008) is the main component of the sponge conceptual model and was demonstrated at the Trout Creek meadow restoration (Tague et al. 2008). This process, and conceptual model, provides a reason to restore degraded meadows using the pond-and-plug technique. The sponge conceptual model (and pond-and-plug restoration in general) modifies the timing of surface flow moving through the meadow, modifies the portion of the meadow aquifer available for recharge and discharge (by elevating water table surface and channel bed), and increases ET.

The valve and drain models examine the influence of outer-meadow, or regional, groundwater inflow or outflow from the meadow. In the valve model, fine meadow sediments have an hydraulic conductivity lower than surrounding bedrock or coarse sediments (Hill 1990). These fine meadow sediments restrict groundwater inflow, slowing it down and maintaining groundwater inflow through the summer season. This inflow would again positively affect stream base flows unless consumed by ET. Conversely, in the drain model, the meadow has coarse sediments, which are again connected to a groundwater system. However, the flow paths are such that water flows out of the meadow as groundwater outflow. This groundwater outflow has a detrimental effect on stream base flows.

Examining hydrology in light of these proposed models can develop understanding about groundwater flow through meadows and may influence pond-and-plug implementation. Anthropogenic ponds provide convenient access to groundwater levels, are distributed through the long axis of meadows, and represent a possible sink for base flows that requires further understanding. This research seeks to augment a larger study examining Sierra Nevada meadow hydrology, conceptual groundwater flow models, and pond-and-plug restoration.

1.1 Purpose and Objectives

To further understand the hydrology of restored meadows we examined three main objectives:

1. Examine pond surface water interaction with groundwater and stream water;
2. Use pond water levels and pond-groundwater interactions to evaluate the three conceptual meadow models;
3. Examine variability among restored meadow flow paths and site characteristics that may influence meadow-to-meadow differences.

2. Environmental Setting

Selected study meadows are located in northern California where many pond-and-plug projects have been completed (Fig 2). Whereas the population of pond-and-plug projects is fairly numerous, to study groundwater flow in meadows using ponds required that at least three consecutive ponds were unconnected from surface flow for the majority of the year. Only nine meadows without limitations on logistics and access met this criterion because of design or channel migration resulting from natural or beaver processes.

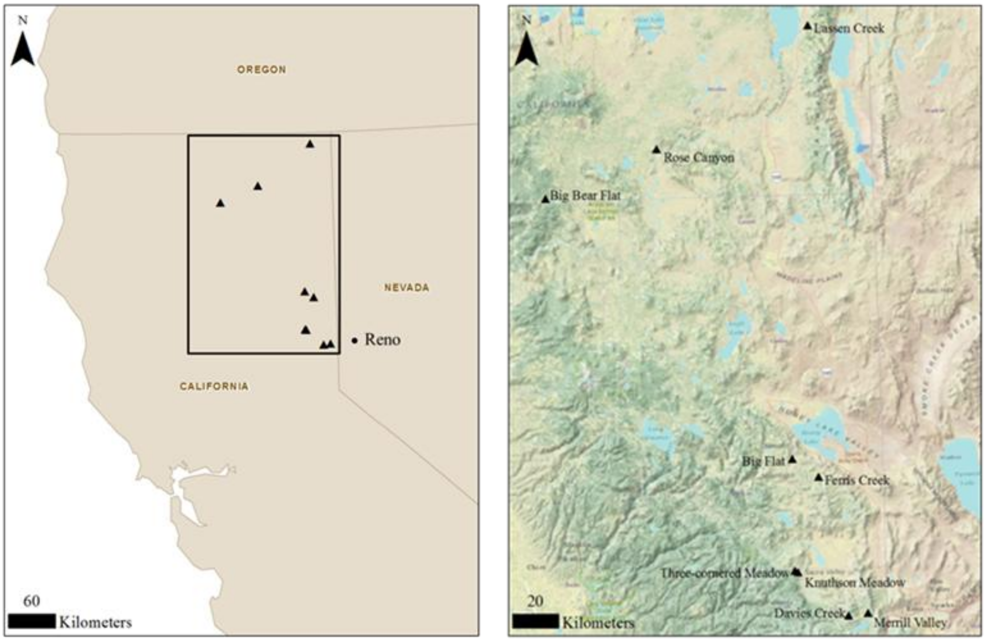


Figure 2. Overview map of study area and specific locations of restored meadows selected for study.

All study sites are located north of Lake Tahoe, generally in the Sierra Nevada (Fig 2). In the Sierra Nevada, six meadows are located on the Plumas and Tahoe National Forests. Farther north, three meadows were located on private lands adjacent to Shasta, Modoc, and Lassen National Forests. All meadows are located in mountainous areas, with the majority of precipitation occurring as snow. Hydrologic processes are snowmelt driven, with the highest stream flow and water table elevations occurring in spring and early summer, coinciding with peak snowmelt runoff. Dry and hot conditions follow through the summer, causing high ET rates that reduce streams and groundwater to base levels.

2.1 Climate

Meadow elevation and mean precipitation and temperature varied among sites (Table I). Precipitation, including snow and rain, varies from year to year by as much as 50 cm at some meadows (Soil Survey Staff). 2012 was a dry year, with annual snowpack

~30% less than the historical average (http://cdec.water.ca.gov/cdecapp/snowapp/swcchart.action). Total snowpack for water year 2012 at Truckee, CA, was ~55 cm (http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=834&state=ca). Temperatures vary widely through the year, with winter temperatures dropping below 0°F, and summer highs exceeding 100°F (http://www.raws.dri.edu/index.html).

Site	Elevation (m)	Mean Annual Precip. (cm)	Mean Annual Air Temp. (°F)
Big Bear	1,233	58	43
Big Flat	1,740	127	
Davies	1,989	116	46
Ferris	1,773	59	
Knuthson	1,512	114	46
Lassen	1,570	39	47
Merrill	2,019	114	46
Rose Canyon	1,392	50	47
Three-cornered	1,532	114	46

Table I. Elevation and average climatic attributes for meadow study sites (Soil Survey Staff).

2.2 Geology and soils

Bedrock geology is generally tertiary volcanic rocks composed of andesite and basalt (Table II). The bedrock saturated hydraulic conductivity (K_{sat}) is generally low, with minimum values of 10^{-5} m/day, but highly fractured volcanic basalts can have much higher values of 10^3 m/day (Hill and Mitchell-Bruker 2010). Hill and Mitchell-Bruker, 2010, complied a range of values for K_{sat}, which were used in this study. The majority of meadows have silty clay loam or coarser soil (Table III) for 1 m or more (Soil Survey Staff) over even coarser subsoils generally composed of alluvium, gravels to finer-grained sandy and silty loams. K_{sat} for silty clay loam is low, on the order of 10^{-2} m/day

(Loheide et al. 2005), whereas K_{sat} values for coarser alluvium vary from 10^2 to 10^4 m/day (Hill and Mitchell-Bruker 2010).

Site	Bedrock Geology	Legend	Min. K_{sat} (m/day)	Max. K_{sat} (m/day)
Big Bear	Q, alluvium, terrace; Qv, andesite, basalt	alluvium; Quaternary volcanic flow rocks	10^{-5}	10^{3}
Big Flat	Tv, andesite, basalt	Tertiary volcanic rocks	10^{-5}	10^{3}
Davies	Ti, andesite, basalt	Tertiary intrusive rocks	10^{-5}	10^{3}
Ferris	Q, alluvium, terrace; Tvp, andesite, rhyolite	alluvium; Tertiary pyroclastic and volcanic mudflow deposits	10^{-4}	10^{-2}
Knuthson	grMz, granodiorite, quartz monzonite	Mesozoic rocks	10^{-4}	10^{-2}
Lassen	Tv, andesite, basalt	Tertiary volcanic rocks	10^{-5}	10^{3}
Merrill	Tv, andesite, basalt	Tertiary volcanic rocks	10^{-5}	10^{3}
Rose Canyon	Tvp, andesite, rhyolite	Tertiary pyroclastic and volcanic mudflow deposits	10^{-5}	10^{3}
Three-cornered	Tv, andesite, basalt	Tertiary volcanic rocks	10^{-5}	10^{3}

Table II. Geology of areas surrounding meadow sites with saturated hydraulic conductivity (K_{sat}) values from (Hill and Mitchell-Bruker 2010). Geology was determined using ArcMap layers created by the USGS from the Geologic Map of California (Jennings et al. 1977).

A range of specific yield (S_y) values is also included for each soil type. S_y is the volume of water released from storage per unit land surface area per unit drop in the water table (Freeze and Cherry 1979). S_y can be estimated by subtracting the water content retained in a soil after gravity drainage (Θ_r) from the saturated soil water content (Θ_s), or Θ_s-Θ_r (Loheide et al. 2005). However, release of water does not happen instantly nor as an abrupt change from saturated to drained. S_y increases with water table depth, hydraulic conductivity, and duration of drainage (Loheide et al. 2005; Nachabe 2002). S_y could increase with depth in meadows, as meadow alluvium often become coarser at depth (Soil Survey Staff). Loheide et al. (2005) found S_y on shorter time scales to actually be much lower than Θ_s-Θ_r, and calculated a readily available S_y (S_y (avail.)), which represents S_y on a 12 hr diurnal drainage cycle common in most meadow systems. Because S_y was not specifically calculated in each meadow, both of these values are included to provide a range of possible values for actual soil types in each meadow.

Site	Meadow Soils	Texture	K_{sat} (m/day)	S_y (avail.)	S_y (θ_s-θ_r)
Big Bear	Esro silt loam	silt loam, silty clay loam	0.11	0.04	0.38
Big Flat	Goodlow-Haplaquolls complex	gravelly sandy loam	2.42	0.26	0.34
Davies	Aquoll and Borolls	siltly clay loam	0.02	0.01	0.34
Ferris	Sattley-Fopiano	gravelly loam, cobbly loam	0.31	0.26	0.35
Knuthson	Aquoll and Borolls	siltly clay loam	0.09	0.01	0.34
Lassen	Calimus loam	loam	0.78	0.08	0.35
Merrill	Aquoll and Borolls	siltly clay loam	0.02	0.01	0.34
Rose Canyon	Aquolls	siltly clay loam	0.02	0.01	0.34
Three-cornered	Aquolls and Borolls	siltly clay loam	0.02	0.01	0.34

Table III. Meadow soils and associated textures (Soil Survey Staff). Hydraulic conductivity and specific yield (S_y) values taken directly from (Loheide et al. 2005). Available is readily available yield for shallow water tables and (θ_s-θ_r) is soil saturation – specific retention.

2.3 Meadow Characteristics

In the Sierra Nevada, meadows form in areas that accumulate fine-textured sediment and establish a shallow water table (Ratliff 1985; Weixelman et al. 2011), especially where a large drainage area meets a low gradient slope (Ratliff 1985). Hydrogeomorphic processes control water sources and movement and have been used to separate meadows into specific types (Weixelman et al. 2011). Riparian meadows form along defined stream channels where flooding and sediment deposition occur. Subsurface flow meadows lack defined stream channels, occur on alluvium or colluvium, and act as a through flow groundwater system. The groundwater table is at a shallow depth below the land surface, likely because of an inflection in the land surface slope.

Using Weixelman et al., (2011), the Big Bear and Lassen meadows had perennial streams and low gradients, making them riparian low gradient meadows. The Big Flat, Davies, Ferris, and Rose Canyon meadows had stream channels throughout the majority of the meadow, but all were intermittent during 2012. With a gradient of 2%, these meadows could be riparian middle gradient. The Knuthson, Merrill, and Three-cornered meadows had stream channels entering and leaving the meadow, but lacked a defined channel through the majority of the meadow. These meadows are subsurface low middle gradient meadows. However, the presence or absence of a continuous stream channel may reflect restoration design and not prehistoric hydrogeomorphic processes. Therefore, individual sampled meadows may be mixtures of riparian and subsurface flow, which also occurs in pristine conditions (Weixelman et al. 2011).

All meadows were located in areas with historic anthropogenic land use, such as logging, railroads, and grazing. These land use practices, in conjunction with large storm events, contributed to gully formation and disturbance of natural hydrologic processes. All meadows were restored using the pond-and-plug technique (Lindquist and Wilcox, 2000), generally from 2000-2010 (Table IV). The Big Flat meadow, was initially restored in 1995, but had stream channel modifications in 2004 to further increase bankfull flooding.

Meadows vary in area and width, with size and design considerations resulting in variation in pond numbers and pond area. The Merrill Valley meadow has in excess of

40 ponds because of multiple pre-restoration gullies. In contrast, the Big Bear meadow has much fewer, larger ponds. Appendix A contains aerial photos of study meadows.

Site	Gradient	Meadow Width (m)	Meadow Area (m^2)	Restoration Date	Gully Depth	Study Ponds	Total Pond Area (m^2)
Big Bear	1%	840	950,656	2009	2.20	6	34,623
Big Flat	1%	231	149,686	1995, 2004	2.76	7	5,979
Davies	2%	46	15,575		1.07	4	429
Ferris	2%	259	175,053	2004	3.02	9	3,812
Knuthson	1%	385	685,676	2001	2.74	15	22,416
Lassen	1%	150	164,571	2005	1.86	25	11,248
Merrill	3%	365	172,253		1.91	24	6,461
Rose Canyon	2%	262	171,050	2010	1.88	11	4,534
Three-cornered	1%	200	116,186	2002	1.90	8	6,175

Table IV. Geographical and historical attributes of restored meadows selected for study.

3. Data Collection and Analysis Methods

3.1 Water elevation

Selected elevations of streams, groundwater, and ponds were surveyed three times in 2012 approximately in July, August, and September. Elevations were surveyed using a Trimble Model LL300 Spectra Precision Laser and standard survey techniques. At each site, a downstream (DS) benchmark was established. This benchmark represented zero elevation and the starting point for every survey in each meadow. An upstream (US) benchmark was established where every survey was completed. The elevation difference between the benchmarks was used to ensure the accuracy of elevation measurements. If the elevation difference for each survey were within 10% of each other, then the surveys were considered accurate. However, every survey for each site was within 5%, with the majority of sites within 1%. The standard deviation for the total elevation change in each meadow, measured during each pond elevation survey, was generally low, 0.02 meters (m), but some sites closer to 0.3 m.

Water levels were measured at selected ponds, stream staff sites, and two groundwater locations, located upstream and downstream in each restored meadow. Occasionally, stream staff sites also functioned as benchmark locations, but effort was made to locate benchmarks off channel. Surface water elevations were measured at the edge of water, near stilling wells if installed, or wherever convenient. Groundwater elevations were adjusted from surveyed surface elevation at the piezometer. During the elevation surveys, a depth to water (DTW) measurement was taken using a DTW tape. Later, groundwater elevation was calculated by subtracting DTW from the piezometer case height and surface elevation.

In addition to elevation, selected water survey locations were surveyed using a Trimble Nomad handheld computer/GPS and the program SOLO Field. Locations were taken in Universal Transverse Mercator coordinate system (UTMs). The easting and northing coordinates were used as x- and y- values to calculate valley distance. The downstream benchmark was considered zero, and the Pythagorean Theorem ($c = \sqrt{(a^2+b^2)}$) was used to calculated valley distance upstream from the downstream benchmark. Valley distance was used to plot water elevations of ponds through time at each meadow.

3.2 Data Loggers

In addition to surveying water elevations in July, August, and September, some water elevations were continuously monitored using pressure transducers installed in stilling wells. For surface waters, stilling wells were constructed of 5 ft (1.524 m) lengths of 1¼ inch (3.175 cm) PVC, drilled with holes to allow filling and draining. Stilling wells were attached to steel fence posts driven into stream or pond sediments. One-meter staff plates with 1 cm increments were attached to the stilling wells for depth reference (Fig 3).

Figure 3. Example image of water level logger installed in staff gauge in a selected monitoring pond.

Groundwater elevations were monitored using shallow piezometers. Piezometers were constructed from 5 ft 1.524 m sections of 1¼ inch (3.175 cm) PVC, threaded at one end and allowing attachment of metal drive points (Figure 4). For connection with the local aquifer, the first 0.30 m of the piezometer from the drive point was slotted by drilling 84 evenly spaced ¼ inch (0.635 cm) holes. Piezometers were installed in meadow sediments using a 1 inch (2.54 cm) rolled steel bar and post pounder. The steel bar was slid inside the piezometer and pounded against the inside of the drive point. Piezometers were generally driven at least 1.3 m deep, leaving a short case above ground.

Once placed, piezometers were primed by pumping with a peristaltic pump. Piezometers were pumped until either dry or discharge became clear. Since recharge rates were often slow, and piezometers small, piezometers were generally pumped dry once or twice to ensure connection with local shallow groundwater.

Figure 4. Image of piezometer prior to installation in meadow sediments. Staff plate is 1 m long for reference.

In each piezometer and stilling well, an In-Situ Rugged Troll 100 pressure transducer water lever logger was suspended 1-2 cm off the bottom by hanging it from a 1¼ inch (3.175 cm) PVC end cap using steel wire. Using In-Situ software, loggers were set to record pressure, water depth, and temperature at 15-minute intervals. Near each meadow, an In-Situ Barotroll 100 barometric pressure transducer was installed above water surfaces to record barometric air pressure, later used with In-Situ Baromerge software to correct pressure transducer data.

At least five water loggers were placed at each site, upstream and downstream of the restored meadow in the streambed, upstream and downstream piezometers, and one logger in a central pond. Several initially screened study sites were determined to be unsuitable, allowing excess loggers for installation in more ponds. Therefore, some sites had multiple monitoring ponds, with loggers located upstream and downstream, generally adjacent to piezometer locations (Fig 5). Appendix A contains the locations of monitoring loggers in all study meadows.

Following a season of monitoring, logger water depths were converted to water elevation by matching surveyed water elevations to logger depths at that date and time.

Figure 5. Typical installation configuration of loggers in study meadows, with one upstream and downstream staff, two pond staffs, and two piezometers adjacent to ponds and between ponds and stream channel.

Logger water depth was adjusted to meadow elevation by adding or subtracting an adjustment value, making the logger depth equal to water elevation. Ideally, a three point relationship was used to create a rating curve converting depth to elevation. However, because of deep draining of the meadows through the dry season, many groundwater piezometers and stream stilling wells became dry, and some pond stilling wells required progressive movement to deeper locations to keep logger under water. Therefore, often only one or two elevation points were available to convert depths to adjusted elevation.

However, points generally agreed within 1-2 cm, and staff depth values were used to verify logger depths and ensure that internal logger calculations did not vary with time. Once pond and groundwater hydrographs were created, relationships between pond and groundwater elevations were assessed visually and by linear trend lines and associated R-squared values.

3.3 Discharge

Discharge was measured upstream and downstream at each site near stilling well locations. Velocity was measured using a Marsh-McBirney 201D Portable Water Current Meter, and discharge was calculated using standard techniques (Rantz and others 1982), which are described in Appendix B. When possible, discharge was measured three times during the season, during which depth and time were recorded. These values were used to create a rating curve for discharge and depth, which was then combined with logger depth data to create a seasonal hydrograph. However, because many systems were intermittent due to a low snowpack, only two sites had measurable flow for the full period of record. Even in flowing streams, stream conditions sometimes caused violation of standard survey techniques, such as more than 10% of the flow contained in less than 10% of the channel. As such, discharge errors are considered high.

3.4 Pond Area

During elevation surveys pond areas were also measured. Generally, ponds with diameters less than 10 m were measured using a distance tape and stakes. In this method, the longest width of the pond was measured, and then the longest pond width perpendicular to that axis was measured. These values were used with standard area equations to calculate pond area. Generally, pond areas were oval, but some ponds had rectangular or triangular shape, and in these instances area equations for these shapes were substituted.

In larger ponds, or ponds with irregular shapes, area was measured using the Trimble Nomad and mapping program SOLO Field. Pond areas were mapped using the "area" function, with numerous GPS points taken around the perimeter of the pond. Once the perimeter was mapped, SOLO Field calculated the enclosed area. The accuracy of this method depends on the GPS connection and accuracy, which is generally good in open meadows. Error in SOLO Field areas was estimated at 17%. A square area was established using a distance tape that was surveyed five times with SOLO Field. Then, percentage error was calculated ((actual area-survey area)/actual area)x100) for each survey. The error was estimated by averaging these five percentage errors.

3.5 Pond Evaporation

Evaporation for each site was estimated using meteorological data from nearby Western Regional Climate Center (WRCC) climate stations (http://www.raws.dri.edu/). These sites averaged 17 km from project sites, but ranged from 6 to 33 km. Daily meteorological data, such as radiation, temperature, and relative humidity was downloaded from the climate stations for the period of summer monitoring. These values were combined with daily average barometric pressure from BaroTrolls at study sites to improve evaporation estimates.

These daily data were input into Ref-ET, an evapotranspiration calculator program developed by Dr. Richard Allen (University of Idaho) available at http://extension.uidaho.edu/kimberly/2013/04/ref-et-reference-evapotranspiration-calculator/. This program uses standard equations to calculate ET. The FAO 56 Penman-

Monteith equation was used to calculate ET_o, which is the ET for a grass reference crop 0.12 m in height and watered weekly (Allen et al. 1998). The FAO 56 Penman-Monteith equation is discussed in detail in Appendix C. Daily ET_o was used for ET from the meadow surface, and was multiplied by 1.05, the adjustment coefficient for surface water less than 2 m deep, to calculate daily pond evaporation (E_p) (Allen et al. 1998).

3.6 Precipitation

Precipitation for each project site was also obtained from nearby WRCC stations (http://www.wrcc.dri.edu/). Daily precipitation for the period of record was used in comparison with pond water elevations, logger data, and in water budget analysis.

3.7 Water Volume Calculations

Water volume calculations were performed to allow for comparison. Total volume calculations were only performed for periods between the first and last pond elevation measurements, but logger, E_p, and discharge data may exist for extended periods of the season. Measured pond volume decline was estimated by multiplying monthly pond decline by pond area at the start of each monthly survey, i.e. July volume decline = July elevation – August elevation multiplied by the average July and August area. Then, monthly volume declines were summed to obtain the total volume lost from ponds through the dry season. In some cases, pond volumes did not differ greatly, and instead an average pond area was multiplied by the total decline to obtain a volume.

Evaporated volume was calculated in the same way, except that monthly precipitation was subtracted from monthly E_p to get net atmospheric losses. Monthly E_p was substituted in for monthly decline, and total volume evaporated was calculated as above. Volume decline was divided by volume evaporated to determine what percentage of decline was due to direct pond evaporation.

To compare E_p and meadow ET, unmeasured pond areas were estimated using aerial photos in ArcMap (http://www.esri.com/software/arcgis). These pond areas were then multiplied by total E_p for the decline monitoring period, and added to measured pond volume evaporated. Total meadow ET was calculated by multiplying total ET_o for the monitored decline period by meadow area minus pond area, again determined in ArcMap.

Additionally, net stream daily discharge was calculated using hourly averages for 15 min interval discharge values. Net discharge was calculated by subtracting incoming (upstream) discharge from outgoing (downstream) discharge, to determine the stream volume gained or lost moving through the meadow.

Lastly, potential groundwater storage gained from restoration in each meadow was determined by multiplying estimated pre-restoration gully depth by estimated S_y. It is presumed that following restoration; groundwater levels would rise to near the meadow land surface, which would represent a gain in local groundwater in the meadow. Gully depth was obtained from pre-restoration elevation surveys and practitioner estimates (Jim Wilcox, FRCRM, unpublished data, 2013; Rick Poore, StreamWise, unpublished data, 2013; Randy Westmoreland, personal communication, 2013).

4. Results

4.1 Pond Elevations

Pond elevations declined from June through September 2012, indicating loss from ponds through evaporation and/or loss to local or regional groundwater systems (Fig 6).

Appendix D contains elevation maps of pond declines at all meadows. The decline in pond water levels varied more than a meter and the average water-level decline for all ponds in the different meadows was 0.58 m (Table V). The average decline in July was twice the decline in August, 0.37 m compared with 0.19 m, respectively. Only the Big Bear meadow ponds, which declined the least through the season, had an average increase in August.

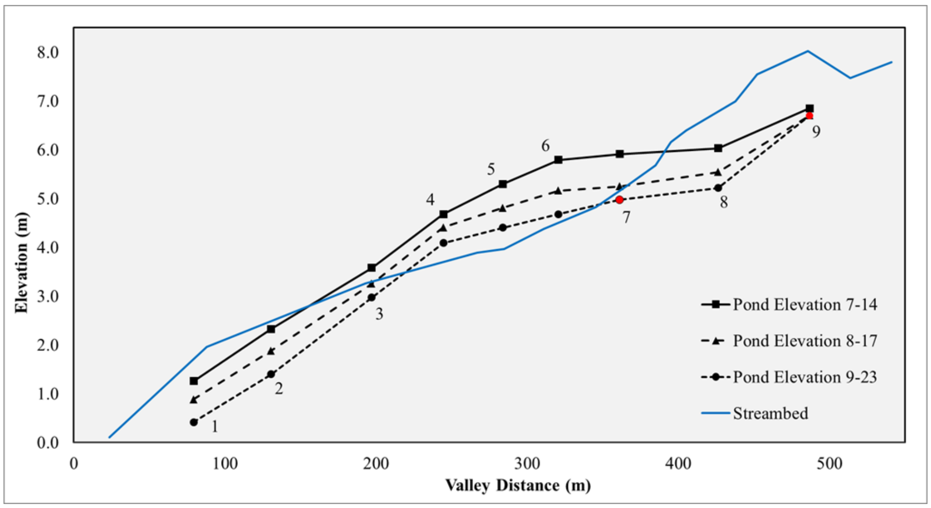


Figure 6. Example of pond elevations through the summer of 2012. Ponds are numbered consecutively moving upstream, with each vertical collection of points representing three measured elevations of one pond. Red points indicate elevations of dry pond beds.

Site	July Avg. Pond Decline (m)	August Avg. Pond Decline (m)	Total Pond Avg. Decline (m)	Std. Dev. of Pond Decline (m)
Big Bear	0.11	-0.06	0.05	0.14
Big Flat	0.3	0.28	0.58	0.45
Davies	0.65	0.1	0.74	0.25
Ferris	0.43	0.34	0.76	0.27
Knuthson	0.42	0.15	0.57	0.22
Lassen	0.05	0.03	0.07	0.15
Merrill	0.4	0.24	0.64	0.35
Rose Canyon	0.33	0.25	0.56	0.22
Three-cornered	0.6	0.42	1.02	0.28

Table V. Average pond declines by month and total for the summer of 2012.

Additionally, within meadow pond declines differed. The Big Bear and Lassen meadows behaved uniformly with low standard deviation in pond declines. The Big Flat and Merrill meadows had the highest standard deviation, and the average standard deviation was 0.26 m for all sites.

4.2 Water Logger Results

Logger data show groundwater and pond water elevations peaking early in the season, followed by steady decline through the dry season, except for brief increases following precipitation events. Following the decline of ET in the late fall and returning precipitation, water elevations start to rebound in late October/early November (Fig 7). Appendix E provides logger hydrographs for every study meadow. Any gaps in data represent drying of the logger, due to water elevations dropping below logger depths in piezometers or stilling wells.

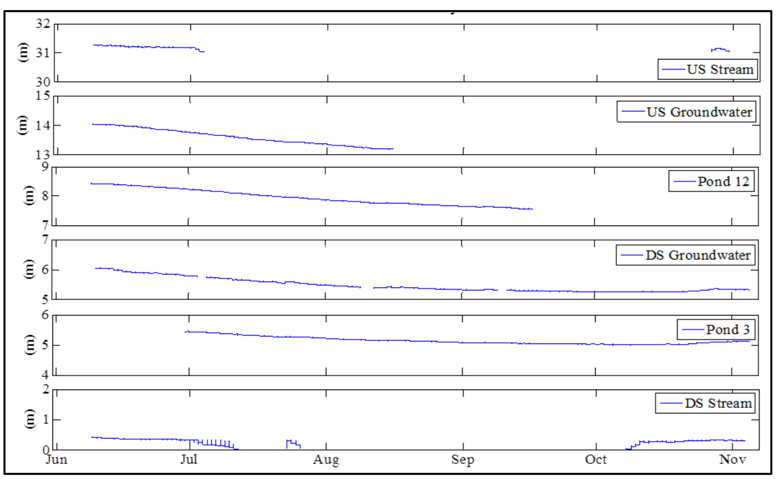


Figure 7. Example of logger data from June to November 2012 at Merrill Valley meadow. The stream went dry at the upstream and downstream sites (indicated by gaps), and the upstream groundwater piezometer also went dry. Pond 12 did not go dry, but declined to the extent that the logger went dry between site visits.

Pond and nearby groundwater loggers have similar hydrographs. At the Merrill (Fig 7) and Three-corned (Fig 8) meadows the ponds and adjacent piezometers have nearly identical hydrographs, showing similar decline through the summer and rise in the fall. This relationship is true for most meadows.

Pond and groundwater elevations are highly correlated, with R-squared values generally above 0.90 (Table VI). Exceptions occur, with the Big Bear, Big Flat and Ferris meadows having lower R-squared values for one or more relationships. However, only the downstream pond and piezometer at the Big Bear meadow had an R-squared value that indicates very low correlation. R-squared plots are provided in Appendix F.

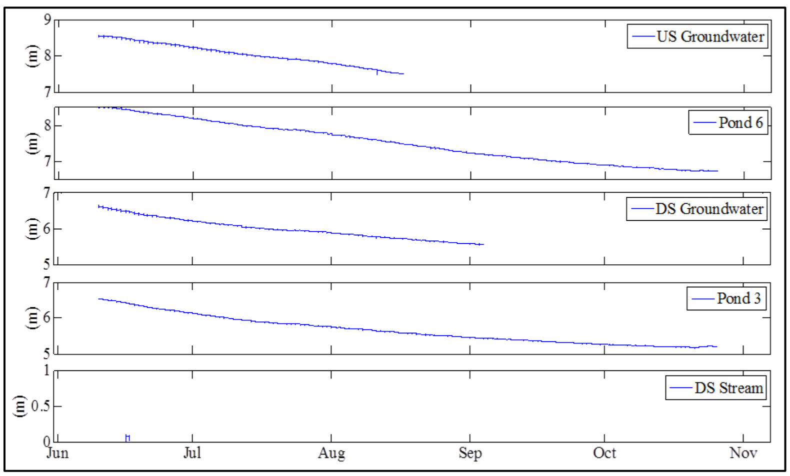


Figure 8. Logger data for Three-cornered meadow from June to November 2012. Both piezometers go dry by September, while the incoming stream was dry for the monitoring period. The downstream staff never had flow, but ponded water for a brief period in June.

