PHYSICAL AND HYDROLOGICAL CHARACTERIZATION OF CLARK'S MEADOW

REPORT

Submitted by

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1.0 ABSTRACT

This report summarizes the methods, results and conclusions of the investigation at Clark's Meadow to determine the subsurface conditions and potential water storage capabilities of meadow sediments. The partially restored nature of Clark's Meadow offered a unique opportunity to observe the consequences of uncheck stream erosion in the lower half of the meadow against restored conditions in the northern half of the meadow.

Volume calculations resulting from seismic delineation of the underlying bedrock and surface topographic surveys suggest that under optimal conditions (fully saturated meadow sediments) as much as 269,028 m^3 of groundwater (218 acre-feet) exist in the approximately 116 acre Clark's Meadow. Under conditions measured during late summer, 2007, only about 93,998 m^3 (76 acre-feet) of groundwater (~35% of optimal) was present throughout the entire meadow. This substantial discrepancy results primarily from dewatering of meadow sediments through unchecked stream channel erosion. This unchecked erosion causes channel incision and widening (which facilitate the dewatering of subsurface sediments) and cause stream banks to become unstable, furthering erosional problems.

2.0 INTRODUCTION

Mountain Meadows are an important link between surface water processes and land use in mountainous terrain providing many beneficial uses to natural systems. Specifically hydrologically functional meadows tend to 1) support root masses that stabilize stream banks against erosion; 2) dissipate stream energy from high flows, reducing erosion, and capturing bedload that aids in floodplain development; 3) enhance floodwater retention and groundwater recharge and; 4) filter sediment, improving water quality (Weixelman et al, 2002, Ponce and Lindquist 1990, Linquist and Wilcox 2000).

Groundwater recharge is partly a function of the storage capacity of meadows which in turn regulates the rate of groundwater discharge to a stream's base flow and helps to maintain stream flow during drier periods (Loheide and Gorelick, 2006).

Any realistic depiction of the role mountain meadows may play in water storage must consider the three dimensional configuration (surface area and depth) of a meadow's subsurface setting and assess the potential of these sediments to store water (porosity). Determining the volume of pore space available in subsurface sediments to store water, the rate at which subsurface fluids can move through these sediments and the variation of these conditions throughout the meadow was the overall objective of this Task. Limited quantified information is available from outside sources and is commonly measured in site-specific instance. Previous reported works in the region that assess restoration activities (Kavvas et. al., 2005) utilized large scale regional values to estimate quantitative conditions. This report measured site specific conditions at Clark's Meadow to generate a quantitative model of subsurface conditions.

In this effort to develop a more quantified understanding of the surface and subsurface flow of water through mountain meadows and the capacity of meadows to store water, Clark's Meadow in the Last Chance watershed was targeted for more detailed study (Figure 1) Clark's Meadow was chosen for three reasons:

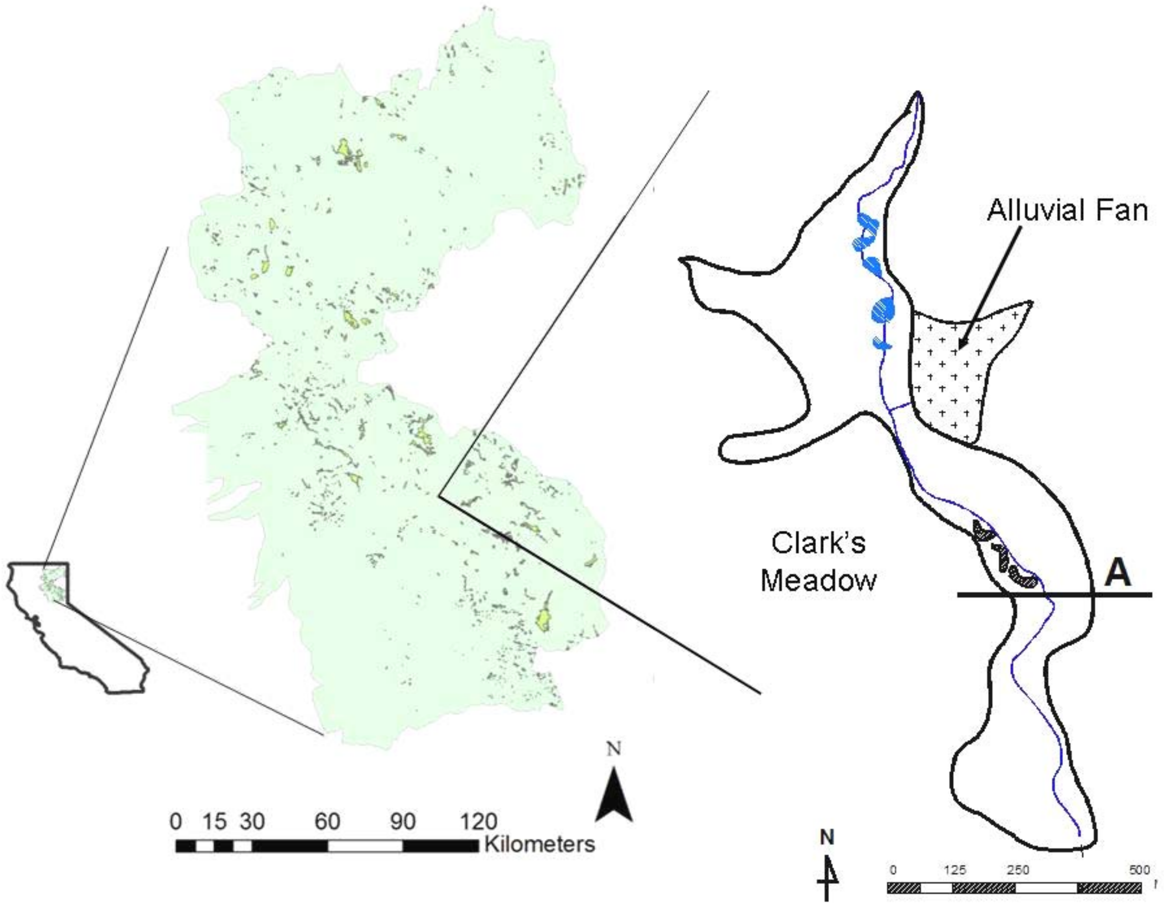

Figure 1. Location of the Clark's Meadow study area. The upper part of the Meadow (above the horizontal line marked A ~ 68 acres) has received restoration action while the lower part (below the line marked A ~ 48 acres) has not. The alluvial fan restricts stream meandering in the narrow neck of the Meadow. Blue shapes (near the alluvial fan) represent ponds with water, black shape (near the boundary for restoration (marked A)) are ponds with no water (summer, 2007).

1. Location. This meadow is readily accessible with field equipment. The Meadow boundary is defined on its eastern, southern and western sides by Primary Forest Route 176. It's located at T26N, R13W, Sec 3, SW/4 and was chosen after site inspection and conversations with Mountain Meadow partners.
2. Size. The meadow is definable in terms of its size (0.46 km^2) and allows us to adequately instrument and measure processes within the meadow effectively.

There is only the one primary perennial stream with flows onto the site from the north (though there are several ephemeral channels that branch off throughout the meadow proper – none of these had flowing water in them during late fall, 2006) and it exits the meadows at the topographic low to the south.

3. Restoration activity. Conversations with the Feather River Coordinated Resource Management group indicated that Clark's Meadow has been partially restored using the pond and plug approach. Specifically, the upper half was restored in 2001 and functions in an hydrologically stable manner. The lower half of the meadow (approximately 48 acres) though has not been restored and functions differently than the upper half (approximately 68 acres). We thought this would make an interesting meadow to study as these conditions would likely offer contrasting views of meadow dynamics.

Restoration Activities in Clark's Meadow

After two years of data collection and analysis by Plumas Corporation and Feather River Coordinated Resource Management group it was determined that Clarks Creek was disconnected from its historic functional floodplain by incision and degradation of the channel (Feather River Coordinated Resource Management Group, 2001). The cause of this condition is speculative but it is likely that overgrazing around the turn of the 20th century induced stream capture by cattle trails on the floodplain (Feather River Coordinated Resource Management Group, 2001).

Restoration efforts had been ongoing on Clarks Creek starting in 1990 and showed some initial success, but frequent moderate to major floods ('93,'95, and '97) and accompanying sediment loads caused additional problems. The deeply entrenched channel caused dewatering of the meadow and a resulting vegetative conversion from perennial moist meadow grasses and forbs to less desirable dry site annuals and forbs (Feather River Coordinated Resource Management Group, 2000).

