# Groundwater and Surface Water Interactions in the Catherine Creek Watershed, Oregon—*Results and Analysis from the 2011 Seepage Run*

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# Abstract

In the fall of 2011, the Oregon Water Resources Department (OWRD), in collaboration with local and regional interest groups, completed a seepage run in the Catherine Creek watershed in the upper Grande Ronde Basin near Union, Oregon. The purpose of the seepage run was to quantify exchanges between the shallow groundwater system and Catherine Creek downstream of a proposed aquifer storage and recovery (ASR) project located in the uplands of the watershed. This information is relevant to OWRD management of summer streamflow in the Grande Ronde Valley (GRV) which may be augmented through seasonal groundwater (GW) pumping at the ASR site.

Results from the seepage run indicate that groundwater exchanges with Catherine Creek were minor in the study area during the fall of 2011—less than discharge measurement uncertainty of the seepage run. In addition, there was no statistically significant longitudinal increase or decrease in streamflow attributable to groundwater exchange upstream of Cove. Downstream of Cove, below Elmer Reservoir #4, the seepage run indicated gains in streamflow that can be attributed to groundwater inflow. Trends in specific conductance of Catherine Creek, measured during the seepage run, agree with these results; except near and upstream of the town of Union where specific conductance values in the creek are higher than expected. The higher conductance values may be caused by hyporheic flow in the stream channel, local intermittent stream–groundwater–stream exchanges, or anthropogenic activities, all of which could cause increases in specific conductance without detectable surface water or groundwater inflow.

Shallow groundwater elevations were monitored in piezometers installed near the stream at three sites along an upper, middle, and lower reach of Catherine Creek in the Grande Ronde Valley. At each piezometer site, the surface–water elevation of Catherine Creek was also monitored using temporary stream gages. Piezometer data collected during the seepage run indicate a downward component of flow between the stream and the aquifer at the upper and middle sites and an upward component of flow at the lower site. Upward flow at the lower site is consistent with gains inferred from seepage run measurements.

However, downward flows at the middle and upper sites were not confirmed by the seepage run analysis since measured gains and losses were all within the measurement errors (typically 1.5–3 cfs) and no statistically significant trends in gain or loss could be detected in these reaches. At the middle site, the streambed consists of silt and clay, low permeability sediments which are likely to impede the rate of vertical flow between the stream and the aquifer. At this site, low rates of vertical flow are expected and stream losses could easily be less than the errors of the seepage measurements. At the upper site, near Union, the streambed consists of gravel and sand with very little silt or clay. These materials should be permeable enough to allow reasonably high rates of vertical flow from the stream to the underlying aquifer. However, well logs in the surrounding area indicate that silt and clay beds may be common in the Catherine Creek fan–delta deposits near Union. If these beds are common at shallow depths below the stream bed, they could limit vertical flow to rates well below the measurement errors of the seepage measurement.

Overall, stream–aquifer head relationships and geologic setting are consistent with the limited groundwater exchange results from the seepage run in most reaches. Near Union, however, anomalously high specific conductance values in the creek, downward head gradients, and the likely presence of relatively permeable vertical pathways, suggest that exchanges between groundwater and surface water may seasonally be more substantial than indicated by seepage measurements. For these reasons, additional studies in the area around Union are recommended. These studies should examine streambed conductance and repeat stream discharge measurements around Union. It is also recommended that stream stage and aquifer head measurements be continued for at least an entire water year at the current piezometer sites to provide additional insights into the potential for the exchange of water between Catherine Creek and the underlying aquifer.

# Introduction

Catherine Creek is a critical salmonid stream in the upper Grande Ronde basin (the drainage area above the confluence with the Wallowa River) where historic anadromous fish runs have undergone marked declines in the last 100 years (Bach and others, 1995; Nowak and Kuchenbecker, 2004). The declines have been attributed to many factors including changes in habitat, water quality, fish passage and streamflow. Some reaches of Catherine Creek are severely depleted during the summer due to irrigation diversions. A variety of projects to improve habitat and streamflow in Catherine Creek are ongoing, coordinated by the Grande Ronde Model Watershed (GRMW). Federal agencies, including the US Bureau of Reclamation (USBR) and the Bonneville Power Administration (BPA), are interested in improving salmonid runs in Catherine Creek as part of a broader effort to mitigate the effects of main–stem dams on the Columbia and Snake Rivers. Since there are no significant reservoirs and associated fish passage barriers in the upper Grande Ronde basin, summer flow augmentation in Catherine Creek could open up significant spawning grounds for the restoration of fish runs.

One proposal to enhance Catherine Creek flows is to pump groundwater into the creek above the Grande Ronde Valley (GRV) during the summer months to augment flow through irrigated lands in the Grande Ronde Valley (fig. 1). The proposed wells would be completed in Columbia River Basalt Group aquifers to reduce the likelihood of an efficient hydraulic connection to Catherine Creek. An efficient connection would greatly reduce streamflow augmentation since the pumping would also cause near–term reductions to streamflow in Catherine Creek. The flow–augmentation project also includes an aquifer storage and recovery (ASR) component, in which groundwater from the shallow alluvial aquifer adjacent to the stream is pumped into the deeper basalt aquifers during winter and spring months. This ASR component was included in the project to prevent over drafting of the local basalt aquifers in the event that local recharge is insufficient to support the proposed groundwater withdrawals.

OWRD manages the distribution of water in Catherine Creek; therefore, the local watermaster will be responsible for shepherding any augmented summer flows through the GRV. Effective management of this water is not possible without a good understanding of the watershed hydrology; especially a knowledge of any water exchanges between the underlying aquifer system and the stream.

To better understand exchanges between groundwater and surface water in the GRV, OWRD completed a seepage run on Catherine Creek in the fall of 2011 in collaboration with local, state, and federal organizations. The study was partly funded by BPA through the National Fish and Wildlife Foundation (NFWF). In addition to the seepage run, OWRD installed nested piezometers (pairs of shallow and deep wells) on opposite banks of Catherine Creek in three locations adjacent to an upper, middle, and lower reach of the creek in the GRV. Piezometers are special observation wells with a narrow open interval that are designed to measure hydraulic head (groundwater elevation) at a particular point in an aquifer. Hydraulic heads from an array of piezometers can be used to determine groundwater head gradients and the associated flow direction. At each of the three piezometer locations, stream gages were also installed to monitor the creek water elevation. The combination of piezometers and stream gages can monitor temporal changes in gradients and flow directions between the stream and the aquifer. As such, they provide additional context for the interpretation of the seepage–run measurements. This information is also useful in determining how the exchange of water between the aquifer and the stream may vary over longer periods of time. Hydraulic heads measurements in the piezometers and stream gages will continue through the upcoming water year and will be analyzed in a follow–up report at the end of 2012.

# Background

Catherine Creek is a tributary of the Grande Ronde River in the southeastern part of the Grand Ronde basin which is located in the Blue Mountains physiographic province of Northeastern Oregon (Baldwin, 1981). Catherine Creek and its principal tributaries originate in the southern portion of the watershed along the steep southwestern slopes of

the Wallowa Mountains, where multiple peaks exceed elevations of 8,000 feet (fig. 1). From these highlands, the creek flows northwest through steep, narrow canyons until it enters the broad Grande Ronde Valley near the town of Union. The creek then meanders across the flat valley floor until its current confluence with the Grande Ronde River about eight miles northwest of Union. Prior to the late 1800s, the confluence was located just west of Cove. In the late 1800s, a four and one–half mile long ditch, the State Ditch, was constructed off of the Grande Ronde River about five miles upstream of the historic confluence with Catherine Creek. The ditch was created to divert river flows from marshy lands north and west of Cove. Over time, the size of the ditch increased until it eventually captured the entire flow of the Grande Ronde River. Since that time, Catherine Creek and a few minor tributaries provide the only water that traverses the old Grande Ronde channel between the historic Catherine Creek confluence near Cove and the terminus of the State Ditch. In essence, the State Ditch moved the mouth of Catherine Creek 23 miles downstream (fig. 1). For this reason, Catherine Creek and the 400 square–mile Catherine Creek watershed, as referred to in this report, include the old Grande Ronde channel and it's drainage area from the historic mouth of Catherine Creek to the new mouth at the downstream terminus of the State Ditch.

As Catherine Creek enters the GRV its character changes from a high–gradient, high–velocity, coarse–substrate, mountain stream to a low–velocity, low–gradient, fine–substrate, meandering stream. This metamorphosis is mostly complete by river mile (RM) 34, at the lower Davis Dam (fig. 1). Above the lower Davis Dam, the streambed is predominantly composed of gravel and sand. From lower Davis Dam to the mouth, the streambed grades from fine sand to silt and clay. Channel gradient and streamflow velocity decrease, and meander sinuosity increases with distance north of Union. However, in some areas between Union and Cove, the creek channel has been straightened to eliminate flooding in the historic floodplain. Channel straightening is most noticeable in and around Union and downstream of Davis Dam. In addition, many oxbows north of Cove have been naturally or intentionally cut off from the main channel and are currently used as off–channel reservoirs. Dikes have also been constructed along most of the channel to alleviate flooding.

The hydrology of the Catherine Creek watershed is predominantly influenced by climate and geology. The watershed lies in the semi–arid continental climate zone and experiences cold wet winters and warm dry summers. Temperatures recorded at Union show an average maximum temperature of 85º F in August and an average minimum temperature of 23º F in January. Precipitation varies with elevation. Nearly 60 inches per year falls in the headwaters of Catherine Creek, predominately as snow, but only 13 inches per year fall in the GRV (fig. 2). Most precipitation falls between November and April, with significant snow accumulations in the mountainous areas of the watershed above the transient snow zone at about 3500 feet. However, precipitation in the form of rain is also common throughout the watershed in the fall and spring. The majority of streamflow originates in the high precipitation mountainous area of the watershed in response to seasonal snowmelt.

The geology of the watershed is described in general terms by Baldwin (1981) and Orr and others (1992); in detail by Hampton and Brown (1964); and in great detail by Ferns and others (2002) and Ferns and others (2010). Only a general summary of the geology, relevant to basin hydrology, is provided in this report.

The oldest rocks in the Catherine Creek basin are pre–Tertiary sedimentary and volcanic rocks that were deposited on an ancient sea floor. These materials were deeply buried, partially metamorphosed and subsequently intruded by large bodies of magma during the Mesozoic era that solidified into the granitic rocks of the Wallowa batholith, which now forms the core of the Wallowa Mountains (Ferns and other, 2010). These older pre–Tertiary rocks are only exposed in a small area along the southeastern margin of the Catherine Creek basin (fig. 3) but they are widely exposed in the Wallow Mountains immediately to the east and they also occur as bedrock at depth beneath the headwaters of Catherine Creek and probably as bedrock at great depths beneath the Grande Ronde Valley. The older bedrock units have very low porosity and do not readily store or transmit groundwater. Hampton and Brown (1964) noted that the pre–tertiary rocks in the upper Grande Ronde basin bear virtually no groundwater.

Lavas of the middle Miocene Columbia River Basalt Group (CRBG) overlie pre–Tertiary bedrock at depth throughout the Grand Ronde Valley. They also occur at land surface in many upland areas in the watershed. CRBG lavas were erupted between 17 and 15.5 million years ago, typically from linear fissure vents that poured out huge volumes of lava that flooded the pre–existing landscape. Ferns and others (2010) note that many of the CRBG flows in the Grande Ronde basin were erupted from vents near the eastern margin of the GRV. Early CRBG lavas were extruded onto a deeply eroded pre–Tertiary landscape and leveled out the pre–existing drainage system. Subsequent lavas flooded huge tracts of land that extend well beyond the present Grande Ronde basin. CRBG flows cover extensive portions of Oregon and Washington in the Columbia and Snake River drainage basins. Individual flows or groups of flows from a single eruptive event have been mapped over hundreds of square miles and in some cases travelled all of the way to the northern Oregon and southern Washington coasts from vents in the eastern regions of these states.

The composite thickness of the CRBG in the GRV exceeds 2000 feet in some areas and probably consists of at least 100 individual flows. In general, flood basalts of the CRBG form laterally extensive flows which range from tens to several hundreds of feet thick. Most CRBG lavas have a thick, dense flow interior which has very little pore space and does not readily transmit water. Rubble zones are common, but not universally present, at flow contacts. These interflow zones, where developed, generally have high porosity and permeability. This physical geometry generally produces a stack of thin, tabular aquifers (interflow zones) separated by thick confining beds (flow interiors). Highly permeable interflow zone are capable of transmitting significant quantities of water to wells. However, the dense basalt flow interiors generally inhibit vertical recharge from precipitation and vertical groundwater flow between overlying aquifers. The combination of inhibited vertical recharge and high horizontal permeability makes CRBG aquifers highly susceptible to overdraft (Sceva, 1966; Norton and Bartholomew, 1984; Lite and Grondin, 1988).

Middle Miocene to Early Pleistocene lavas of the Powder River Volcanic Field (PRVF) overlie CRBG lavas in many areas of Grande Ronde basin. PRVF lavas were probably erupted from small vents, many of which are local to the Grande Ronde Basin. PRVF lavas are more compositionally diverse than those of the CRBG but individual flows are not as extensive. However, the composite lava field reaches thicknesses of at least 1200 feet and is the predominant unit at land surface in many upland areas along the eastern and southern margins of the Catherine Creek basin. Water wells indicate that at least several hundred feet of PRVF lavas overlie CRBG lavas at depth below most of the GRV. Early basalt lavas of the PRVF appear to have properties similar to the CRBG flows and can host thin but productive aquifers. Later dacite and andesite flows are poorly permeable and rarely host productive aquifers.

The current topography of the GRV began to form about 10 million years ago when regional compression began to up warp the highlands that now form the Blue Mountains and steep northwest–trending faults developed in the basin. By about 8 million years ago, the Grande Ronde Valley began to form as a subsiding lowland between several major faults and began receiving sediments from streams that drained the adjacent highlands. Continued rise of the adjacent highlands and subsidence of the valley produced a broad, 250–square mile, sediment–filled basin that is bordered by the steep, fault–bounded range–fronts of the Wallowa Mountains on the east and the Blue Mountains on the west. Cumulative displacement along the main range–front faults probably exceeds 3000 feet and the maximum thickness of the basin–fill sediments ranges up to about 2000 feet.

As streams entered the developing Grande Ronde Valley from the adjacent highlands, stream velocities decreased and stream sediment loads were dropped on the valley floor. On the margin of the valley, sediments accumulated as alluvial fans or fluvial fan deltas. In either case, coarse–grained sediments were deposited near the apex of the fans and fine–grained sediments were deposited near the outer fan edges as stream gradients and velocities decreased. Toward the center of the basin, silts and clays were deposited in low–gradient alluvial plains or lakebeds.

High–angle, northwest–trending faults are a prominent feature of the modern landscape in the Catherine Creek basin (fig. 3) and influence the flow paths of surface water and groundwater. Just upstream of Union, for example, Catherine Creek follows the linear path of a fault trace for about 5 miles**.** High–angle faults are likely to be barriers to horizontal groundwater flow in CRBG aquifers and in PRVF aquifers since substantial vertical movement on either side of the fault is likely to offset thin, permeable interflow zones against dense, poorly permeable flow interiors. These faults may also be barriers to vertical flow if the fault plane is clogged with fine–grained fault gouge or secondary minerals. However, if a fault is continually reactivated, the fault zone may be sufficiently permeable to enhance vertical migration of groundwater. Hampton and Brown (1964) note that many fault zones in the CRBG lavas contain a clayey gouge that is likely to impede the movement of groundwater. However, mineralized hot springs, such as those associated with the Hot Lake fault along the southwest edge of the GRV near Union, suggest that some faults allow upward movement of groundwater in the basin. This suggests that active faults in the upland may allow some downward flow of groundwater.