Site	Downstream Pond and Piezometer	Upstream Pond and Piezometer
Big Bear	0.149	0.653
Big Flat	0.812	0.625 (mid), 0.953 (upper)
Davies	0.906	0.994
Ferris	0.709	0.998
Knuthson	0.941	0.949
Lassen	0.935	0.957
Merrill	0.991	0.996
Rose Canyon	0.950	n/a
Three-cornered	0.998	0.998

Table VI. R-squared values between pond and piezometer elevations from June to November 2012. Big Flat meadow is compared with wells installed and monitored by U.C. Merced.

Both pond and groundwater hydrographs have diurnal cycles (Fig 8) resulting from daytime ET, which ceases at night, allowing groundwater elevations to recover (Loheide et al. 2005). All hydrographs show these cycles, especially early in the dry season when daily ET is at its highest.

4.3 Discharge Results

Only the Big Bear and Lassen meadows provided stream hydrographs throughout the monitoring season. The Big Bear meadow had three stream hydrographs, as a tributary to the main channel also entered through the meadow (Fig 10). The tributary enters the upper part of meadow from the west, immediately entering and exiting the uppermost pond in the project. It then flows along the upper part of the meadow, nearly along the upstream edge of the meadow. After entering the main channel at the upstream meadow edge, the combined tributary and incoming flow constitute the upstream main gauge. The main stream then flows along the northern edge of the meadow, exiting at the meadow bottom.

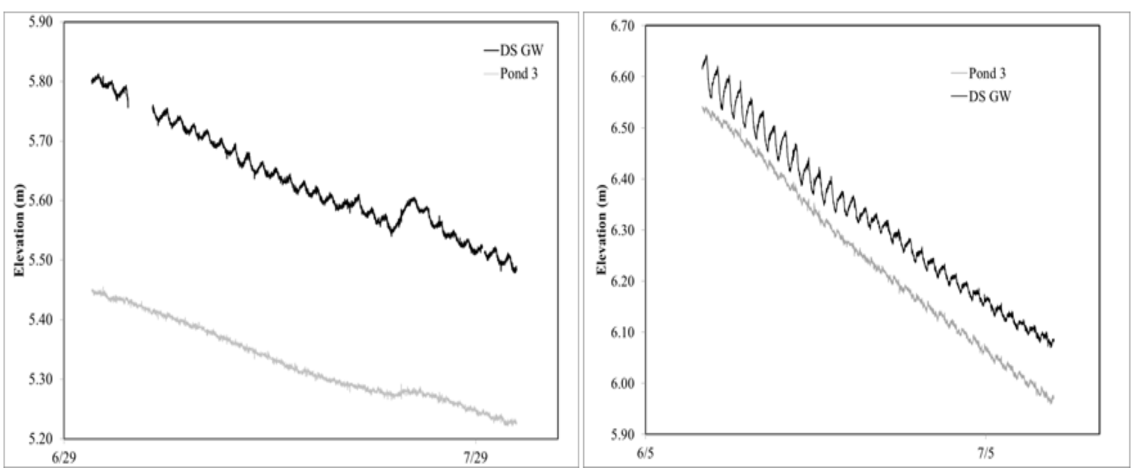


Figure 9. Diurnal flucuations in Three-cornered (left) and Merrill (right) meadows from June to July 2012. The larger spike in Three-cornered meadow during mid-July is more likely groundwater recharge. Flucuations are generally larger in piezometers, likely because much of the subsurface is occupied by sediments, which is not the case in ponds.

The hydrograph for this period of record indicates a snowmelt driven system, with high flow occurring during early summer and tapering to base flows by August. The main stem is a gaining reach flowing through the meadow, as the stream discharge leaving the meadow is always greater than the discharge entering main stream. However, the tributary is always a losing reach, as the combined flow entering the meadow is always greater than where the tributary enters the meadow. By mid-September the net incoming US Stream is nearly negligible and the Tributary inflow equals DS Stream outflow.

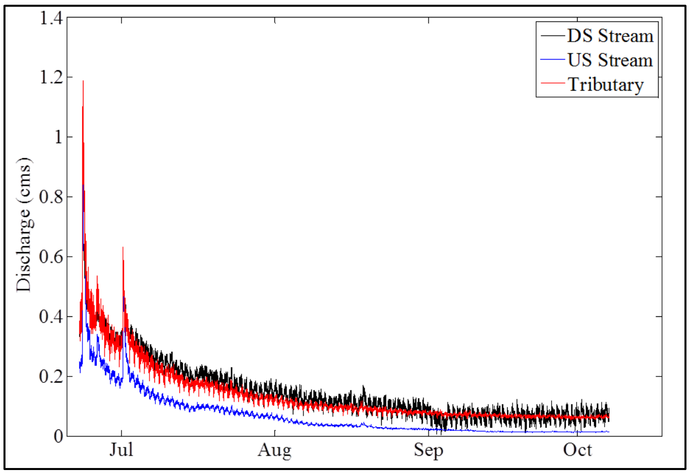


Figure 10. Stream hydrographs for Big Bear meadow from June to November 2012. Hydrograph indicates a snowmelt driven system, with high spring flow persisting through July, and slowly tapering to base flows by August 2012.

Lassen Creek flowed for the entire monitoring period. However, flow dropped to undetermined discharge values that were not measureable with the Marsh-McBirney. The rating curve for Lassen resulted in negative flow values, which were converted to 0. Regardless, the Lassen Creek hydrograph indicated a snowmelt driven system, with peak flows in the early summer tapering to base flows by August (Fig 11). In early spring, the stream through the meadow is a gaining reach, with incoming discharge less than outgoing. However, by mid-August, this trend reverses, and outgoing flows are less or equal to incoming flows.

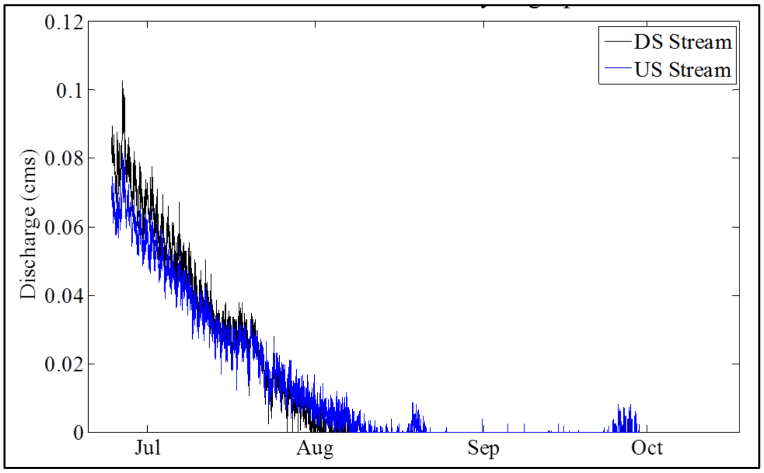


Figure 11. Stream hydrographs for Lassen from June to October 2012. Discharge declines from high spring flows to base levels by August, and starts to rebound in early October. While the figure indicates the stream went dry, flow did occur during this period.

4.4 Evaporation Results

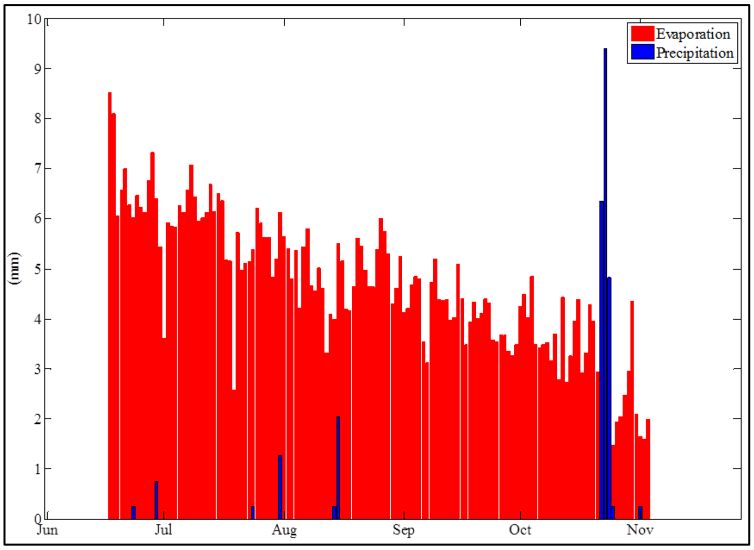


Figure 12. Typical evaporation and precipitation plot for study meadows from June to November 2012. Evaporation rates peak during the hottest, driest periods in June, and decline to low levels by November. Precipitation increased in October. Only values from the pond-monitoring period (July to September 2012), were used for water budget analysis.

Evaporation rates were consistent with a semi-arid climate, with peak values occurring during the hot, dry parts of summer and decreasing in the late summer and fall as temperature and radiation decline (Fig 12). Plots of evaporation and precipitation for each study meadow are shown in Appendix F.

Site	Max E_p (mm/day)	Avg. E_p (mm/day)	Total E_p (m)
Big Bear	6.98	4.92	0.34
Big Flat	8.10	4.60	0.37
Davies	8.22	5.04	0.41
Ferris	8.52	4.63	0.35
Knuthson	8.47	5.55	0.39
Lassen	8.74	6.55	0.45
Merrill	8.22	5.09	0.40
Rose Canyon	8.85	6.01	0.36
Three-cornered	8.47	5.55	0.44

Table VII. Values of maximum and average pond evaporation for study meadows between July and September 2012.

Average daily E_p was 5.33 mm/day and maximum values reached nearly 9 mm/day (Table VII). The average Total E_p was 0.39 m, with the Big Bear meadow having the lowest evaporation and the Lassen meadow the highest.

4.5 Water Volume Results

Collective pond decline volumes per meadow ranged widely (Table VIII), with an average decline of approximately 3,700 m³ from July through September 2012. E_p volumes were generally less, with the average approximately 2,800 m³. Evaporation made up 40 to 70% of the total decline in seven meadows, indicating that direct pond evaporation is not the only source of loss in pond water budgets. The exceptions are the Big Bear and Lassen meadows, where evaporation greatly exceeded pond declines, indicating groundwater discharge to the ponds, as all study ponds received no incoming or outgoing surface flow for the summer. Meadow ET_o volume ranged widely (Table IX), with the average approximately 100,000 m³. Pond E_p was much less, with the average approximately 4,000 m³. Direct pond evaporation was only 4% of total ET loses from meadows.

Additionally, depending on S_y values used, total meadow ET_o was either double or half of gained storage, with the average storage gained using available S_y approximately 40,000 m³ and the average storage gained using θ_s-θ_r approximately 250,000 m³ (Table X).

Site	Decline Volume (m³)	E_p Volume (m³)	Budget Percentage
Big Bear	767	4,293	560%
Big Flat	5,256	2,271	43%
Davies	268	109	41%
Ferris	3,207	1,354	42%
Knuthson	7,684	5,364	70%
Lassen	638	4,149	650%
Merrill	944	714	76%
Rose Canyon	3,093	1,654	53%
Three-cornered	6,588	2,792	42%

Table VIII. Decline and evaporated volumes for monitored ponds in study meadows from July through September 2012, with part of total decline as evaporation.

S_y (avail.) represents S_y on shorter diurnal time scales, which many meadows exhibit. Since ET is the main driver of water drainage in restored meadows, S_y (avail.) may be a better value to use, as it may represent the actual water released. However, given the long duration examined and deeper water table depths, Θ_s-Θ_r values may be reached by the end of the season.

Site	ET_o (m³)	E_p Volume (m³)	Budget Percentage
Big Bear	297,051	11,807	4%
Big Flat	51,067	2,230	4%
Davies	5,919	176	3%
Ferris	56,217	1,315	2%
Knuthson	246,195	8,742	4%
Lassen	65,612	5,062	8%
Merrill	62,490	2,559	4%
Rose Canyon	56,286	1,609	3%
Three-cornered	45,860	2,705	6%

Table IX. Estimated total ET and E_p volumes from study meadows from July through September 2012.

Therefore, local meadow S_y estimates, at the beginning and end of the season, are likely needed to determine actual amounts of water released from storage.

In Big Bear and Lassen, the two meadows with flowing streams for this period, the net stream flow was 52,663 m^3 and -5689 m^3 respectively. These values indicate that Big Bear Creek had a net gain in stream discharge while Lassen Creek did not. Again, these calculations are only for July through September 2012 and represent conditions following a winter below normal snowfall.

Site	Est. Storage Gained (avail.) (m^3)	Est. Storage Gained (θs-θr) (m^3)
Big Bear	77,534	802,579
Big Flat	107,415	142,531
Davies	199	5,656
Ferris	137,451	186,088
Knuthson	22,545	640,654
Lassen	22,958	107,748
Merrill	39,38	111,896
Rose Canyon	3,859	109,657
Three-cornered	2,649	75,277

Table X. Estimated storage gained in each meadow from restoration. Calculations are done with two estimates of S_y, as specific yield is not homogeneous in time or space.

5. Discussion

5.1 Meadow Types

5.1.1 Sponge

The majority of meadows did not exhibit evidence of the sponge conceptual model during the summer of 2012 following a winter snowfall 30% below average (http://cdec.water.ca.gov/cdecapp/snowapp/swcchart.action). Pond elevations declined through the summer, without any evidence of a large pulse of water moving downstream through the meadow. However, because of permitting and budget constraints, data collection did not begin until late June, probably too late to capture the filling of the meadow with spring runoff. The sponge model implies receiving overbank flooding and storage for later release. The meadows in this study are perennial or intermittent flow systems, and recharge and subsequent peak water elevations likely occurred in early May as would the majority of overbank flooding (Tague et al. 2008; Loheide and Gorelick 2007). However, this also implies that following winters of low snowfall, overbank flooding and meadow water storage is too minimal to sustain base flows for an extended period of time into the dry season, decreasing the benefit of the sponge conceptual model.

There was evidence of the sponge conceptual model, or meadow water storage, in some meadows, namely the Big Bear and Lassen meadows. In the Big Bear meadow, the stream hydrographs indicates that Big Bear Creek is a gaining reach, with the outgoing discharge in excess of the incoming discharge in the main incoming channel (Fig 10). In Lassen Creek, flowing through the Lassen meadow, the hydrograph data indicate a gaining reach early in the season (Fig 10). Since snowmelt has likely stopped by this point, and groundwater recharge into the meadows has likely ceased, this gain may be indicative of floodwaters stored during peak runoff being released to the stream as it moves through the meadow. This occurs when groundwater elevations are higher than stream water elevations, which is evident in two shallow wells. The downstream piezometer, which is slightly upstream from the downstream stream staff, has higher water elevations than the stream early in the growing season (Fig 13). However, by late July, these elevations reverse, and the stream becomes a losing reach, also evident in water budget calculations.

These findings are congruent with previous research (Loheide and Gorelick 2007). By July 2005, groundwater flow paths were away from stream channels at the Big

Flat meadow, and increases in stream discharge following restoration generally ended by August from 2001-2004 in Trout Creek (Tague et al. 2008).

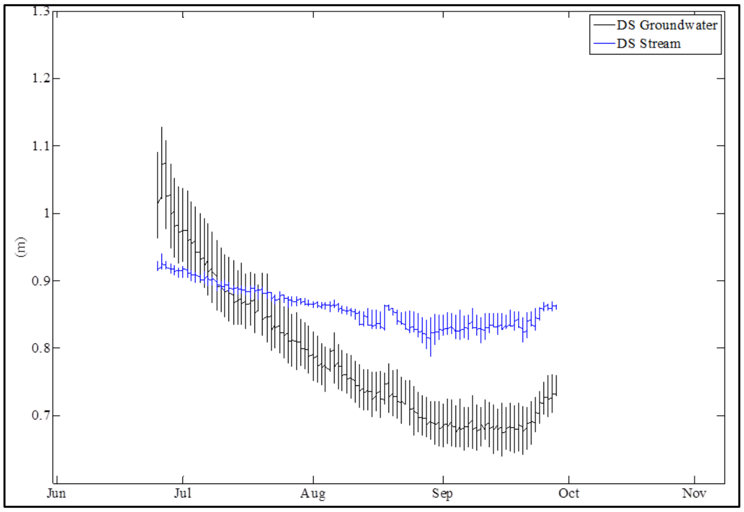


Figure 13. Downstream piezometer and stream logger elevations in Lassen meadow from June through September 2012.

Therefore, during wet conditions in the early spring and summer, Lassen Creek is a gaining stream caused by shallow groundwater. However, later in the dry season, the water table declines below the level of the stream, causing the stream to lose flow across the meadow.

The filling of Ferris in the fall indicates the sponge conceptual model, with incoming water filling meadow sediments. Following the decrease in ET rates during fall, water elevations start to recover in upstream ponds and in wells (Fig 14). Upstream elevations recover rapidly following a large precipitation event in late October, resulting in incoming stream flow. The rapid increase in the upstream ponds and well is not evident in downstream ponds and well, indicating that the incoming recharge from the precipitation event first fills the upstream end of the meadow, then the pulse of water travels downstream, presumably reaching the downstream meadow at a later date.

Lastly, the Three-cornered and Rose Canyon meadows had groundwater discharge into stream channels downstream of the pond-and-plug restoration during the dry season. In both cases, this discharge only persisted for a couple hundred of meters, suggesting that groundwater elevations were only high enough to contribute to stream flow for a short distance. This shallow discharge was un-measurable using the Marsh-McBirney flow meter. Therefore, what part of the each meadow water budget this accounts for is not known. Regardless, this discharge represents outgoing discharge from the meadow when no incoming stream flow was occurring, and in the case of the Rose Canyon meadow, did not exist prior to restoration (Don Lindsey, personal communication, 2012). These meadows are discussed in more detail in the surface water discussion below.

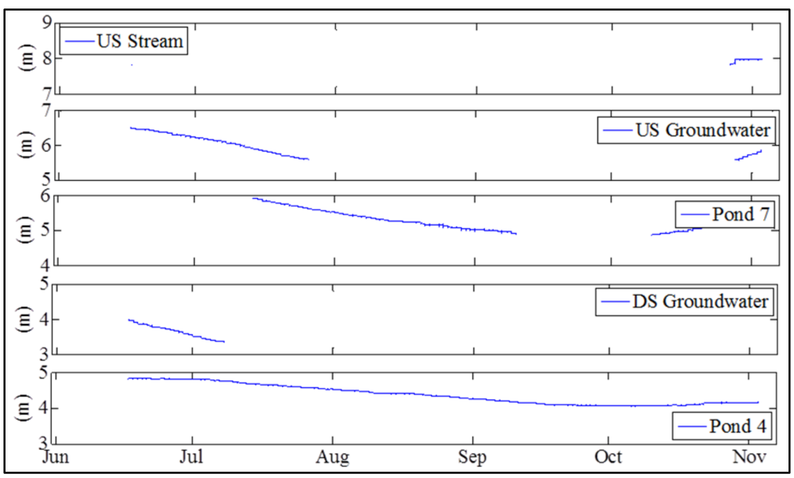


Figure 14. Logger elevation data in Ferris meadow from June to November 2012. The downstream staff is dry for the whole period, while the upstream staff has flow briefly in the fall. The upstream pond and piezometer go dry and refill at similar times.

5.1.2 Valve

To evaluate the valve and drain models, pond volume losses were used in conjunction with pond elevation plots. The assumption is that pond volume declines much greater or less than evaporation losses could indicate either valve or drain models, and pond elevations could indicate specific locations of recharge or drainage. Direct measurements of pond evaporation were not done at each pond, rather pond evaporation was estimated from weather data from meteorological stations which were 6 to 33 km distant and within 5 to 350 m of study meadow elevations. The rate estimated from the weather stations is within the range reported by previous studies (Hammersmark et al. 2008; Loheide and Gorelick 2005; Hill and Neary 2007). Assuming pond evaporation rates are reasonable, estimated pond evaporation volumes for July through September 2012 were compared with actual volumes lost from the ponds estimated from measurements of pond stage and area.

Big Bear and Lassen meadow ponds declined much less than estimated from estimated evaporation (Table VIII). This indicates that ponds must receive some groundwater inflow to keep net decline less than evaporated decline. Since monitoring ponds are disconnected from surface flow, this implies that these ponds are receiving some sort of inflow. This inflow could be water released from storage (sponge conceptual model). However, this is unlikely. Pond water elevations would have to drop below groundwater elevations to induce flow from the meadow into the pond, which is not likely because local meadow groundwater is held in sediments. Thus, groundwater levels will decline much more than pond water levels, as pond water is not held in sediments.

In addition, both of these meadows have lower readily available S_y values. S_y is not constant in time or space, and deepening groundwater depths could access coarser meadow sediments, with higher S_y values (Loheide et al. 2005). However, the groundwater levels in these systems decline less 0.5 m, making the readily available S_y values reasonable (Loheide et al. 2005). In addition, in both of these meadows, total meadow evaporation exceeds storage gained significantly, which would require groundwater levels to drop to gully depths of approximately 2 m. Since groundwater levels did not drop significantly from July to September 2012 and storage is low, groundwater flow from outside the meadow must be maintaining groundwater and pond levels in the Big Bear and Lassen Meadows.

Therefore, these systems exhibit valve model characteristics. In addition to having evidence of groundwater inflow from outside the meadow, these meadows also have soils with lower K_{sat} values than the possible max K_{sat} values for the surrounding bedrock, another characteristic of the valve model. Big Bear particularly exhibits valve characteristics, with numerous seeps and saturated soils, which are associated with artesian or upwelling conditions (Lord et al. 2011). Therefore, this meadow may be a combination of a riparian and discharge slope meadow types (Weixelman et al. 2011). While Lassen does lose stream water into groundwater through the summer, the volume is significantly less than the amount of ET from this meadow, and stream recharge could not account for maintained groundwater and pond elevations.

Valve characteristics are not as evident in the remaining meadows. Ponds declined more than calculated from estimated evaporation, which could result from transpiration from meadow vegetation. In most meadows, E_p only accounted for approximately 50% of the pond volume decline. Additionally, piezometer and pond elevations are highly correlated, implying a connection between the two. Since ponds and piezometers decline through the summer, one or the other must be causing the other to drop. Since meadow soils have a specific yield, while ponds do not, ET losses during the day will result in groundwater elevations dropping below pond water elevations, causing seepage from the pond into the meadow groundwater. Whereas evaporation rates in wetlands can be high, seepage rates from wetlands into groundwater can be higher than 40 mm/day (Hill and Neary 2007).

Seepage into meadow groundwater may be the major driver of water loss in ponds. If so, then ponds where E_p makes up a majority of pond decline could indicate meadows with valve characteristics, as groundwater inflow to the meadow would offset ET declines and thus reduce pond seepage. These meadows are Knuthson and Rose Canyon.

The Knuthson meadow also has variance in pond level declines. Some ponds decline less and possibly indicate areas of groundwater inflow (Fig 15). Pond 4 is notable for its minimal decline, and this location in the meadow is associated with saturated soils (personal observations) that indicate groundwater upwelling (Weixelman et al. 2011; Lord et al. 2011).

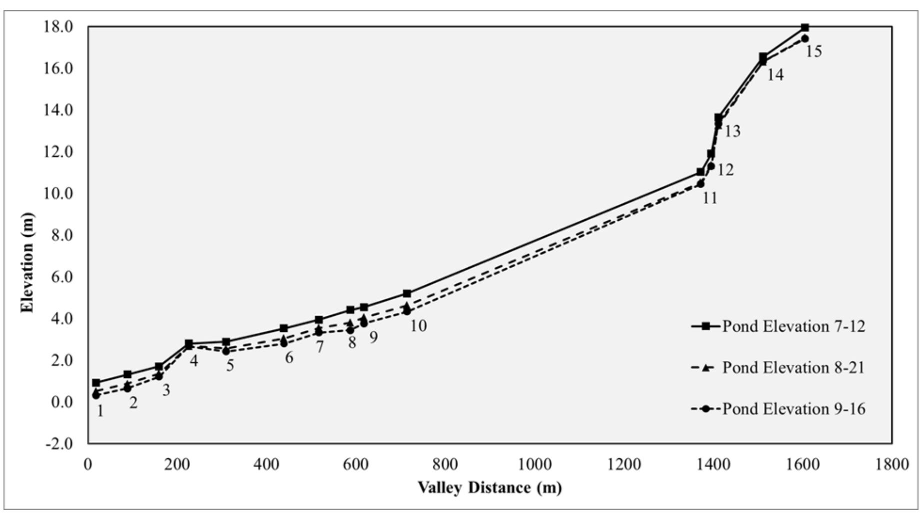


Figure 15. Pond elevations in Knuthson meadow between July and September 20012. Pond 4 and most upstream ponds indicate areas of groundwater inflow. This meadow does not have a stream channel through the meadow, and has a significant gap in ponds mid-meadow.

Up-meadow ponds also have lower declines, but the majority of the ponds in the meadow do not indicate widespread groundwater inflow into the meadow as in the Big Bear and Lassen meadows.

Merrill Valley meadow pond elevations also indicate localized areas of groundwater inflow from outside the meadow (Fig 16). Downstream pond elevations decline little through the season, while mid-meadow ponds and groundwater decline deeper. Indeed, some of these ponds go dry and the groundwater table drops deeper than 1 m below the meadow surface. Also, up-meadow ponds have minimal declines and wetland vegetation indicating a consistent, high water table and groundwater inflow.

In other semi-arid environments, minimal seasonal fluctuations in groundwater levels indicate areas of regional groundwater inflow while larger seasonal fluctuations indicate areas affected by large variations in groundwater inflow (seasonal runoff) or outflow (ET) (Prudic et al. 2007; Constantz et al. 2007; Constantz and Essaid 2007). Great Basin meadow complexes often exhibited areas influenced by regional and local groundwater sources, often with the downstream ends of meadow more influenced by regional sources (Lord et al. 2011). While the hydrogeomorphology of Great Basin and Sierra Nevada meadows is different, study meadows in this paper also reflect heterogeneity in hydrogeomorphology found in other studies.

While both Knuthson and Merrill meadows have valve characteristics, the locations of groundwater discharge are variable and localized in each meadow. Therefore, while these meadows exhibit localized valve characteristics, classifying their overall hydrologic processes as valve would be an oversimplification that does not accurately represent groundwater flow in these two meadows.

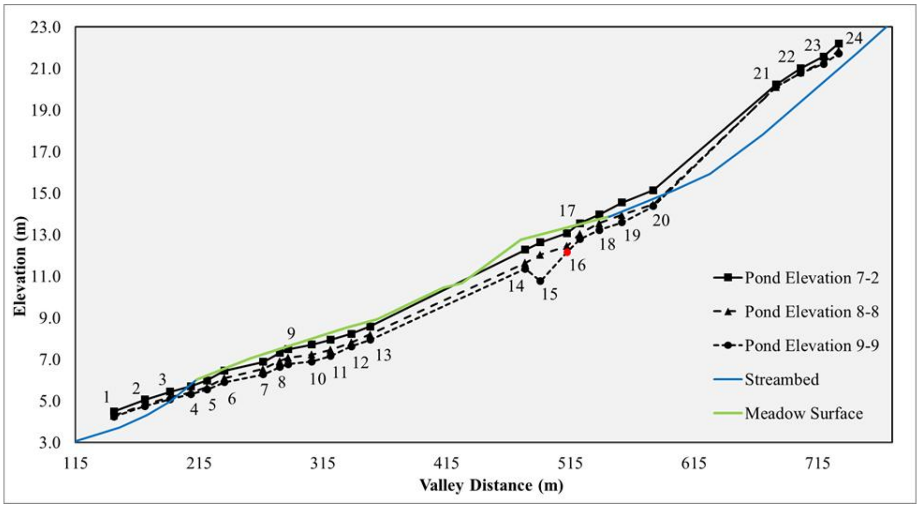


Figure 16. Pond elevations in Merrill Valley meadow from July to September 2012. Both upstream and downstream ponds decline less than mid-meadow ponds, which also lacks a defined stream channel.

5.1.3 Drain

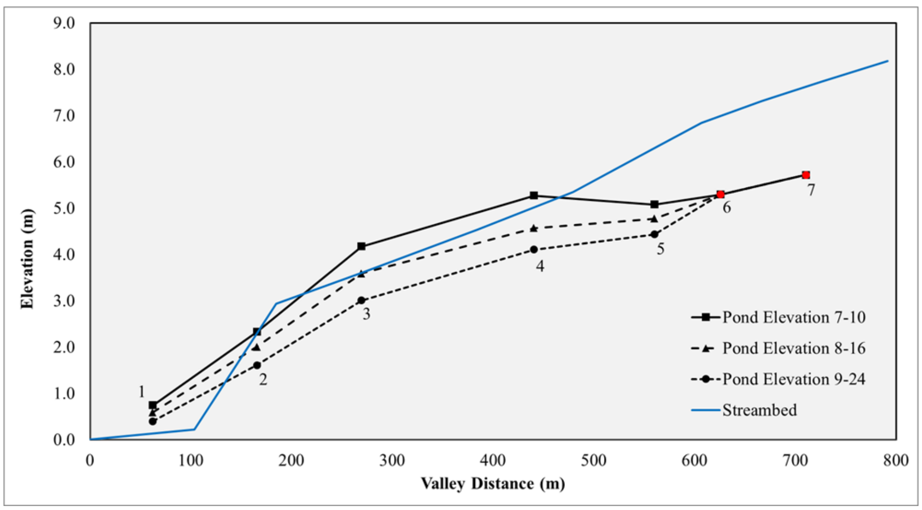


Figure 17. Pond elevations in Big Flat meadow from July to September 2012. Downstream ponds maintain higher elevations through the summer, while upstream ponds drain to the point of going dry.