Renewed restoration efforts in the upper Clark's Meadow were initiated in late July of 2001 and completed in August, 2001. The existing channel was returned to its original grade (a 1070 m gully was filled in) using the pond and plug method , and the stream was returned to remnant channels on the meadow surface and reconnecting with 50 acres of its natural floodplain (Feather River Coordinated Resource Management Group (204), 2001 and Feather River Coordinated Resource Management Group, 2001). No restoration work has been attempted in lower 48 acres of Clark's Meadow.

The aim of this initial research was to:

- Determine the 3-dimensional subsurface configuration of Clark's Meadow,
- Calculate subsurface water storage potential in the Meadow, and,
- Measure the transfer capabilities of subsurface materials.

To this end, field work to delineate the subsurface geometry, collect representative subsurface samples to determine hydraulic properties and measure in-situ properties of meadow sediments was conducted during Summer, 2007. The specific methods, results and interpretation of this data are presented in this Report.

3.0 METHODS

To calculate the three-dimensional nature of Clark's Meadow, two crucial pieces of data are necessary: a determination of the overall thickness of the subsurface sediments (from the surface to the bedrock below) and a measurement of the surface are of the meadow. Seismic surveys were conducted to measure the thickness (depth) of sediments at select locations in the meadow. Seismic test sites were chosen to generate data in as broad and representative a fashion as possible across the meadow. To that end, 17 surveys were conducted throughout Clark's Meadow.

Since the thickness of sediments throughout the meadow are not consistent (thinner near meadow edges and thicker towards the center of the meadow), geometric accommodations were made in the volume calculations to account for this variation. Surface area of Clark's Meadow was determined using ARCGIS (v. 9.2) mapping software.

Recharge rates (infiltration tests) across the Meadow surface were measured at 17 localities throughout the meadow and yielded an assessment of the rate of recharge throughout various surface conditions.

Boreholes were advanced to delineate the geologic nature of subsurface sediments, to collect samples for laboratory analysis, to measure depth of groundwater, to conduct hydraulic conductivity experiments and to verify the thickness of subsurface sediments as determined through seismic surveys.

A detailed outline of the methods used follows.

3.1 Seismic surveys

To determine the general depth of sediment throughout Clark's Meadow, a multi-channel signal enhanced engineering seismograph (EG&G model 1225) was used to measure sediment thickness at 34 different points scattered throughout Clark's Meadow. This tool was chosen in part because of its low impact to the study area (it offers a virtually non-destructive method of obtaining subsurface information) and its relative portability in the field (no trucks or drill rigs driving on sensitive meadow

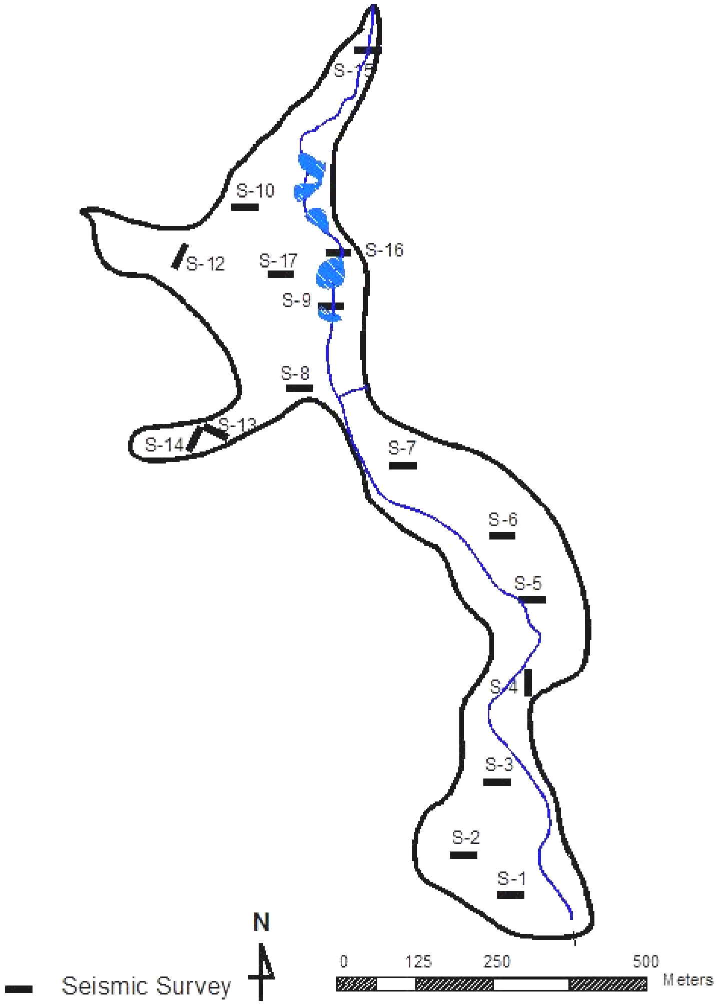

Figure 2. Distribution of Seismic survey lines throughout Clark’s Meadow.

surfaces). Seismic refraction surveys induce a sound wave into the ground (by striking an iron plate seated in the ground with a sledgehammer) and through a series of geophones spread out over the meadow surface records the relative travel time of the resultant energy waves. This travel time is a direct function of the relative density of the subsurface materials and can be used to calculate the depth to higher velocity (i.e. higher density) layers. Seismic refraction techniques require a critical assumption to be made – that density of materials increases with depth. Considering the likely subsurface scenario in the Clark's Meadow (unconsolidated lower density meadow sediments overlying higher density bedrock) this assumption seemed reasonable. Seventeen seismic surveys (each 34 m in length) were conducted at strategic locations throughout Clark's Meadow (Figure 2). The locations provided depth determinations at two points along the survey line (yielding a total of 34 data points across Clark's Meadow) and allowed for the ultimate determination of the underlying bedrock depth. This data was then used to determine the thickness of unconsolidated sediment throughout Clark's meadow.

3.2 Topographic surveys

Topographic data was collected at Clark's Meadow in an effort to further define the surface topography and aid in thickness calculations. Data was collected using a Leica TOTAL Surveying Station and from digital elevation models (DEM) created for the study meadow. USGS DEM data was downloaded from the online "GIS Data Depot" site and processed using ARCGIS software (v. 9.2). Results of the topographic survey are illustrated as a topographic contour map in Figure 3. The topographic map was developed further using ArcMAP (v. 9.2) software to create an outline of the Meadow area. This topographic outline was then manipulated to yield the surface area and perimeter of the Meadow.

3.3 Infiltration tests

Infiltration tests were conducted across the study meadow in an effort to characterize infiltration variations, a measure of groundwater recharge conditions. The infiltration test (Figure 4) allowed for frequent testing of infiltration in diverse parts of the meadow environment. The infiltration test involved the installation of a 4 inch diameter PVC tube into the top ½ to 1 inch of topsoil - just deep enough to prevent water from seeping out of the side of the apparatus where the tube meets the soil. This can be difficult to achieve as abundant root masses (common in the meadow sedge) don't provide very effective seals. In these instances, the PVC tube was installed to about 1 inch depth. Once a good seal was attained, the PVC tube was filled with water and a Styrofoam ball and measure were inserted into the tube. As the water slowly drained into the subsurface, the length (cm) of water drop per minute was recorded. Seventeen infiltration tests were conducted for a minimum of 30 minutes or until three consecutive readings were obtained.

Figure 3. Topographic map of the Clark's Meadow created with ARCMAP using USGS DEM data.

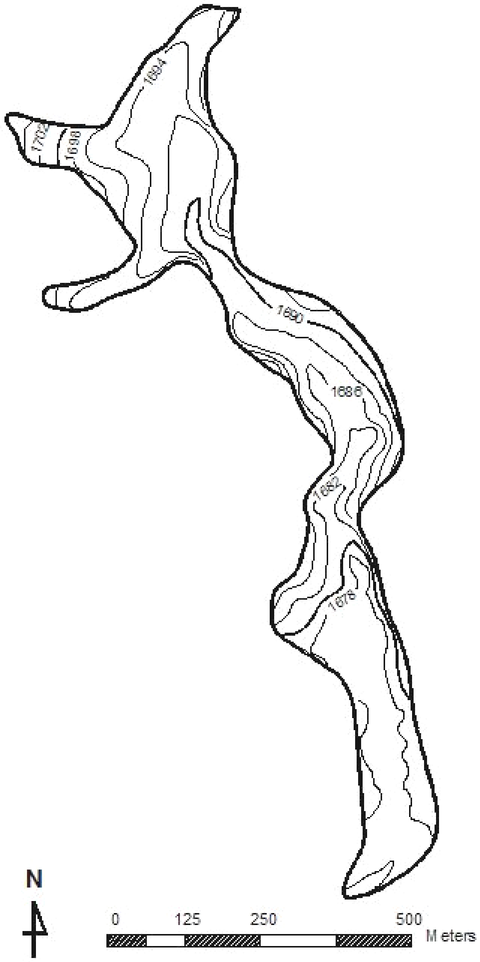

Figure 4. Infiltration field test set-up. White ball is styrofoam and when placed in the 4 inch PVC (protruding from the ground) slowly sinks as water infiltrates the soil. Simple yardstick and stop watch allows for measuring infiltration distance over time.