Overall, the geologic setting indicates that surface runoff processes should be the dominate mechanism for precipitation leaving the upper watershed where most precipitation falls (other than evapotranspiration {ET}). Groundwater recharge in the uplands of the Catherine Creek watershed is likely to be limited by the low vertical permeability of bedrock units (CRBG & PRVF lavas). This is consistent with streamflow observed at OWRD gage # 13320000 upstream of Union (fig. 4). The annual average hydrograph at this gage is typical of streamflow produced predominately by snowmelt runoff. Streamflow is low and relatively constant until snowmelt begins in the spring. Peak flows occur during the spring melt, but late snowmelt also elevates stream discharge into early August. Annual instantaneous peak flows commonly exceed 750 cubic feet per second (cfs), whereas summer baseflows average only 30 cfs. Some of this baseflow, which is normally attributed to groundwater discharge to the stream network, appears to originate from daily cycles of snowmelt in the upper watershed as the 15–minute hydrographs show many diurnal fluctuations throughout the summer and fall. Overall, the

annual runoff for Catherine Creek at stream gage #13320000 is approximately 75,000 acre–feet.

Despite the limited potential for groundwater recharge in the uplands, regional groundwater flow paths give rise to substantial artesian pressures in flowing artesian wells that produce from CRBG aquifers deep below the GRV floor. However, high rates of regional discharge into the stream network on the valley floor, such as those that occur in the Deschutes and Klamath basins (Lite and Gannett, 2002; Gannett and others, 2007) are precluded by the low vertical permeability of the thick silt and clay deposits in the GRV and by limited recharge in the uplands where most precipitation falls. Regional groundwater flow is also likely to be disrupted by the extensive network of faults in the basin which are likely to impede lateral flow in bedrock units. This is confirmed by the lack of large springs that discharge to basin–floor streams and the lack of significant baseflows in Catherine Creek during summer and fall months.

The geologic formations that are most pertinent to groundwater interactions with Catherine Creek in the study area are the sedimentary deposits that fill the GRV and Catherine Creek canyon upstream of Union (fig. 3). Water table maps by Hampton and Brown (1964) indicate that Catherine Creek should loose water to the sedimentary groundwater system as it enters the valley near Union. A few miles to the north, the water table is at or near land surface and some wells encounter water–bearing zones with sufficient head to flow at land surface during a portion of each year. However, shut–in pressures appear to be relatively low. These observations indicate the presence of a local groundwater–flow system within the sediments and indicate possible recharge (downward flow) from Catherine Creek as it enters the valley floor and discharge (upward flow) to the creek in reaches downstream from Union. Similar flow systems are associated with the drainages in alluvial fans along the eastern and western margins of the valley (Hampton and Brown, 1965).

As Catherine Creek first enters the GRV several miles upstream of Union, it follows a broad linear valley that is underlain by a thick deposit of glacial outwash gravels (Ferns

and other, 2002) which are likely to be highly permeable. The streambed in this reach is largely sand and gravel so water should be able to move freely between the stream and the adjacent aquifer.

Near Union, the streambed is incised into the Catherine Creek fan, a fluvial fan delta that has formed at the margin of the valley where the stream gradient decreases abruptly (fig. 22). The fan delta is a wedge of sand and gravel that reaches a thickness of at least 450 feet a few miles north of Union and then progressively thins farther to the north. The distal edges of the coarse–grained fan sediments interfinger with, and are overlain by, lake–bed silts and clays. Near the valley margin, fan–delta sands and gravels are directly overlain by the sand and gravel bed of Catherine Creek. This stream reach is expected to have the greatest potential for loss because head gradients are downward (Hampton and Brown, 1965) and the hydraulic continuity between the streambed and the aquifer is likely to be efficient. Although the Catherine Creek fan is largely sand and gravel, local well logs indicate the presence of significant beds of clay and silt within the fan (Ferns and others, 2002). If these fine–grained beds are laterally continuous or if they occur at shallow depths beneath significant reaches of the streambed, they may impede the downward flow of water from the stream to the aquifer.

A few miles downstream from Union, gravel and sand continue to line the streambed of the creek but fan–delta sands occur at depth beneath a layer of lower–permeability silt and clay. The presence of flowing–artesian wells indicate an upward gradient from the aquifer to the steam but stream gains are likely to be small since vertical groundwater flow is likely to be impeded by the silts and clays. Farther to the north, streambed sediments transition to sand and then to silt and clay and are underlain by thick sequences of floodplain and lacustrine silts and clays. Upward vertical gradients are also expected in these lower reaches of the basin but stream gains are again expected to be small because of the thick beds of silt and clay beneath the streambed.

# Approach

Groundwater exchanges with Catherine Creek were evaluated by conducting a seepage run in late October of 2011 and by determining the three–dimensional distribution of hydraulic heads (water–level elevations) in the shallow aquifer relative to the stream using piezometer nests and temporary stream staff gages at three sites along the creek (fig. 7). This analysis was augmented by evaluating specific conductance measurements made during the seepage run, stream temperature data from previous studies (Watershed Sciences, 2000; USBR, 2012) the influence of the geologic setting, and observations from previous studies.

### Seepage Run

Seepage runs are made by measuring streamflow at various points along a stream and by measuring all surface–water inflows (tributary inflows and ditch return flows, for example) and outflows (irrigation diversions) during a short period of time. Ideally, all measurements are made over one or two days when streamflow is constant (that is, steady state). By accounting for all surface inflows and outflows in a stream reach, simple arithmetic can determine if the reach gains or loses water. Any gain or loss is usually attributed to inflow from, or outflow to, the underlying aquifer system.

Seepage runs are typically performed during low flow periods to reduce measurement uncertainty (typically five percent of the measured flow). Early fall is generally the best season to perform the measurements because irrigation diversions are generally minor, and rainfall is less likely. Irrigation diversions increase the number of discharge measurements, each with its own level of uncertainty. Irrigation return flows also need to be measured. Precipitation can elevate streamflow and tributary inflow, and create local runoff; which is difficult to measure. Precipitation can also produce unsteady (rising or falling) streamflow. Finally, precipitation can elevate groundwater levels compared to the dry season. For these reasons, most seepage runs are performed in the fall.

The seepage run for this study was scheduled for the end of October 2011, after the end of the main irrigation season when few diversions were expected to be active. Prior to the seepage run, OWRD personnel scouted all potential inflows and diversions from just below the proposed ASR project (RM ~ 50) to the new mouth of Catherine Creek at the State Ditch terminus. The day before the seepage run, all teams performed a check–discharge measurement at the OWRD "Catherine Creek near Union" stream gage (#13320000) to verify that equipment was properly calibrated and proper procedures were followed to minimize measurement errors. These values were compared to the four–hour, moving–average, stream–gage reading. The moving average was used to reduce random noise inherent in raw 15–minute gage data. The average difference between the check measurements and the gage reading was –2.0 %. The sampling error, or estimated measurement error, calculated from the standard deviation of all the check measurements was 6 percent, which is within acceptable limits.

On October 19$^{th}$ and 20$^{th}$ of 2011, the seepage run was completed by OWRD, USBR, FWT, and GRMW personnel. Eighteen main–stem discharge measurements were made on Catherine Creek at predetermined locations, resulting in 17 reaches of interest (Fig. 7). All surface–water inflows or diversions from Catherine Creek were measured or, in some cases, estimated when site conditions (such as low flows) prevented the use of measurement devices.

Wading measurements, using USGS standard protocols and equipment, were used at each measurement location by seven of the eight teams. Two sequential discharge measurements were made at each site. If the difference between the first and second measurement exceeded five percent of the average, a third measurement was performed and all three measurements were averaged to estimate discharge at the site. At a few locations, this measurement process was repeated on the first and second days to confirm steady–state conditions and reduce measurement uncertainty.

A USBR team used a SonTek acoustic Doppler profiler (ADP) mounted on a hydroboard coupled with a laptop running the SonTek RiverSurveyor Live software to measure

discharge at various stream sites. Up to seven sequential traverses across the stream were made with the Doppler unit at each site and averaged for a final flow estimate (USBR, 2011).

At two of the tributary locations, very shallow and/or narrow channels prevented the use of measurement gear (even the handheld acoustic Doppler velocity profiler) or other hydraulic devices such as portable weirs. At these locations, a visual estimate of discharge from two independent observers was averaged and used as the final flow estimate with a 100% uncertainty rating. Fortunately these locations had very little flow (which was the main contributor to the poor site conditions) and had little impact on the overall study.

**Nested piezometers and temporary stream gages**

OWRD installed nested piezometers (pairs of shallow and deep wells) on opposite banks of Catherine Creek in three locations adjacent to an upper, middle, and lower reach of the creek in the GRV. Piezometers are special observation wells that have a narrow completion interval designed to measure hydraulic head (groundwater elevation) at a particular point in an aquifer. All of the piezometers in this study had a one–foot segment of slotted PVC casing at the bottom of the well which was packed with about three feet of fine silica sand and sealed to land surface with bentonite grout. Each piezometer nest included a shallow well with an open interval near the water table and a deeper well with an open interval about 10 feet below the open interval of the shallow well. This configuration was designed to determine the vertical component of groundwater flow relative to the stream (upward from the aquifer to the stream or downward from the stream to the aquifer). A piezometer nest was installed on both banks of the stream at each reach (except for the upper reach where only a deep well was installed on the east bank of the creek due to poor well–drilling conditions). The slotted casings of the shallow and deep wells on opposite sides of the creek were installed at the same elevation. These pairs of wells on opposite sides of the creek were designed to determine the horizontal direction and gradient of groundwater flow relative to the creek (toward or away from the creek).

Stream staff gages were also installed to monitor the surface–water elevation (SWE) of Catherine Creek at each site.

All of the piezometers and staff gages were equipped with data loggers and pressure transducers programmed to measure water levels at 15–minute intervals. Surveyed well–head and stream–gage elevations were used to convert all water levels to a common elevation datum for comparing hydraulic heads in the aquifer and the adjacent stream. These hydraulic heads were used to help interpret the seepage run results and to assess temporal changes in the GW/SW flow system in the valley.

**Specific Conductance**

Specific conductance (SC) was measured at each flow–measurement site in Catherine Creek and at all tributary measurement locations. SC measures the ability of water to conduct an electrical current and is proportional to the concentration of dissolved ions in water. In the absence of groundwater or tributary inflows, dissolved–ion concentration in a creek is expected to remain relatively constant or to increase slightly between the headwaters and the mouth since the short travel time for water in a stream (usually days) generally precludes any significant dissolution of materials in the streambed. However, because of longer residence times, dissolved–ion concentrations in groundwater are generally higher than in surface water. Therefore, groundwater inflows generally increase SC in streams. Inflows from irrigation return flows can also elevate SC in streams, due to shallow sub–surface flow (a typical component of return flow) interaction with soils. Given the measurement uncertainties inherent in seepage runs, trends in SC can help determine whether a calculated gain to the river is real or due to measurement error.

**Stream Temperature**

Forward Looking InFared (FLIR) water temperatures from ODEQ and stream–temperature data collected by USBR (McAffee, 2012) were also used to interpret the results of the seepage run. Summer stream temperatures generally decrease downstream of areas where groundwater enters a stream, and generally increase in reaches that have no groundwater inflow or channel losses. However, diversions, channel shading, and

hyporheic flow can also affect stream temperatures. In addition, thermal stratification can make FLIR data unusable for interpreting GW inflow.

# Results

## *Seepage Run*

A series of small storm systems passed through the basin beginning in the first week of October, 2011. The effects of these storms on streamflow entering the study area were captured by the uppermost OWRD stream gage (#13320000, see fig. 8). One small rainfall event occurred on the weekend prior to the seepage run and caused a minor increase in streamflow with a corresponding peak runoff early in the afternoon of October 16$^{th}$ (fig. 8). At the time of the seepage–run measurements (October 19$^{th}$ and 20$^{th}$), streamflow at gage #13320000 had stabilized, but it was then uncertain whether flow would remain constant or whether the storm surge had exited the lower reaches of Catherine Creek. Flow conditions during the seepage run could not be evaluated until the end of the run when additional flow data was available to determine if streamflow had stabilized during the discharge measurements. For these reasons and because the onset of fall storms in the basin might preclude better flow conditions later in the fall, the seepage run was performed even though steady–state (constant) streamflow was not guaranteed.

By examining the stream stage at OWRD gages prior to and after the seepage run, it was determined that stream levels were still declining in the lower reaches (from Woodruff Lane downstream) from the runoff event, but were constant upstream of Pyles Creek (fig. 9). Seepage run measurements confirm this fact, as measurements made on both days of the seepage run at the “above–Pyles–Creek” stream gage (#13320310) were nearly identical. In contrast, discharge measurements made just above the State Ditch were significantly higher on the first day of the seepage run compared to measurements made on the second day. Some of this difference can be attributed to measurement error, but part of the difference was due to residual flow declines related to the runoff event (see the recession limb of the hydrograph in figure 8). To properly calculate the steady–state water

balance of a stream reach during a seepage run, compensations must be made for variable streamflow.

The two lower stream gages on Catherine Creek continued to show a decline in water–surface water elevation (WSE) during the duration of the seepage run (fig. 9). Unfortunately, the change in flow cannot be determined by these stage–only gages. The gages were installed at the piezometer sites to measure head differences between the stream and the aquifer. Low channel gradients and slack water behind downstream dams make these sites unsuitable for developing the stage/discharge relationships needed to calculate streamflow.

However, the effect of the unsteady flows on the seepage run measurements can still be estimated in these lower reaches by comparing upstream and downstream hydrographs to estimate the travel time between sites (fig. 9). This comparison shows that the peak of the October 16$^{th}$ runoff event observed at the uppermost gage site (#13320000, upstream of Union) took approximately 7, 10, and 32 hours to travel to the upper, middle, and lower piezometer stream gage sites, respectively. By shifting the observed stream–stage hydrographs by the estimated travel time (fig. 9) and comparing the general hydrograph shapes at each measurement site, the validity of the travel time estimate can be verified (fig. 10).

Using this information, non–steady–state streamflow measurements can be corrected to steady–state values. For example, the first set of discharge measurements at the “above–the mouth–of–Catherine–Creek” site (RM ~ 0.9), were made at approximately 1:00 pm on 10/19/2011 and averaged 57.6 cfs (USBR, 2011). The travel time between that measurement site and the uppermost gage (#13320000) is estimated to be 46 hours, (based on an extrapolation of the 32 hour travel time from gage #13320000 to the lower gage site at RM 13.5). In other words, the “packet” of water measured near the mouth of the creek passed by the upper stream gage 46 hours earlier (fig. 11). At that time (10/17/2011 3:00 pm), flow at the uppermost stream gage was 2.5 cfs higher than the steady–state flow of about 37 cfs (fig. 11). This means that approximately 2.5 cfs of the

measured flow near the mouth (57.6 cfs) was due to higher streamflow entering the study area prior to the development of steady–state flow conditions. The measured flow near the mouth (57.6 cfs) can be corrected to a steady–state flow by subtracting this 2.5 cfs of extra flow (the difference between pre–steady–state and the steady–state flow observed at stream gage #13320000 shown in figure 11). Therefore, the steady state flow at RM 0.9 is estimated to be 55.1 cfs (57.6 cfs – 2.5 cfs).