Several study meadows exhibit drain conceptual model characteristics. Big Flat, Davies, Ferris, Rose Canyon, and Three-cornered meadows all have relatively higher drainage volumes than evaporation losses. In the upstream end of Big Flat meadow, ponds had declines greater than 1 m during the summer of 2012 with some completely drying. Pond water levels were more than 1.5 m below the streambed (Fig 17).

However, the lower ponds decline much less, possibly indicating recharge from storage or regional groundwater. Also, meadow sediments become finer moving downstream in this meadow (Jim Wilcox, personal communication, 2013), which can create vertical hydraulic gradients, and higher, stable water elevations (Lord et al. 2011).

The Ferris meadow has similar processes, with deeper draining ponds in the upstream end of the meadow and less decline in downstream ponds (Fig 18). However, the differences are less dramatic, and may be because meadow sediments do not become as fine moving downstream (Jim Wilcox, FRCRM, personal communication, 2013).

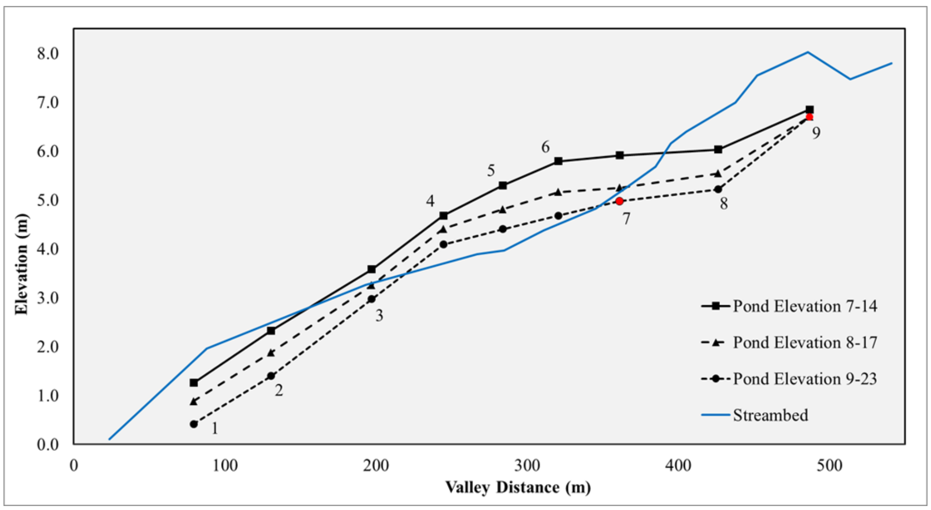


Figure 18. Ferris meadow pond elevations from July to September 2012. Upstream ponds decline more than downstream ponds, but mid-meadow ponds 3 and 4 decline the least, possibly indicating localized recharge.

In the Rose Canyon meadow up-meadow ponds decline more than down-meadow ponds, and to deeper levels below the streambed, again possibly indicating heterogeneity in groundwater inflow or water release from storage (Fig 19).

In the Davies meadow, pond elevations declined much more in July than in August, with the downstream pond going dry (Figure 20). This decrease corresponds with low ET rates later in the fall, as groundwater elevations likely drop below plant rooting depth, indicated by brown meadow vegetation at Davies meadow by early August. However, it is also possible that this meadow declined deep enough that a gradient was created for groundwater inflow, which reduced the later season declines.

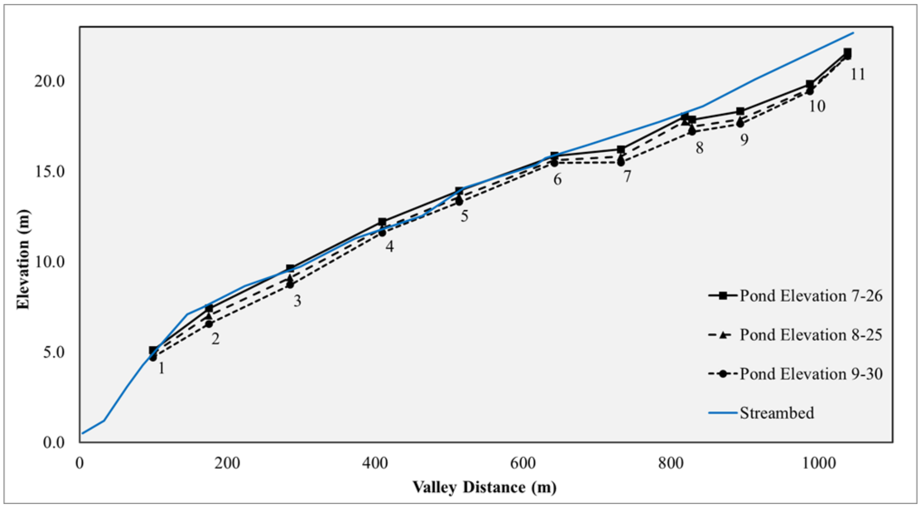


Figure 19. Rose Canyon meadow pond elevations from July to September 2012. Ponds decline fairly uniform through the summer, but upstream ponds drop further below the streambed. Pond 1 declines the least of all.

In the Three-cornered meadow, pond elevations declined uniformly (Fig 21). Again up-meadow pond water elevations declined more than down-meadow pond water elevations. This may be the result of a tall, compacted downstream grade structure, located directly down-meadow of the ponds, which could restrict local groundwater flow out of the meadow. However, the higher pond elevations could again indicate groundwater inflow into the meadow.

Whereas these meadows exhibit drain characteristics, the majority of meadows show heterogeneity in pond declines, which likely reflects differences in groundwater sources. It is possible most of these meadows reflect the sponge conceptual model, and are dependent on yearly snowmelt recharge to raise and maintain groundwater elevations.

Therefore a low snowpack year could result in large pond and groundwater declines seen in 2012, and not necessarily indicate areas of groundwater outflow.

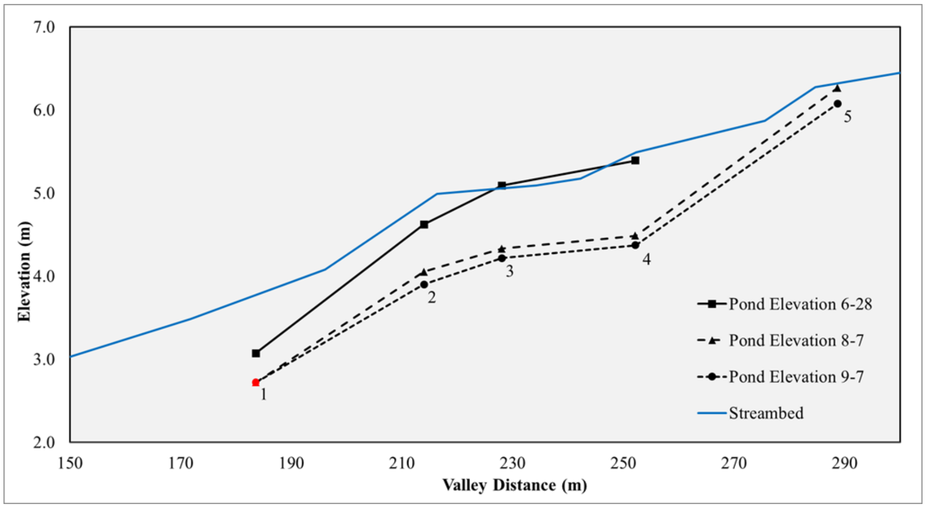


Figure 20. Davies meadow pond elevations from June to September 2012. Pond 1 goes dry by August, indicated by a red symbol. Early season declines are large, while late season are extremely low, possibly a result of reduced ET and/or incoming groundwater.

However, to better assess this, a meadow water budget would need to be estimated, as these drops could result from either groundwater outflow (drain conceptual model), or a decrease in groundwater inflow to the meadow as the dry season progresses.

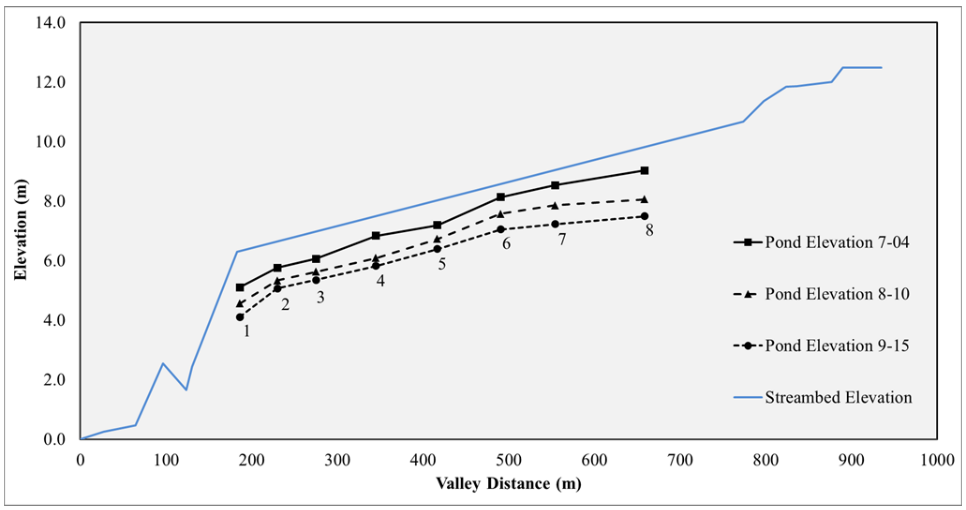


Figure 21. Three-cornered meadow pond elevations from July to September 2012. Downstream ponds decline less than upstream, and a steep downstream grade control likely influences groundwater movement in this meadow.

5.2 Pond and Meadow Evaporation

While direct evaporation losses from ponds were significant, 60 % or more of the loss in ponds volumes from July to September 2012 was because of seepage to meadow groundwater (Table VIII). The driver of this seepage is likely ET in the meadow near and downstream of the ponds. Declines in groundwater were much greater than in ponds, because sediments occupy much of the volume beneath the land surface. Total estimated pond evaporation was less than 5% of total ET from meadows, and the average evaporation loss from ponds in all meadows was 2,522 m^3 (Table IX). Thus, while ponds present a persistent area of open water subject to evaporation, this loss is much less than meadow ET losses. However, in many pond-and-plug meadows, streams flow directly through ponds. These meadows were not included in this study, but it is likely pond evaporation could play a slightly more significant role in reducing base flows, in these meadows, as there would be a surface connection between the two and this could maintain pond surface area for evaporation. This would require further study.

5.3 Surface Water Interactions

In many meadows, pond water elevations were less than dry streambed elevations for part of the monitoring period from July to September 2012 (Appendix D). However, this relationship was not consistent through time or space. For instance, in the Ferris meadow, upstream and downstream pond water elevations were generally lower than the dry streambed, while mid-meadow ponds were higher for the whole monitoring period (Fig 18). In the Big Flat meadow, mid-meadow ponds start out above the dry streambed elevation, then decline below in late season (Fig 17). Also, the downstream pond water elevation in this meadow is above the dry streambed and the upstream pond water elevation is below the dry streambed for the entire summer season.

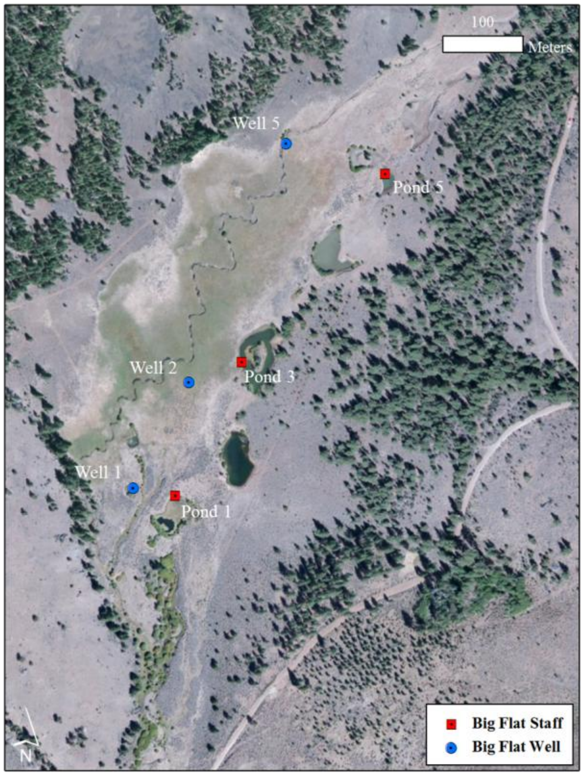


Figure 22. Big Flat meadow site photo and map with installed loggers and the streambed to the west of the ponds.

Despite pond water elevations in some ponds being above the adjacent dry streambed elevation, the streams in the Big Flat and Ferris meadows were dry for this period. This indicates that in some meadows, pond water is not flowing into streams. Loheide and Gorelick (2007) found that flow direction by early July 2005 was away from the stream and towards the meadow edges. In Big Flat, the distance between the stream channel and restored gully is greater than 60 m mid-meadow (Fig 22). Also, the ponds are located on the meadow edge, against a hill slope, and could have been receiving groundwater inflow. If groundwater inflow was occurring, ET demand could reduce this inflow such that the groundwater table is below the streambed.

In the Ferris meadow, the distance between mid-meadow ponds and the streambed is not as great, but is still greater than at the upstream and downstream ends. Again, the streambed is dry for this period. In this meadow, the middle meadow surface slope gradient is much lower than at the upstream or downstream ends, where the pond water gradient is steeper. Streambed gradient is less variable. Therefore, the dominant groundwater flow direction could be down valley, and not towards the streambed. Meadow groundwater flow can also be focused through the ponds (Loheide and Gorelick 2007) so pond water may not contribute to the stream.

However, in the downstream end of the Big Flat meadow, pond water elevations are not only above the dry streambed, but they are geographically close. This relationship also occurs in the Merrill Valley meadow at the upstream and downstream ends of the meadow (Figs 16, 17). In both meadows, despite pond water elevations higher than dry streambed elevations, the stream channels exiting these meadows were dry. It seems likely that such ponds would contribute to stream flows, as groundwater flow paths could be across valley, from pond to stream. However, principal groundwater flow paths may be down valley and not necessarily intersect the stream channel until much farther downstream, beyond the end of the meadows.

Some meadows exhibited discharge from the downstream end of the project for much of the season. In the Rose Canyon and Three-cornered meadows, the downstream end of each meadow restoration ends with a large grade control structure (plug) which transitions to a steeper canyon, evident in stream channel profiles (Figs 19, 21). In both cases, this means that pond water elevations are higher than downstream streambed elevations. This would indicate groundwater flow from ponds to stream channels, which was observed.

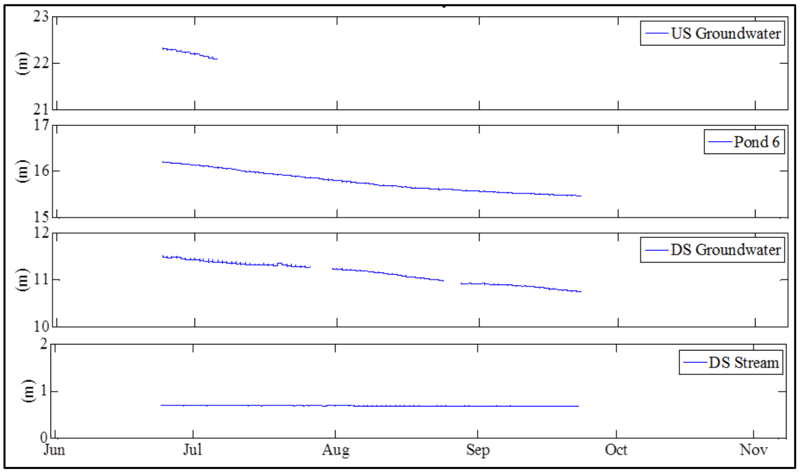


Figure 23. Rose Canyon meadow logger elevation data from June to September 2012. Upstream stream (not shown) and piezometer remain dry for much of the season, but pond 6 and the downstream piezometer decline ~1m. The downstream stream maintains a steady seepage pool for the whole summer.

The Rose Canyon meadow maintained a consistent seep and pool in the stream channel below the downstream gully plug from July to September 2012 (Fig 23). This discharge is a result of restoration, as the stream channel generally went completely dry prior to the pond-and-plug restoration (Don Lindsey, landowner, personal communication, 2012). This discharge is likely influenced by the downstream grade control structure, which is composed of compacted, lower permeability materials that must resist annual runoff. Having low hydraulic conductivity, this plug would restrict groundwater flow out of the meadow and prolong base flows. Conversely, this plug maintains higher groundwater levels that are subject to longer ET. Nevertheless, discharge persists where it did not before.

While drainage did occur in the downstream exiting stream channel, it was minimal through the season. In both cases, discharge was too small to be measured using the Marsh-McBirney velocity flow tracker. The surface flow persists only for a couple hundred meters during July and August. In the Three-cornered meadow, the downstream stream staff remained dry, although streambed seepage was observed just upstream.

In the Big Bear and Lassen meadows, perennial streams allowed examination of surface water interactions. In Big Bear, the majority of pond water elevations are above the streambed, with ponds and the stream channel on opposite edges of the meadow (Fig 24). Overall, the meadow is tilted southeast, with the highest point occurring where the tributary enters the meadow and the lowest point where the main stream exits. Groundwater flow paths presumably follow this direction and much of the meadow surface is above the streambed.

Numerous seeps and saturated soils occur adjacent to the stream, generally recharging the stream flow and creating a gaining reach (see above discharge discussion). While downstream pond elevations were not monitored because of surface flow connections, the lowest pond is clearly higher than the stream as surface water flowed from the pond into the stream from July to September 2012 (Fig 25, personal observations). Because of this surface flow, this pond was not included in decline monitoring. In this meadow, pond elevations are much higher than streambed elevations. Stream water elevations are not known, but assuming reasonable stream depths of 1 m, stream water elevations would still be much lower than these ponds, implying pond contribution to stream discharge.

In the Lassen meadow, the majority of pond elevations are above, or near the streambed elevations, indicating opportunity for groundwater flow from ponds into stream channels, if the water levels in the streams are below the pond water elevations (Fig 26).

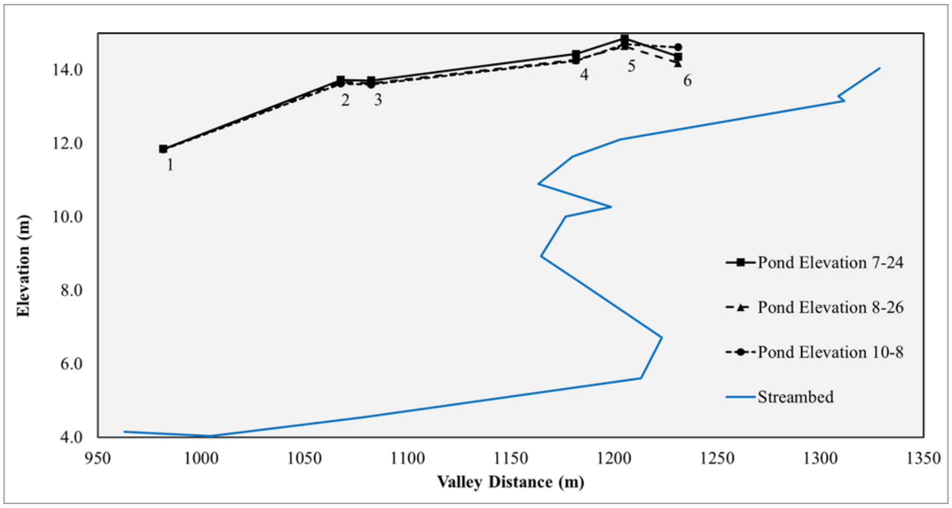


Figure 24. Big Bear meadow pond elevations from July to September 2012. The stream channel is generally much lower than the ponds and likely receives inflow from them farther downstream.

However, later in the season, this stream becomes a losing reach through the meadow (see above discharge discussion). During August and September, some ponds are above and others below streambed elevations, indicating possible variability in recharge and discharge to the stream channel, common in many meadow systems.

In meadows with perennial streams, pond water elevations were above the streambed, indicating that ponds did not represent an additional drain from stream discharge. However, in the Lassen meadow this relationship was variable by location and season. In other meadow streams that went dry during the summer of 2012, water levels in ponds were higher than the streambed, possibly indicating no interaction between ponds and the stream. However, most meadows contained intermittently flowing streams, and unfortunately it was not possible to judge pond and stream interactions while streams were flowing.

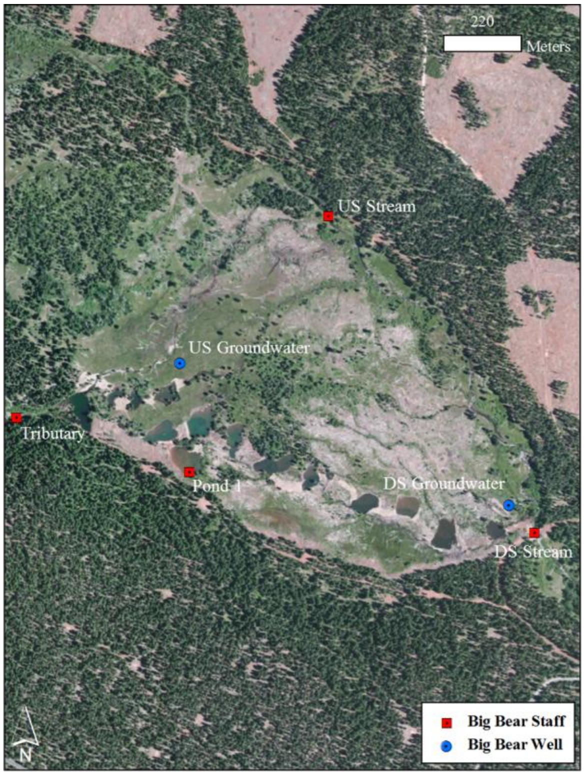


Figure 25. Big Bear meadow site photo and map of logger locations. Numerous seeps and channels between ponds are evident, flowing north and northeast to the main stream channel, which forms the northeastern meadow border.

Groundwater levels are often below streambed elevations, particularly in meadows where stream cease flowing during the summer. Thus perennial flow may not be supported under most conditions (Lord et al. 2011). In the Davies meadow, the stream channel is rocky and wide (Fig 27), which can be characteristic of intermittent channels that only transport snowmelt and precipitation runoff (Lord et al. 2011). In these instances, when the stream is flowing, stream flow losses in the meadow recharges local meadow groundwater (Constantz et al. 2007).

Since there is such a short interaction period between the channel and groundwater, in a dry season such as 2012, the duration of bank storage and base flow augmentation would be short (sponge conceptual model).

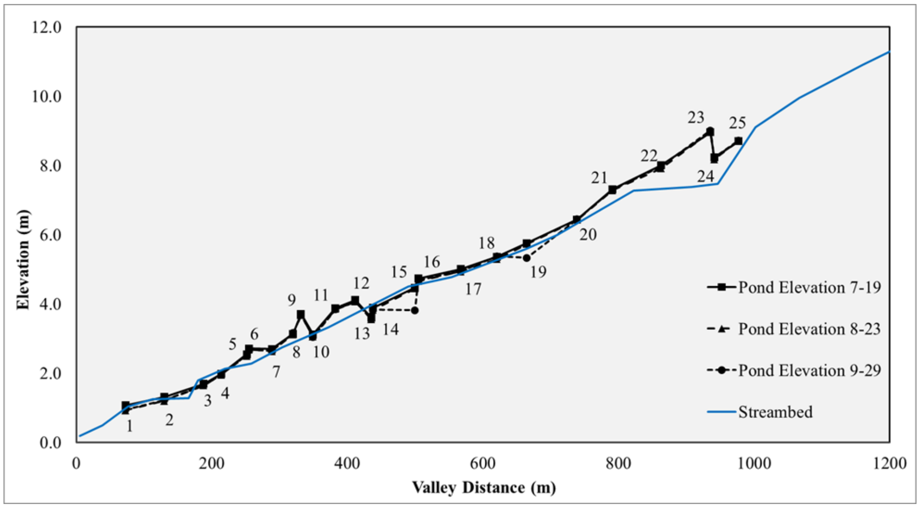


Figure 26. Lassen meadow pond elevations from July to September 2012. Pond elevations decline little through time, but there is variability in whether ponds are below or above the streambed elevation.

However, groundwater flow paths could be laterally down channel, and intersect the streambed further downstream. This was only evident in sites where downstream pond water elevations were much higher than exiting stream channel elevation, which also had a steep gradient exiting the meadow (Rose Canyon, Three-cornered).

Subsurface meadows (as defined in Weixelman et al. (2011)) are dominated by groundwater and have channels that only enter and exit the meadow, may not see significant base flow increases following restoration. In their pristine state, incoming discharge would only become outgoing discharge after traveling through the meadow groundwater system. This groundwater is subject to high ET rates, which gullying would reduce while creating a new base level. Therefore, there would be a conduit for stream flow to travel through the meadow without being subject to ET. In meadows with the valve function, any groundwater inflow, would flow directly into a gullied stream channel, as groundwater gradients would be towards the lowest discharge point in the meadow (Loheide et al. 2009).

Figure 27. Downstream staff location at the Davies meadow. The bed is fairly coarse, possibly indicating flow only during runoff events. However, discharge over multiple water years would better determine this.

6. Summary and Conclusion

Pond water elevations declined through the dry season from July to September 2012 in restored meadows, indicating volume loss to evaporation and seepage into local groundwater. However, diurnal fluctuations also indicate inflow from shallow groundwater beneath the meadow. On longer time scales, pond hydrographs closely mirror groundwater hydrographs, indicating similar hydrologic regimes and processes.

Pond water elevations through the season indicate differing groundwater processes and sources. Relatively elevated pond water elevations indicate regional groundwater discharge. Large pond water level declines during the summer of 2012 show areas dependent on seasonally local sources of recharge and outflow to groundwater.

Using elevation patterns, valve and drain characteristics were observed in this population of meadows. However, less than half of this population exhibits strong drain or valve characteristics, and the majority of meadows indicate heterogeneity in groundwater flow paths and sources.

Evidence of the sponge conceptual model was minimal, possibly, because of the dry summer of 2012 and monitoring being limited to July through September. Perhaps this process is short lived in below average snowpack years. Stream and groundwater interactions likely differ from meadow to meadow. Dry streambeds were above groundwater levels for much of the season and likely had little influence on groundwater elevations through the season. When perennial streams are present, stream and groundwater interactions change through time, from gaining to loosing reaches through the summer of 2012.

It may not be possible, or fruitful, to separate restored meadows into differing conceptual models. The majority of sampled meadows demonstrated heterogeneity in groundwater sources and stream discharge through space and time. Big Bear and Lassen meadows appear to fit the ideal restored scenario, where high rates of groundwater inflow maintain high groundwater level elevations and sustain base flow through the late summer season. Conversely, some meadows have much less groundwater inflow from outside the meadow and depend on local meadow groundwater that is recharged seasonally, resulting in little to no base flow. These meadows had intermittent streams that were elevated above groundwater for much of this year and their base flows may not have benefited much from increased floodplain storage that was not accessed by low peak flows.

Further research is needed to examine a full range of flows over multiple years to understand restored meadow hydrology. Additional methodologies, such as geochemical analysis, should be used to intensively study heterogeneity in groundwater sources in meadows and in specific ponds. Lastly, bank storage effects and stream base flow attenuation could be modeled in pond-and-plug projects, to help quantify the volumes and processes presumed in the sponge conceptual model and restoration influences on stream base flows (Mau and Winter, 1997; Pinder and Sauer, 1971).

Literature Cited

Allen RG, Pereira LC, Raes D, Smith M (1998) Crop evapotranspiration. Guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. In: FAO (ed), Rome, pp. 300.

Baxter CV, Hauer FR, Woessner WW (2003) Measuring groundwater-stream water exchange: New techniques for installing minipiezometers and estimating hydraulic conductivity. Transactions of the American Fisheries Society 132: 493-502 DOI 10.1577/1548-8659(2003)132<0493:mgwent>2.0.co;2

Business Plan for Sierra Nevada Meadow Restoration (2010) http://www.nfwf.org/Content/ContentFolders/NationalFishandWildlifeFoundation/GrantPrograms/Keystones/WildlifeandHabitat/Sierra_Meadow_Restoration_business_plan.pdf. Cited 12 January 2012 2012

Constantz J, Adams KS, Stonestrom DA (2007) Overview of ground-water recharge study sites. In: Stonestrom DA, Constantz J, Ferre TPA, Leake SA (eds) Ground-water recharge in the arid and semiarid southwestern United States: US Geological Survey Professional Paper 1703-C:61-82.

Constantz J, Essaid H (2007) Influence of groundwater pumping on streamflow restoration following upstream dam removals. Hydrological Processes 21: 2823-2834 DOI 10.1002/hyp.6520

Ferone JM, Devito KJ (2004) Shallow groundwater-surface water interactions in pond-peatland complexes along a Boreal Plains topographic gradient. Journal of Hydrology 292: 75-95 DOI 10.1016/j.jhydrol.2003.12.032

Freeze RA, Cherry JA (1979) Groundwater Prentice-Hall, Upper Saddle River, N.J.

Hammersmark CT, Rains MC, Mount JF (2008) Quantifying the hydrological effects of stream restoration in a montane meadow, northern California, USA. River Research and Applications 24: 735-753 DOI 10.1002/rra.1077

Heede BH (1979) Deteriorated watersheds can be restored - case-study. Environmental Management 3: 271-281 DOI 10.1007/bf01866499

Hill AJ, Neary VS (2007) Estimating evapotranspiration and seepage for a sinkhole wetland from diurnal surface-water cycles. Journal of the American Water Resources Association 43: 1373-1382

Hill B, Mitchell-Bruker S (2010) Comment on "A framework for understanding the hydroecology of impacted wet meadows in the Sierra Nevada and Cascade Ranges, California, USA": paper published in Hydrogeology Journal (2009) 17:229-246, by Steven P. Loheide II, Richard S. Deitchman, David J. Cooper, Evan C. Wolf, Christopher T. Hammersmark, Jessica D. Lundquist. Hydrogeology Journal 18: 1741-1743 DOI 10.1007/s10040-010-0634-9

Hill BR (1990) Groundwater discharge to a headwater valley, Northwestern Nevada, USA. Journal of Hydrology 113: 265-283 DOI 10.1016/0022-1694(90)90178-z

Hoffman J, Duenas A, Gardiner K, Mulder C, Westmoreland R, Drake B, Kaplan-Henry T, Stewart C, Sable K, Martynn D, Wilcox D, Benoit T, Mink L, Nickerson R, Hopkins T, Garcia G, Rotta G, Urich D, Roby K, Foote R, Friend M, Belsher-Howe J, Lusk S, Kliejunas M, Nupen R, Berry J, Francine N, Dillingham A (2009) The Pond-and-Plug Treatment for Stream and Meadow

Restoration: Resource Benefits and Risks, Design Considerations. A Briefing Paper for Plumas National Forest Deciding Officials and Resource Specialists. In: Service USF (ed).