Vegetation and geomorphic features were also noted at each testing site to evaluate the role that they may play in infiltration variations across the study meadow. Vegetations types were either grassy meadow (short grass and sedge), sage meadow (sage and short grass), willows (meadow willows near stream channels) and alluvial fan.

3.4 Borehole Drilling

Five hand auger borings were advanced in Clark's Meadow to collect representative samples of subsurface materials, measure groundwater levels and confirm depth to bedrock from seismic surveys. Figure 5 outlines the locations of the five borings. Borehole AH-2, AH-3, AH-4 sites were strategically chosen because they were close to sites where seismic data was collected and therefore allowed us to confirm the seismic depths. AH-1 was located near the edge of the meadow to give us a sense of depth and sediment profile towards one side of the meadow. AH-5 was drilled directly next to AH-4 because AH-4 was stopped due to an obstruction (probably a pebble or cobble). Due to the coarse nature of subsurface materials, two of the boreholes reached refusal after almost 2 meters of penetration. The other two borings reached depths of 3.5 and 4.5 meters before encountering refusal. All boreholes were drilled in the upper restored portion of the meadow to get a better understanding of groundwater levels in these sediments.

Borings were advanced using a SOILTEST Hand Augering set-up where split spoon samples (representative, somewhat undisturbed samples) were advanced and collected ahead of the actual auger bit. The undisturbed samples were collected in plastic tubes measuring 15 cm in length and 3.8 cm diameter. In most boreholes, the undisturbed samples could not be taken from below the water table because the soil material was not cohesive enough and would fall out of the hollow tube. Once collected, the tubes were capped on both ends and kept upright during transport back to the lab.

Borings were advanced until refusal was encountered or until all equipment was utilized (4.5 m). After sample collection was obtained, the auger bit was used to clean the borehole out to the depth of the next sampling interval. Continuous sampling of all boreholes was done to provide soil samples for classification and laboratory testing. Depth to groundwater was determined after borehole completion using a Solinst electric water level meter. The soils were logged according to color variations (Munsell Color Chart), moisture content and overall grain-size characteristics.

Boring logs are located in Appendix A

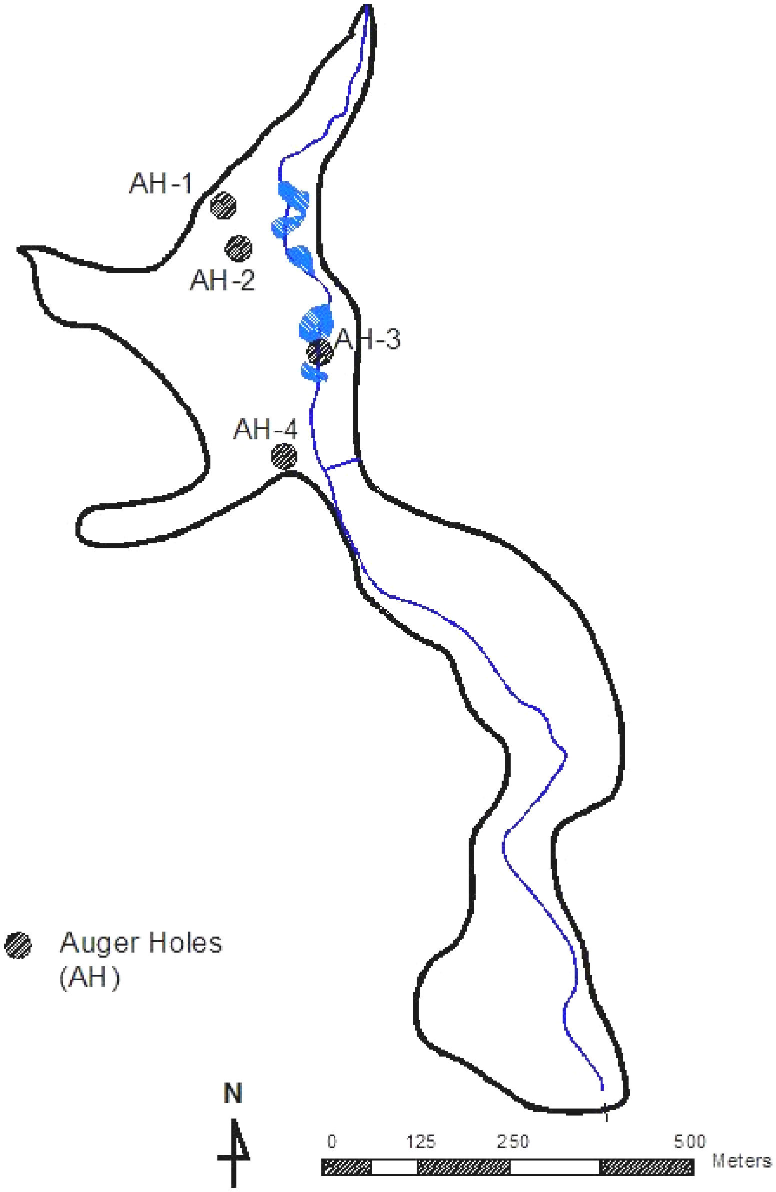

Figure 5. Location of hand auger holes in Clark's Meadow.

3.5 Borehole Hydraulic Conductivity Methods

In-situ hydraulic conductivity tests were conducted in boreholes (AH-2, AH-3 and AH-5) to measure the rate of groundwater flow in a somewhat undisturbed setting. In-situ hydraulic conductivity test follow the auger hole method outlined by van Beers (1983). This entailed drilling the hole at least 60-70 cm below the water table and then using a hand bailer to reduce the water level in the hole by 20-40 cm. Water depth was determined using the electric water level meter. Immediately following bailing, the electric water level meter was moved to 0.05 feet above the bailed water level. The amount of time it took for the water to reach that level was recorded. Five to six such measurements were taken as the water level rose in the hole. Not more than 25% of the volume of the water removed flowed back into the hole by the end of measurements. These measurements yield change in water level over time and ultimately hydraulic conductivity from borehole sediments below the water table to a few decimeters below the bottom of the hole.

3.6 Laboratory Hydraulic Conductivity Methods

A Flexible Wall Permeameter from the USGS Soil Science Lab at the California Water Science Center was used to measure hydraulic conductivity from representative, undisturbed soil samples collected from Clark's Meadow boreholes following the procedures outlined in ASTM D 5084-90 (1990). This technique generates sample specific hydraulic conductivity data to better characterize subsurface groundwater flow. To prepare the soil samples for analysis, the soil tubes were sealed in a metal drum and all air was vacuumed out of the drum. Once the samples were under vacuum, de-aired water was slowly pumped into the drum until it reached a fraction of a centimeter below the top of the soil sample tubes. This effectively forced all of the air out of the samples so that they were 100% saturated. They were left sitting in water and under vacuum for a minimum of 24 hours.

Once the samples were 100% saturated, they were transferred to the permeameter. This entailed putting a porous stone on each end and fitting the sample tube inside the flexible, impermeable membrane and then sealing the membrane to permeameter. The sample was then sealed inside the permeameter chamber and a confining pressure was applied. A hydraulic gradient was created between the bottom of the sample tube and the top of the sample tube and the change in volume in the annuluses over time was recorded. The test was complete when at least four readings were taken that gave hydraulic conductivities within 75-125% of the average hydraulic conductivity for those four readings. Falling head as well as constant head hydraulic conductivities were calculated.

3.7 Porosity Test Methods

Porosity values were measured in collected subsurface sediment samples to allow calculation of potential storage volume in these sediments. Once the hydraulic conductivity readings were taken for saturated samples, porosity measurements were possible. The fully saturated samples were first weighed then dried in a 105ºC oven for a minimum of 24 hours. The dry samples were then weighed and porosity was calculated using the equation:

$$n = \left[\frac{\text{volume of voids}}{\text{total volume}} \right] * 100$$

Since 1g of water equals 1cm^3 of water, the volume of voids equals the saturated weight of the sample minus the dried weight of the sample. The total volume equals the dimensions of the full sample tube.