Using travel–time estimates and the process just described, streamflow measurements at each site were corrected to steady–state flows (table 2.0). As previously mentioned, discharge measurements on successive days at the stream gage above Pyles Creek confirm that streamflow was essentially constant at this site and, therefore, for all measurement locations above this site during the seepage run (table 2.0). The stream stage variation observed at the “Woodruff Lane” gage (fig. 9) during the seepage run corresponded to only minimal variations in streamflow (table 2.0). In fact, substantive steady–state corrections to the seepage run measurements were only necessary from Godley Road downstream to the mouth of Catherine Creek.

The raw data collected from the seepage run are shown in figure 12. Significant tributary inflows occurred just downstream of Union, at Pyles and Little Creeks; just downstream of Cove, at Mill Creek; and further downstream of Cove, at Warm Creek. Increases in streamflow just below the confluence with these creeks are evident in figure 12. All other tributaries, sloughs, or ditch returns were either dry or had flow less than 0.2 cfs of flow.

The smaller tributary inflows were from intermittent creeks draining Gassett Bluff, the eastern ridgeline of the basin, north of Cove. Although flow in some of these creeks was on the order of 0.5 cfs where they passed under Lower Cove road (for example Eckesley Creek), discharge at the mouths of these tributaries were significantly less and sometimes zero (fig. 12). This indicates significant flow loss as the creeks cross their alluvial fan deposits, consistent with observations reported by Hampton and Brown (1964). This constitutes a local source of recharge for the sedimentary aquifer in this area. The only other inflows to Catherine Creek were small flows (~ 0.25 cfs) from a drain and a slough

just downstream of Union. All other diversions were shut off, except within Union where four ditches were still flowing and therefore measured during the seepage run: Redmill, 0.4 cfs; Townly–Dobbin, 1.2 cfs; Prescott, 0.8 cfs; and Swackhamer, 3.9 cfs.

Seepage run measurements are typically interpreted by calculating a water balance between reaches on the main–stem of the stream being evaluated. The water balance for each reach is simply the measured flow at the bottom of the reach, minus the measured flow at the top of the reach, minus all inflows and plus all outflows within the reach (equation 1).

[eq'n 1]: water balance = reach outflow – reach inflow – $\sum$ inflows + $\sum$ diversions

A positive water balance indicates the stream gains water from groundwater (inflows); a negative balance indicates the stream loses water to groundwater (outflows). The water balance for each reach must be interpreted in the context of measurement uncertainty. If the water balance is less than the measurement uncertainty then the gain or loss is attributed to measurement error, unless there is corroborating evidence to support real gains or losses.

Water balance calculations for Catherine Creek reveal that all of the gains or losses are less than the measurement uncertainty, except the balance for the reach between the city of Union water intake and state highway 203 just above Union (fig. 13). The initial balance in the lower reach (below Elmer Reservoir #4) indicated gains that exceeded measurement uncertainty. However, after subtracting the effects of unsteady flows, these gains were also determined to be less than the measurement uncertainty (fig. 13).

Another way to evaluate seepage run results is to examine spatial trends in streamflow that cannot be attributed to tributary inflows or diversions. This analysis is performed by adjusting each main–stem measurement for upstream tributary inflows or diversions to derive a main–stem natural streamflow (MNSF), an estimate of the streamflow at each location if there were no tributary inflows or diversions. Any trends or changes observed in the MNSF are generally attributed to groundwater inflow or outflow. A regression of the

MNSF estimates reveals if there is a statistically significant trend in streamflow attributable to groundwater inflow or outflow. Two regressions were performed on the Catherine Creek MNSFs. The first regression used the average of all measurements taken at a specific location to represent streamflow at that location, then adjusted that averaged streamflow rate to a MNSF value (fig. 14) before the regression was performed. The results show a statistically significant ($P < 0.05$), increasing trend in MNSF throughout the measured reaches (blue–dashed line in figure 14). Thus, there is an apparent increase in streamflow that cannot be attributed to surface inflows. However, if the data below Elmer Reservoir #4 are removed from the regression, there is no statistically significant trend in flow ($P = 0.53$, red–dashed line in figure 14) above the lower piezometer site (RM 13.6). This suggests that gains from, or losses to, the groundwater system are negligible above the lower piezometer site. Furthermore, the statistically significant trend in MNSF from the regression all of the measurement sites (blue–dashed line in figure 14) appear to be solely due to measurements downstream of the lower piezometer site, an indication that groundwater inflows are occurring in these lower reaches.

The second regression was identical to the first, except that each individual measurement was corrected to a MNSF before the regression was applied. The results (fig. 15) are similar to those of the first regression. An initial regression on all of the measurements showed a significant increasing trend ($P = 0.01$) in streamflow in the study area. A subsequent regression on only the measurements above Elmer Reservoir #4 did not show a significant trend ($P = 0.55$), again suggesting the groundwater exchanges to the creek above the lower piezometer site are negligible.

## *Specific Conductance*

The raw specific conductance (SC) measurements are shown in figure 12. Note that diversions have no impact on the SC of water in Catherine Creek. The specific conductance of water in the creek is identical above and below a diversion. However, tributary inflows (either SW or GW) can influence the specific conductance of a stream reach based on the following mass balance equation.

$$\text{[eq'n 2]: } (Q \times SC)_{\text{downstream site}} = \sum (Q \times SC)_{\text{inflows}} + (Q \times SC)_{\text{upstream site}}$$

The equation indicates that any change in the main–stem (or receiving stream) SC is proportional to the flow and SC of the tributary (or groundwater) inflow. Significant increases in Catherine Creek SC occur below Pyles Creek and Mill Creek, as a result of higher SC in those tributaries (fig. 12). The significant tributaries on the east side of the basin (Little, Mill and Warm Creeks) all had somewhat similar specific conductivity (130–160 µS, see figure 12). Eckesley Creek, another east–side creek downstream of Warm Creek, also had similar conductivity but much smaller flow (0.1 cfs). Further downstream to the north, smaller un–named tributaries had larger SC values (210–460 µS). Pyles Creek, the other significant tributary to Catherine Creek and located near Union, also had a much higher SC (290 µS) than other major tributaries. The higher values in Pyles Creek are probably caused by significant return flows from flood irrigated lands and some flow from a number of mineral springs along the east side of Mount Craig.

To determine whether changes in the specific conductance of Catherine Creek can be attributed to groundwater inflow, the effects of surface–water inflows on the main–stem SC were removed by calculating a main–stem natural specific conductance (MSNSC), using equation 3, in a manner similar to the calculation of MSNF.

$$\text{[eq'n 3]: } (Q_{MNSF^*} \times SC_{MSNSC}) = (Q \times SC)_{\text{measured}} - \sum (Q \times SC)_{\text{inflows}}$$

Several regressions were then performed on the resulting MSNSCs. The results show a highly significant ($P < 0.001$), increasing trend in Catherine Creek SC throughout the entire study area that cannot be attributed to surface–water inflows (fig. 16). This agrees with the regression analysis of all of the seepage measurements. Together, these results suggest that the overall increase in Catherine Creek streamflow in the study area can be attributed to groundwater inflow.

Recall that the seepage–run trend analysis (fig. 14) indicates that statistically significant GW inflows only occur below Elmer Reservoir #4 [RM 13.6]. A regression analysis on MSNSC by sub–area reveals a significant trend ($P < 0.01$) upstream of the first piezometer location (gage #13320310, above Pyles Creek). From the upper piezometer location to the top of the study area, Catherine Creek SC increases in nearly a linear fashion. The seepage run results did not detect groundwater inflows in this area and no surface inflows occurred either, so the cause of the increase is unknown.

Downstream of the city of Union (RM 37.8 to RM 26.6) to Godley Road (just upstream of the town of Cove), the sampled SC values are virtually identical. This result agrees with the seepage run results—no net groundwater gains. However, for reasons discussed earlier, the SC results neither confirm nor deny the existence of streamflow losses. The seepage run results show no channel losses in this area (fig. 15).

Near Cove, there is a slight jump in specific conductance that is probably due to a small amount of subsurface inflows to Catherine Creek, occurring near the Mill Creek confluence near Phys point. The SC of water in Phys Slough, which joins Mill Creek just above its mouth, is 260µS—similar to Pyles Creek. Water in Phys Slough consists primarily of subsurface irrigation returns collected in drains and small springs, which is also similar to Pyles Creek. If Phys Slough SC is representative of shallow groundwater SC in the area, then only 0.25 cfs of inflow (0.5% of Catherine Creek streamflow and well within the measurement error) would be required to increase the SC of Catherine Creek by the observed amount.

Further downstream of Cove, between Booth Lane and the mouth, there is a statistically significant increase ($P < 0.01$) in Catherine Creek SC that again is not attributable to surface inflows. This result is in agreement with the seepage run data that groundwater inflows are occurring and elevating the SC in Catherine Creek. A back calculation of the resulting SC of the groundwater inflow using equation two gives a value of 256µS for GW in this area; almost identical to the observed SC of water in Phys Slough and Pyles Creek.

The SC increase in Catherine Creek below Booth Lane could be a result of interaction of water in the stream with the channel substrate. However, Catherine Creek SC is relatively constant between RM 37.8 and RM 26.6 (near the middle piezometer site), which has a similar substrate. This fact indicates that it is unlikely that the SC increase in the lower study area is due to stream interactions with the channel substrate.

### *Stream Temperature Data*

FLIR stream temperature data for Catherine Creek was collected for the Oregon Department of Environmental Quality (ODEQ) by Watershed Sciences in the summer of 1999 (fig. 17). Most of the stream temperature declines that might possibly be attributed to groundwater inflows appear to be caused by releases from in–channel reservoirs,(Elmer reservoir #4 at RM 13.5 and Davis dam at RM 34), and thermal stratification of slack water in reservoirs. FLIR data estimates the surface temperature of streams so wherever stratification occurs, FLIR temperatures do not accurately reflect average stream temperature (Watershed Sciences, 2000).

Initial analysis of the FLIR data by Watershed Sciences (2000) indicates that Catherine Creek was probably thermally stratified from the mouth (RM 0) to Davis dam (RM 34, upstream of Woodruff Lane), rendering the data unusable below Davis dam. Upstream of Davis dam, backwater conditions can also exist up to Miller Lane (RM 36.1). However, no mention of thermal stratification is mentioned upstream of Davis dam in the FLIR report.

Above Davis dam, FLIR data shows an apparent decrease in stream temperature, which may indicate possible groundwater inflow, in the reach downstream of the uppermost OWRD stream gage #13320000 (fig. 17) above Union. Within the city of Union, stream temperatures fluctuate within a narrow range, but generally remain relatively constant. Overall, the FLIR data was of limited value in interpreting the seepage run data.

Additional stream–temperature data was collected by USBR in the summer of 2010 and early spring of 2011 (USBR, 2012). The data generally shows lower stream temperatures near the mouths of oxbow channels (oxbow reservoirs) and sloughs. The USBR author

hypothesized that the coarse–grained alluvial deposits of these paleo–drainages provide preferential flow paths for groundwater inflow. Downstream of Cove (Phys Point), USBR stream–temperature data agrees with the seepage run data. At Phys point, lower stream temperatures are consistent with the seepage run results which show sub–surface inflows at this location. Upstream of Phys Point, the stream temperature is lower near the confluence of Pyles and Ladd Creek, probably because of the cooler temperature of these surface inflows. Near the confluence of the Little and Catherine Creek canyons, upstream of Union, stream temperatures also decrease in agreement with the FLIR data. The USBR did not measure Catherine Creek temperatures through the town of Union.

### *Piezometer Data*

Hydraulic heads (groundwater elevations) from the three piezometer sites were also used to evaluate the seepage run results. Vertical head gradient and streambed conductivity are the main parameters that control channel losses or gains. A downward head gradient (creek water elevation higher than the groundwater elevation) is required for stream losses to occur through the channel bed. However, the rate of loss is proportional to the hydraulic conductivity of the streambed. Streambed conductivity is related to the grain size and sorting of streambed materials. All else being equal, a sand and gravel streambed will have higher streambed conductivity than a streambed composed of silt and clay.

Piezometer data collected during the seepage run indicate a downward component of flow from the stream to the aquifer at the upper and middle sites, and an upward component of flow from the aquifer to the stream at the lower site (figs. 18–29). The results at the lower site are consistent with streamflow gains measured during the seepage run. However, no streamflow losses (greater than the measurement error) were measured at reaches adjacent to the middle and upper piezometer sites despite the presence of downward gradients between the stream and the aquifer. In addition, no statistically significant trends in streamflow attributable to GW exchanges were found above the lower piezometer site, which includes the stream reaches near middle and upper piezometer sites. At the middle site, the streambed consists of silt and clay which are likely to impede the rate of vertical flow between the stream and the aquifer. At this site, low rates of vertical flow would be

expected and could easily be less than the errors of the seepage measurements. At the upper site, the streambed consists of gravel and sand with very little silt or clay. These materials should be permeable enough to allow reasonably high rates of vertical flow between the stream and the underlying aquifer. However, hydraulic head differences between the stream and the aquifer at this site were relatively small during the seepage run and may not have been sufficient to cause losses greater than the measurement error of the seepage measurements. Alternatively, as noted by Ferns and others (2002), beds of silt and clay appear to be common in the fan delta deposits that underlie streambed sediments at the upper piezometer site. Low permeability beds at shallow depths below the stream channel (below the bottom of the piezometers) could result in low overall rates of vertical flow from the river to the aquifer. A deeper well at each site or an inventory of local wells would be needed to assess this possibility.

The head difference between the left and right bank nested piezometer pairs at the upper, middle, and lower piezometer sites also suggests a horizontal component of groundwater flow at an unknown angle to the stream channel. Alternatively, the difference in heads might simply be due to the fact that the piezometers are not exactly at the same distance from the stream at each site due to topographic and access constraints affecting the piezometer locations. At the upper piezometer site, the hydraulic head indicated possible horizontal flow component of groundwater from right to left bank. Head data at the middle piezometer site indicate a possible horizontal component of flow from the left bank to the right bank during the seepage run. As previously indicated, at both locations the aquifer hydraulic heads were below that of the creek, thus the transverse horizontal groundwater flow should not be contributing flow to the creek. In contrast, the groundwater and stream elevations at the lower piezometer site indicate a possible horizontal component of groundwater flow that could at times be interacting with the stream (fig. 20). This possibility is described further in the examination of runoff events effects on groundwater elevation.

The small runoff events prior to and after the seepage run provide additional information about the hydraulic connection between the creek and groundwater (figs 18—21).

Hydraulic heads in piezometers at the upper site show a direct response to changes in stream stage (fig. 18). In contrast, heads in piezometers at the middle site (fig. 19) show a subdued response to changes in stream stage. These observations suggest a relatively efficient connection between the streambed and the aquifer at the upper site and a less efficient connection at the middle site, consistent with the nature of the streambed sediments and the geologic setting.

The runoff response at the lower piezometer site (above Elmer Reservoir #4) is shown in figure 20. The piezometers at the lower site are located about 375 feet upstream from a dam where boards are installed seasonally to create an in–channel reservoir from which irrigation water is more easily diverted. Peak reservoir level is about eight feet above normal stream stage. Prior to the early October storm event the check boards on this dam were in place and the Catherine Creek surface water elevation is coincident with the right bank groundwater elevations from both the deep and shallow piezometers, and about 0.25 feet above the left bank piezometers. This suggests the creek was contributing water to the aquifer (and oxbow reservoirs) along the left bank of the creek. During the early October storm event, when the reservoir was close to peak level, hydraulic heads in all of the lower–site piezometers showed a relatively direct response to changes in stream stage (fig. 20). These rapid responses suggest a relatively efficient connection between the stream and the upper part of the aquifer near peak reservoir level even though the stream banks and the adjacent aquifer are predominantly composed of silts and clays. Channel permeability may be enhanced by paleo–channels, or burrowing animals or plant macro–pores. Also, during the October storm event, peak stream level was about 0.1 feet higher than hydraulic heads in the right–bank piezometers and about 0.2 feet higher than heads in the left–bank piezometers, consistent with downward vertical flow from the stream to the aquifer.