Jennings CW, Strand RG, Rogers TH (1977) Geologic Map of California: California Division of Mines and Geology, scale 1:750,000.

Lindquist DS, Wilcox J (2000) New Concepts for Meadow Restoration in the Northern Sierra Nevada Feather River Coordinated Resource Management, Quincy, CA.

Loheide SP, Booth EG (2011) Effects of changing channel morphology on vegetation, groundwater, and soil moisture regimes in groundwater-dependent ecosystems. Geomorphology 126: 364-376 DOI 10.1016/j.geomorph.2010.04.016

Loheide SP, Butler JJ, Gorelick SM (2005) Estimation of groundwater consumption by phreatophytes using diurnal water table fluctuations: A saturated-unsaturated flow assessment. Water Resources Research 41 DOI W07030
10.1029/2005wr003942

Loheide SP, Deitchman RS, Cooper DJ, Wolf EC, Hammersmark CT, Lundquist JD (2009) A framework for understanding the hydroecology of impacted wet meadows in the Sierra Nevada and Cascade Ranges, California, USA. Hydrogeology Journal 17: 229-246 DOI 10.1007/s10040-008-0380-4

Loheide SP, Gorelick SM (2005) A local-scale, high-resolution evapotranspiration mapping algorithm (ETMA) with hydroecological applications at riparian meadow restoration sites. Remote Sensing of Environment 98: 182-200 DOI 10.1016/j.rse.2005.07.003

Loheide SP, Gorelick SM (2006) Quantifying stream-aquifer interactions through the analysis of remotely sensed thermographic profiles and in situ temperature histories. Environmental Science & Technology 40: 3336-3341 DOI 10.1021/es0522074

Loheide SP, Gorelick SM (2007) Riparian hydroecology: A coupled model of the observed interactions between groundwater flow and meadow vegetation patterning. Water Resources Research 43 DOI W07414
10.1029/2006wr005233

Lord ML, Jewett DG, Miller JR, Germanoski D, Chambers JC (2011) Chapter 4: Hydrologic Processes Influencing Meadow Ecosystems.Geomorphology, hydrology, and ecology of Great Basin meadow complexes : implications for management and restoration General technical report RMRS-GTR ; 258.

Lowry CS, Deems JS, Loheide SP, Lundquist JD (2010) Linking snowmelt-derived fluxes and groundwater flow in a high elevation meadow system, Sierra Nevada Mountains, California. Hydrological Processes 24: 2821-2833 DOI 10.1002/hyp.7714

Mau DP, Winter TC (1997) Estimating ground-water recharge from streamflow hydrographs for a small mountain watershed in a temperate humid climate, New Hampshire, USA. Ground Water 35: 291-304 DOI 10.1111/j.1745-6584.1997.tb00086.x

McCallum JL, Cook PG, Berhane D, Rumpf C, McMahon GA (2012) Quantifying groundwater flows to streams using differential flow gaugings and water

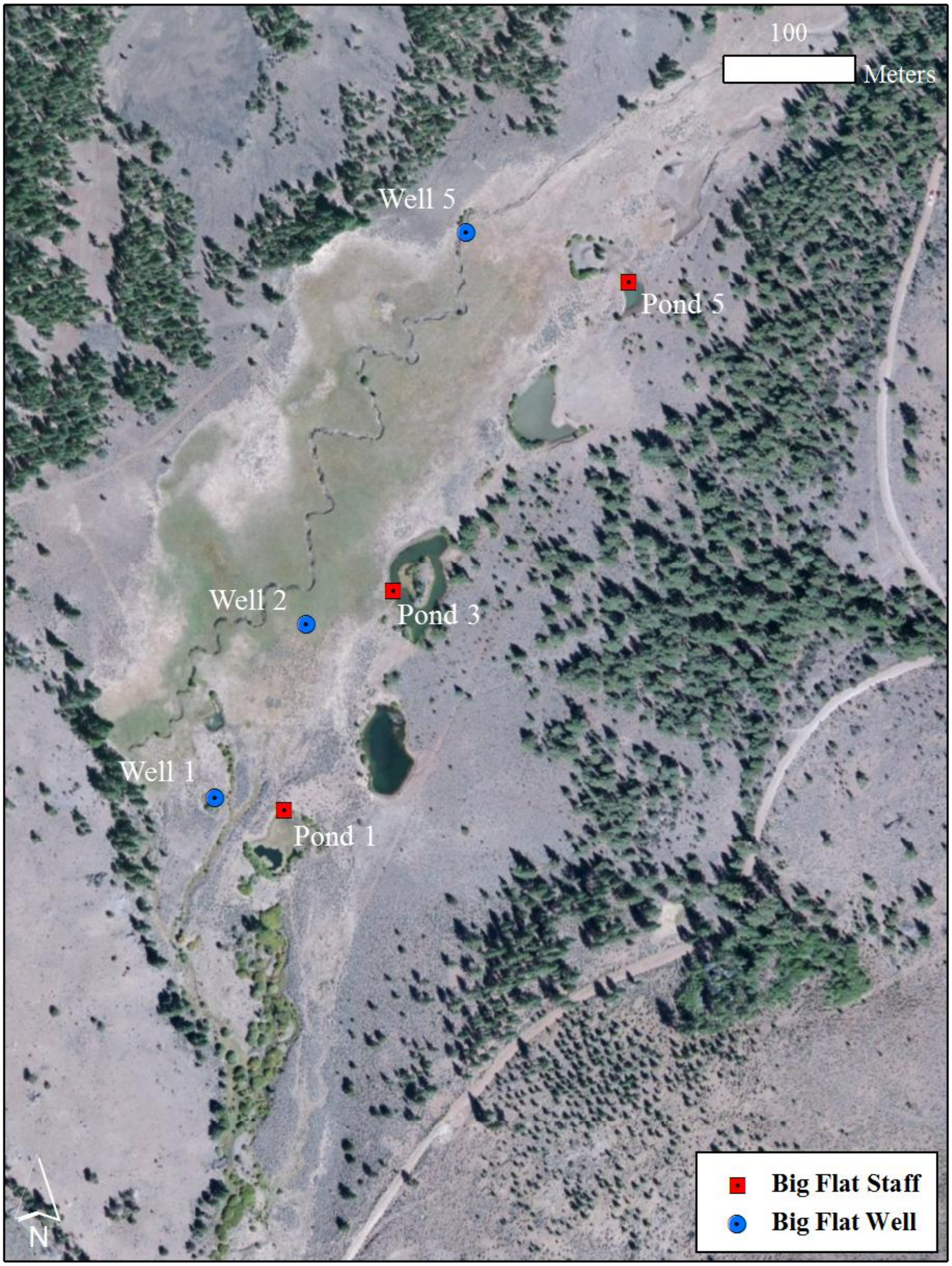
chemistry. Journal of Hydrology 416: 118-132 DOI 10.1016/j.jhydrol.2011.11.040
Nachabe MH (2002) Analytical expressions for transient specific yield and shallow water table drainage. Water Resources Research 38 DOI 10.1029/2001wr001071
Pinder GF, Sauer SP (1971) Numerical simulation of flood wave modification due to bank storage effects. Water Resources Research 7: 63-& DOI 10.1029/WR007i001p00063
Ponce VM, Lindquist DS (1990) Management of baseflow augmentation - a review. Water Resources Bulletin 26: 259-268
Prudic D, Green J, Wood J, Henkelman K (2005) Changes in Ground-Water Flow and Chemistry after Completion of Cattlemans Detention Basin, South Lake Tahoe, California--November 2001 to November 2003.
Prudic DE, Niswonger RG, Harrill JR, Wood JL (2007) Streambed infiltration and ground-water flow from the Trout Creek Drainage, an intermittent tributary to the Humboldt River, north-central Nevada. In: Stonestrom DA, Constantz J, Ferre TPA, Leake SA (eds) Ground-water Recharge in the arid and semiarid southwestern United States: US Geological Survey Professional Paper 1703-K:313-351.
Rantz SE, others a (1982) Measurement and Computation of Streamflow: Volume 1. U.S. Geological Survey Water-Supply Paper 2175.
Ratliff RD (1985) Meadows in the Sierra Nevada of California : state of knowledge / Raymond D. RatliffGeneral technical report PSW ; no 84.
Rosgen D (1996) Applied River Morphology Wildland Hydrology, Pagosa Springs, CO
Web Soil Survey., http://websoilsurvey.nrcs.usda.gov/. Cited 02/22/2013
Sophocleous M (2002) Interactions between groundwater and surface water: the state of the science. Hydrogeology Journal 10: 52-67 DOI 10.1007/s10040-001-0170-8
Swanson S, Franzen D, Manning M (1987) Rodero Creek - rising water on the high desert. Journal of Soil and Water Conservation 42: 405-407
Tague C, Valentine S, Kotchen M (2008) Effect of geomorphic channel restoration on streamflow and groundwater in a snowmelt-dominated watershed. Water Resources Research 44 DOI W10415
10.1029/2007wr006418
Turner JV, Townley LR (2006) Determination of groundwater flow-through regimes of shallow lakes and wetlands from numerical analysis of stable isotope and chloride tracer distribution patterns. Journal of Hydrology 320: 451-483 DOI 10.1016/j.jhydrol.2005.07.050
Weixelman DA, Hill B, Cooper DJ, Berlow EL, Viers JH, Purdy SE, Merrill AG, Gross SE (2011) Meadow Hydrogeomorphic Types for the Sierra Nevada and Southern Cascade Ranges in California: A Field Key. General Technical Report R5-TP-034.
Westbrook CJ, Cooper DJ, Baker BW (2006) Beaver dams and overbank floods influence groundwater-surface water interactions of a Rocky Mountain riparian area. Water Resources Research 42 DOI W06404
10.1029/2005wr004560

Winter TC (2007) The role of ground water in generating streamflow in headwater areas and in maintaining base flow [electronic resource]. Journal of the American Water Resources Association 43: 15-25 DOI http://www.awra.org/jawra/index.html

Appendix A: Site maps for study meadows.

Big Bear Flat meadow site map.

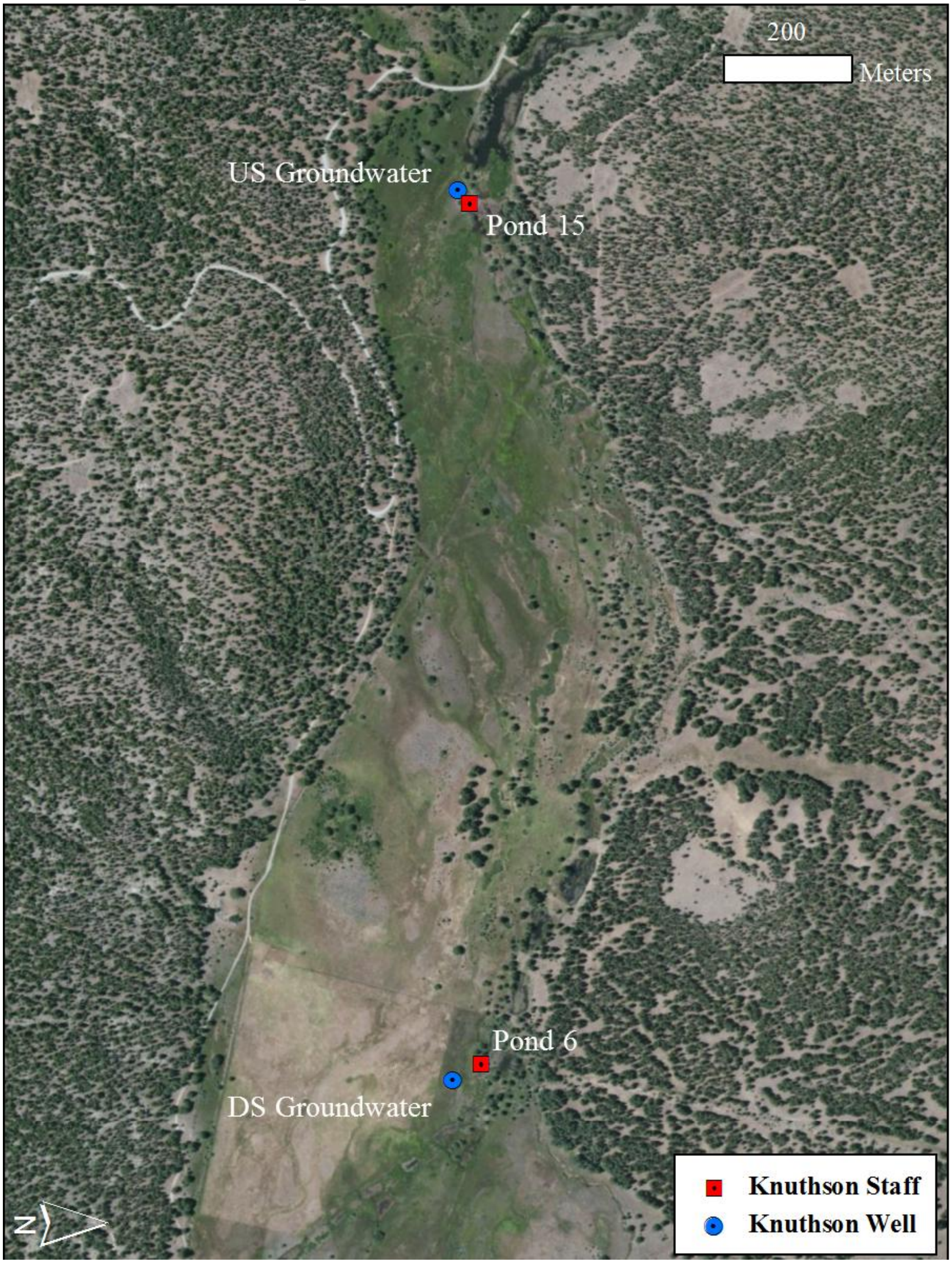
Big Flat meadow site map.



Davies meadow site map.

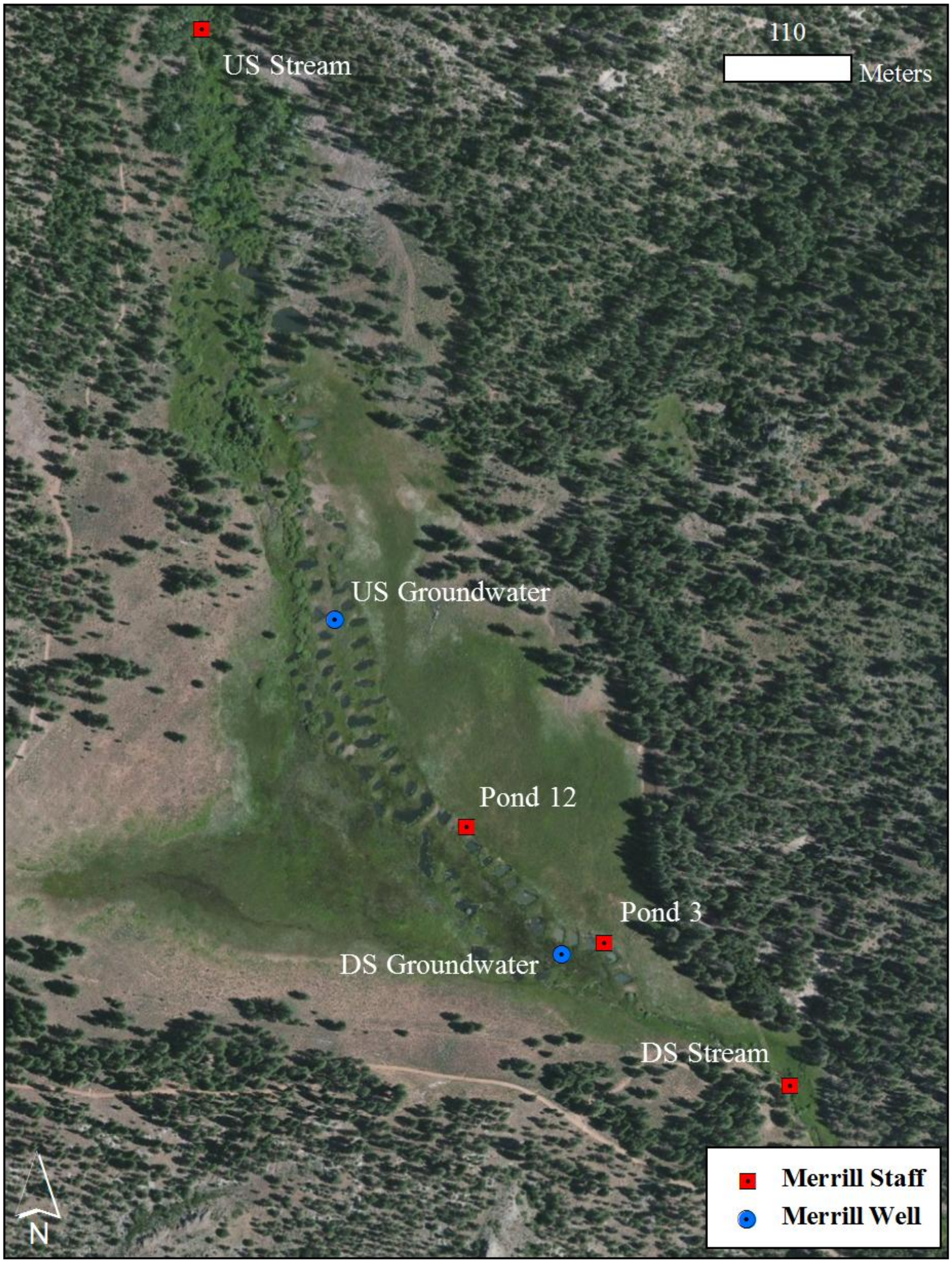
Ferris meadow site map.

Knuthson meadow site map.



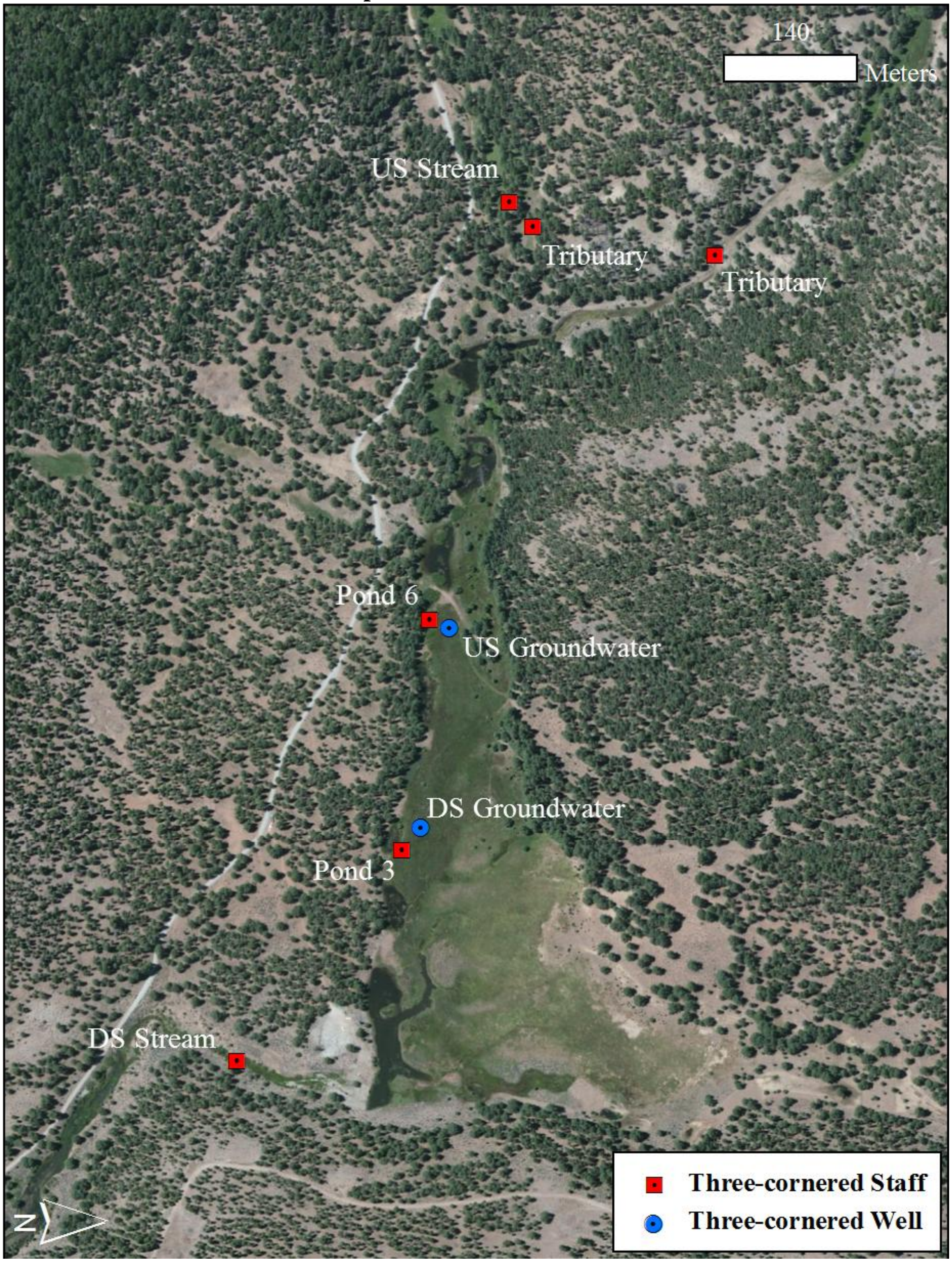
Lassen meadow site map.

Merrill Valley meadow site map.



Rose Canyon meadow site map.

Three-cornered meadow site map.



Appendix B: Discharge and rating curve discussion

At stream staff gauge locations discharge was measured using a Marsh-McBirney Model 201D Portable Water Current Meter and standard USGS protocol (Rantz and others, 1982). Staff gauge locations were also established following standard protocols (Rantz and others, 1982). They were located in the stream channel above and below restored meadows, generally in pools that allow measuring of discharge in a variety of flow conditions. Ideally, these were sections of stream that were stable (not aggrading or degrading), and had straight sections of stream channel above and below. Lastly, they were locations were laminar stream flow occurred.

At these locations, discharge was measured several times through the dry season. Measuring discharge consisted of dividing the stream into smaller segments in which discharge was measured, with the goal that not more than 10% of the entire discharge was contained in one segment. In addition, at least 10 individual cells must exist.

To begin, a distance tape is stretched across the stream channel, perpendicular to the flow. Once the total width is known, the channel is broken into at least 10 segments. Each segment is considered a trapezoid, for which the area is calculated by:

$$A = d \ \frac{h_1 + h_2}{2}$$

where:

A = area of the trapezoid (ft^2),

h_1 = depth of starting edge of the trapezoid (ft),

h_2 = depth of ending edge of the trapezoid (ft),

d = distance between each edge of the trapezoid (ft).

In the middle of this trapezoid ($\frac{d}{2}$), velocity of the stream is measured. Since streams were generally ≤ 2.5 ft (0.76 m) deep, one velocity measurement, at 0.6 of depth was adequate (Rantz and others, 1982). Then discharge in each segment is calculated by:

$$Q = A \times v$$

where:

Q = discharge (cfs, ft^3/s),

A = area of trapezoid (ft^2),

v = velocity of stream (ft/s).

Starting from the left edge of the stream channel, trapezoid depths and distances are recorded and associated velocities measured until the right edge of the channel is reached. Once discharge in each segment is calculated, total discharge is determined by:

$$Q_T = \quad A_n \times v_n$$

where:

Q_T = total stream discharge (cfs),

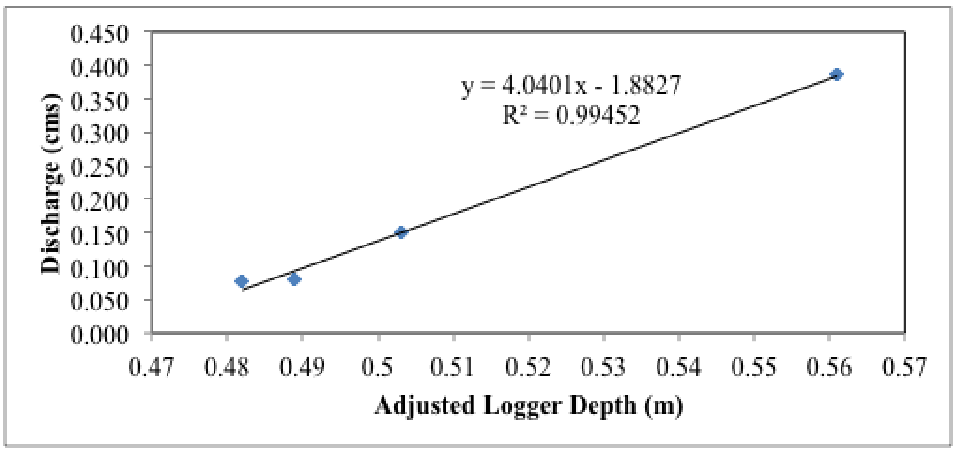
A_n = area of individual segments,

v_n = velocity of associated individual segments.

After discharge was measured, time, date and staff depth were recorded. These values, in conjunction with discharge, were used to develop a rating curve. Discharge was converted to cubic meters per second (cms). A rating curve develops a relationship between depth and discharge, so that a continuous stream hydrograph can be created. In each staff gauge, a pressure transducer was installed, which recorded depth at 15 min intervals through the monitoring period. With these data and a rating curve, a hydrograph is created for a longer time period without continuous measures of discharge. Rating curve data for each site is provided.

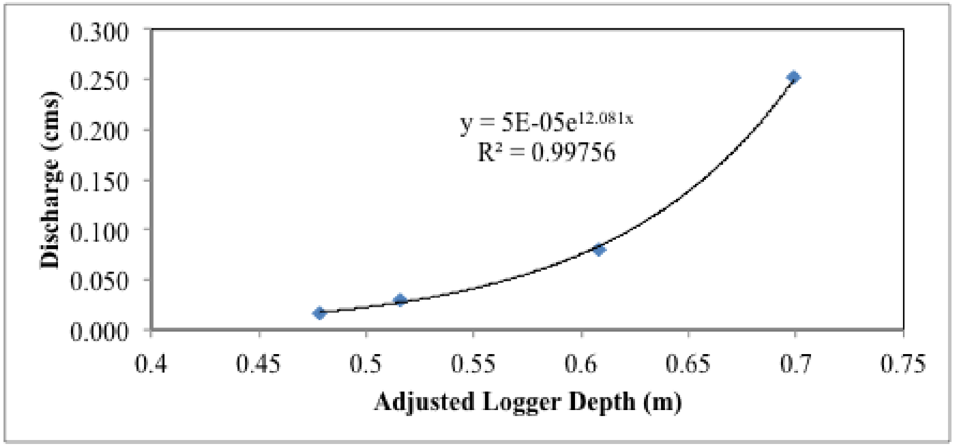
Big Bear:
Downstream main channel:

Date	Time	Staff (m)	Discharge (cfs)	Discharge (cms)	Adjusted Logger Depth (m)
6/22/12	1745	0.55	13.6	0.385	0.561
7/25/12	1613	0.51	5.27	0.149	0.503
8/27/12	741	0.49	2.8	0.079	0.489
10/6/12	1631	0.49	2.73	0.077	0.482



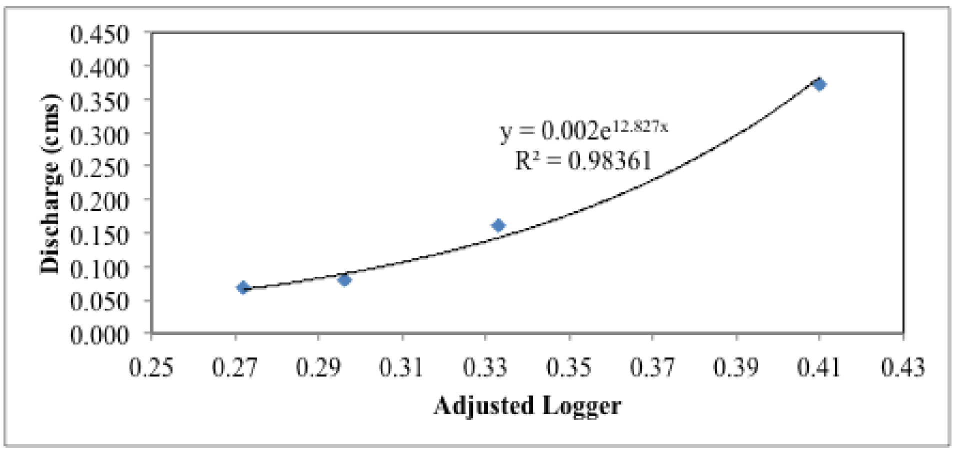
Upstream main channel:

Date	Time	Staff (m)	Discharge (cfs)	Discharge (cms)	Adjusted Logger Depth (m)
6/22/12	1300	0.69	8.88	0.251	0.699
7/25/12	1320	0.61	2.85	0.081	0.608
8/27/12	937	0.52	1.05	0.030	0.516
10/6/12	1752	0.48	0.58	0.016	0.478



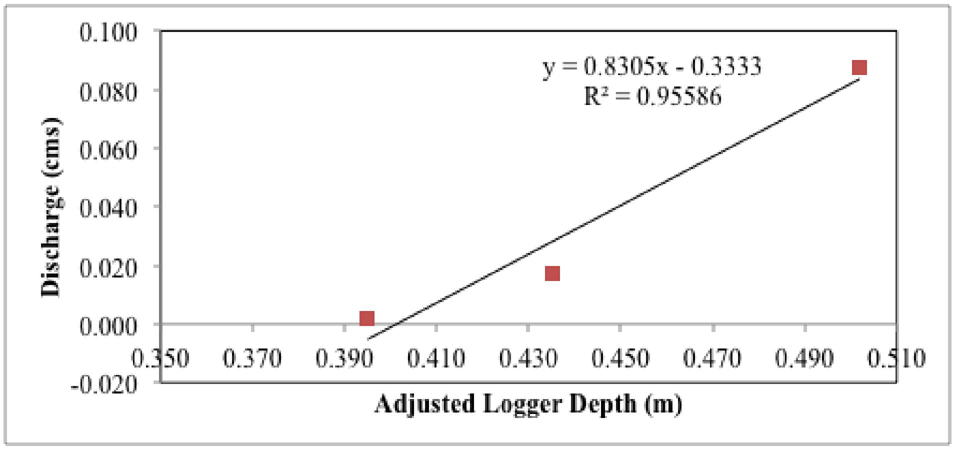
Upstream tributary:

Date	Time	Staff (m)	Discharge (cfs)	Discharge (cms)	Adjusted Logger Depth (m)
6/22/12	1530	0.4	13.12	0.372	0.410
7/25/12	1100	0.34	5.68	0.161	0.333
8/27/12	837	0.29	2.79	0.079	0.296
10/6/12	1138	0.28	2.38	0.067	0.272



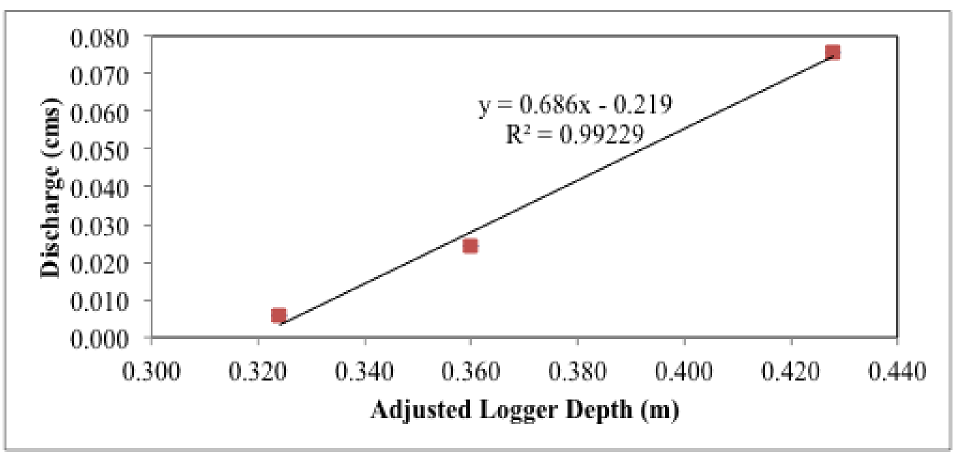
Lassen Creek:
Downstream channel:

Date	Time	Staff (m)	Discharge (cfs)	Discharge (cms)	Adjusted Logger Depth (m)
6/24/12	1215	0.55	3.1	0.088	0.502
7/18/12	1800	0.435	0.6	0.017	0.435
9/28/12	1736	0.395	0.06	0.002	0.395



Upstream channel:

Date	Time	Staff (m)	Discharge (cfs)	Discharge (cms)	Adjusted Logger Depth (m)
6/24/12	1330	0.425	2.68	0.076	2.720
7/18/12	1950	0.36	0.86	0.024	0.900
9/28/12	1950	0.32	0.2	0.006	0.240



Literature Cited

Rantz SE, others a (1982) Measurement and Computation of Streamflow: Volume 1. U.S. Geological Survey Water-Supple Paper 2175.