3.8 Grain Size Analysis

Grain size analysis was done on all the soil samples collected from the boreholes to further characterize the nature of the sediments. In general, coarser grained sediment generally have higher hydraulic conductivity values while finer grain sediments generally yield lower hydraulic conductivity values. The samples were collected from the end of the auger at each one foot interval in each borehole and were then logged, put in plastic bags and labeled.

To prepare samples for grain size analysis, each was dried at 100°F in a dry oven for a minimum of 24 hours. They were then weighed to determine the sample dry weight. The sample was then emptied onto a series of sieves arranged in progressively smaller order beginning with a #4 mesh, #10 mesh, #40 mesh and #200 mesh. If it was impossible to extract the sample from its container when dry, it was gently washed onto the sieve. The sieves with sample were put on a Rototap (sieve shaker) and vibrated for 5 minutes. The samples were then washed with a gentle stream of water through the sieves and then put on the Rototap for an additional 5 minutes. The samples from each sieve were then dried, weighed and totaled. This yielded the weight for each sieve size as well as the fines that were washed through all sieves. The mass of sample sustained on each sieve size was then plotted on a grain size plot (Appendix A) and incorporated into the stratigraphic section.

3.9 Meadow Groundwater Storage Calculations

Meadow volume was calculated from depth characteristics (determined from seismic surveys and the resulting three-dimensional image of the meadow (Figure 6)), topographic DEM and aerial photo datasets. The Meadow was broken up in a series of

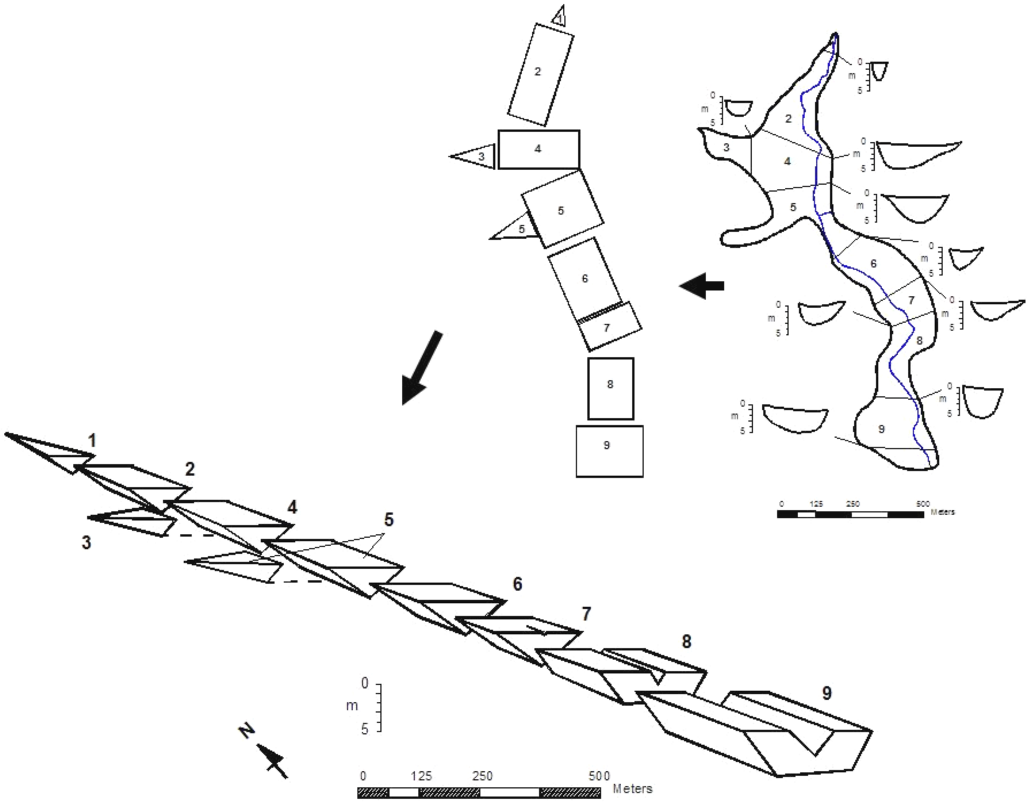

Figure 6. Three-dimensional perspective of Clark's Meadow based on topographic and seismic survey data. Numbered sections refer to individual meadow blocks that were used to calculate volume of subsurface sediment.

blocks to aid in the calculation. Specifically, initial block volumes were calculated according to the expression:

Volume = (Length * Width * Depth * Shape Factor)

Since the block is not a rectangular box in volume, some accommodation was necessary for the irregular shape of such a feature. We assumed an overall triangular-shape to each block (Figure 7) with the deepest part approximately in the center of the meadow cross-section. Block volumes were then multiplied by a shape factor (ranging from 0.5 (triangular shape) to 0.9 (almost rectangular in shape)) that approximates the volume difference from a triangular shape to a rectangular box. Boxes that ranged to higher shape factor values showed depth conditions that resembled more of a rectangular box shape than triangular shape.

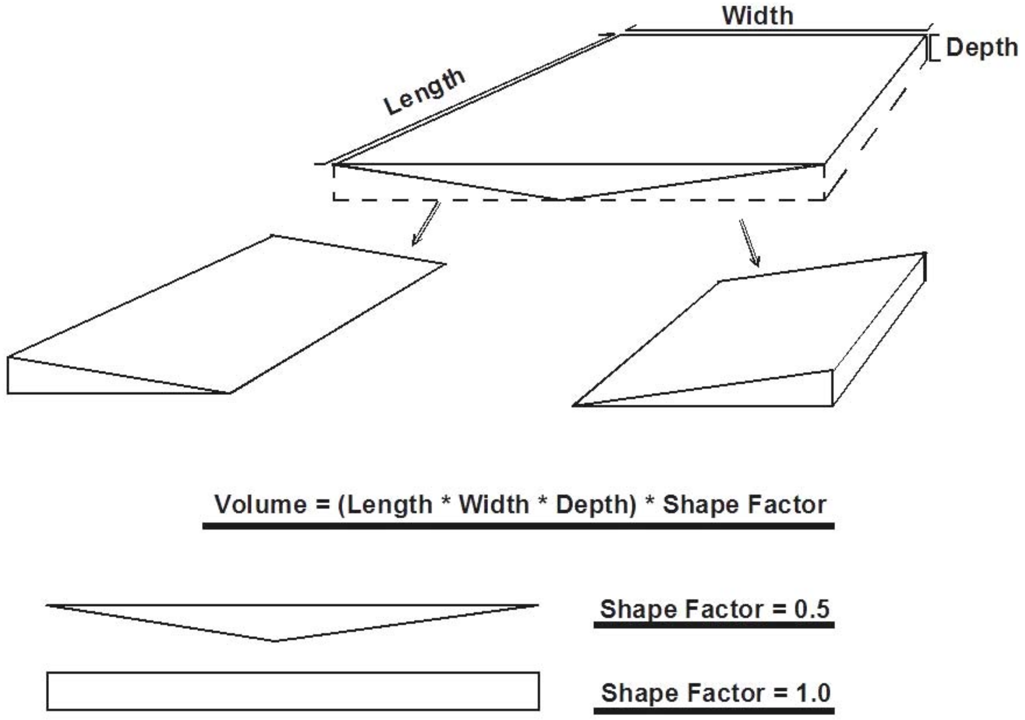

Figure 7. Three-dimensional view of block calculations for volume determinations.

Water volume losses (from dewatering and evapotranspiration) were calculated by dividing up the triangular shapes (Figure 8) and calculating water volume at depths of 1.5 m below surface and 4 m below surface.

4.0 RESULTS

The results of the various techniques used to define the subsurface shape and hydraulic properties of Clark's Meadow are compiled below. These are the data sets used to calculate the three-dimensional shape of the Meadow and estimate its capacity to store groundwater. The infiltration table outlines the variation of infiltration rates across the meadow surface. Porosity values generated in the laboratory analysis are outlined here and are used to calculate water storage capacity in the Meadow. All of the figure were drafted using AutoCAD LT and all calculations were performed in spreadsheets built in the MicroSoft EXCEL program.