After the check boards were removed on October 7th, stream stage dropped about four feet over about one week followed by six weeks of relatively stable levels and then by two weeks of less rapid stage decline (fig. 21). Hydraulic heads in the piezometers also declined rapidly in the first week after board removal followed by less rapid but continuous

declines over the next eight weeks. In addition, after the boards were removed, heads in the piezometers were always higher than the adjacent stream and heads in the left bank piezometers were always higher than heads in the right–bank piezometers. These observations indicate that groundwater levels adjacent to the reservoir increase after the boards are installed in the summer. The long–sustained head declines in the piezometers following board removal suggest that water is stored in the adjacent aquifer during the summer when the reservoir is filled and that groundwater is released to the stream at slow rates for at least several months after the boards are removed (fig. 21). The slow head–decline rates are also consistent with relatively low aquifer permeability in the aquifer below the peak level of the reservoir.

Water levels in each pair of adjacent piezometers never varied by more than a few one–hundredths of a foot before and after the removal of the dam boards. This indicates that the movement of water between the stream and the aquifer was predominantly lateral rather than vertical and that horizontal permeability is greater than vertical permeability in the aquifer along this reach. Enhanced lateral permeability may be due to the deposition of somewhat coarser sediments in the modern and historic meander channels that occur in a one–mile wide belt parallel to this reach of the stream. This is consistent with stream–temperature observations collected by the USBR (2012) which show cooler stream temperatures near the mouths of oxbow reservoirs and sloughs that are probably caused by groundwater inflow through coarse–grained paleo–channel sediments.

# Conclusion

General watershed characteristics suggest that Catherine Creek is likely to gain water from the groundwater system in the steep highlands above Union but groundwater influx is expected to be relatively small since the highland bedrock has relatively low permeability. Where the creek enters the flat Grande Ronde Valley, the stream is expected to lose water through a permeable sand and gravel streambed to an underlying wedge of permeable sand and gravel that was deposited in an alluvial–fan, fluvial fan–delta complex in the area around Union. The amount of losses could be smaller than

expected due to the presence silt and clay beds in the fan delta. Between Union and Cover, the groundwater exchanges to the creek are expected to be minimal due to the low permeable sediments and channel bed in the area. North of Cove, groundwater inflows to Catherine Creek are expected due to local aquifer recharge from tributary streams draining Gassett Bluff that lose water as they cross their alluvial fans. However, the gains are expected to be relatively small because the streambed in these areas consists of low–permeability silt and clay that should impede the vertical flow of water.

Seepage run data collected in the Fall of 2011 on Catherine Creek demonstrate that groundwater exchanges between the creek and the alluvial aquifer were minor, essentially falling within the uncertainty of the discharge measurements except downstream of Elmer Reservoir #4 where groundwater increased streamflow. Specific conductance data collected during the seepage run generally agrees with these results, except around and upstream of the town of Union. Catherine Creek specific conductance increased in this area for unknown reasons; no groundwater inflows were measured during the seepage run. Hyporheic flow exchange, unknown anthropogenic sources, or spatially limited surface to groundwater back to surface water exchanges could be the source of the specific conductance increase without an accompanying increase in streamflow.

Stream temperature generally data agrees with the seepage run data, showing decreasing water temperatures in the lower reaches where the seepage run indicated groundwater inflows were occurring. However, the temperature data also suggests groundwater inflows may be occurring near the confluence of the Little and Catherine Creek canyons upstream of Union, although no increases were measured there during the seepage run.

Groundwater elevation data from the piezometers collected during the seepage run indicate a downward head gradient (downward flow) between the stream and the aquifer at the upper and middle sites, and an upward head gradient at the lower site. The upward head gradient at the lower site is consistent with groundwater inflows inferred from seepage run measurements. However, near the middle and upper piezometer sites,

where the head gradient is downward, no stream losses were measured during the seepage run. In addition, no trend in streamflow attributable to groundwater exchanges was found through these reaches either. At the middle site, the streambed consists of silt and clay; low permeability sediments which are likely to impede the rate of vertical flow between the stream and the aquifer. At the upper site, near Union, the streambed and sedimentary deposits consists of gravels and sands, and are presumed to be relatively permeable. Well logs in the surrounding area indicate that silt and clay beds may be common in the Catherine Creek fan–delta deposits near Union. If these beds are common at shallow depths below the stream bed, they could limit vertical flow to rates well below the measurement errors of the seepage measurement.

Overall, the data sets and seepage run are generally consistent and demonstrate limited groundwater exchange in the Grande Ronde Valley. Near Union, however, the geologic setting, anomalously high specific conductance values in the creek, local small decreases in stream temperature, downward head gradients, and the likely presence of relatively permeable vertical pathways, suggest that exchanges between groundwater and surface water may seasonally occur at rates greater than indicated by the seepage measurements.

# Recommendations

To provide additional insights into the potential for the exchange of water between Catherine Creek and the underlying aquifer, it is recommended that stream stage and aquifer head measurements be continued for at least an entire water year at the current piezometer sites. Seasonal changes in the head gradient may affect groundwater exchanges, especially near Union.

Streambed conductivity tests from additional temporary, in–stream, piezometers would provide another method to estimate groundwater exchanges with Catherine Creek near Union. This approach is an effective alternative to estimate groundwater exchanges with the streams that are less than the discharge measurement error of the seepage runs.

Additional streamflow measurements made on a sub–set of the seepage run location near Union are also recommended. These measurements could reduce the uncertainty with the initial seepage run and provide insight as to any seasonal variations in groundwater exchanges in the area. Ideally, the measurements would be made during the summer low–flow season in the town of Union.

Finally, reference specific conductance measurements from nearby alluvial and basalt wells, from springs, seeps and tributaries would help with the conceptual understanding analysis of the groundwater system and exchanges in the study area. This data collection effort is critical in determining the unknown cause of the specific conductance trend near Union.

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# FIGURES and TABLES

**Table 1.0**: Check discharge measurements at OWRD gage #13320000

| Check Measurement Comparison using OWRD gage near Union (# 13320000) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Team | date: time | Q (cfs) | observed GH (ft) | GH from record (ft) | Q from gage (cfs) | Diff mmt-gage (cfs) | % difference with gage | Notes |
| OWRD (JL) | 10/18/2011 16:26 | 36.2 | 1.02 | 1.02 | 37.88 | -1.68 | -4.4% | GH from OG. Getting very dark by end of mmt. |
| FWT (SP) | 10/18/2011 16:40 | 35.3 | 1.02 | 1.02 | 37.94 | -2.64 | -7.0% | GH from OG. Getting very dark by end of mmt. |
| OWRD (JS) | 10/18/2011 11:29 | 38.3 | 1.02 | 1.02 | 38.06 | 0.24 | 0.6% | GH taken from recorder |
| OWRD (CN) | 10/18/2011 11:29 | 39.5 | 1.02 | 1.02 | 38.06 | 1.44 | 3.8% | GH taken from recorder |
| USBR (CC) | 10/18/2011 17:40 | 41.24 | 1.03 | 1.02 | 37.76 | 3.48 | 9.2% | GH from OG |
| GRMW (CM) | 10/18/2011 13:17 | 35.57 | 1.02 | 1.02 | 37.94 | -2.37 | -6.2% | GH from OG |
| OWRD (JH) | 10/18/2011 16:26 | 34 | 1.02 | 1.02 | 37.88 | -3.88 | -10.2% | GH from OG. Getting very dark by end of mmt. |
| FWT (JF) | 10/19/2011 11:35 | 35.8 | 1.01 | 1.01 | 36.88 | -1.08 | -2.9% | mmt during seepage run |
| | | | | | mean >> | -0.8 | -2.0% | |
| | | | | | SD (cfs) >> | 2.4 | | |
| | | | | | est mmt error % >> | 6% | | |

**Table 2.0**: Steady–state corrections for seepage run measurements on main–stem Catherine Creek.

| Location | | Time of discharge measurement during seepage run | | | | travel time mmt locale to #13320000 | lookup time for measured flow "packet" as it passed upper most stream gage (nr Union, #1332000) | | | observed flow as it passed gage and subsequently measured at given location | | | mmt adjustment \|observed flow - steady state flows\| @ gage #13320000 | | | original measurement | | | | modified mmt to account for unsteady streamflow | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RM (from State Ditch) | Description | mmt #1 | mmt #2 | mmt #3 | mmt #4 | Lookup Shift (hr) | mmt #1 | mmt #2 | mmt #3 | mmt #1 | mmt #2 | mmt #3 | mmt #1 | mmt #2 | mmt #3 | mmt #1 | mmt #2 | mmt #3 | mmt #4 | mmt #1 | mmt #2 | mmt #3 | mmt #4 |
| 0.9 | CC abv State Ditch | 10/19/11 13:00 | 10/20/11 9:40 | 10/20/11 10:22 | | 46 | 10/17/11 15:09 | 10/18/11 11:49 | 10/18/11 12:31 | 39.5 | 38.0 | 38.0 | 2.7 | 1.2 | 1.1 | 57.6 | 52.7 | 53.5 | | 54.9 | 51.5 | 52.3 | |
| 6.8 | CC @ Market Ln | 10/19/11 11:55 | | | | 39 | 10/17/11 20:33 | | | 39.0 | | | 2.2 | | | 54.3 | | | | 52.1 | | | |
| 13.5 | CC @ Elmer Res #4 | 10/19/11 10:30 | 10/20/11 12:35 | 10/20/11 11:50 | | 32 | 10/18/11 2:30 | 10/19/11 4:35 | 10/19/11 3:50 | 38.7 | 36.9 | 36.9 | 1.8 | 0.0 | 0.0 | 50.4 | 50.1 | 51.6 | | 48.6 | 50.1 | 51.6 | |
| 15.7 | CC @ Booth Lane | 10/19/11 9:00 | | | | 30 | 10/18/11 3:25 | | | 38.8 | | | 1.9 | | | 52.0 | | | | 50.0 | | | |
| 21.5 | CC @ St Hwy 237 | 10/20/11 8:40 | 10/19/11 9:25 | | | 23 | 10/19/11 9:27 | 10/18/11 10:12 | | 36.9 | 38.1 | | 0.0 | 1.3 | | 45.0 | 46.0 | | | 45.0 | 44.7 | | |
| 23.8 | CC @ Gecker Ln | 10/20/11 9:15 | 10/19/11 10:20 | 10/19/11 10:45 | | 21 | 10/19/11 12:34 | 10/18/11 13:39 | 10/18/11 14:04 | 36.7 | 37.9 | 37.9 | -0.1 | 1.0 | 1.0 | 42.7 | 48.4 | 49.1 | | 42.8 | 47.3 | 48.0 | |
| 26.6 | CC @ Godley Rd | 10/20/11 16:30 | 10/19/11 10:25 | 10/19/11 8:55 | | 18 | 10/19/11 22:53 | 10/18/11 16:48 | 10/18/11 15:18 | 37.0 | 37.8 | 37.8 | 0.2 | 1.0 | 1.0 | 36.0 | 36.9 | 39.9 | | 35.9 | 35.9 | 38.9 | |
| 29.3 | CC abv McAlister S | 10/19/11 12:10 | 10/19/11 13:20 | | | 15 | 10/18/11 21:31 | 10/18/11 22:41 | | 37.1 | 37.1 | | 0.3 | 0.2 | | 36.7 | 37.9 | | | 36.4 | 37.7 | 0.0 | |
| 31.7 | CC @ Wilkinson Rd | 10/19/11 14:54 | 10/19/11 15:50 | | | 12 | 10/19/11 2:54 | 10/19/11 3:50 | | 36.9 | 36.9 | | 0.0 | 0.0 | | 36.8 | 38.5 | | | 36.8 | 38.5 | | |
| 33.5 | CC blw Woodruff Ln | 10/19/11 9:20 | 10/19/11 8:45 | | | 10 | 10/18/11 23:18 | 10/18/11 22:43 | | 37.0 | 37.1 | | 0.2 | 0.2 | | 37.2 | 38.7 | | | 37.1 | 38.5 | | |
| 36.1 | CC @ Miller Ln | 10/20/11 11:15 | 10/19/11 13:20 | 10/19/11 13:56 | | 8 | 10/20/11 3:35 | 10/19/11 5:40 | 10/19/11 6:16 | 37.0 | 36.9 | 36.9 | 0.2 | 0.0 | 0.1 | 35.5 | 31.4 | 32.4 | | 35.3 | 31.4 | 32.3 | |
| 37.8 | CC abv Pyles Cr @ OWRD gage | 10/19/11 9:15 | 10/19/11 9:15 | 10/20/11 10:15 | 10/20/11 11:00 | 6 | 10/19/11 3:08 | 10/20/11 4:08 | 10/20/11 4:08 | 36.9 | 37.0 | 37.0 | 0.0 | 0.2 | 0.2 | 29.9 | 29.4 | 30.5 | 30.2 | 29.9 | 29.4 | 30.3 | 30.0 |
| 39 | OWRD gage @ 10th st | 10/19/11 10:30 | 10/19/11 10:30 | | | 5 | 10/19/11 5:28 | 10/19/11 5:28 | | 36.9 | 36.9 | | 0.0 | 0.0 | | 31.1 | 30.1 | | | 31.1 | 30.1 | | |
| 40.2 | blw City Return flow | 10/19/11 13:22 | 10/19/11 13:22 | | | 4 | 10/19/11 9:26 | 10/19/11 9:26 | | 36.9 | 36.9 | | 0.0 | 0.0 | | 38.8 | 38.6 | | | 38.8 | 38.6 | | |
| 41.9 | abv city diversion | 10/19/11 15:33 | 10/19/11 15:34 | 10/19/11 15:34 | | 2 | 10/19/11 13:09 | 10/19/11 13:10 | 10/19/11 13:10 | 36.7 | 36.7 | 36.7 | -0.1 | -0.1 | -0.1 | 35.9 | 33.7 | 37.1 | | 36.0 | 33.8 | 37.2 | |
| 46.1 | OWRD gage nr Union | 10/19/11 11:10 | 10/19/11 11:10 | | | 0 | 10/19/11 11:10 | 10/19/11 11:10 | | 36.9 | 36.9 | | 0.0 | 0.0 | | 36.5 | 35.8 | | | 36.5 | 35.8 | | |
| 47.9 | @ campground | 10/19/11 13:20 | 10/19/11 13:20 | | | -3 | 10/19/11 16:24 | 10/19/11 16:24 | | 36.8 | 36.8 | | -0.1 | -0.1 | | 36.1 | 34.9 | | | 36.2 | 35.0 | | |
| 49.1 | blw Milk Cr and ASR project | 10/20/11 12:40 | 10/20/11 13:20 | | | -4 | 10/20/11 16:49 | 10/20/11 17:29 | | 37.0 | 37.0 | | 0.2 | 0.2 | | 37.1 | 36.1 | | | 36.9 | 35.9 | | |