Appendix C: Penman-Monteith discussion

Reference crop evapotranspiration (ET_o) was calculated using the FAO Penman-Monteith equation (1). This equation uses weather station data and a series of equations to determine ET_o. Allen et al. (1998), established standard guidelines for using this equation to determine ET_o. ET_o is defined as evapotranspiration of an area of well watered green grass cut to a uniform height of 0.12 m. The methodology and equations are described below:

$$ET_o = \frac{0.408\Delta(R_n - G) + \dfrac{\gamma 900}{T+273} * u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{1}$$

Where

ET_o = reference evapotranspiration (mm day^{-1}),

R_n = net radiation at the crop surface (MJ m^{-2} day^{-1}),

G = soil heat flux density (MJ m^{-2} day^{-1}),

T = mean daily air temperature at 2 m height (°C),

u_2 = wind speed at 2 m height (m s^{-1}),

e_s = saturation vapor pressure (kPa),

e_a = actual vapor pressure (kPa),

$e_s - e_a$ = saturation vapor pressure (kPa),

Δ = slope of vapor pressure curve (kPa °C^{-1}),

g = psychometric constant (kPa°C^{-1}).

Net radiation, Temperature, and Wind Speed were calculated as daily averages from the climate station. Soil heat flux density was assumed to be small relative to R_n, and was ignored (Allen et al, 1998). Saturation vapor pressure was calculated from Equations 2 and 3(Allen et al, 1998):

$$e_s = \frac{e°(T_{max}) + e°(T_{min})}{2} \tag{2}$$

where $e°(T_{max})$ and $e°(T_{min})$ are calculated using Equation D3 (Allen et al, 1998) :

$$e°(T) = 0.6108 \exp\left[\frac{17.27T}{T + 237.3}\right] \tag{3}$$

where $e°(T)$ is the saturation vapor pressure at the air temperature (°C) and is calculated twice (T = daily T_{min} and T = daily T_{max}).

Actual vapor pressure was calculated using Equation 4 (Allen et al, 1998):

$$e_a = \frac{e°(T_{min})\frac{RH_{max}}{100} + e°(T_{max})\frac{RH_{min}}{100}}{2} \tag{4}$$

where RHmin and RHmax are the daily minimum and maximum relative humidity, from weather station data.

Slope of vapor pressure curve was calculated using Equation 5 (Allen et al, 1998):

$$\Delta = \frac{4098\left[0.6018 \exp\left(\frac{17.27T}{T + 237.3}\right)\right]}{(T + 237.3)^2} \tag{5}$$

where T is the daily average temperature.

The psychometric constant was calculated from Equation 6 (Allen et al, 1998):

$$\gamma = \frac{c_p P}{\varepsilon \lambda} = 0.665x10^{-3} P \tag{6}$$

where

P = atmospheric pressure (kPa),

λ = latent heat of vaporization, 2.45 (MJ kg^{-1}),

cp = specific heat at constant pressure,1.013 10^{-3} (MJ kg^{-1} °C),

ε = ratio of the molecular weight of the water vapor to dry air =0.622. P is a function of elevation above sea level and was determined using meadow study site elevation and Equation 7 (Allen et al, 1998):

$$P = 101.3\left(\frac{293 - 0.0065z}{293}\right)^{5.26} \tag{7}$$

where

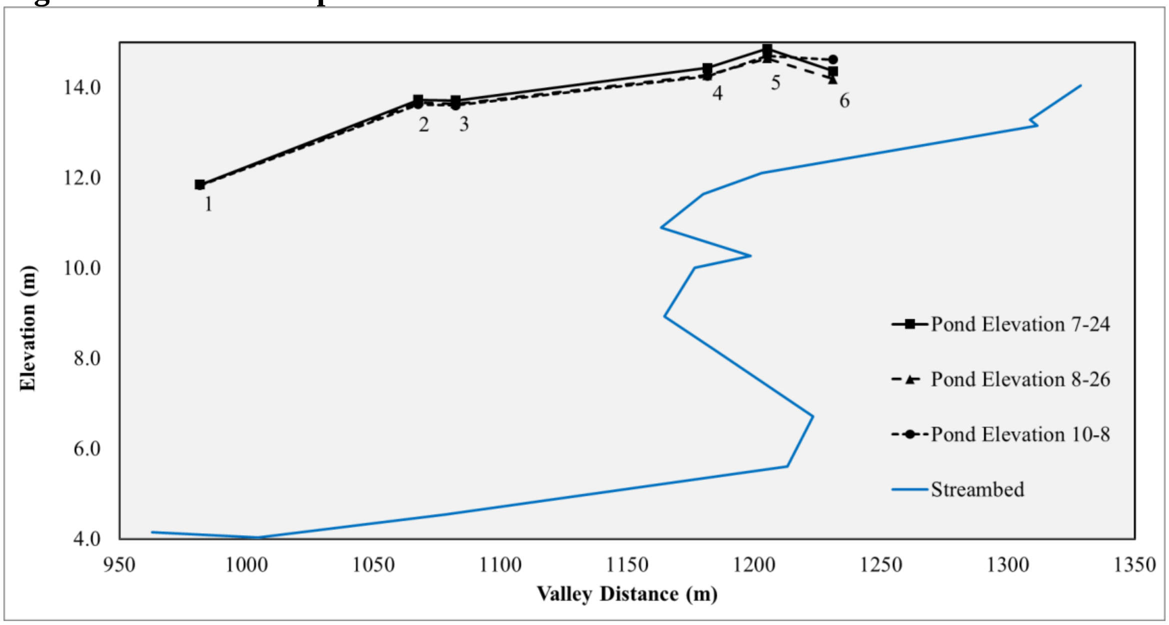
P = atmospheric pressure (kPa),

z = elevation above sea level (m).

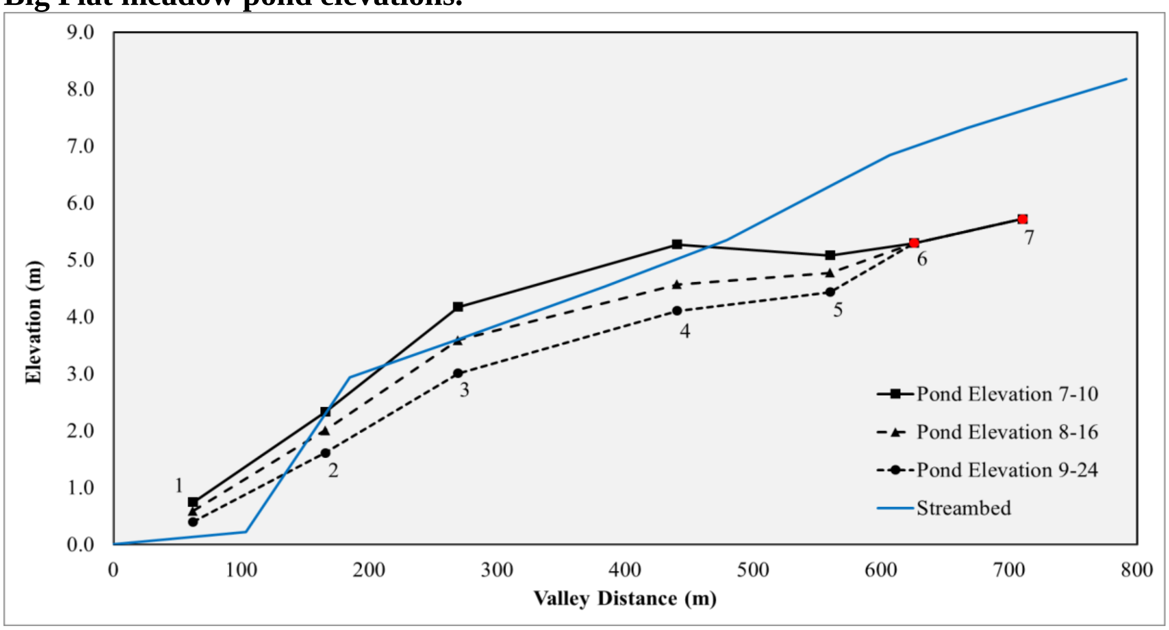
Appendix D: Pond elevation plots through the season

Streambed elevation is indicated by a blue line, and meadow surface elevation by a green line. Ponds are indicated by symbols, with differing symbols for each sample date. Ponds are numbered consecutively moving upstream, and a red symbol indicates that the pond is dry for that sample date.

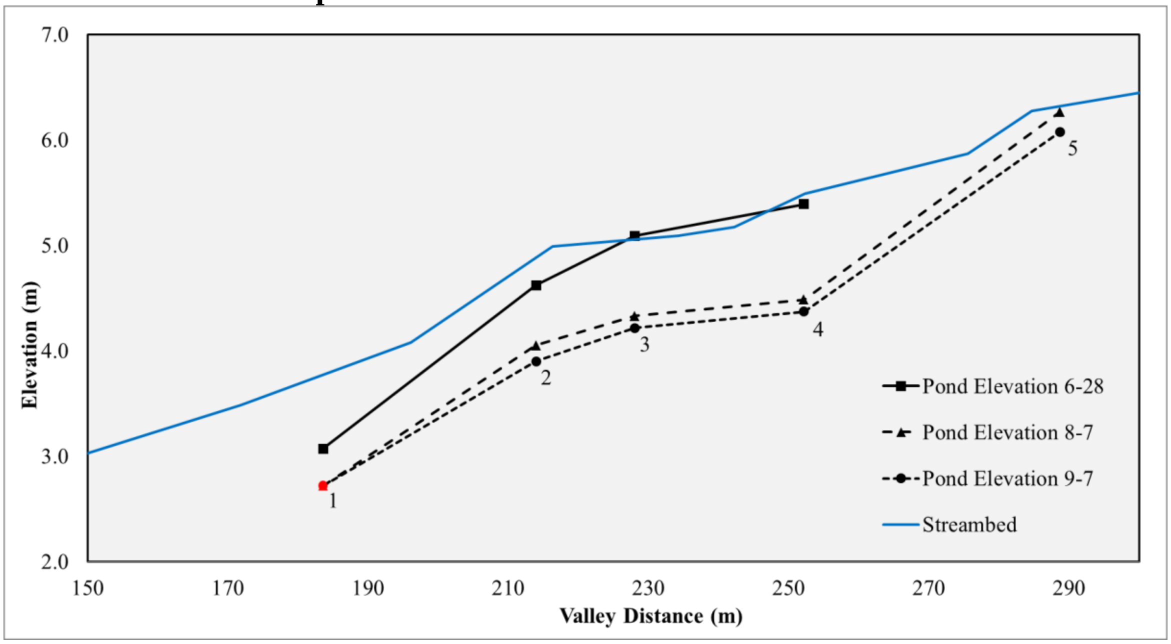
Big Bear Flat meadow pond elevations.



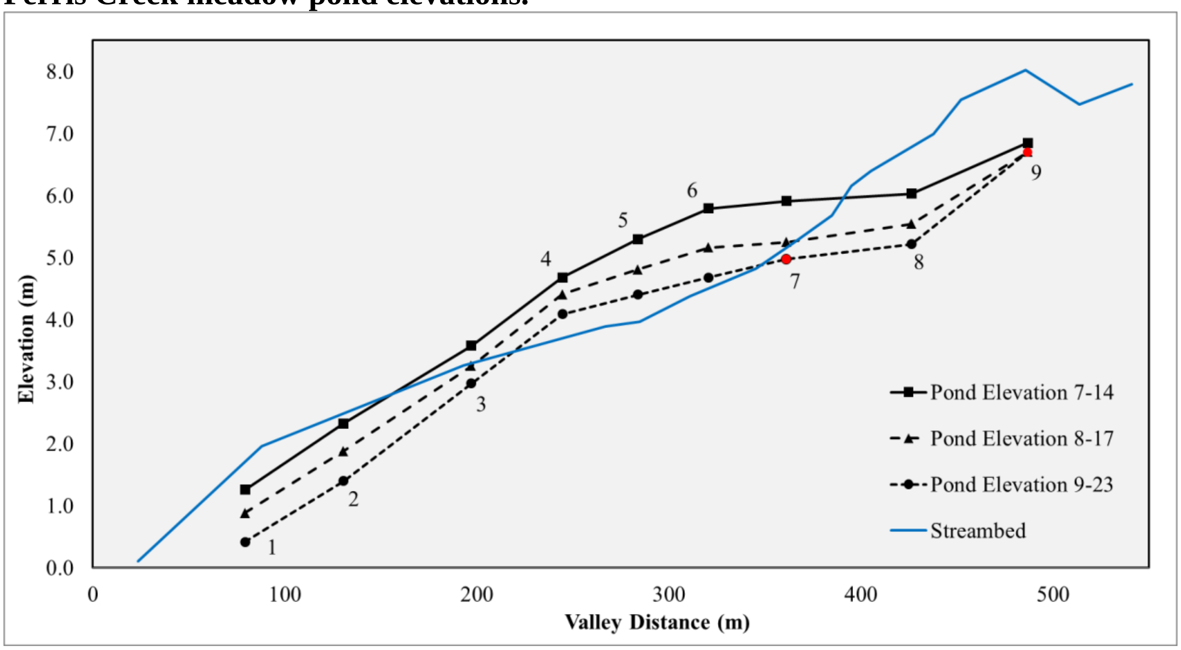
Big Flat meadow pond elevations.



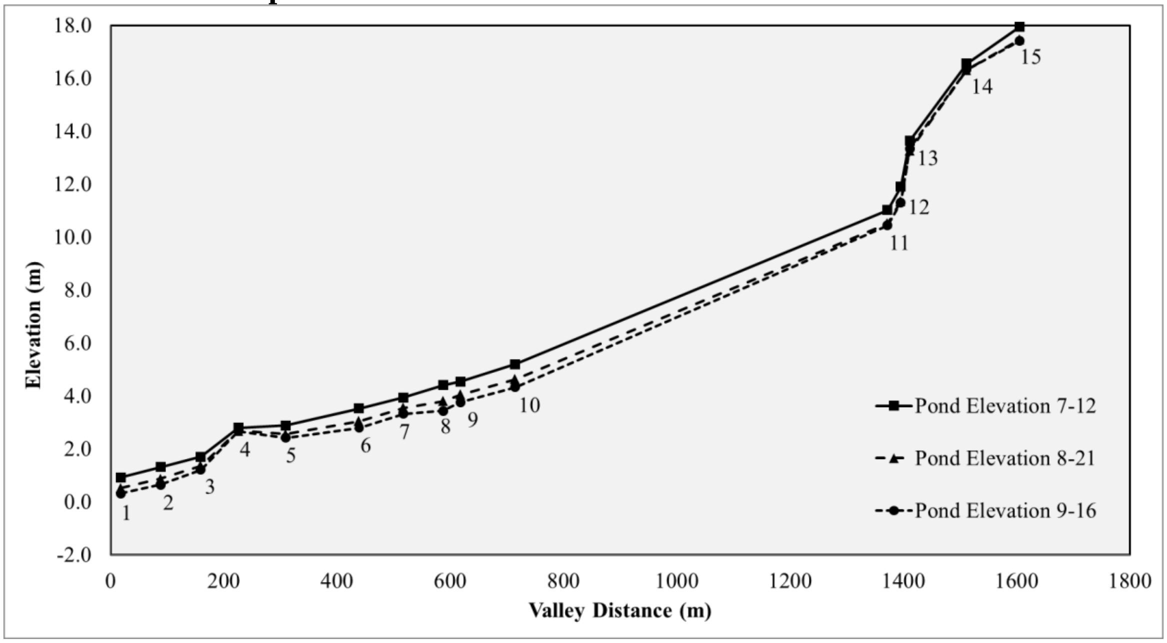
Davies Creek meadow pond elevations.



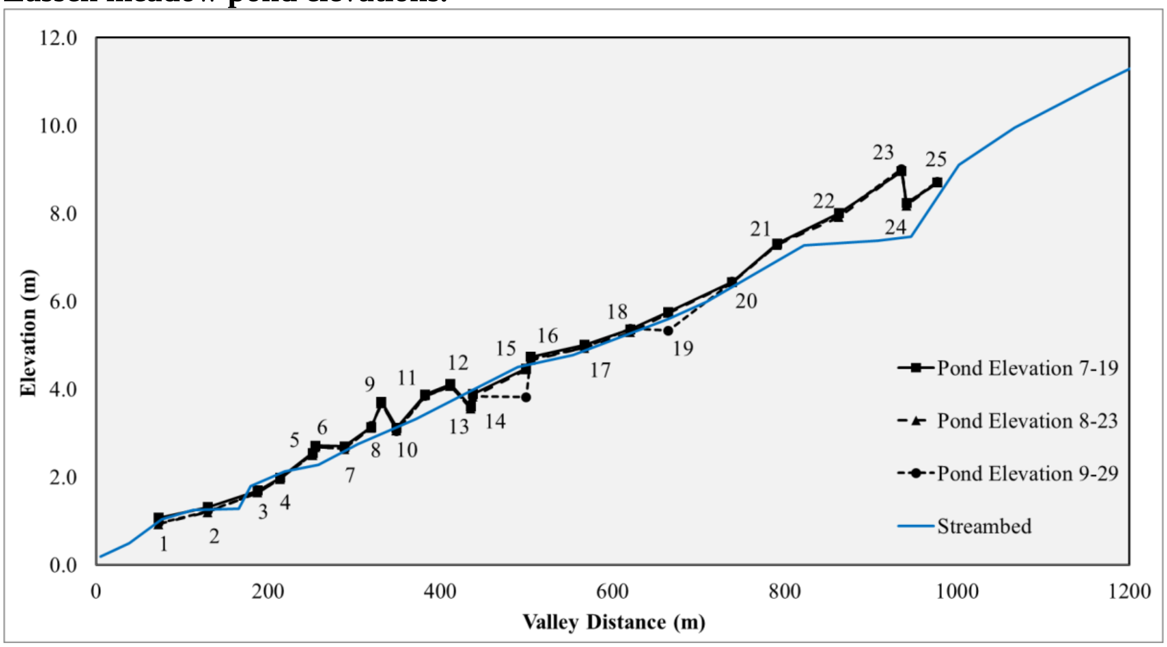
Ferris Creek meadow pond elevations.



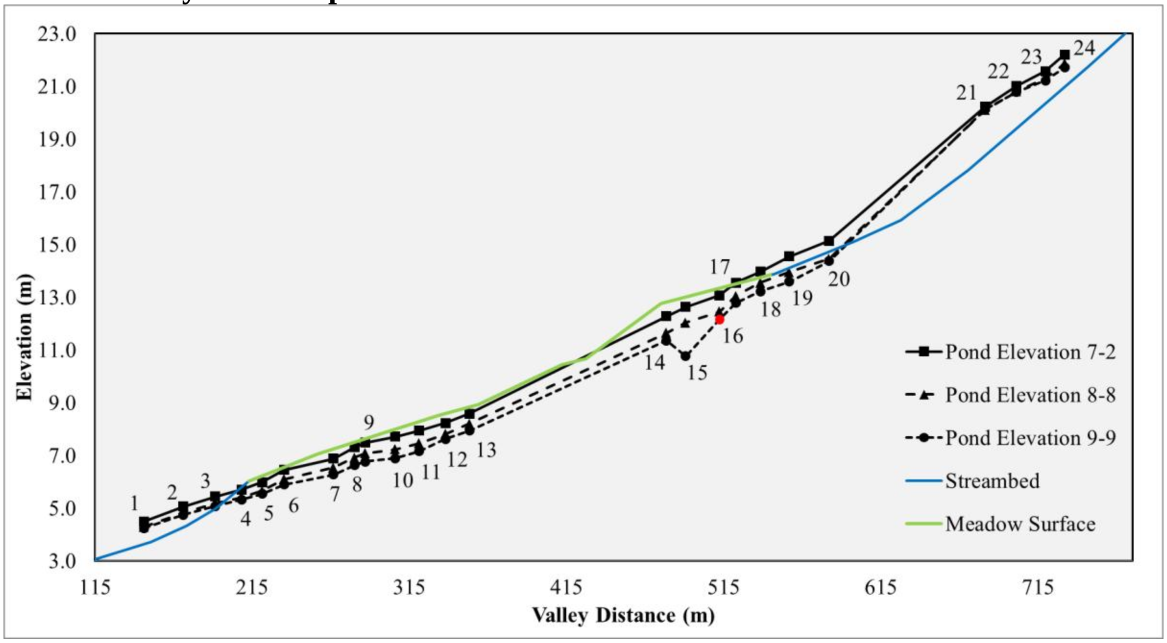
Knuthson meadow pond elevations.



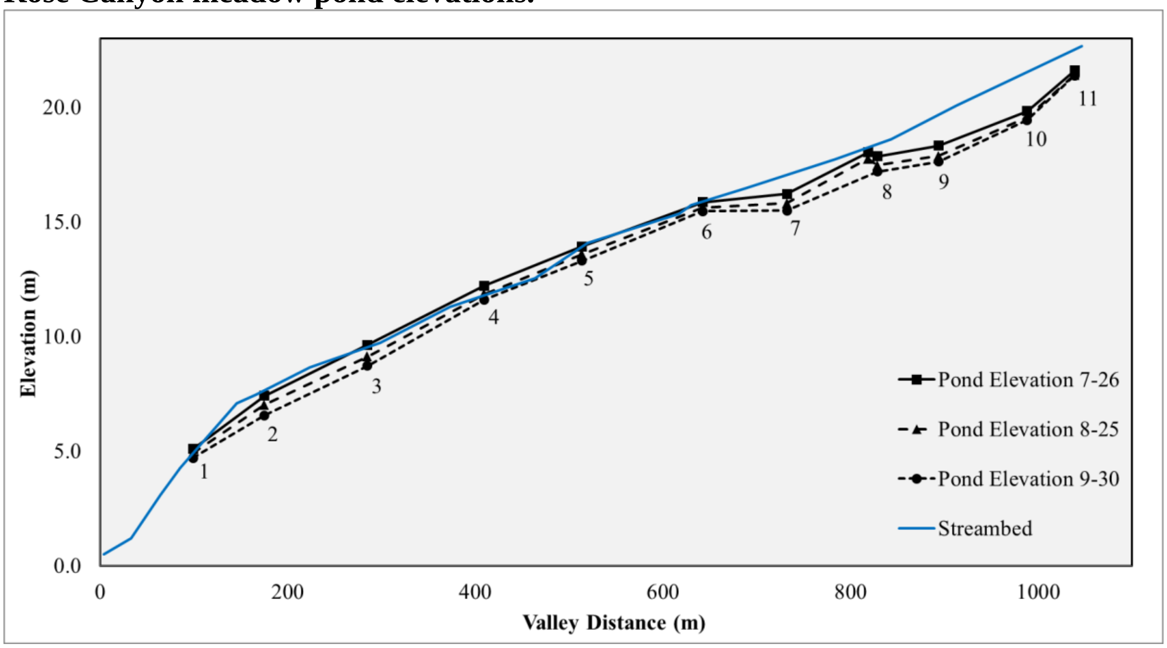
Lassen meadow pond elevations.



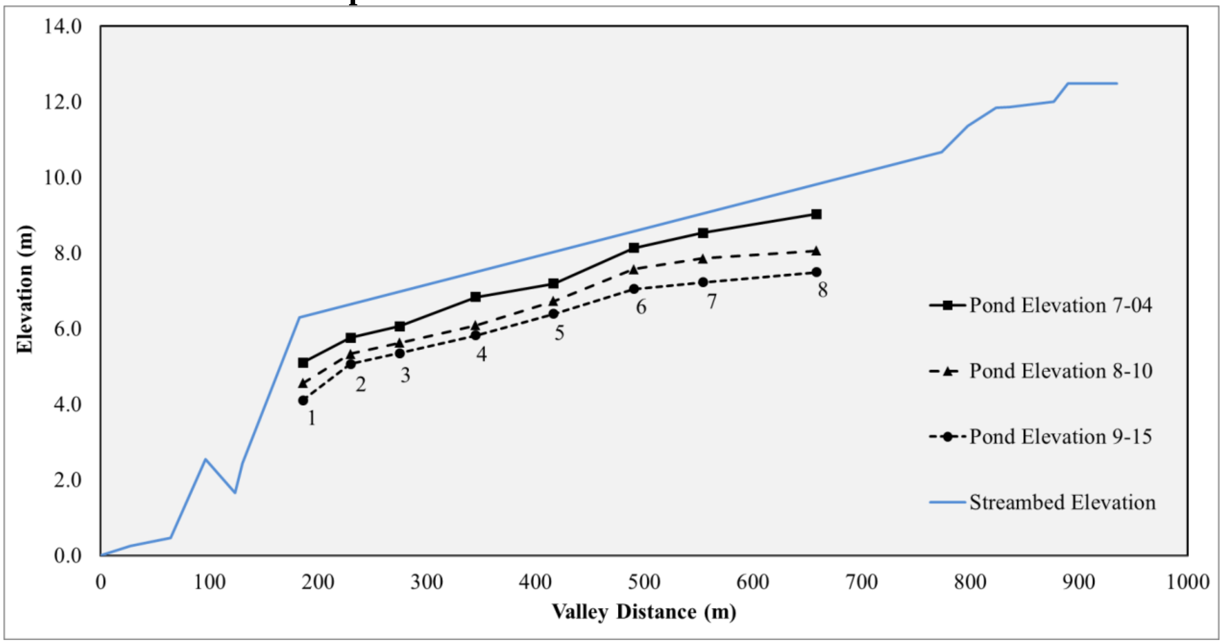
Merrill Valley meadow pond elevations.



Rose Canyon meadow pond elevations.