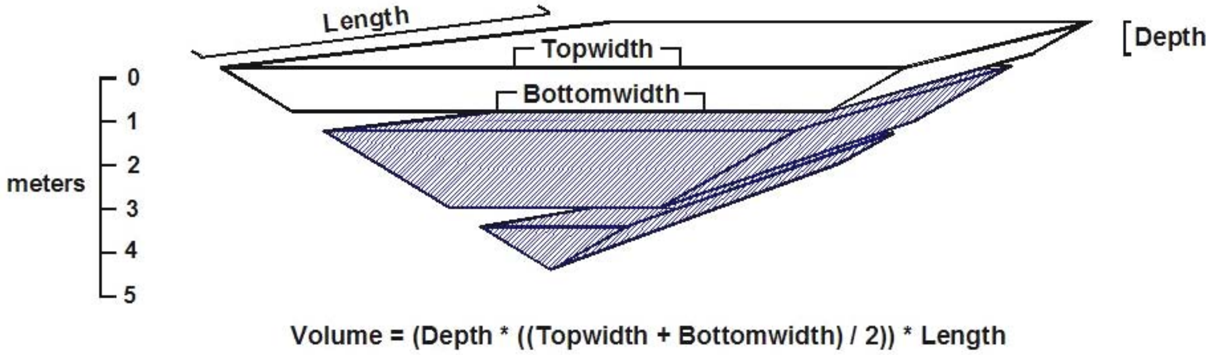

Figure 8. Water volume model used to calculate the amount of remaining water if the block volume is lowered X depth.

4.1 Seismic Surveys

Summary data from the seismic surveys is outlined in Table (1). Surveys were conducted from both directions along the survey line and generated 2 sets of seismic data. Surveys were considered to be representative and of good quality if the travel times resulting from each survey ended within 10% of each other. There were some field battery issues with survey 11b and consequently the data set collected from that survey was not useful.

In general, velocity means for the first horizon averaged about 387 m/sec – consistent with low density, loosely consolidated sedimentary material. For the second subsurface layer (V2) velocities averaged near 2,350 m/sec but there was a lot more range of variation in the velocities (ranging from 1,420 m/sec to 4,490 m/sec).

Table 1. Summary results of Clark's Meadow seismic surveys.

Survey Number	V1 Velocity V1a	in (m/s) V1b	V2 Velocity V2a	in (m/s) V2b	Depth (a) (m)	Depth (b) (m)
1	409	349	1992	2224	3.5	3.6
2	329	400	2382	1960	2.7	2.5
3	345	358	2967	2993	3.8	4.5
4	352	343	2043	2095	1.8	1.7
5	438	469	3046	2177	4.4	2.7
6	386	379	1891	3314	1.8	3.4
7	318	377	1471	1417	2.8	4.1
8	346	356	3279	1745	4.5	3.2
9	541	350	4486	2719	4.7	3.0
10	404	372	2309	3333	3.4	4.1
11	393	CD	1804	CD	2.4	CD
12	416	491	2073	1543	2.4	2.2
13	365	365	1784	3428	3.1	5.1
14	336	379	2713	3646	3.6	4.5
15	406	409	1557	1681	2.7	3.2
16	466	400	1991	2251	1.8	1.9
17	334	393	1691	1678	1.5	2.0
Mean	387	387	2322	2388		

CD – corrupted data

The collected data, time-distance plots and resulting depth calculations are contained in Appendix B

4.2 Infiltration Data

Infiltration data is located in Appendix C. Infiltration data was collected in four different vegetation/landform settings: grassy meadow (characterized by sedge grasses with dense root masses), meadow willows (dense sedge grasses and small (2-3 m high) willow trees), sage and short grass (sedge grasses and sage) and on an alluvial fan complex (predominantly sage and rock). Figure 9 outlines the relative distribution of infiltration rates across the study meadow. Values ranged from high infiltration rates (>0.7 cm/min in areas typified by meadow willows (mean infiltration at 0.57 cm/min) to lows on the alluvial fan complex (mean infiltration at 0.10 cm/min). In general, meadows characterized by short sedge grasses (grassy meadows) and sage (sage and sedge) have very similar infiltration rates (0.30 and 0.35 cm/min respectively) and cover the largest geographic area across the meadow. This data suggests that the infiltration rates in the grassy meadow environment are quite variable, likely a result of pedogenic clay production in the soil profile. Detailed characterization of this variability would require many more tests targeted within the grassy meadow. Infiltration rates near the willow trees that occasionally line the channel floor are relatively high and on the alluvial fan relatively low. Both of these sites however, only had two tests conducted, More tests would be necessary to characterize these conditions in greater detail.

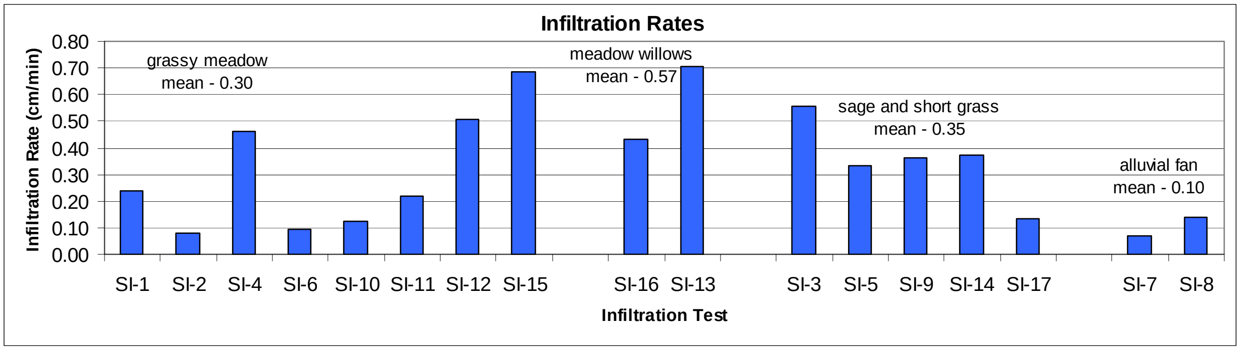

Figure 9. Infiltration data plotted with respect to vegetation and local landforms.

4.3 Borehole Drilling

Boring data (Appendix A) outlines the stratigraphic arrangement of sediment underling Clark’s Meadow (Figure 10).   Surface sediments tend to be organic rich and predominantly silt and clay. These sediments likely are the result of ongoing pedogenesis and occasional stream flooding.   The thickness of these sediments varies from about 0.5 m to slightly over 1 m thick throughout the different borings. Groundwater was encountered in AH-1 within this shallow sediment. Below the upper silt and clays the sediment becomes coarser, grading to a silty sand in AH-1 and AH-2, a fine to coarse sand in boring AH-3, and a sand and gravel in AH-4. Groundwater was encountered in this coarser material in AH-2 and AH-3. With depth, material continues to be of a coarser grain nature than the overlying surface sediments. In two borings (AH-3 and AH-4) a thin silty clay seam is encountered at depth (about 1 m in AH-3 and 1.5 m in AH-4) and separates coarse materials. The extent of this silty clay seam is unknown. Groundwater occurs in this fine grained seam in AH-4.