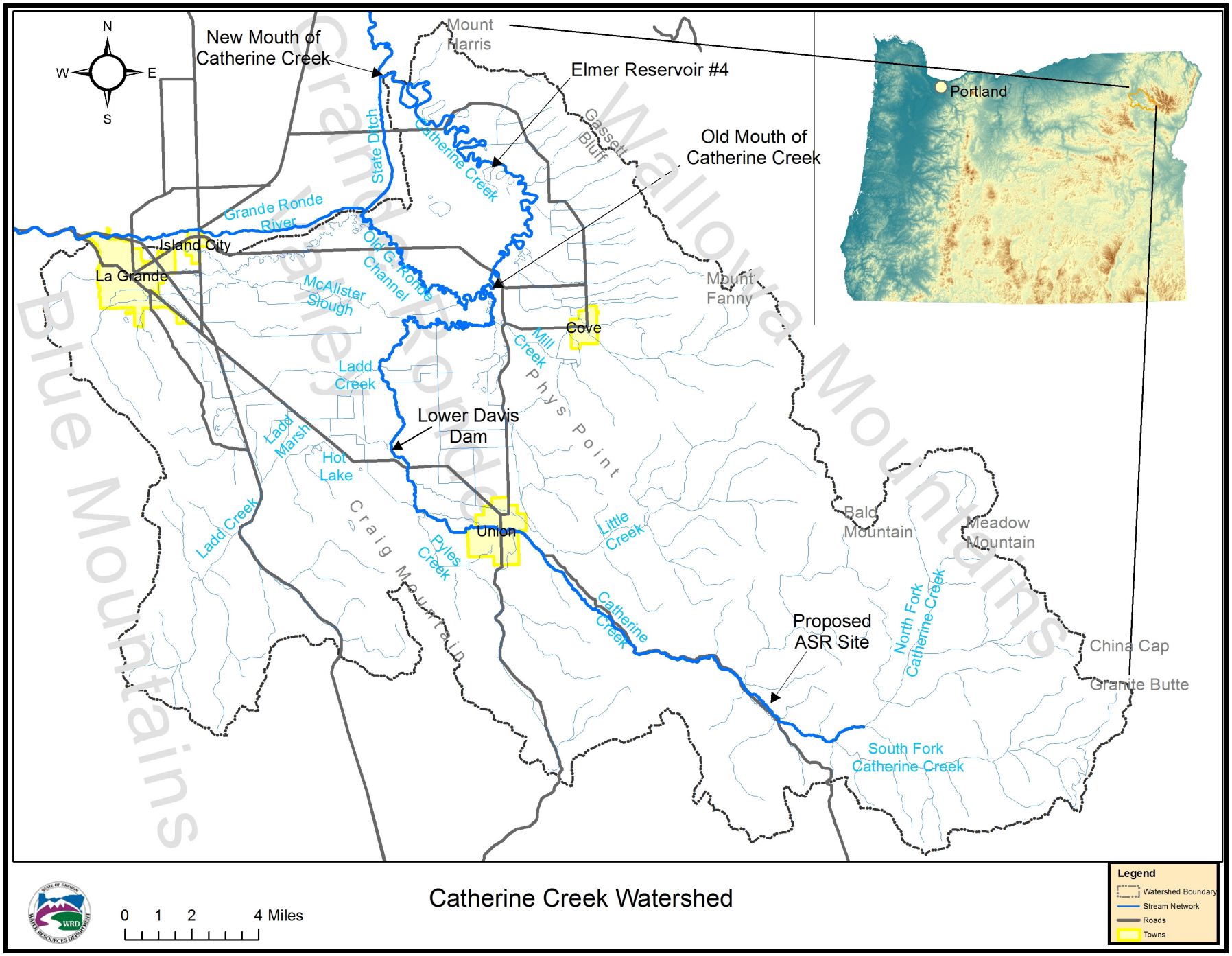


**Figure 1**: Catherine Creek watershed location and topographic features.

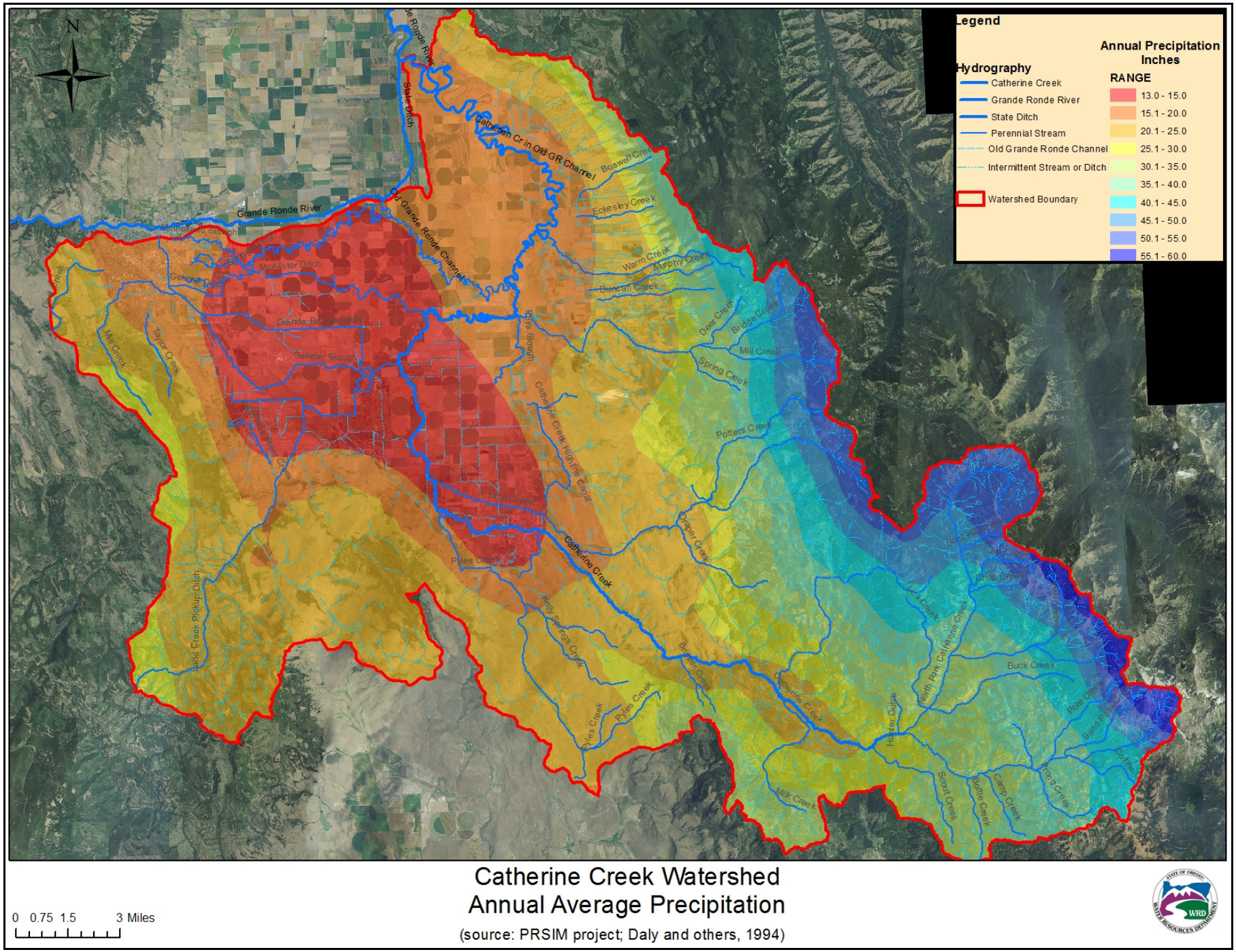


**Figure 2**: Mean Annual Precipitation (1971-2000) [PRISM data accessed 12/1/2011; Daly and others, 1994; Daly and others, 2002]

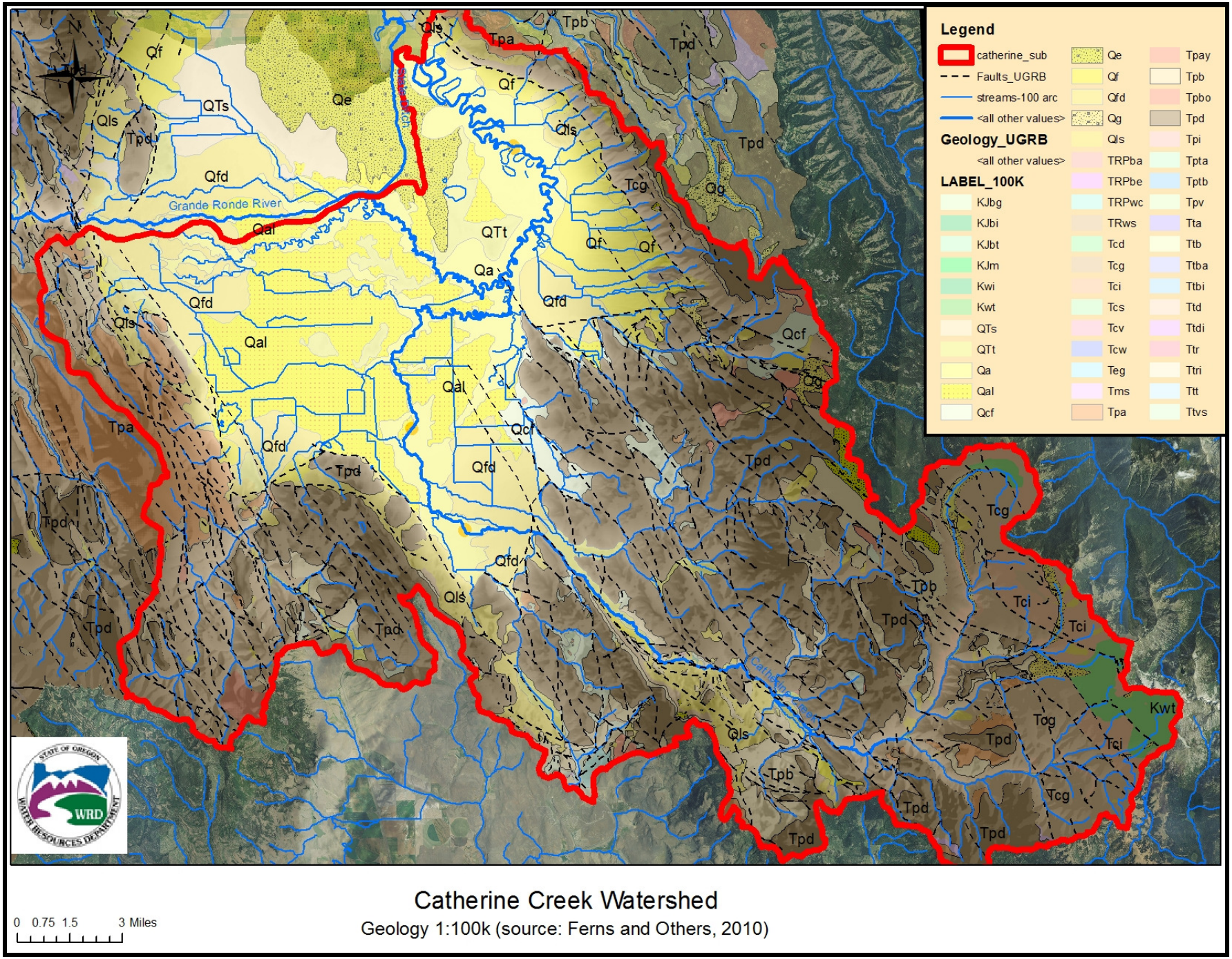


**Figure 3**: 1:100k Catherine Creek Watershed Geologic Map (from Ferns and Others, 2010)

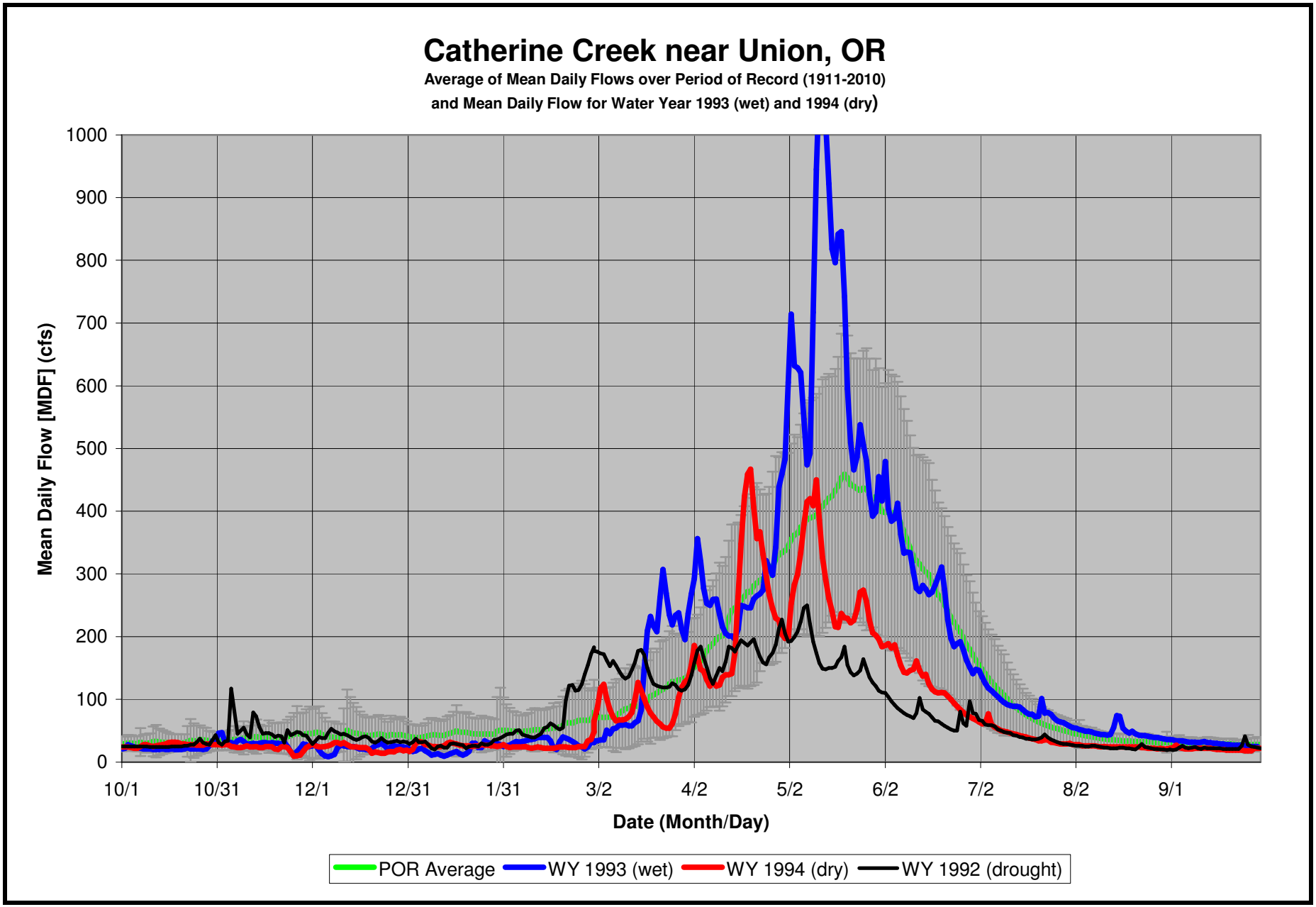


**Figure 4**: Mean Daily Flows recorded for Catherine Creek near Union, OR (above all diversions): blue = wet year; green = POR average; red = dry year; black = drought. Envelope shows +/- 1 standard deviation of POR mean. Snowmelt derived runoff is evident from March through July.