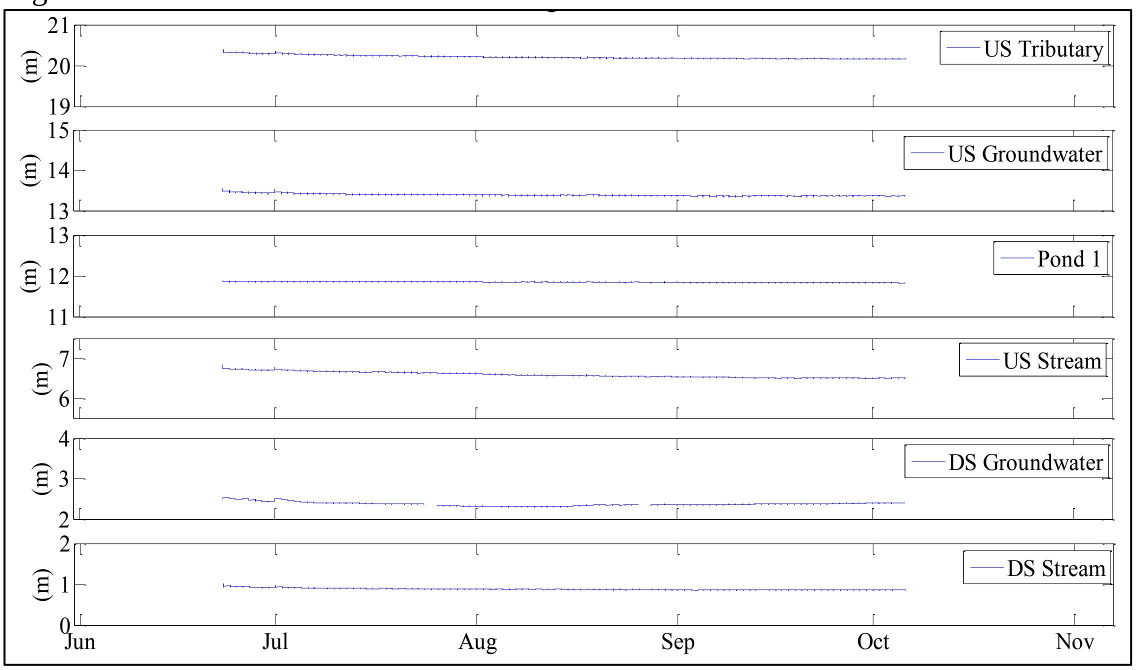
Three-cornered meadow pond elevations.



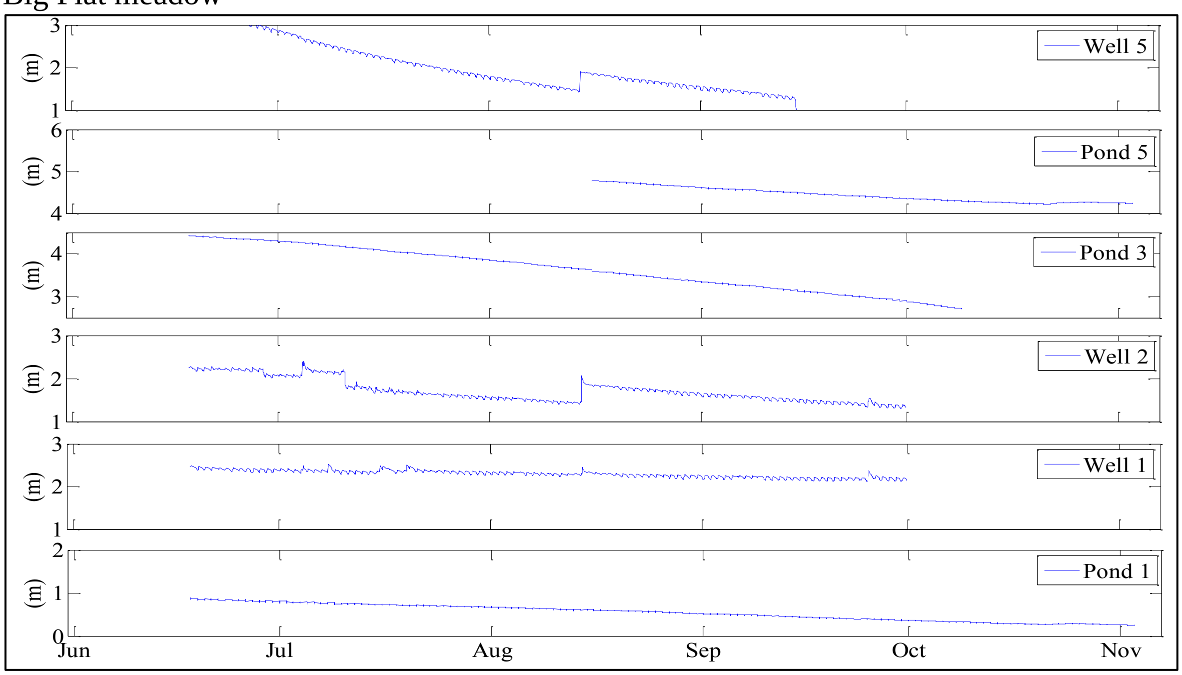
Apendix E. Logger hydrographs

Logger hydrographs for each site through the season, as indicated by a blue line. Any gaps in data represent the loggers going dry, generally occuring in August.

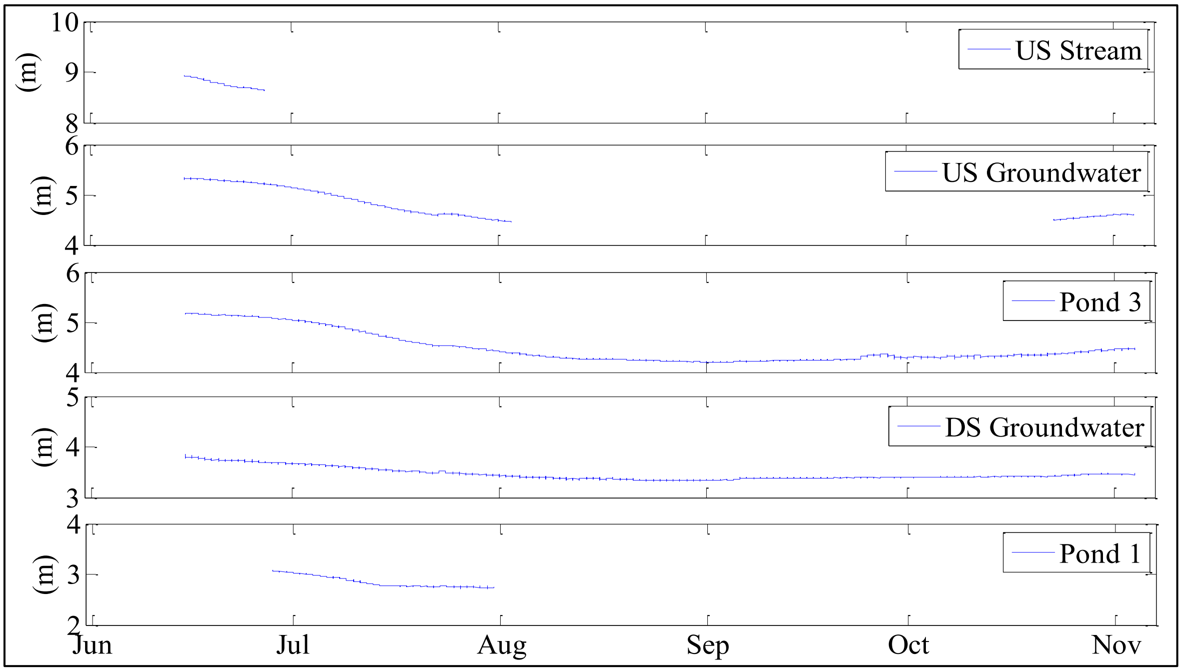
Big Bear Flat meadow



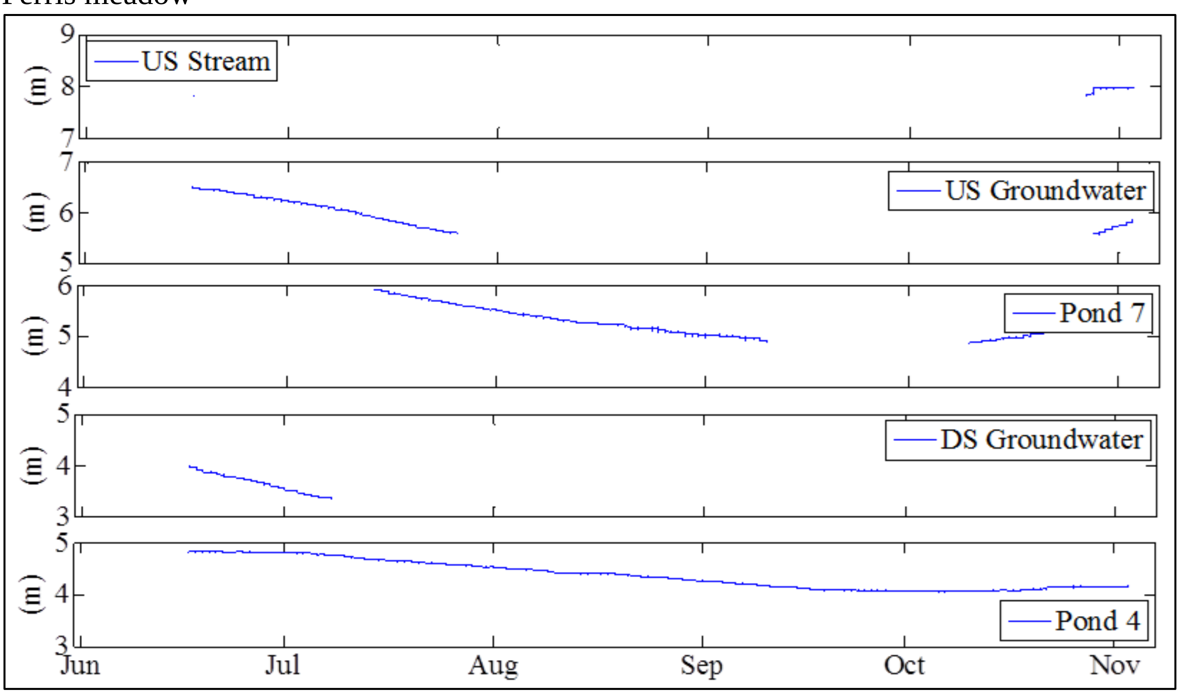
Big Flat meadow



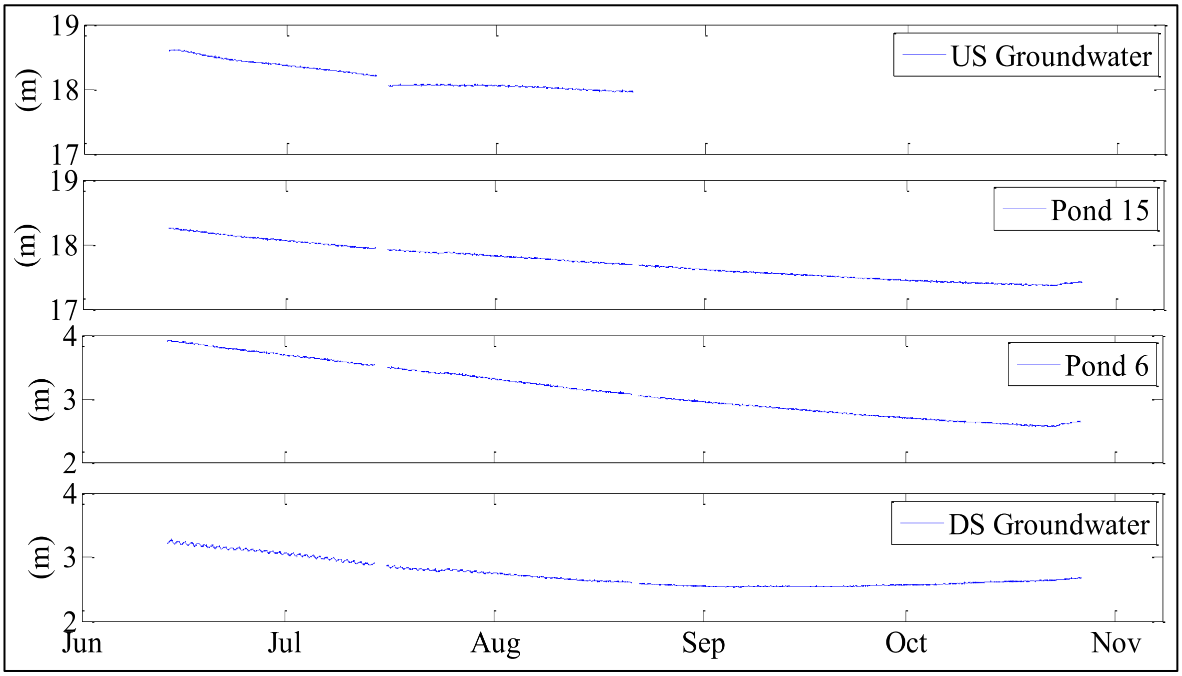
Davies meadow



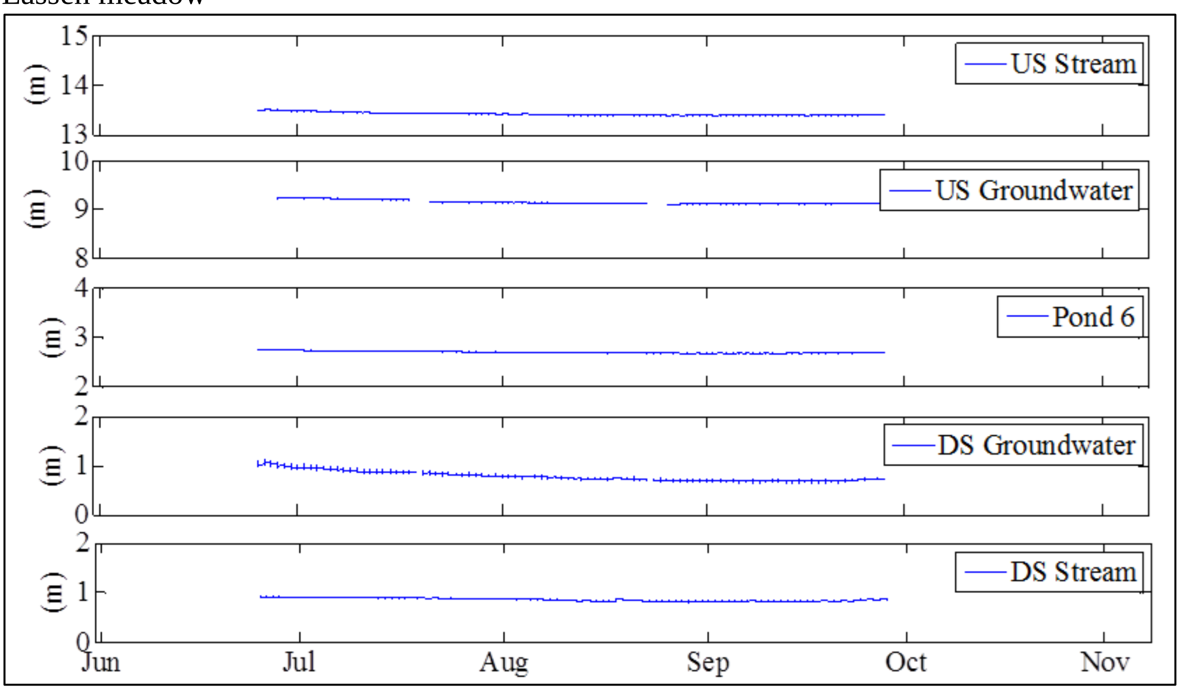
Ferris meadow



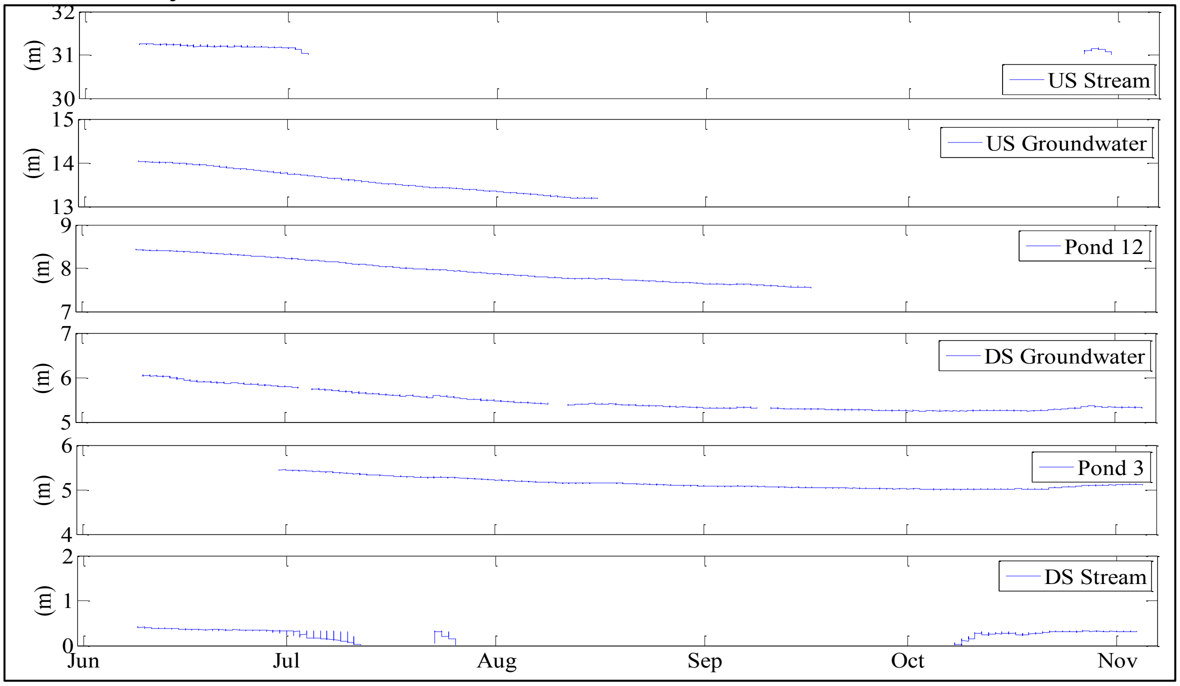
Knuthson meadow



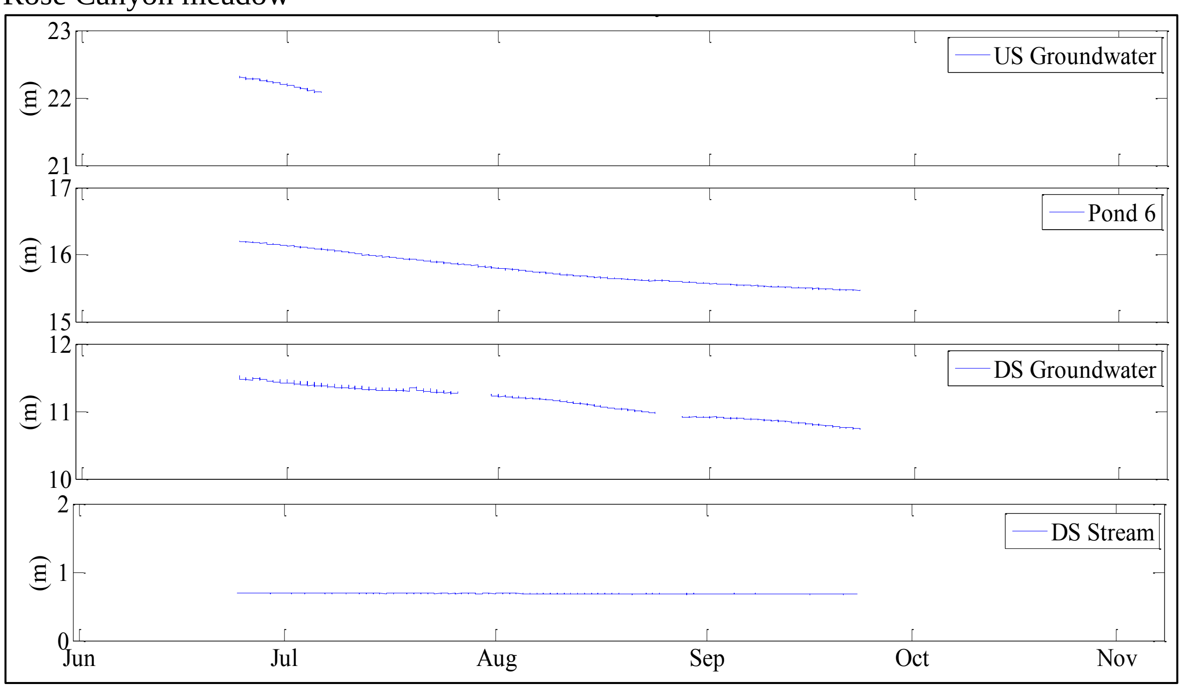
Lassen meadow



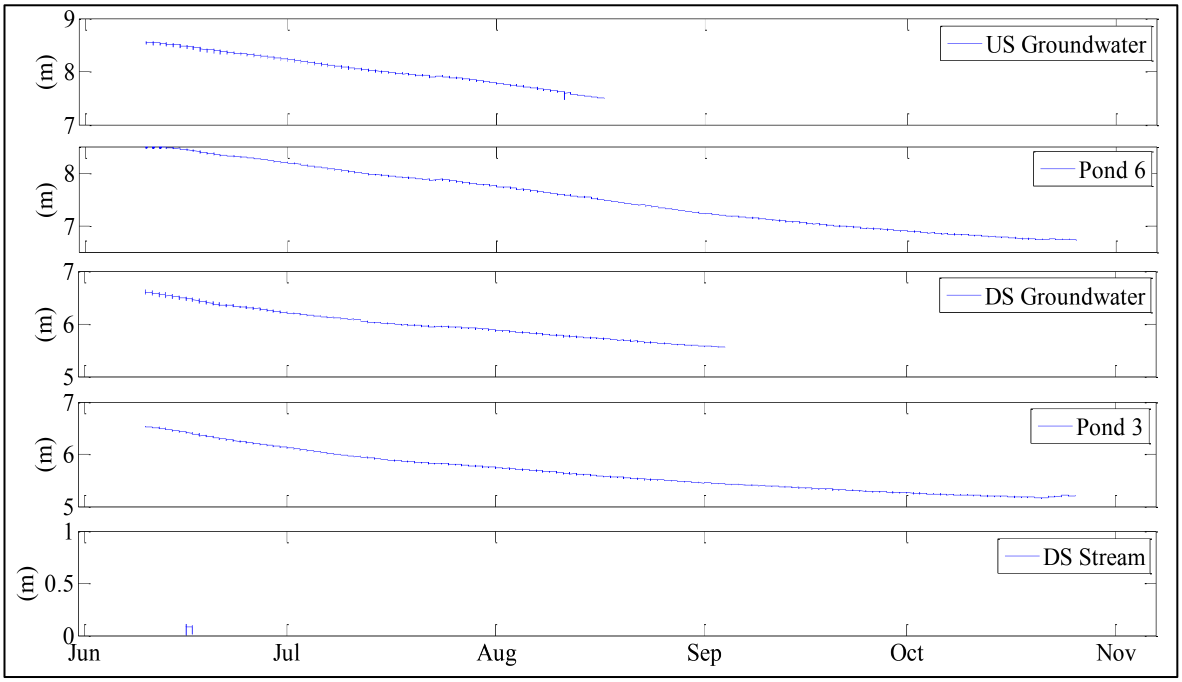
Merrill Valley meadow



Rose Canyon meadow

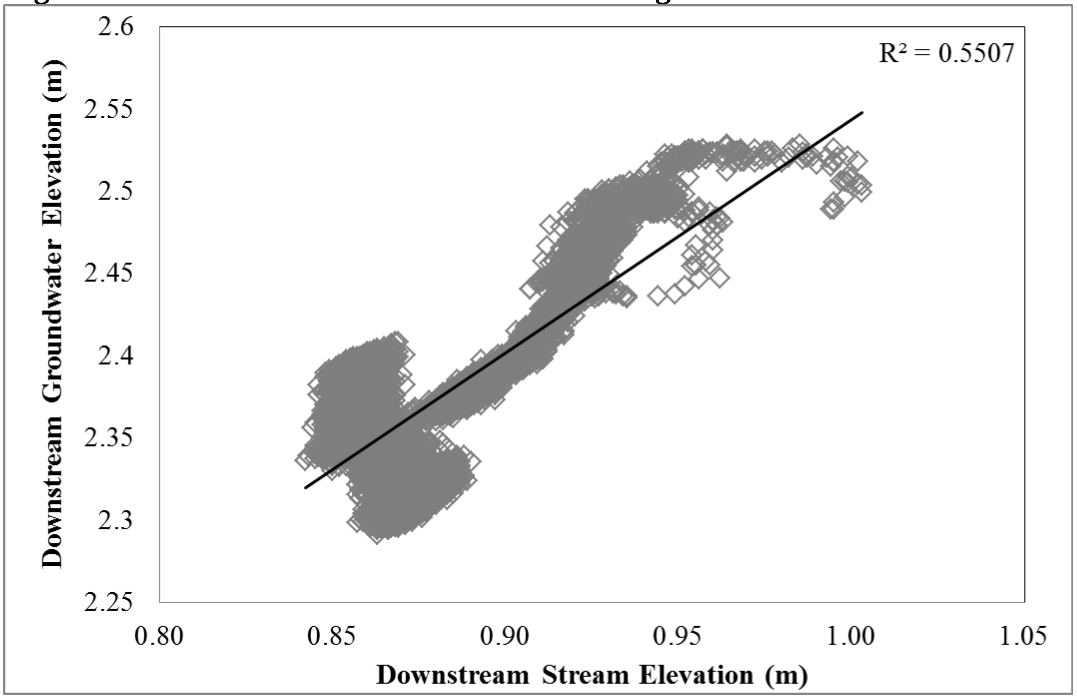


Three-cornered meadow

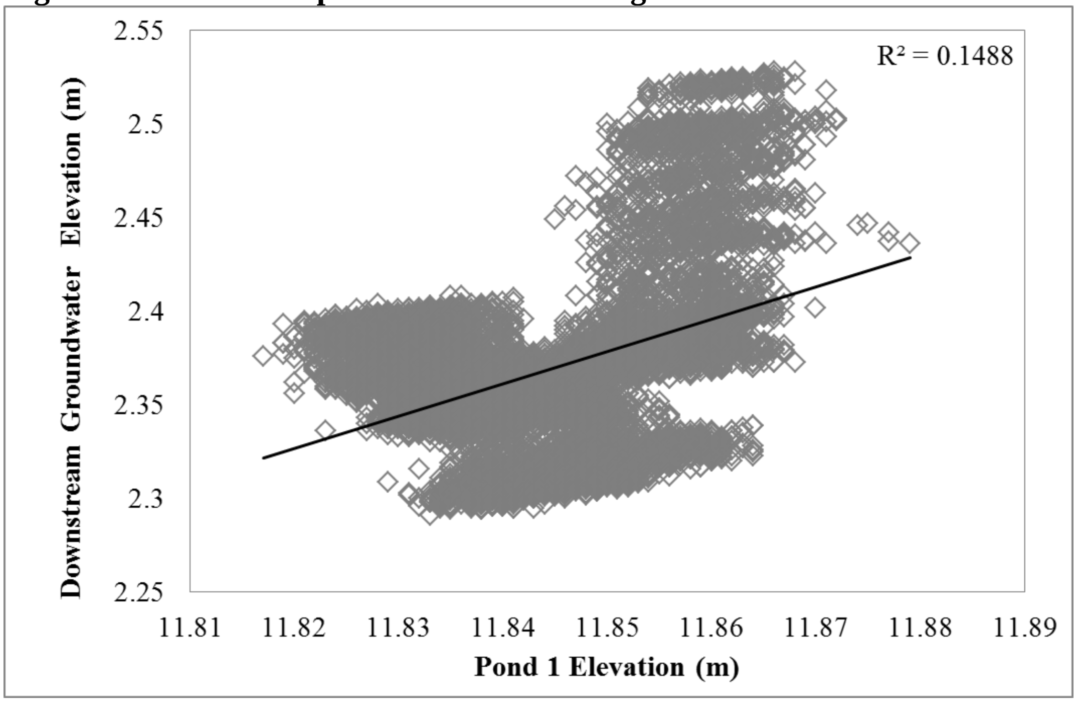


Appendix F: Logger data comparisons with linear relationships.

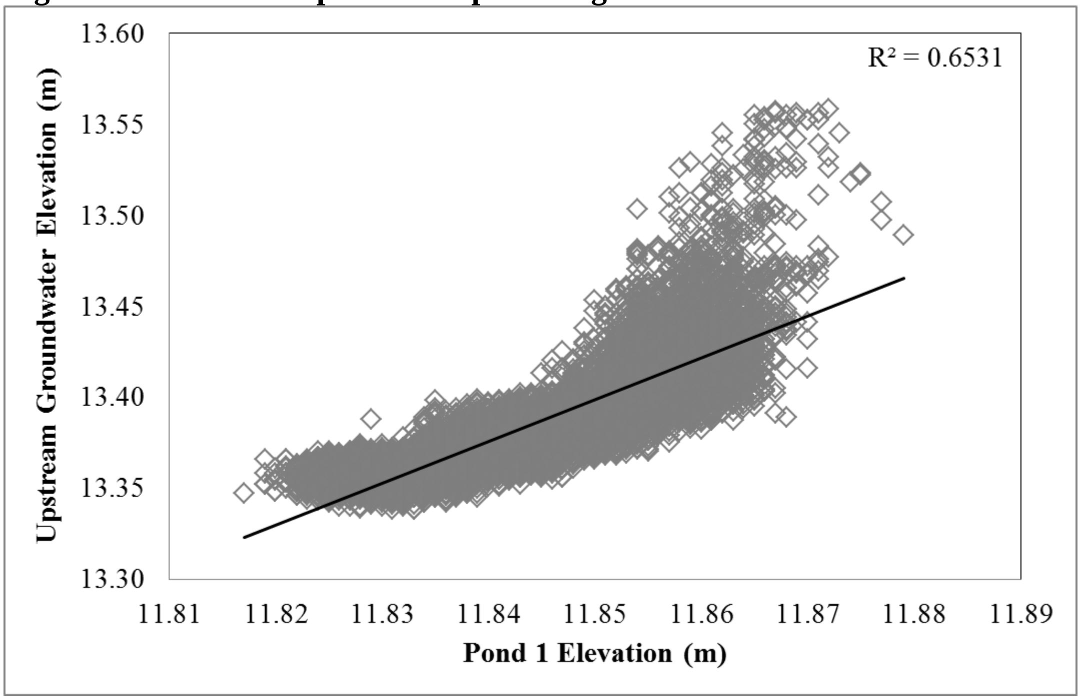
Big Bear Flat meadow downstream stream and groundwater.