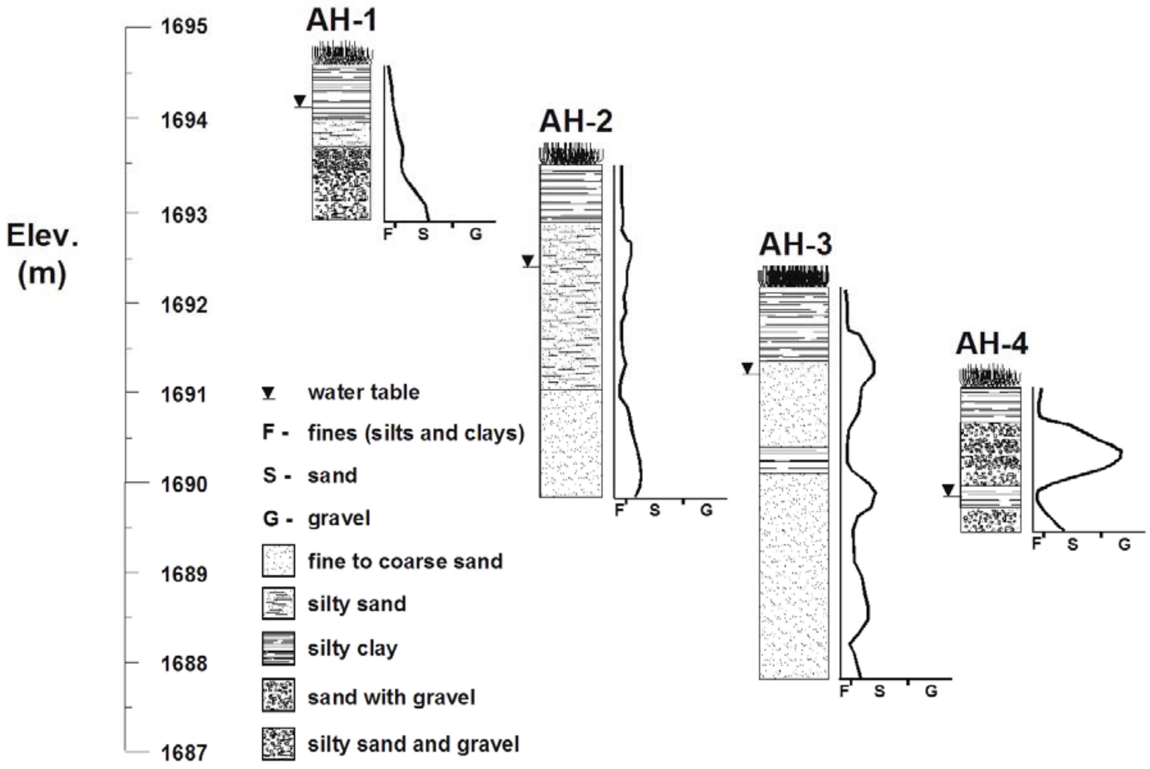

Figure 10. Borehole data from the 4 hand augerings conducted at Clark's Meadow. Grain size data is plotted on the right side of the stratigraphic section and in general shows a coarsening with depth.

4.4 Porosity and Hydraulic Conductivity

Porosity values calculated for collected undisturbed soil samples are outlined in Table 2. Porosity values range from a low of less than 27% in Borehole 4 (0.2 – 0.3 m depth) to over 43% in Borehole 4 (0.0 – 0.2 m) and has a mean value of almost 35%. This translates into a substantial void volume that stores groundwater and provides water to surface flow throughout the year. It’s important to note, however, that fine-grained sediments (silts and clays) generally have higher porosities than do coarse grained sediments (sands and gravels) and auger sampling of subsurface materials is most effective in finer grained sediments as the clays offer more cohesion to the sample and it is more easily retrievable from the drilling effort. Consequently, the values report here may be slightly skewed to the higher porosities found in finer grained sediments.

Table 2. Porosity calculations based on laboratory work. Porosity is equal to the (volume of voids / total volume of sediment) * 100.

Porosity Data					
Sample #	**Hole #**	**Depth(m)**	**Total Volume (cm^3)**	**Volume of Voids (cm^3)**	**Porosity %**
1	2	0.6-0.8	106.99	43.88	41.01
3	3	0.9-1.1	134.42	49.72	36.99
5	4	0-0.2	118.12	51.38	43.50
6	4	0.2-0.3	103.71	27.63	26.64
7	4	0.3-0.5	101.45	41.08	40.49
8	4	0.5-0.6	89.19	25.64	28.75
9	4	0.6-0.8	112.48	37.4	33.25
10	4	0.8-0.9	141.06	40.98	29.05
				Mean	34.95

Hydraulic conductivity values measured for collected undisturbed soil samples are outlined in Table 3. Hydraulic conductivity values range from a low of less than 3.7 E-06 in silty sands and gravel (sample 7R1) at a depth of about 0.5 m in borehole #4 to a maximum hydraulic conductivity of 4.2 E-04 (sample 8R1) at a depth of about 0.6 m also in borehole #4. The close proximity of both the maximum and minimum in the same borehole (within 10 cm of each other) is likely a result of the sampling through the developed soil horizon. Sample 8R1 samples the B horizon in this profile which is characterized as an accumulating zone where finer clays and dissolved components in the overlying A horizon were transferred and ultimately collected in this horizon. Considering the sediment source is generally overbank flood deposits, substantial variations in sediment deposition and ultimately hydraulic conductivity is typical and expected.

Table 3. Hydraulic conductivity values for undisturbed samples collected from study borings.

Hydraulic Conductivity Data					
Sample ID	**Hole #**	**Depth (m)**	**Gradients**	**Saturated Hydraulic Conductivity (cm/s)**	**Saturated Hydraulic Conductivity (cm/day)**
1 R1	2	0.8	20 kPa	3.7E-05	3.2
2 R1	2	1.4	10 kPa	3.8E-06	0.3
3 R1	3	1.0	10 kPa	3.3E-05	2.9
5 R1	4	0.2	10 kPa	4.1E-05	3.5
6 R1	4	0.3	5 kPa	1.5E-04	13.0
7 R1	4	0.5	10 kPa	3.7E-06	0.3
8 R1	4	0.6	5 kPa	4.2E-04	36.3
9 R1	4	0.8	5 kPa	1.7E-04	14.7
10 R3	4	0.9	5 kPa	1.5E-04	13.0

In-situ hydraulic conductivity tests are outlined in Table 4. Values from these tests are noticeably larger than values from the laboratory tests. It should be noted that in-situ tests are conducted across the range of exposed sediment in a borehole setting and consequently the most conductive material drive the results. It should also be understood that in-situ test are more representative of actual field conductivity because very little change is introduced to the sampled section (with the exception of the boring operation which may smear clays across more conductive materials in the borehole). Laboratory test, on the other hand, involve the physical removal and transport of the sample from the borehole setting to the laboratory. Results of the hydraulic tests are included in Appendix D.

Table 4. In-situ hydraulic conductivity results from boreholes.

Borehole	Depth	S	K (cm/s)	K (cm/d)	K (m/d)
AH-2	1.1 – 1.8 m	S > 0.5 H	0.055	4772.4	47.7
		S = 0	0.060	5206.2	52.1
AH-3	0.9 – 1.8 m	S > 0.5 H	0.073	6303.5	63.0
		S = 0	0.069	5953.3	59.5
AH-4	1.2 – 1.7 m	S > 0.5 H	0.363	31350.9	313.5
		S = 0	0.341	29469.8	294.7

5.0 DISCUSSION

Data generated from this study has been used to construct a three-dimensional model of Clark's meadow and measure the hydraulic properties of the sediment in an attempt to evaluate subsurface storage and transit capabilities. This three-dimensional understanding then facilitates the evaluation and calculation of the meadow's ability to store subsurface waters and provide subsurface water transit throughout the meadow. Seismic data throughout the meadow area was incorporated into a series of cross-sectional views that illustrate the variation in meadow sediment thickness across the study area. Figure 11 illustrates this relationship in a three-dimensional aspect. Seismic surveys suggest that the overall thickness of the meadow's subsurface sediments is not great ranging from a maximum depth of about 5 m in several locations along the center of the meadow to less than 3 m in other smaller sections of the meadow. An isopach map detailing the depth to bedrock (as determined from seismic data) is illustrated in Figure 12.

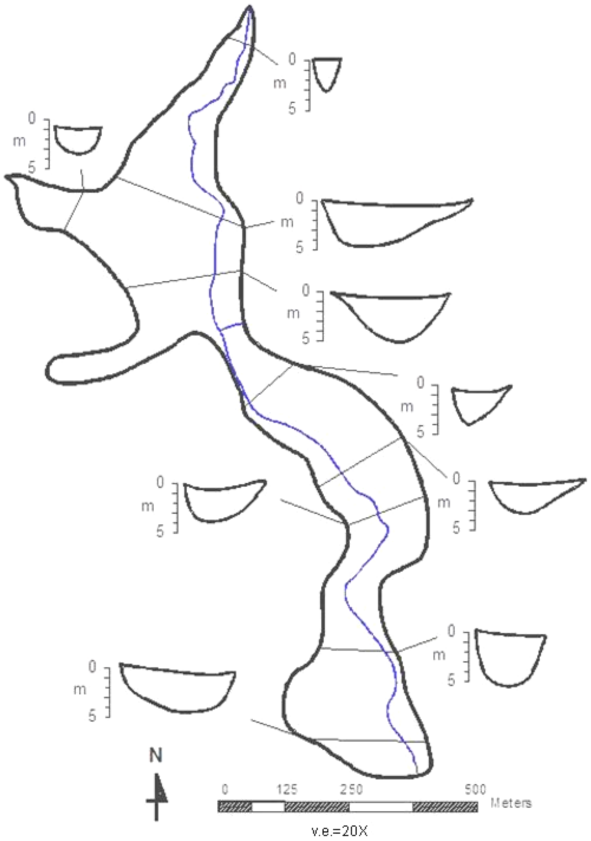

Figure 11. Cross-sectional views across the Clark’s Meadow. Cross-sections were constructed from seismic survey data generated throughout the meadow.