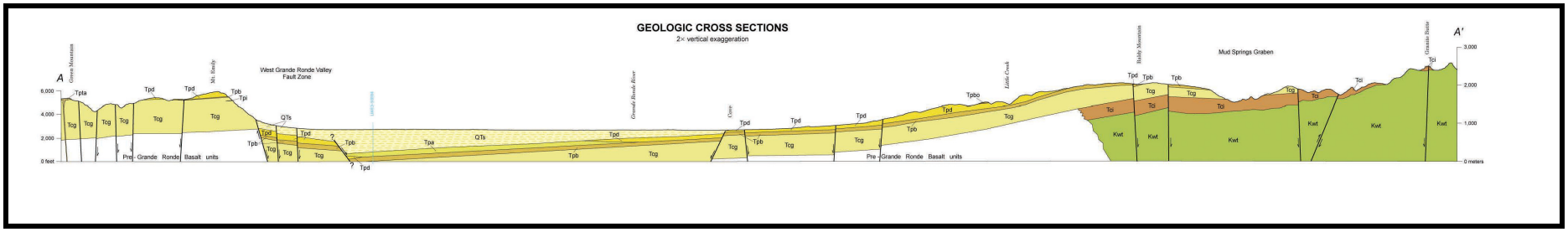


**Figure 5**: Geologic Cross section of upper Grande Ronde Basin from Ferns and Others (2010).

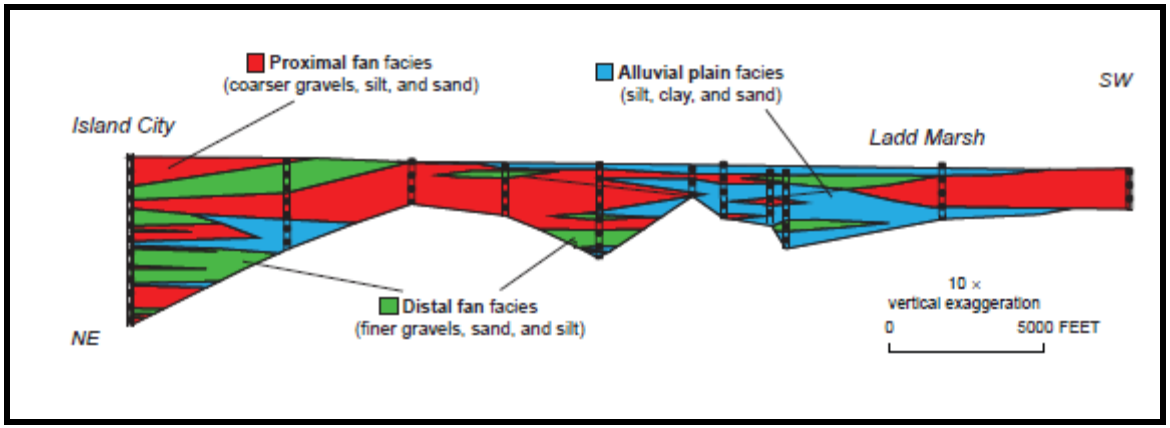


**Figure 6**: Example of subsurface variability in sediment deposits in the Grande Ronde Valley. From Ferns and Others (2010).

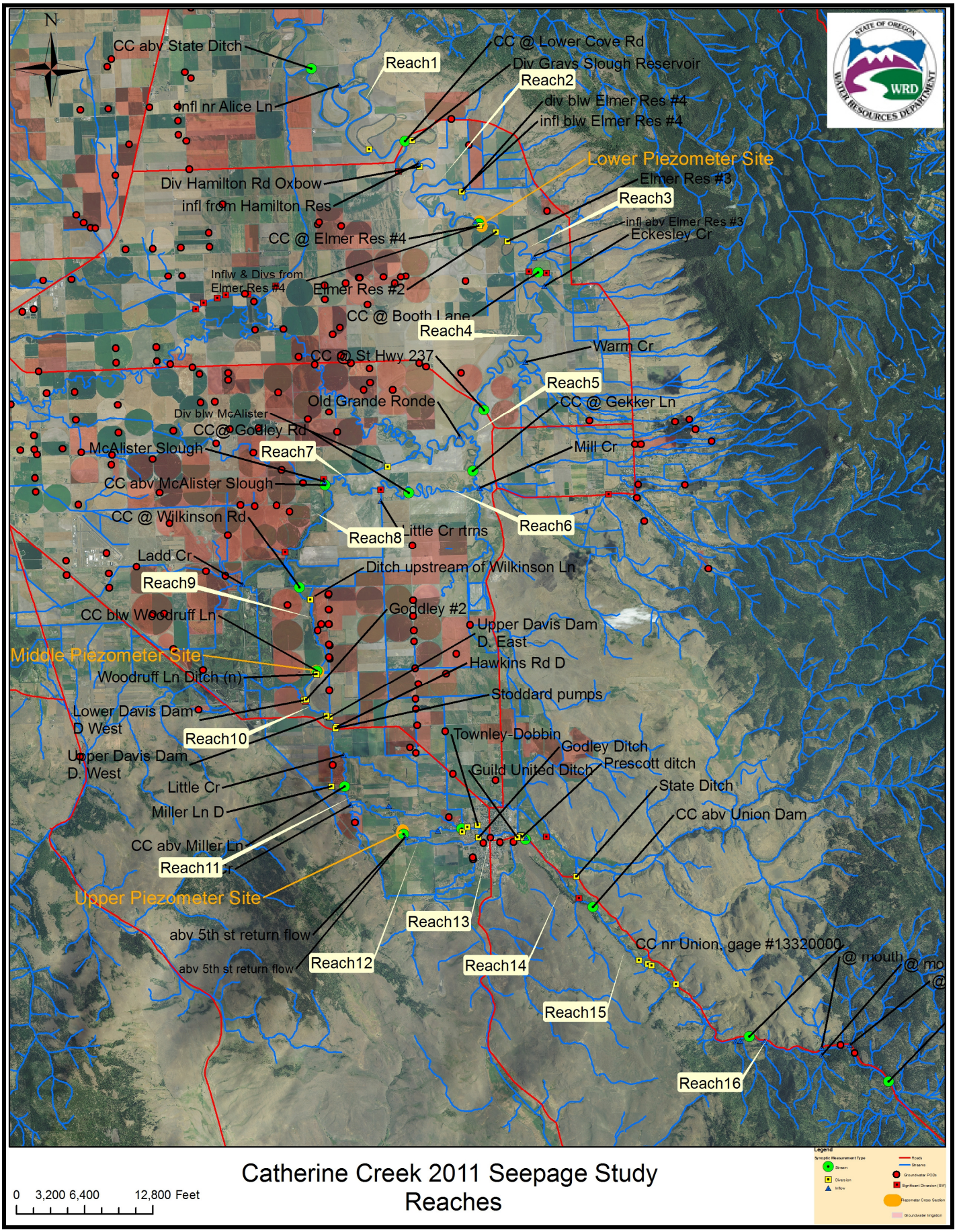


**Figure 7**: Catherine Creek measurement and piezometer cross section locations

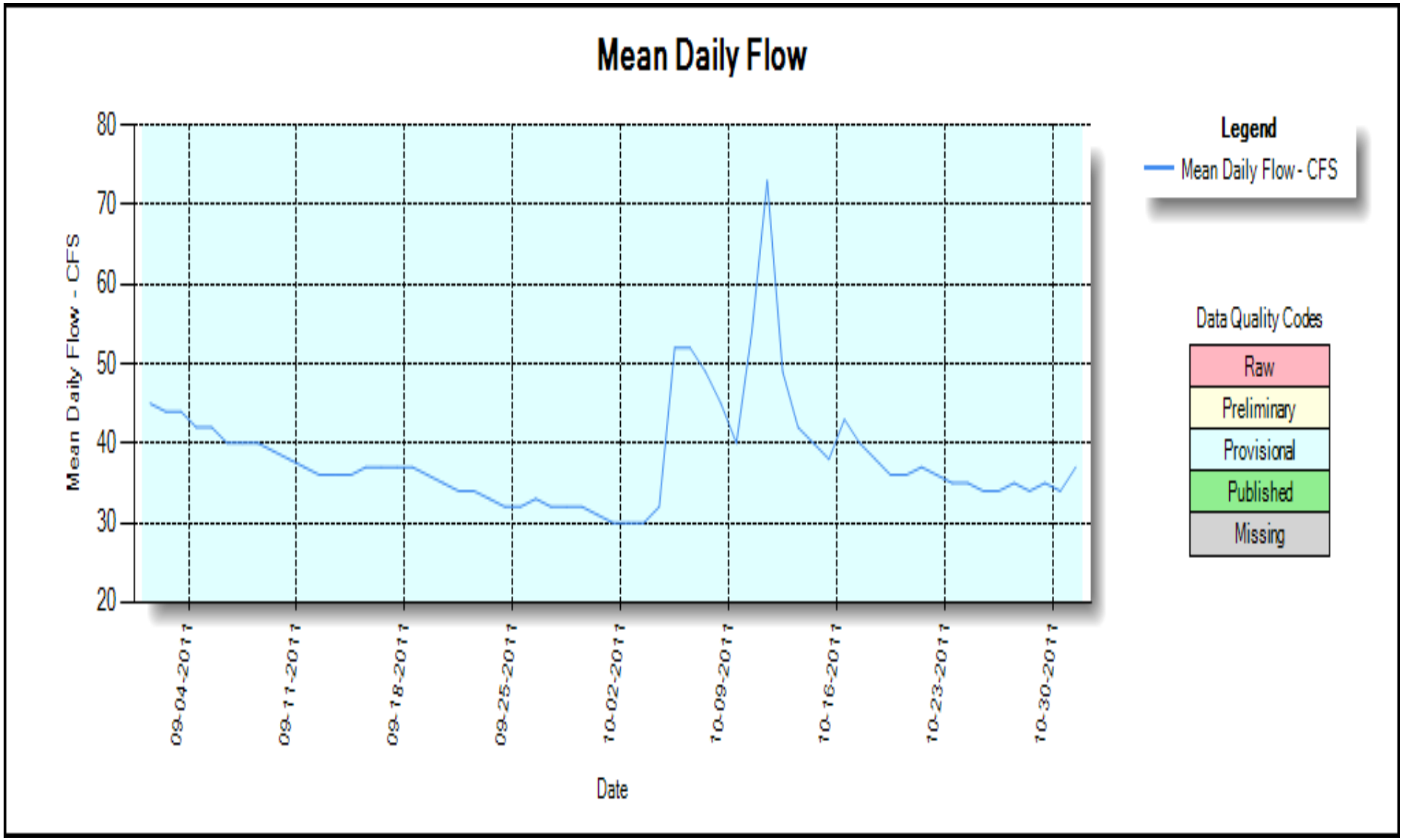


**Figure 8**: Variation in mean daily flow (MDF) in response to storm events for October as recorded by the Catherine Creek near Union (# 13320000) stream gage.

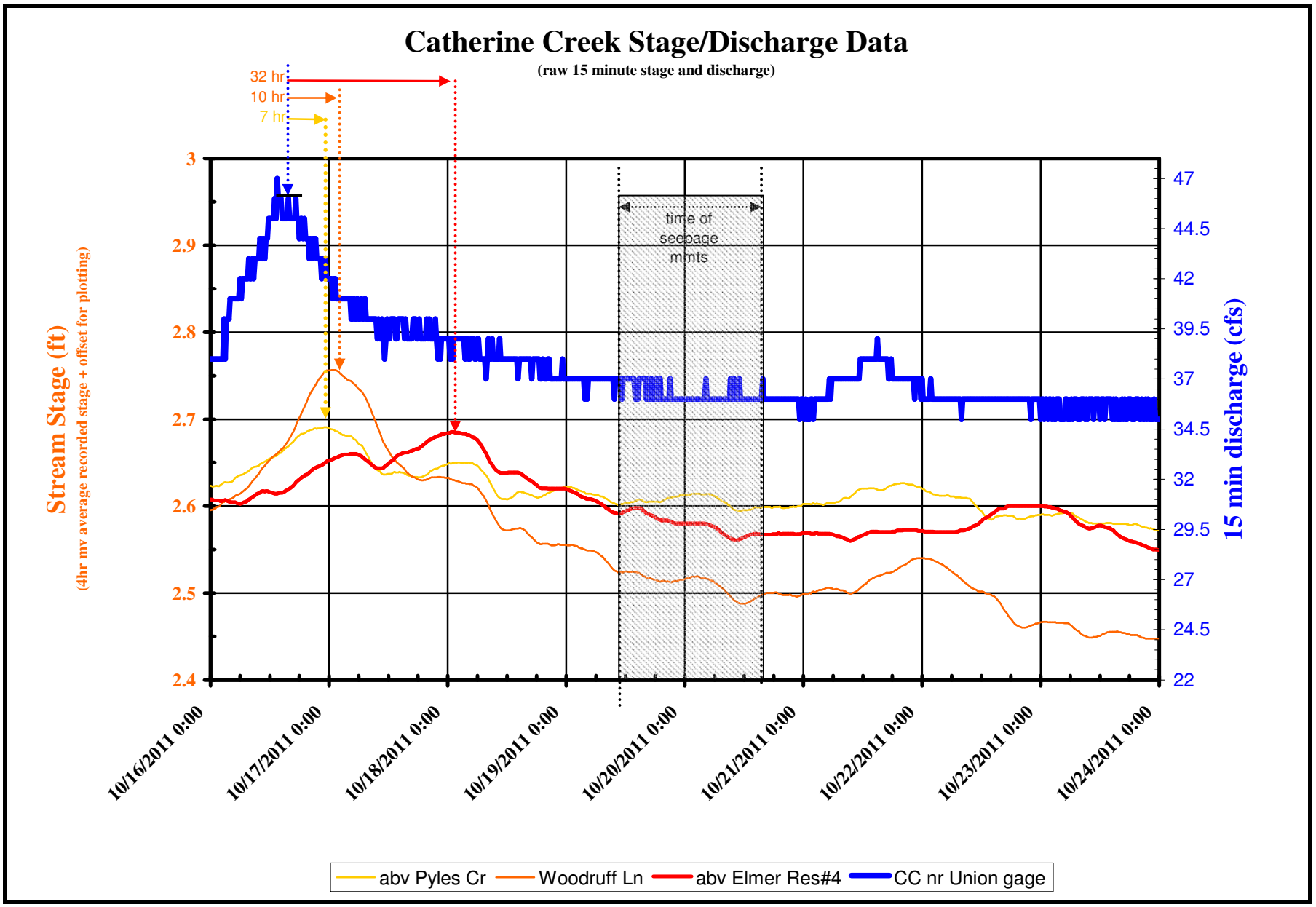


**Figure 9**: Flow conditions prior to and during seepage run measurement. Time to peaks between upper most stream gage site and lower stream gage sites used to determine travel times to adjust discharge measurements for flow variability during seepage run.