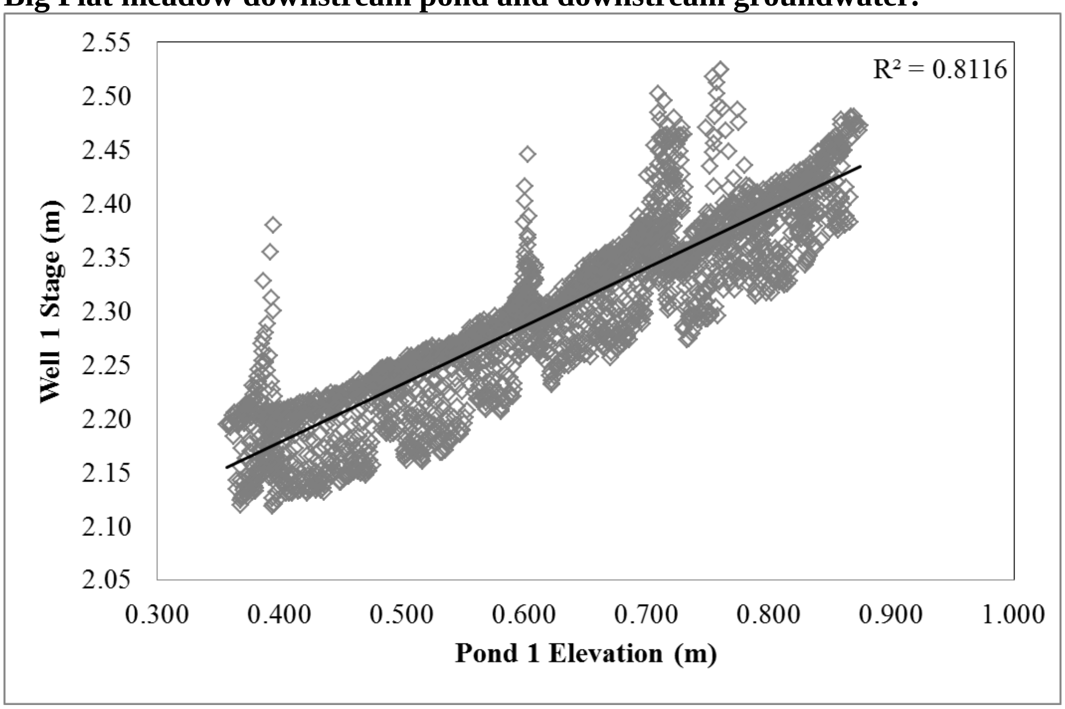
Big Bear Flat meadow pond and downstream groundwater.



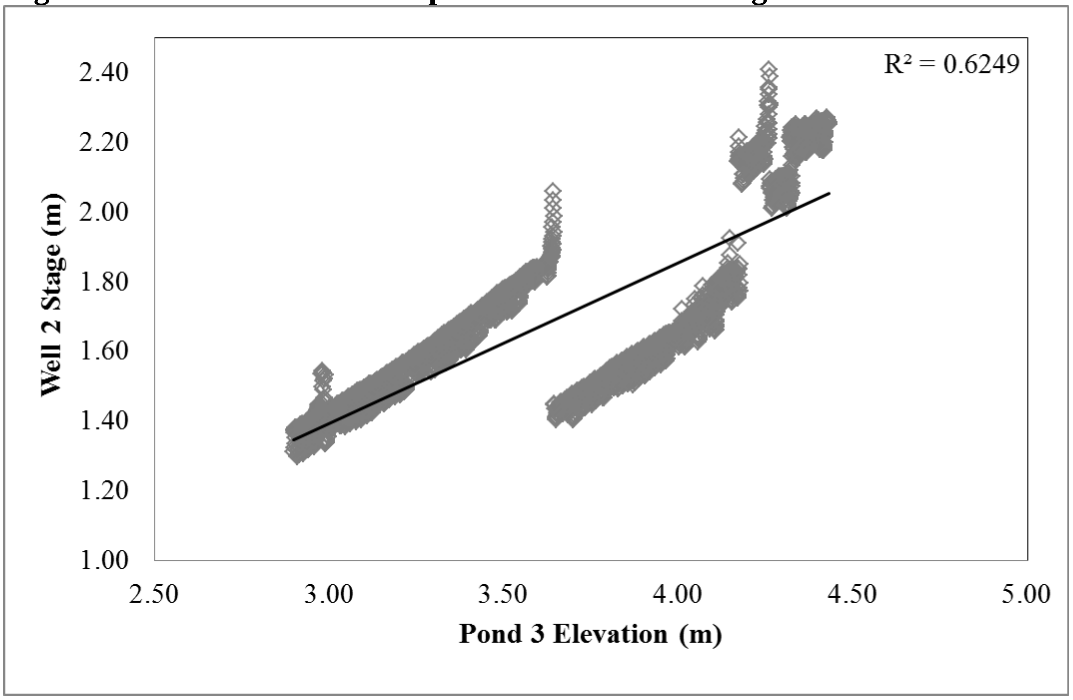
Big Bear Flat meadow pond and upstream groundwater.



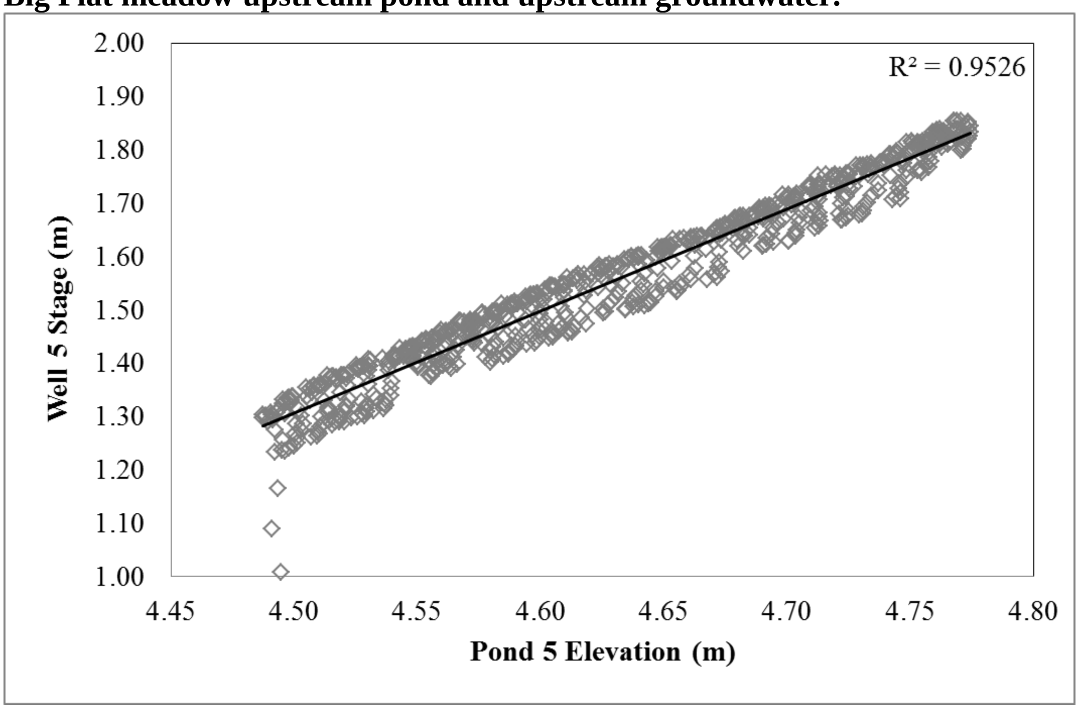
Big Flat meadow downstream pond and downstream groundwater.



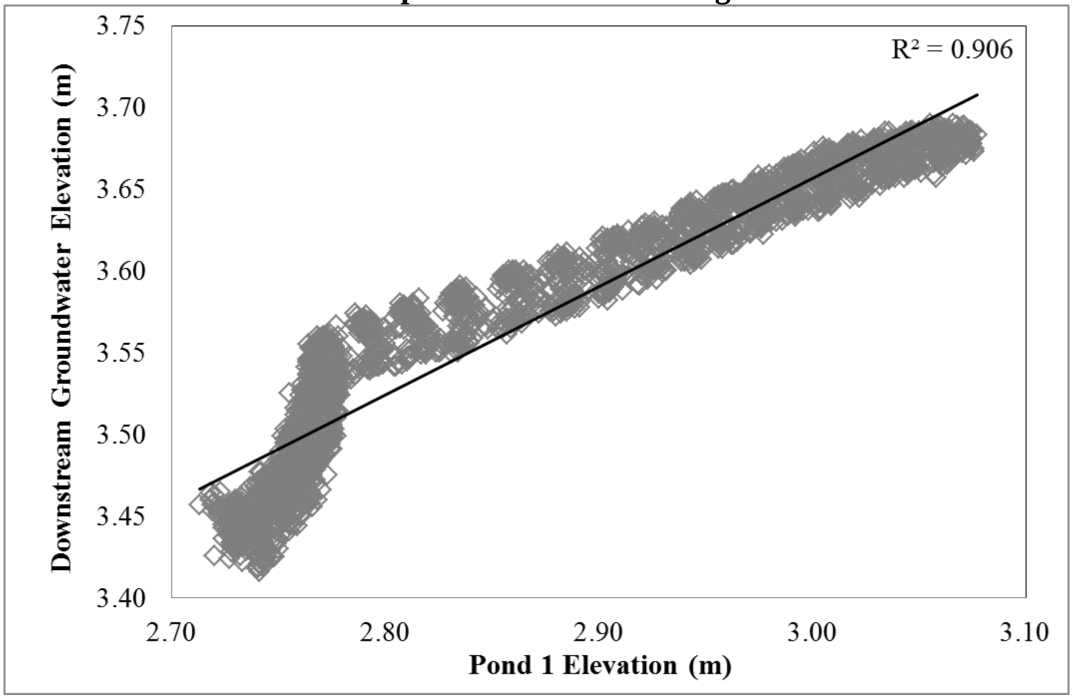
Big Flat meadow mid-meadow pond and mid-meadow groundwater.



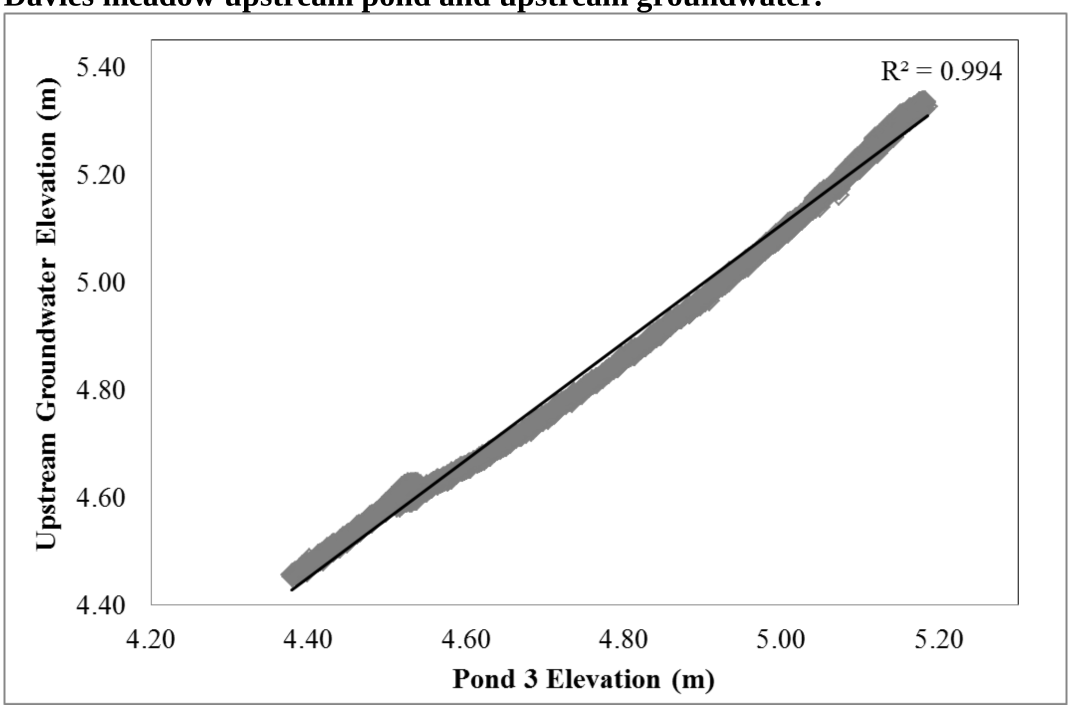
Big Flat meadow upstream pond and upstream groundwater.



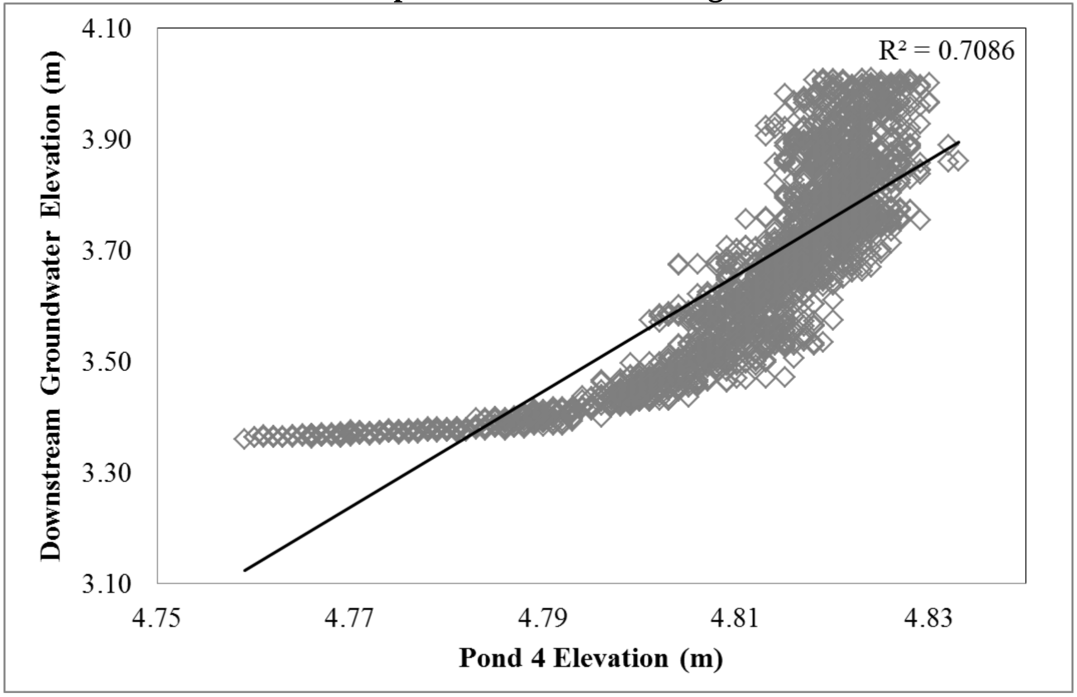
Davies meadow downstream pond and downstream groundwater.



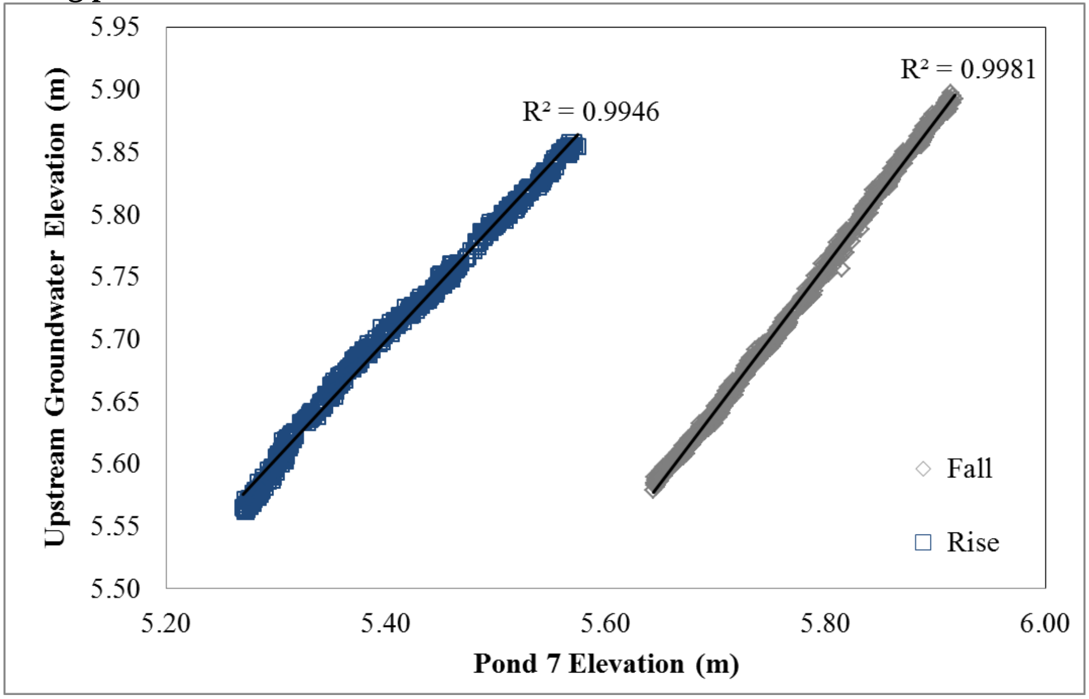
Davies meadow upstream pond and upstream groundwater.



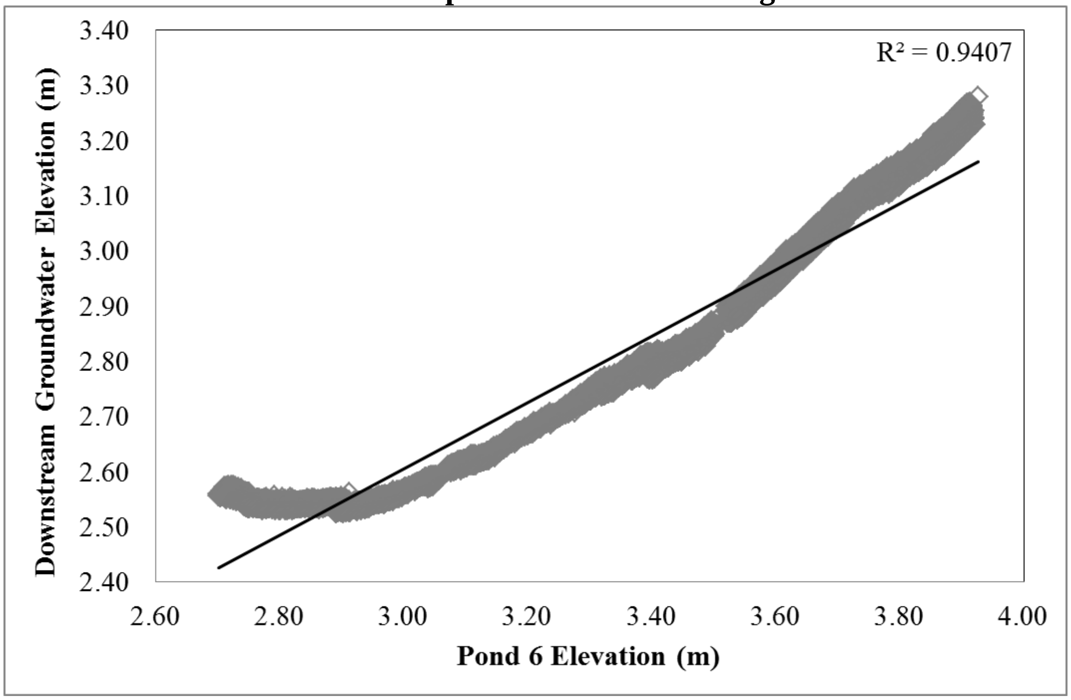
Ferris meadow downstream pond and downstream groundwater.



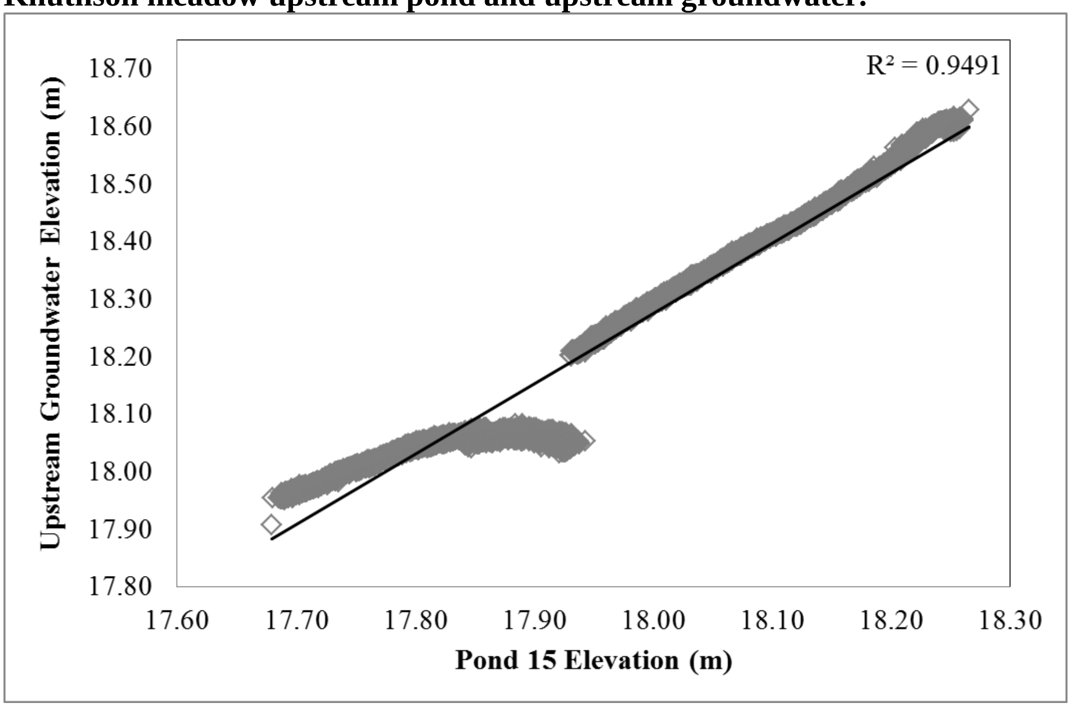
Ferris meadow upstream pond and upstream groundwater, with draining and filling periods.



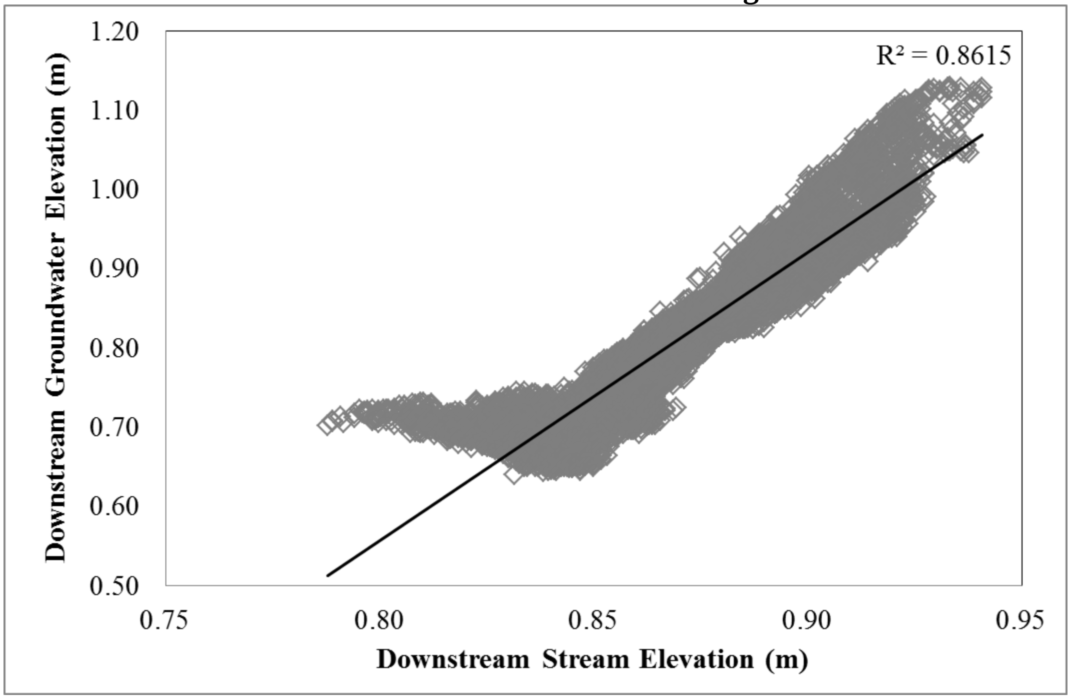
Knuthson meadow downstream pond and downstream groundwater.



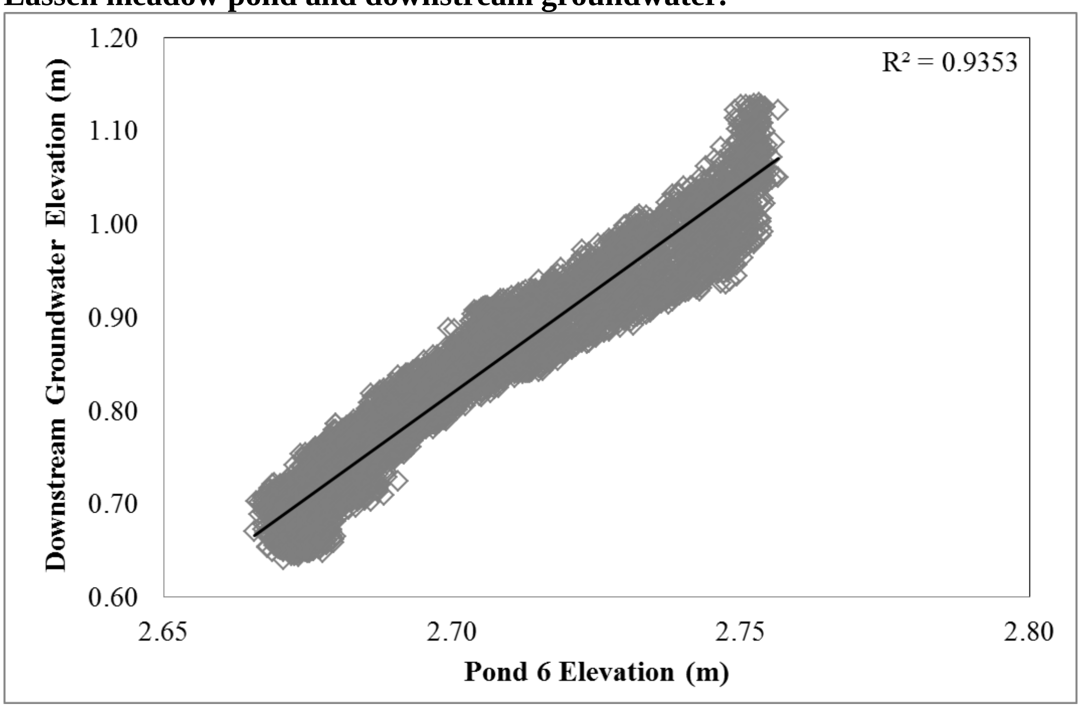
Knuthson meadow upstream pond and upstream groundwater.



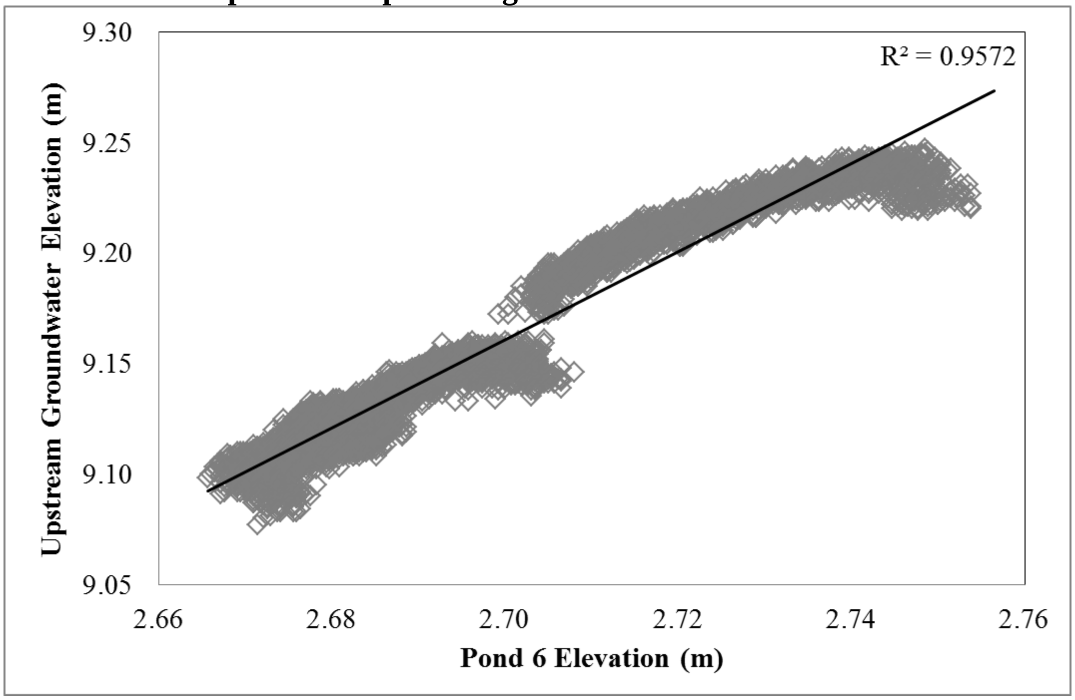
Lassen meadow downstream stream and downstream groundwater.