Boring data further suggests that groundwater in the northern part of the meadow is relatively high (within 1.5 m of the surface) when borings were conducted in August, 2007. In the un-restored southern part of the meadow the stream has substantially incised and widened its banks through erosion. Seeping groundwater does not occur in the almost 4 meters of meadow sediments exposed by this incision. Figure 13 illustrates the difference in channel cross-sections between the mean channel in the upper, restored part of the meadow

(X-Section 3) and lower, non-restored part of the meadow (X-Section 6). The upper channel is characterized by a distinct v-shaped channel that is relatively

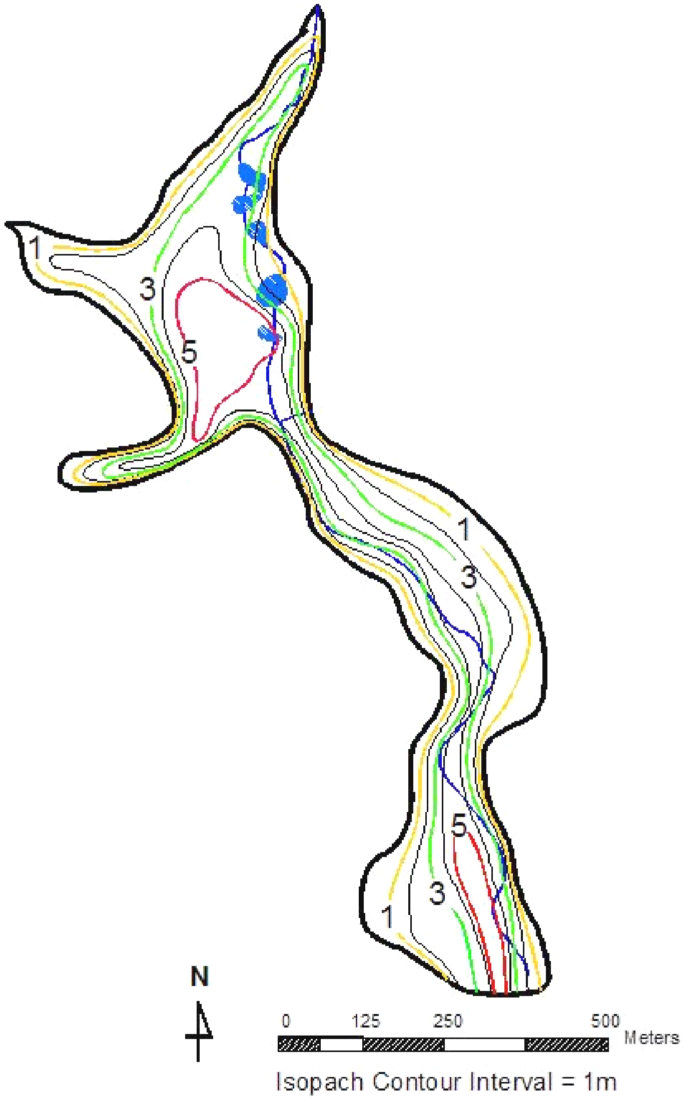

Figure 12. Isopach map of Clark's Meadow. 1 m contour intervals outline the relative thickness of meadow sediments throughout the study area. Index contours (1, 3 and 5 m) are colored for clarity.

small (~ 0.5 m deep and less than 10 m wide) which would frequently overflow and slowly drain overflow waters through sedge grasses and willow trees. The lower channel has experienced substantial bank erosion and channel widening (~ 3 m deep and over 40 m wide) and is therefore disconnected from its floodplain and is dewatering the groundwater table. Flows through this reach of the channel do not overflow the banks and does not support sedge grasses. Sage vegetation populates the meadow here.

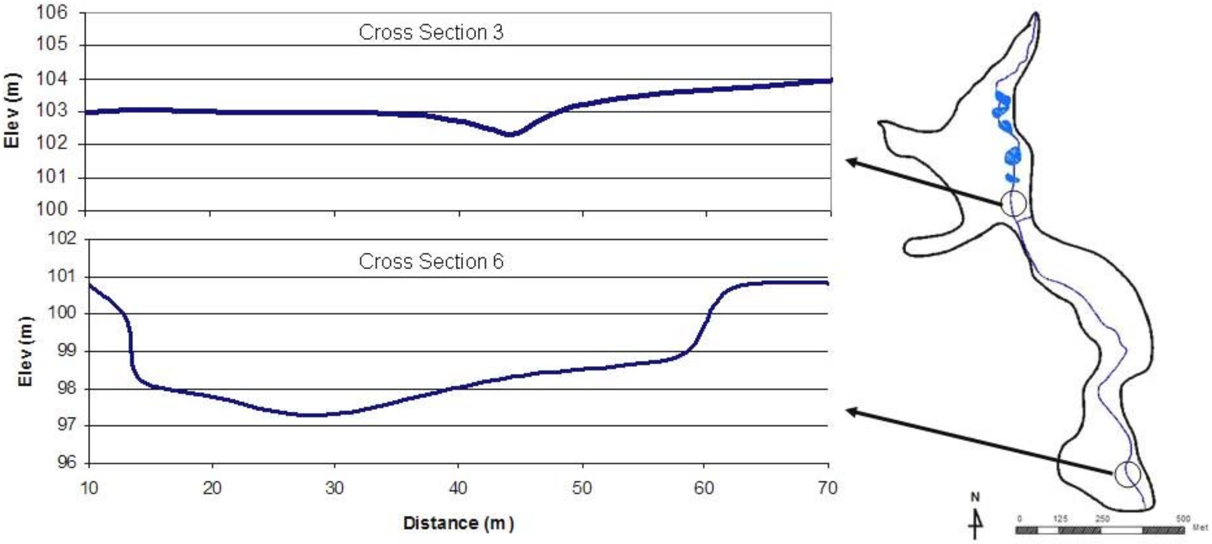

Figure 13. Cross-sectional views of the stream channel through Clark’s Meadow. X-Sec 3 illustrates a narrow and shallow channel in the northern restored section of the Meadow, while X-Sec 6 shows a much wider and deeper channel in the southern un-restored part of Clark’s Meadow.

The topographic analysis of the Clark’s Meadow (Figure 3) shows no substantial topographic barriers that might influence surface water flow or temporarily pond waters on the meadow surface (with the obvious exception of the engineered ponds that do exist in the northern part of the meadow). Overall Meadow gradient along the stream channel are about 0.01.

Meadow sediments store subsurface waters and transit these waters through the subsurface to outlet points such as stream channels and springs. Volume calculations for the meadow suggest about 768,651 m^3 of sediment exist below the surface. When that volume is multiplied by the mean porosity of sampled sediments (0.35), a void volume of 269,028 m^3 in the subsurface is produced.

Water depths encountered in auger holes (August, 2007) showed subsurface water at about 1.5 m below the surface suggesting that during the warm and dry summer season, groundwater evaporates in the upper part of the sediment column. It is unlikely though, that all of this 1.5 m loss is due to evaporation. It is probable that perhaps a sizable portion of this loss is due to aquifer dewatering. This 1.5 m depth to groundwater represents unsaturated storage within the restored section of Clark's Meadow. Furthermore since this part of the meadow has been restored, it is reasonable to assume that this fluctuation in water depth from saturated and visible surface flow during wet months to unsaturated conditions with no surface flow in dry months reflects a somewhat normal cycle of meadow hydrology.

The lower portion of Clark's Meadow has not been restored and as outlined above in Figure 13 substantial bank erosion and incision has occurred. The incision of the stream channel in this part of the meadow has enhanced meadow aquifer dewatering as erosion has cut down into water-bearing sediments with higher hydraulic conductivity than surface soils. This has lowered the water table in this part of the meadow by at least 4 m – 2.5 m lower than the water table in the upper Meadow during the dry season. This lowering of the water table translates up-meadow as well and likely dewaters sediments somewhat removed from the parts of the meadow actually undergoing channel erosion and incision. The ponds produced in the middle of the meadow by the restoration effort had no water in them during 2007 summer and fall field work suggesting that dewatering of the meadow aquifer had translated this far up stream.

Table 5. Volume calculations from Clark's Meadow blocks, and corresponding water volume losses under various scenarios assuming a meadow average porosity of 0.35.