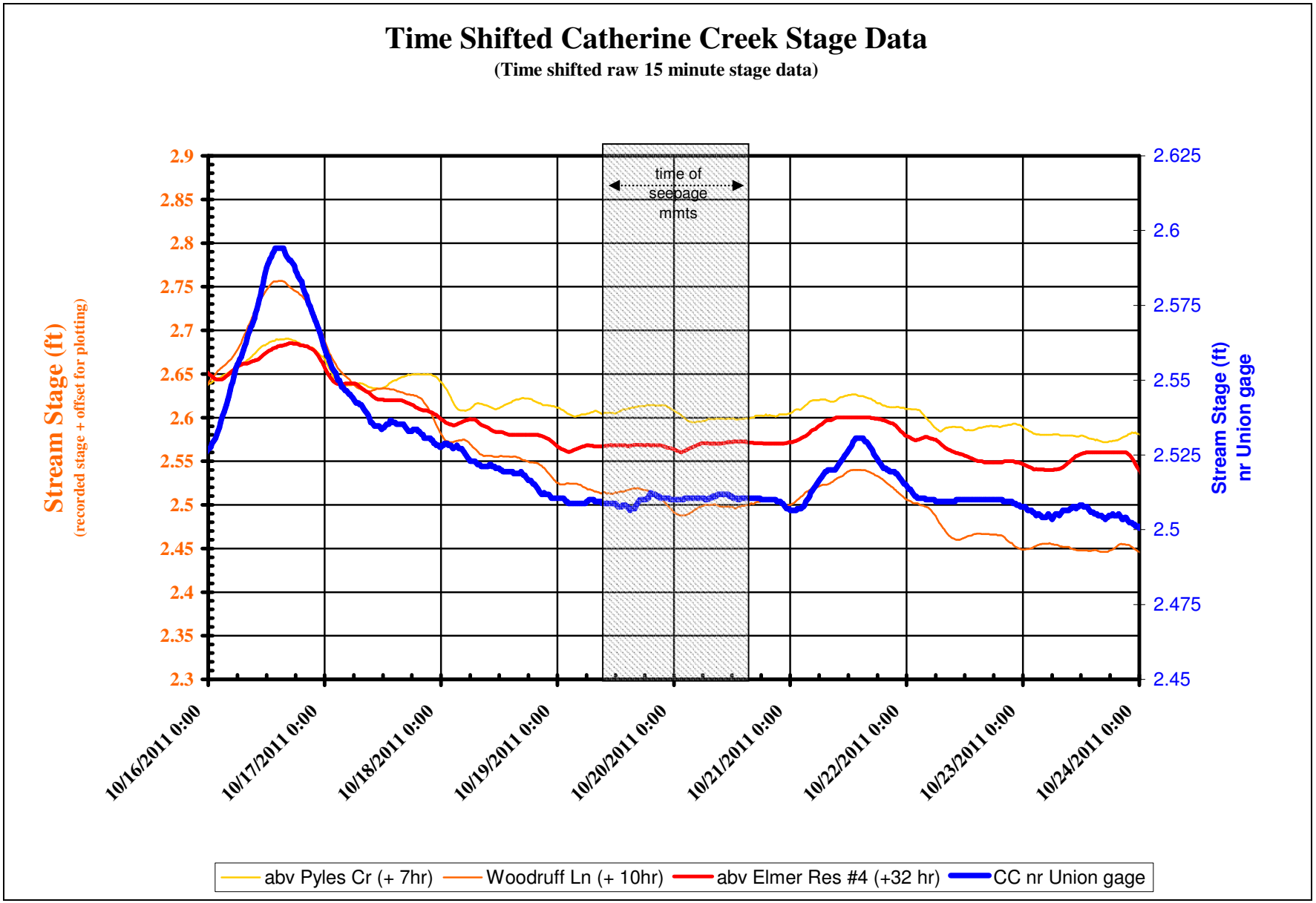


**Figure 10**: Time shifted stage data (4hr moving average) at lower stream gage sites (in valley) compared to non-shifted stage data at upper most gage site (near Union, #1332000).

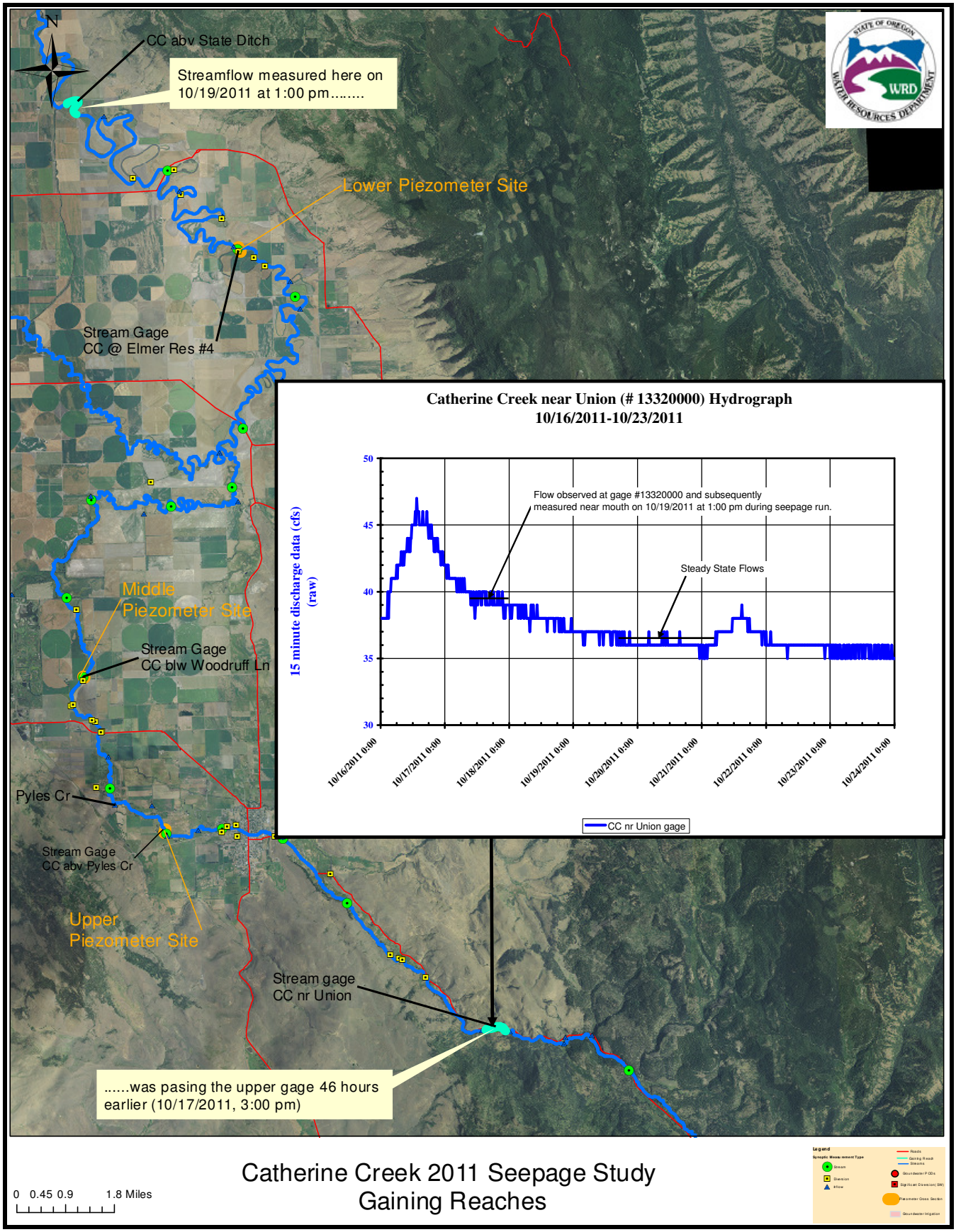


**Figure 11**: The effects of unsteady flow on seepage run measurements. The effects can be estimated by examining how the "packet" of water being measured differed with steady state conditions when it was "observed" (i.e., passed by) at gage #13320000 (CC nr Union)

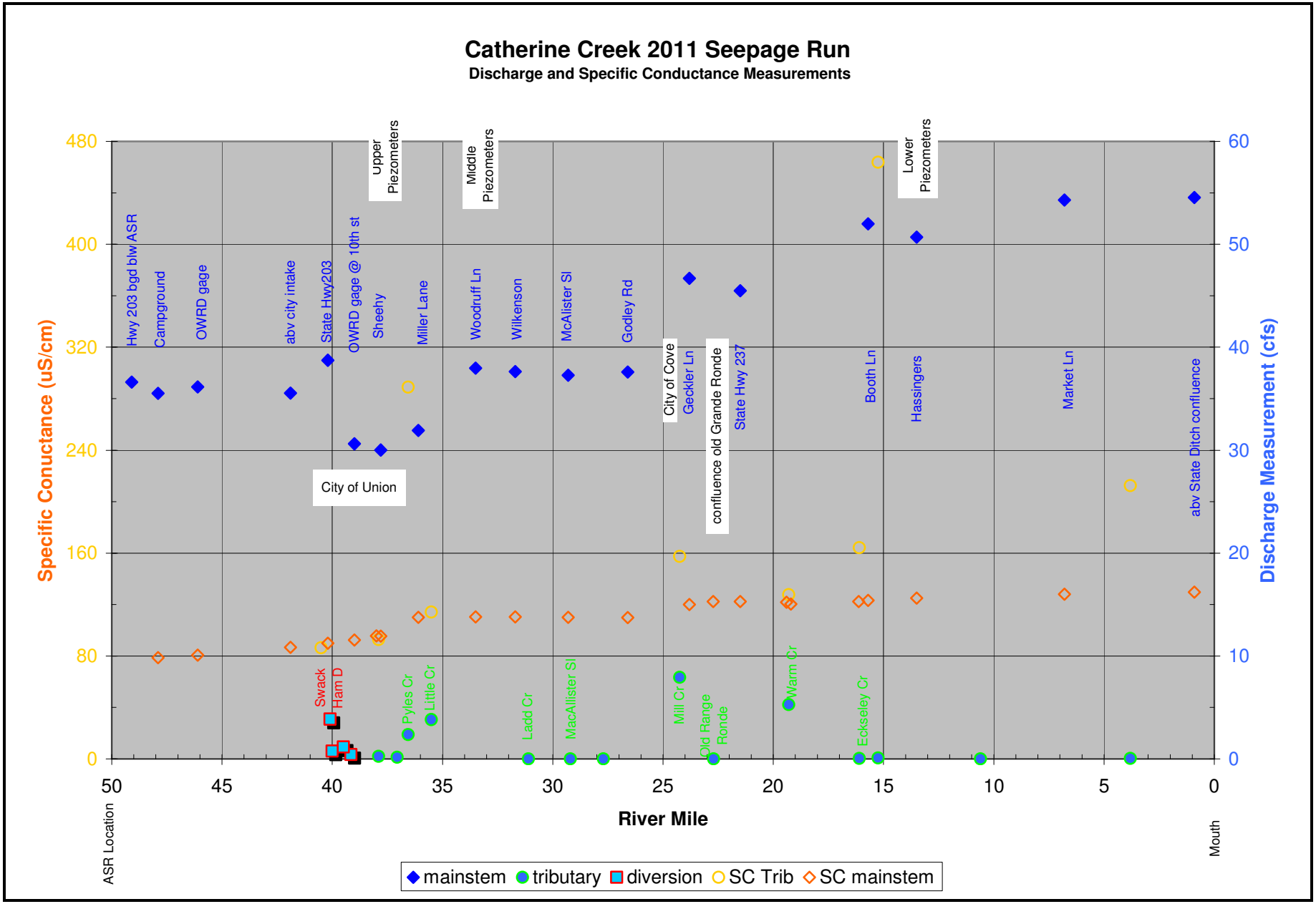


**Figure 12**: Catherine Creek seepage run raw results. Solid markers represent discharge measurements: diamonds = mainstem, circles = tributaries, squares = diversions. Open markers represent specific conductance measurement. Diamonds = mainstem, circle = tributary.