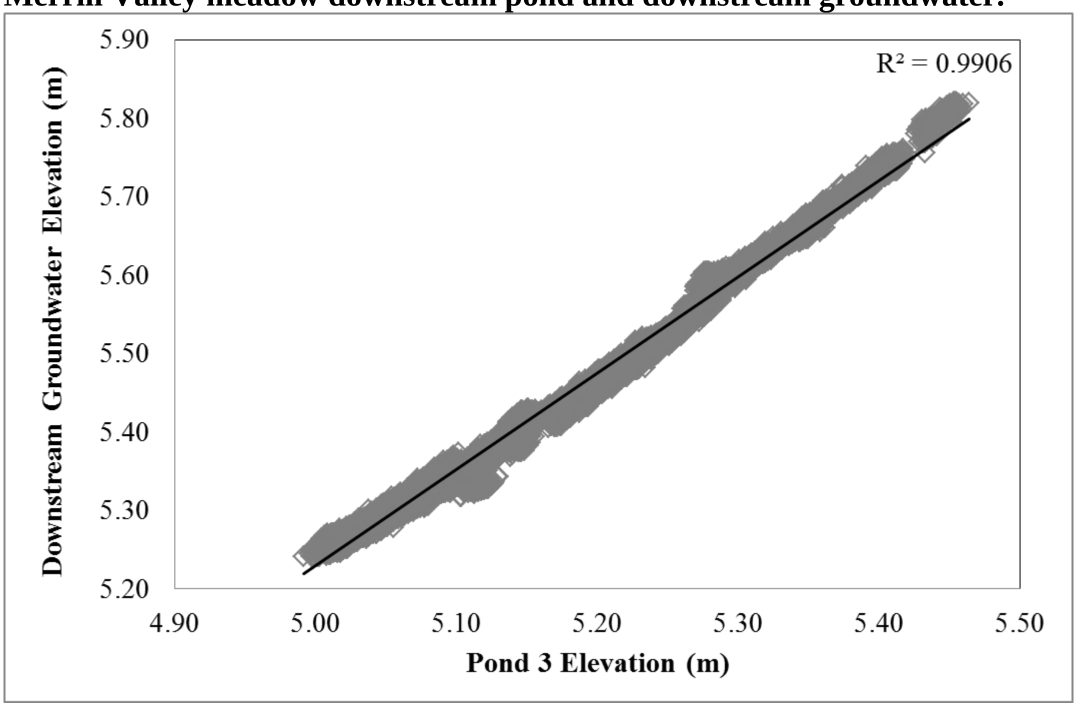
Lassen meadow pond and downstream groundwater.



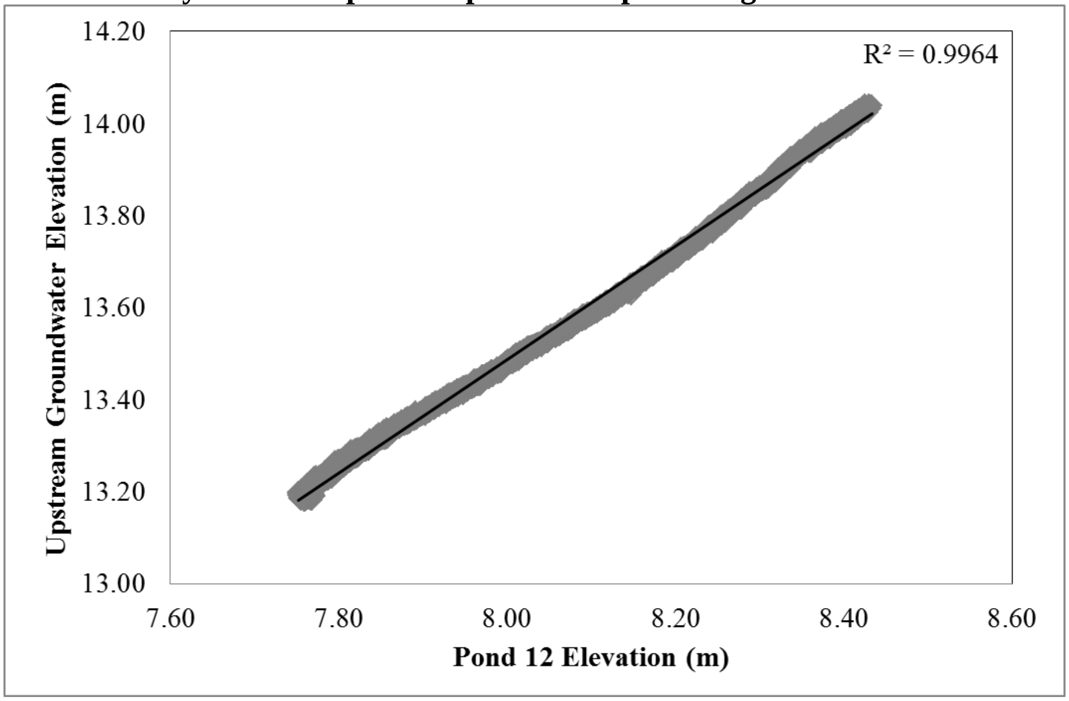
Lassen meadow pond and upstream groundwater.



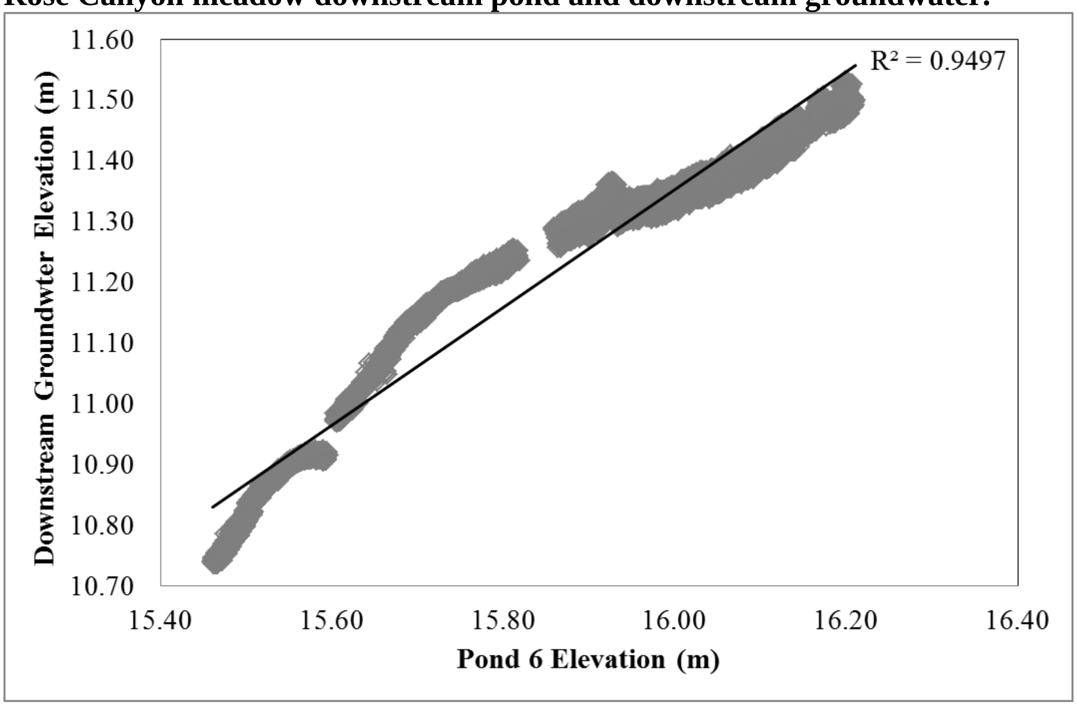
Merrill Valley meadow downstream pond and downstream groundwater.



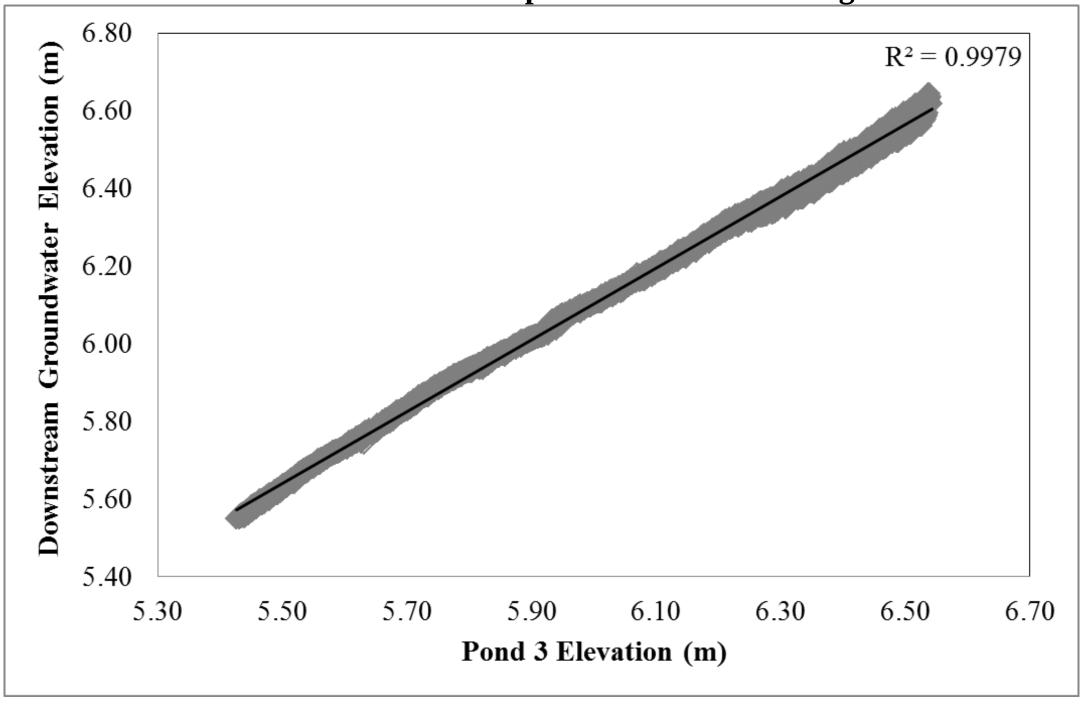
Merrill Valley meadow upstream pond and upstream groundwater.



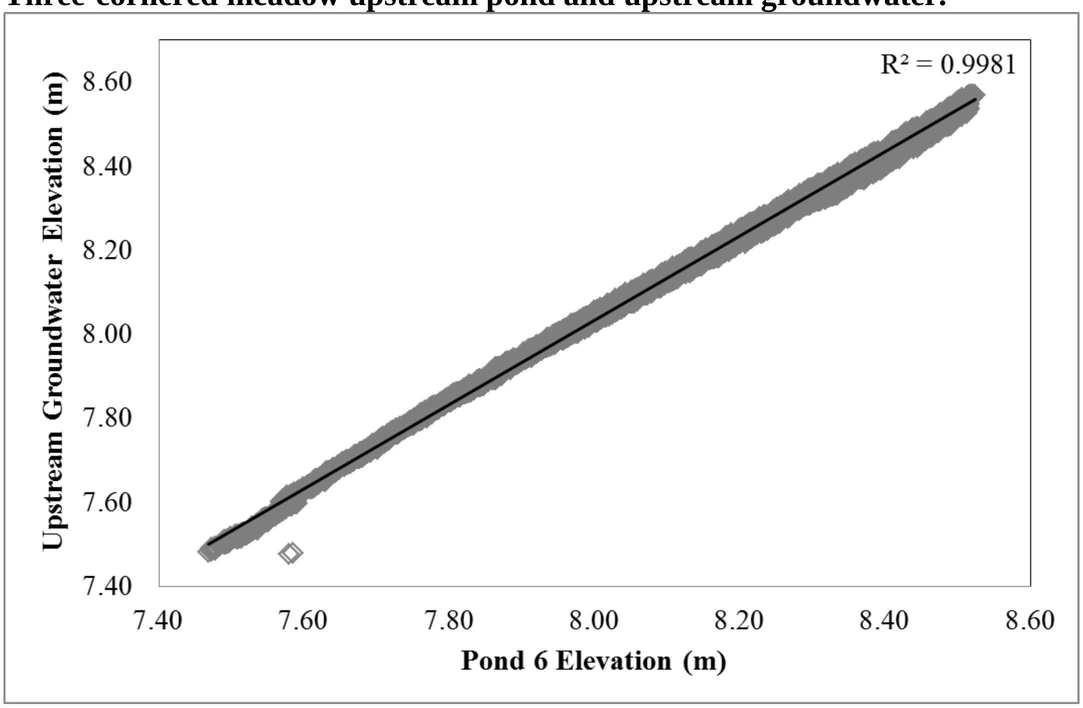
Rose Canyon meadow downstream pond and downstream groundwater.



Three-cornered meadow downstream pond and downstream groundwater.

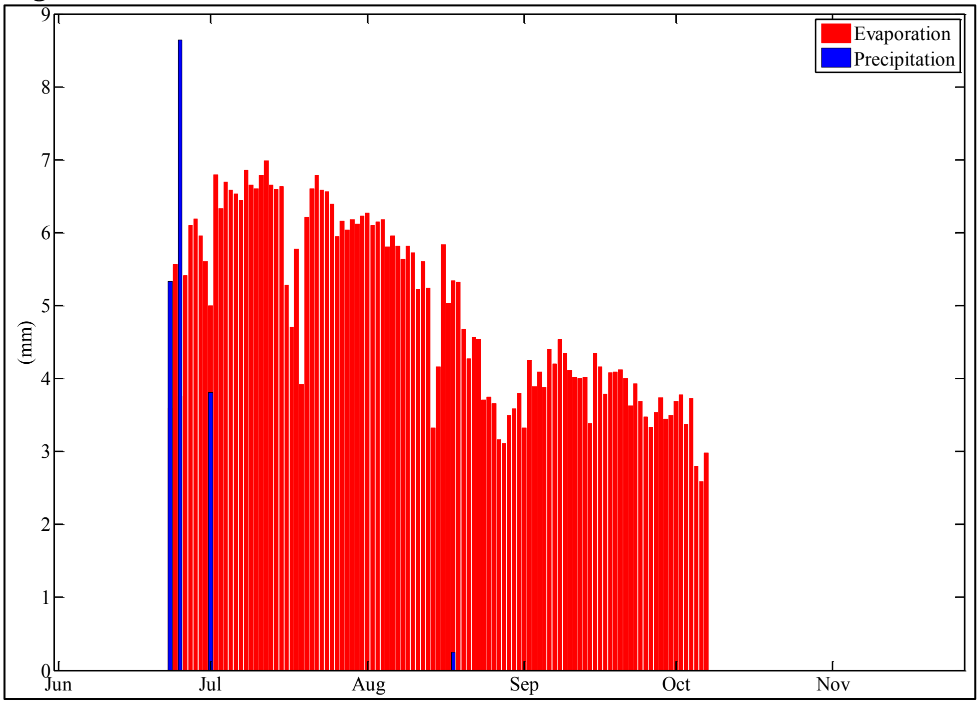


Three-cornered meadow upstream pond and upstream groundwater.

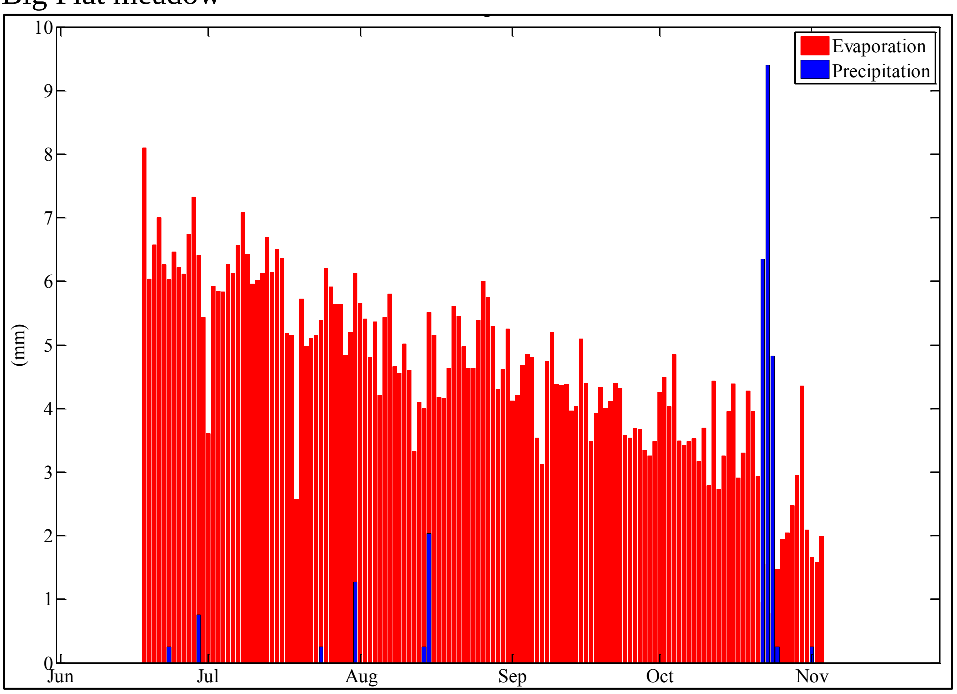


Appendix G: Evaporation and precipitaion results for each study meadow.

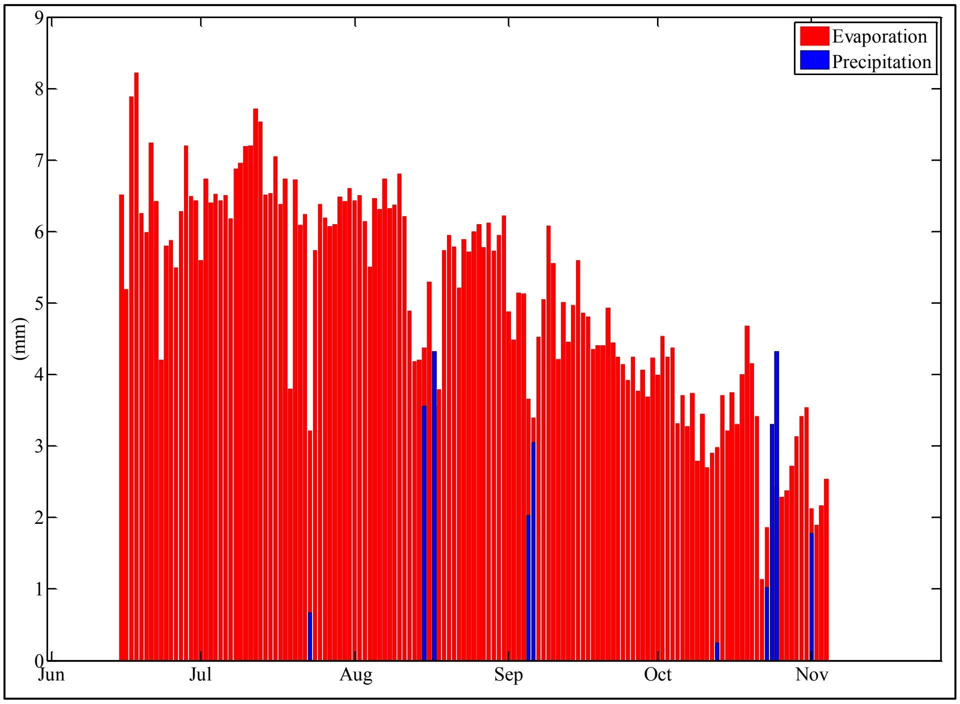
Big Bear Flat meadow



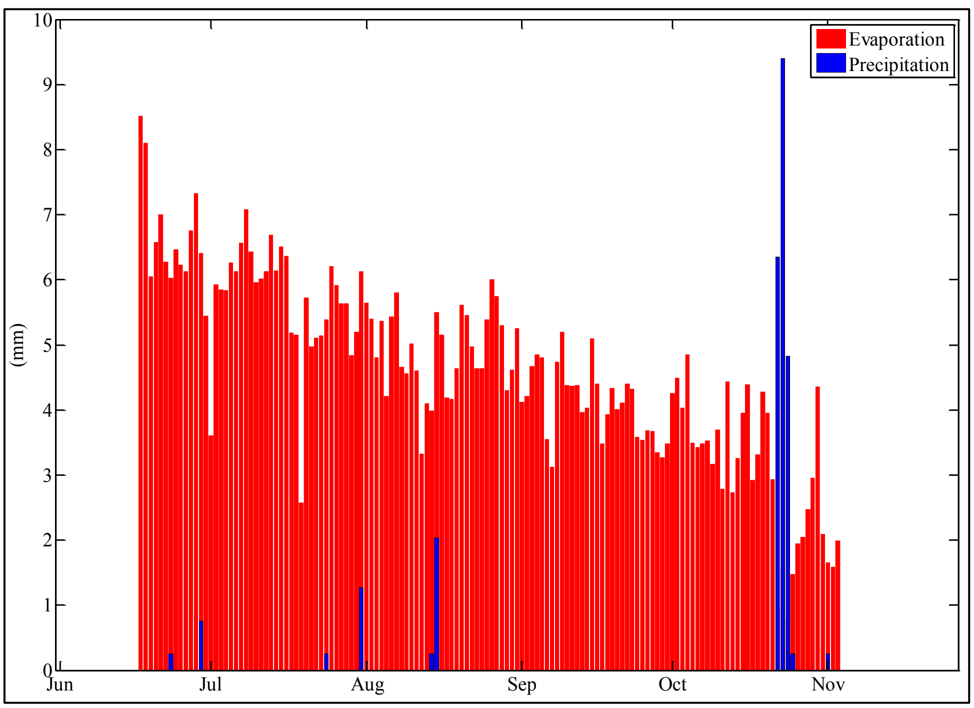
Big Flat meadow



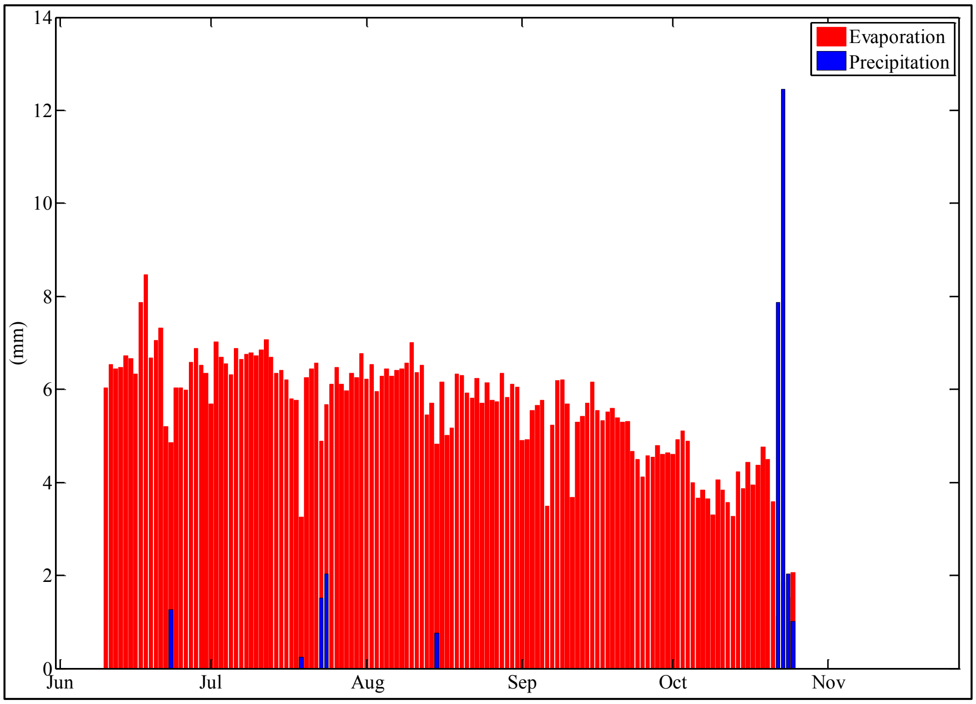
Davies meadow



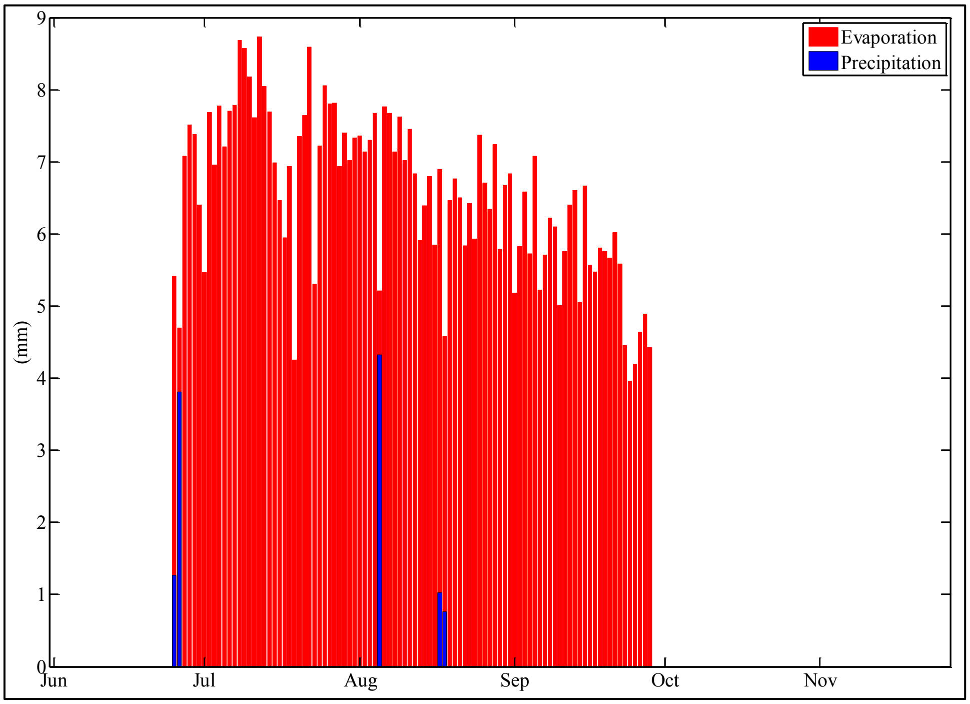
Ferris meadow



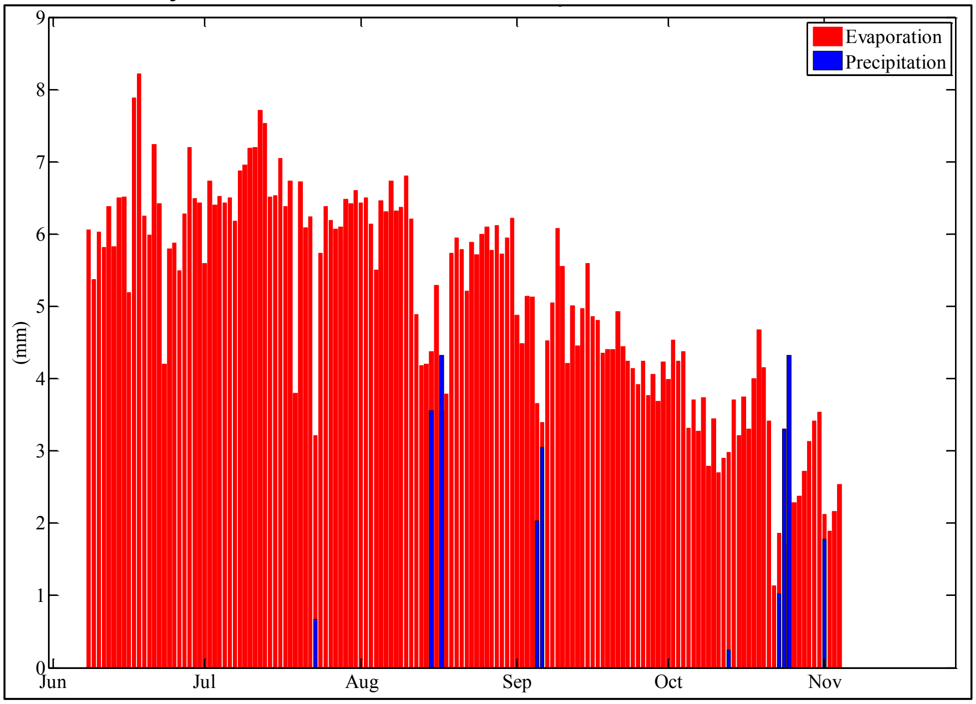
Knuthson meadow



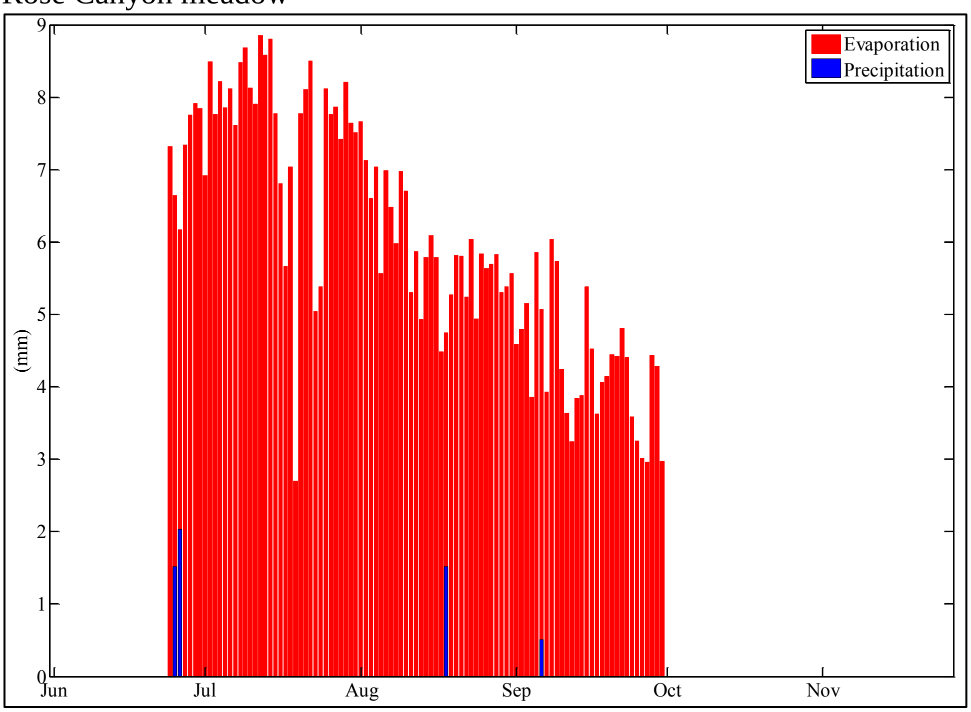
Lassen meadow



Merrill Valley meadow



Rose Canyon meadow



Three-corned meadow