Section Number	**Meadow Sediment Volume**	**Total Meadow Potential Water Volume**	**Water Volume Left at 1.5 m loss**	**Water Volume Left at 4 m loss**
	(m^3)	**(m^3)**	**(m^3)**	**(m^3)**
1	9,300	3255	733	733 [a]
2	70,080	24528	8222	8222 [a]
3	23,562	8247	3604	3604 [a]
4	131,178	45912	26124	26124 [a]
5	51,093	17883	5090	5090 [a]
6	94,738	33158	17108	14164 [b,c]
7	66,983	23444	11910	4476 [c]
8		71400	48034	27418 [c]
9	117,717	41201	25597	3567 [c]
Total Volume (m^3)	**768,651**	**269028**	**146422**	**93998**
Acre-Feet		**218**	**119**	**76**
% water loss		**0**	**46%[d]**	**65%[e]**

[a] upper meadow loses 1.5 m to ET/dewatering
[b] assumes partial dewatering (50%) as upstream block has not dewatered
[c] assumes dewatering of meadow sediments to a depth of 4 m.
[d] 1.5 m loss throughout entire meadow
[e] 1.5 m loss throughout entire meadow and additional 2.5 m loss (4 m total) in lower blocks 6, 7, 8, and 9

During the drier part of the summer and early fall, substantial dewatering and evapotranspiration take place resulting in a significant change is stored groundwater volume throughout the meadow. Table 5 outlines storage potential and probably water loss under several observed conditions. Under fully saturated conditions, the meadow can store up to 218 acre-feet (269,028 m^3) of subsurface water within the pore space of meadow sediment. In mid August, 2007, borings encountered groundwater in the restored portion of the meadow at an approximate depth of 1.5 m. At peak runoff conditions (mid to late spring), the meadow sediments are fully saturated and standing water is present on the meadow surface. This drop (from fully saturated conditions to

1.5 m below the surface) is a result of evapotranspiration, lack of surface (and probably groundwater) recharge and dewatering through downstream spring and bank seeping conditions. This 1.5 m drop corresponds to a loss of 99 acre-feet (146,422 m^3) of stored water.

In the lower un-restored section of the meadow, groundwater was below 4 m from the surface (incised channels cut to about 4 m depth with no visible water in the channel and no seeping channel banks). This water loss was primarily a function of channel incision and subsequent dewatering of the meadow aquifer. When the loss of this stored water is considered (in blocks 6, 7, 8 and 9) the meadow water loss totals 142 acre-feet (175,000 m^3), almost two-thirds of the total volume of water stored in the meadow during fully saturated conditions.

Table 6. Estimated volume of groundwater stored in mountain meadows throughout the Feather River watershed (assumes a hydrologically healthy meadow and Clark's Meadow subsurface characteristics and porosities (0.40) translate reasonably to these other watersheds).

Watershed Area	Estimated Meadow Area	Estimated Meadow Volume [a]	Estimated Meadow Water Volume [b]
Feather River (m^3)	190,700,000	318,400,000	133,490,000
Feather River (acre-feet)		309,000	108,150

[a] - assumes a 4 meter thick sediment package and a 0.5 shape factor.

[b] – assumes a 0.35 porosity

The subsurface conditions and relationships measured in Clark's Meadow have been coarsely extrapolated across the Feather and CABY study regions (Tables 6 and 7). Specifically it was assumed that the meadow area to volume relationship and mean porosity conditions measured at Clark's Meadow are representative of mountain meadows throughout the study region although there is no extensive data set to confirm this very general assumption.

Table 7. Estimated volume of groundwater stored in mountain meadows throughout the CABY watershed (assumes a hydrologically healthy meadow and Clark's Meadow subsurface characteristics and porosities (0.35) translate reasonably to meadows in this watershed).

Watershed Area	Estimated Meadow Area	Estimated Meadow Volume [a]	Estimated Meadow Water Volume [b]
CABY (m^3)	66,700,000	133,400,000	46,690,000
CABY (acre-feet)		108,000	37,800

[a] - assumes a 4 meter thick sediment package and a 0.5 shape factor.
[b] – assumes a 0.35 porosity

Estimated total water volume (stored as groundwater) in mountain meadows in both the Feather and CABY watersheds totals 145,950 acre-feet ($18.0 *10^6$ m^3) of water. This water source likely provides stream flow through mountain meadows throughout much of the year. The physical condition of most these meadows (hydrologically healthy or undergoing incision/erosion) are unknown so the potential loss from this volume is also unknown.

In-situ hydraulic conductivity borehole tests suggest that groundwater transit through the meadow can be fairly rapid (almost 300 m/day – Table 4) in the coarser subsurface sediments (sands and gravel). Shallower sediments are generally finer grained and yield slower overall transit times (~50 to 60 m/day). It should be understood that there is a likely bias between the field in-situ tests and the laboratory test of hydraulic conductivity. The field tests are conducted in the saturated borehole below the water table and sample that entire open interval instead of discreet sediment units within that interval. Sediment units will contribute groundwater to the test according to their inherent properties but the test will record their combined contribution over the entire interval.

In the laboratory tests, bias enters into the sample interval as the more cohesive sediments are better retained in the sampling device than the coarser, non-cohesive materials. Consequently, the more cohesive sediments (finer grained - low hydraulic conductivity results) are better represented in the sampling program than are the coarser (higher hydraulic conductivity) sediments.

The unrestored portion of Clark's Meadow showed substantial signs of active erosion (incised channel, collapsing banks, sediment bars in the active channel). This condition appears to have dewatered the lower unrestored meadow by facilitating groundwater sapping through the incised river channel. This process likely accounts for the absence of water in the several small basins that are remnant from the restoration activity. Ponds and basins in the upper restored meadow, still contained water in late summer and early fall, 2007 suggesting that the absence of groundwater sapping in this portion of the meadow allowed for a much slower rate of groundwater loss.

6.0 CONCLUSION

This study defined the subsurface geological conditions of Clark's Meadow, a 0.46 km^2 mountain meadow in the Last Chance drainage basin. The meadow itself transits flow from about 48 km^2 of the upstream watershed. Clark's Meadow drains directly to the Last Chance stream.

Unchecked historical erosion problems had resulted in a hydrologically unstable condition in the Meadow with substantial channel incision, channel widening and groundwater dewatering occurring. In summer 2001, pond and plug restoration efforts were conducted in the northern half (68 acres) of Clark's Meadow. The goal of the restoration work was to restore ecological and hydrological balance to that part of the meadow by filling in the incised channel (plugging) and allowing runoff flows to re-establish a natural channel or series of channels on the floodplain. Restoration efforts were in late summer 2001. The lower half of the Meadow (48 acres), however, has not received restoration efforts and continues to undergo channel incision, stream bank erosion, and groundwater dewatering.

Seismic surveys and borehole data collected throughout Clark's Meadow suggest the relative thickness of meadow sediments ranges between about 3 and 5 meters and varies in sediment size from fine-grained silts and clays (generally near the surface) to coarser grained sands and gravels at depth. Sediment properties (hydraulic conductivity and porosity) were measured from in-situ borehole tests and laboratory analysis of borehole samples. The volume of void space in the meadow (the potential to store groundwater) was calculated from the porosity and volumes measured in the meadow and indicate that substantial groundwater storage is possible in the Meadow. Using a meadow-wide mean porosity value of n = 0.35, and multiplying that void space through the volume of sediment in the meadow, a total storage potential (under fully saturated conditions) of 269, 028 m^3 (218 acre-feet) is produced.

Clark's Meadow however, is experiencing substantial subsurface water loss as a function of unchecked channel erosion and incision in the lower part of the meadow. Restoration efforts in the upper half of the meadow have effectively re-established a more ecologically sound hydrologic condition where the stream channel is shallow and narrow, groundwater is more closely connected to surface water conditions and higher stream flows spread out across the floodplain during downstream transit. Indeed, shallow groundwater (about 1.5 m at depth) during the dry late summer (2007) in the upper restored part of the meadow strongly suggests a more balanced surface water - groundwater condition exists there. The non-restored lower part of the meadow shows the legacy of stream erosion and channel incision. The resulting channel is deeper and wider with unstable channel walls. No surface water flow or groundwater seeping was visible in the incised channel to a depth of about 4 meters (late summer, 2007) suggesting that the meadow had dewatered to at least 4 meters below the surface. If these conditions are typical during summer months and almost total dewatering occurs in the lower non-restored part of the meadow, a total water loss of 142 acre-feet (175,000 m^3) is experienced. This loss of groundwater equates to about 65% of the total stored volume of groundwater. In other words, water that might be available to streams and springs during the drier summer months is lost in the late spring early summer months to rapid dewatering.

Extrapolating Clark's Meadow subsurface conditions to mountain meadows across the Feather and CABY watersheds (a necessarily coarse extrapolation), yields a rough understanding of the volume of groundwater in play in this region (almost 150,000 acre-feet of groundwater). Of course not all meadows are hydrologically impaired in these watersheds and specific subsurface conditions will vary between meadows.

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