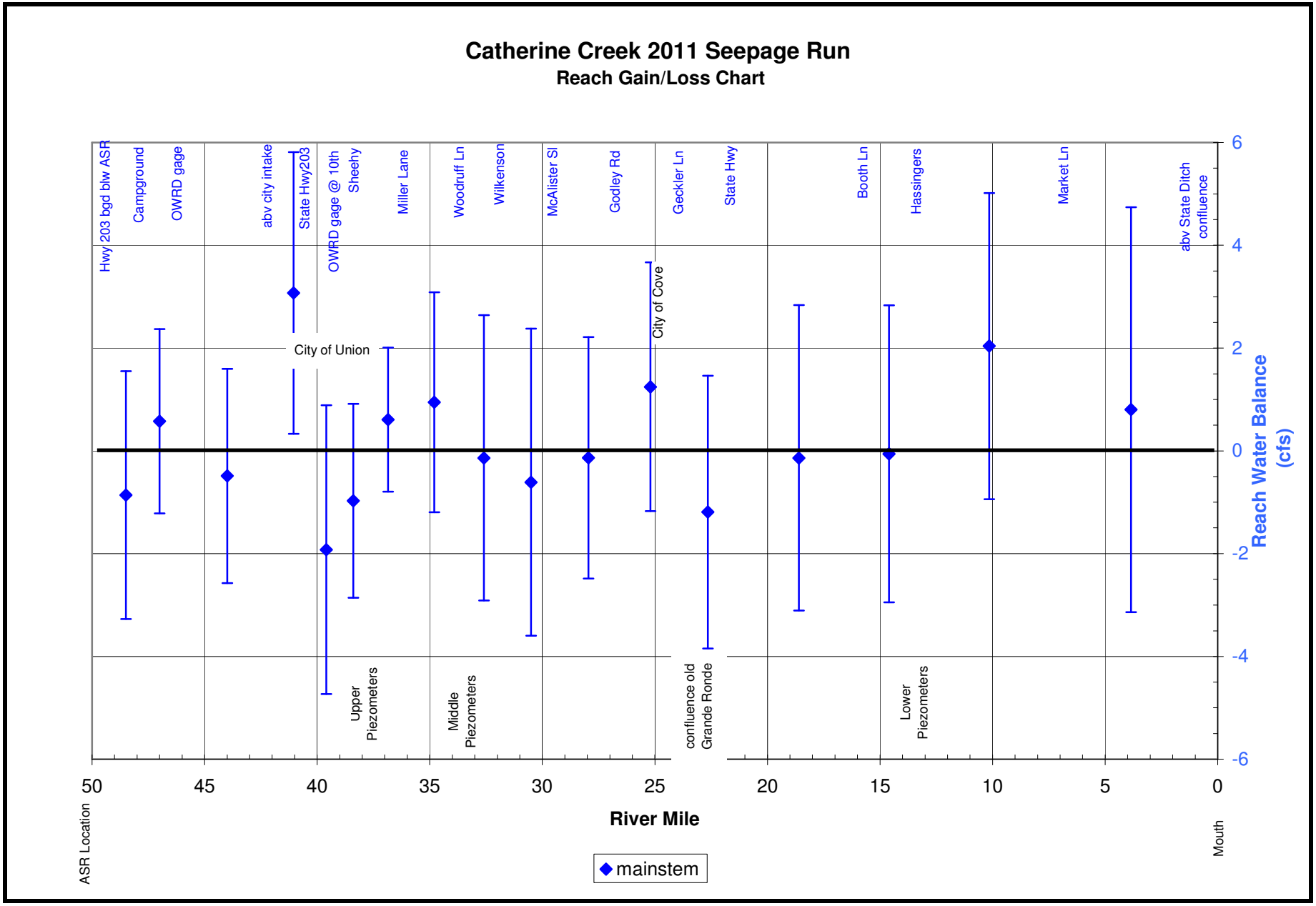


**Figure 13**: Catherine Creek reach gain/loss with uncertainty (bars)

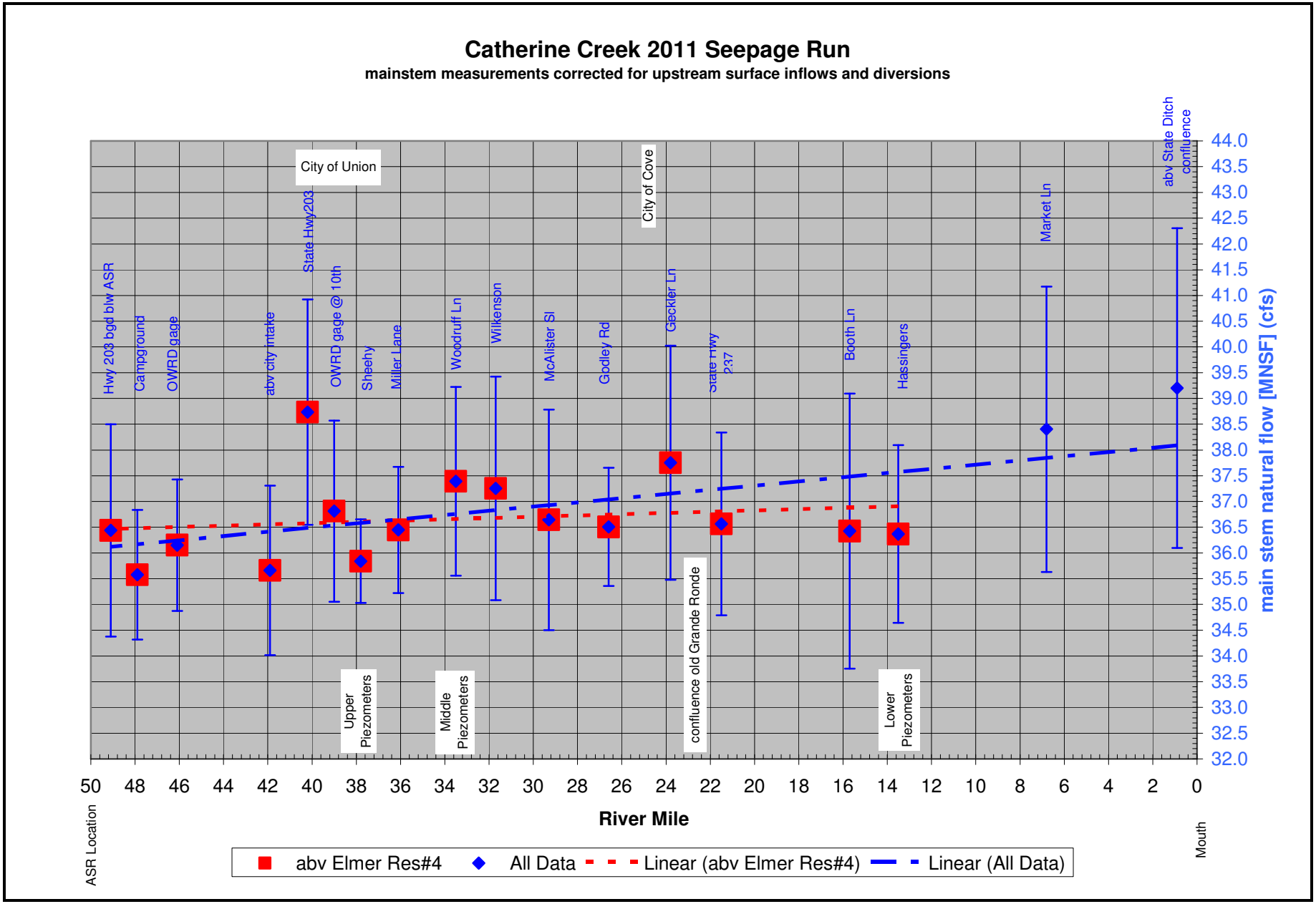


**Figure 14**: Trends in Catherine Creek streamflow attributable to groundwater interactions. Graph is based on the average of flow measurements at each site, corrected for the effects of upstream surface water inflows or diversions (main stem natural flow, MNSF).

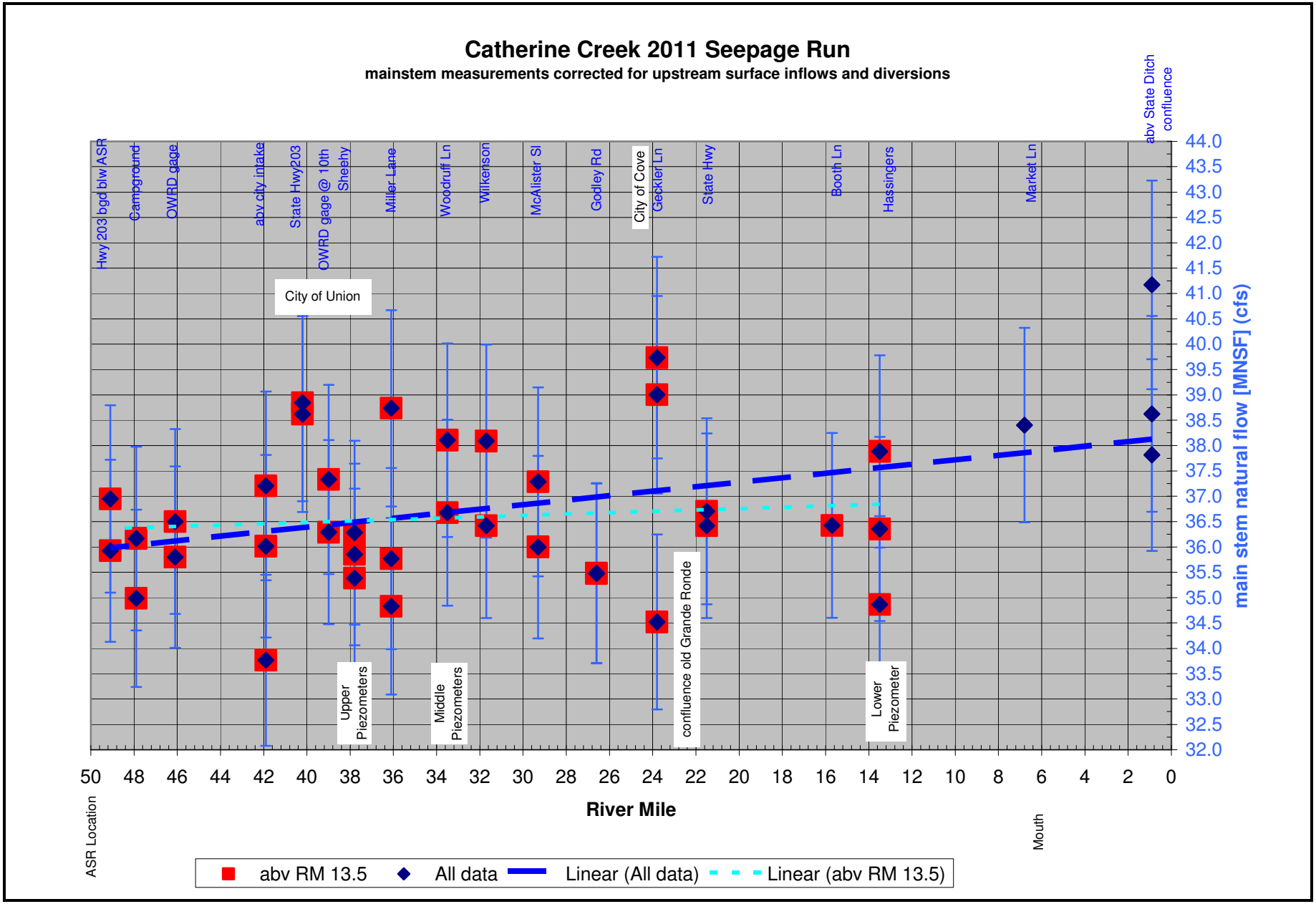


**Figure 15**: Trends in Catherine Creek streamflow attributable to groundwater interactions. Graph is based on all main stem streamflow measurements, corrected for the effects of upstream surface water inflows or diversions (main stem natural flow, MNSF)

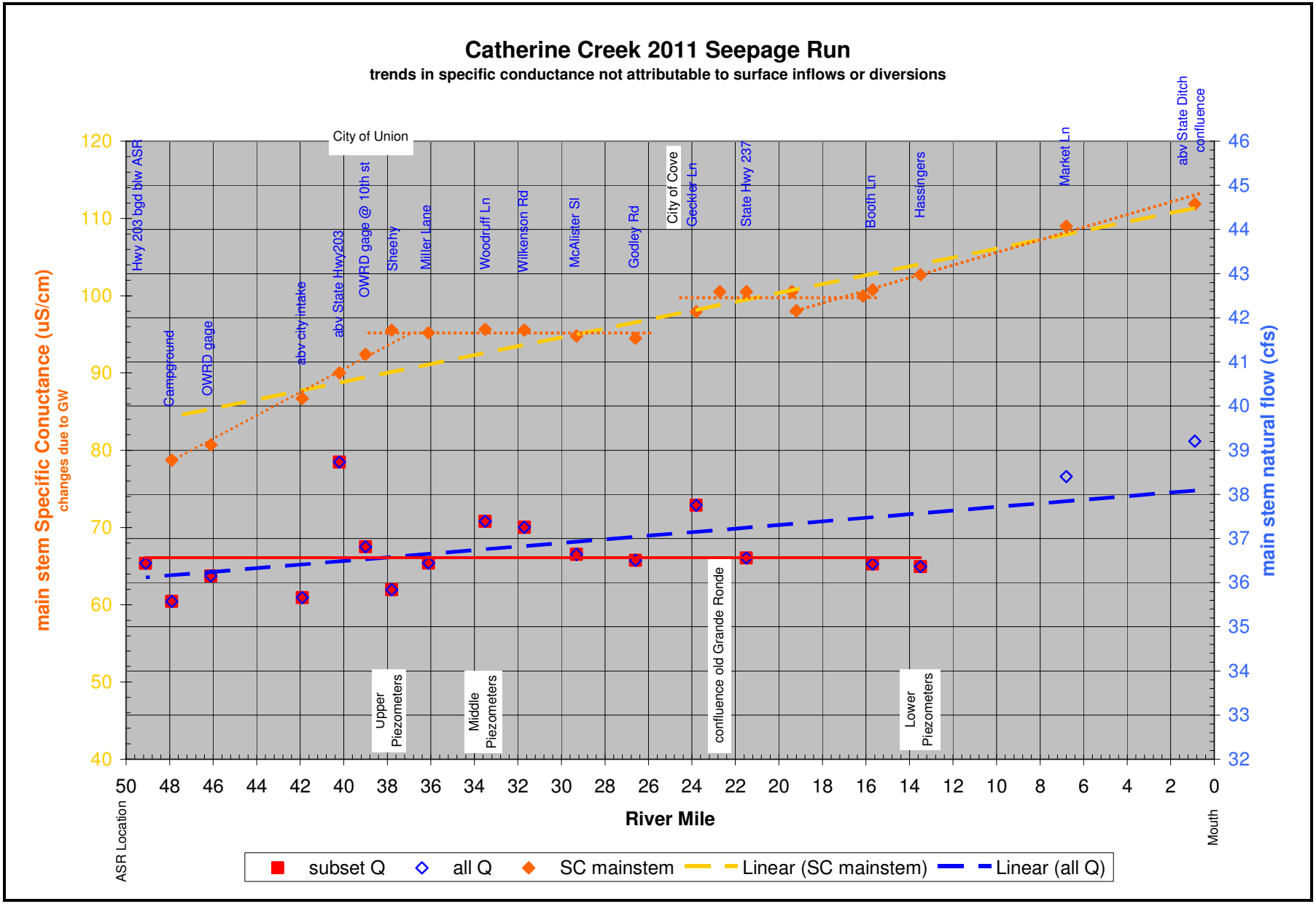


**Figure 16**: Trends in Catherine Creek specific conductance ostensibly attributable to groundwater interactions. Graph is based on specific conductance measurements on Catherine Creek corrected for the effects of upstream surface inflows. MNSF shown for reference purposes (red and blue data).

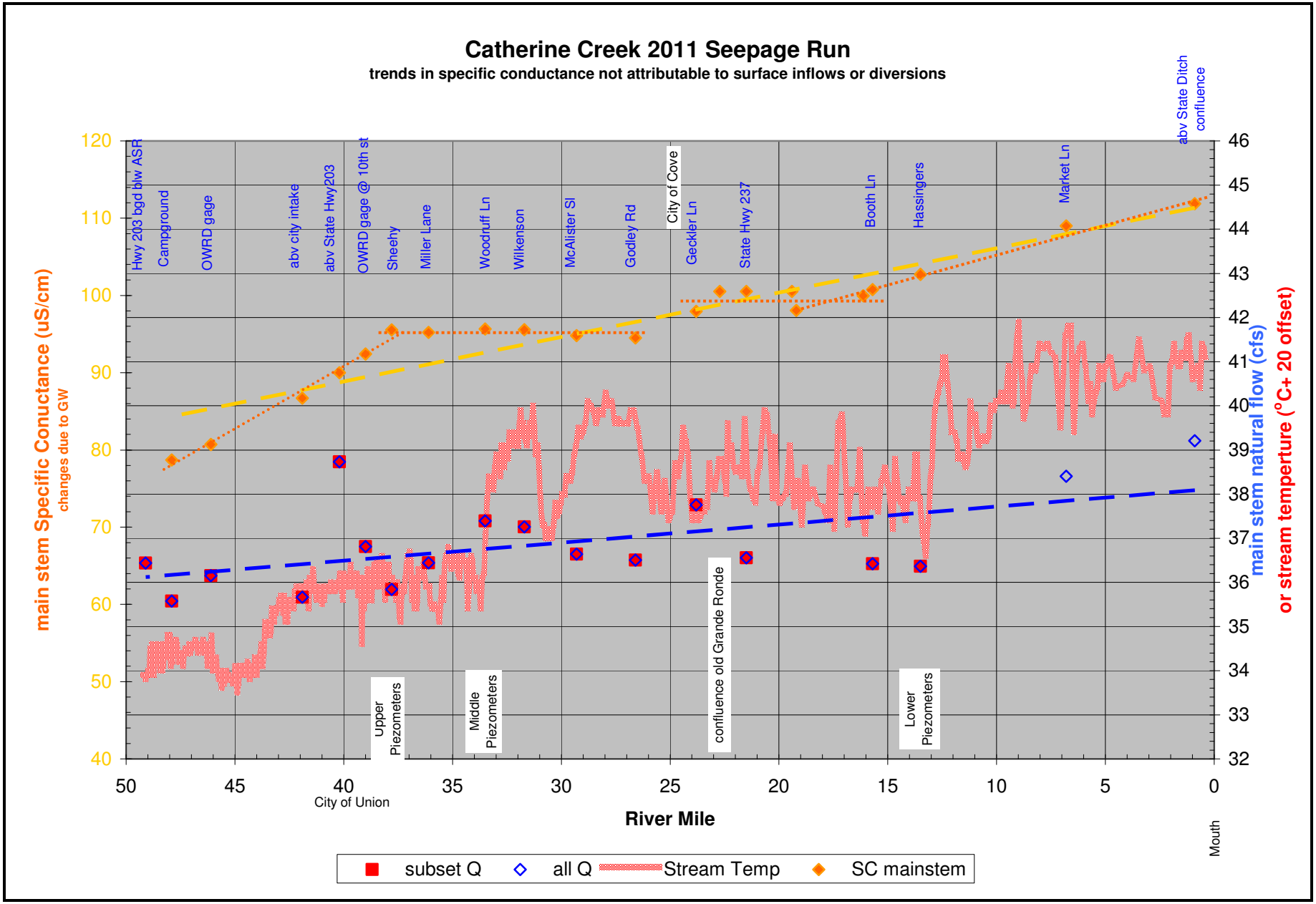


**Figure 17**: Results from the FLIR stream temperature data set collected by Watershed Sciences (2000) for ODEQ.

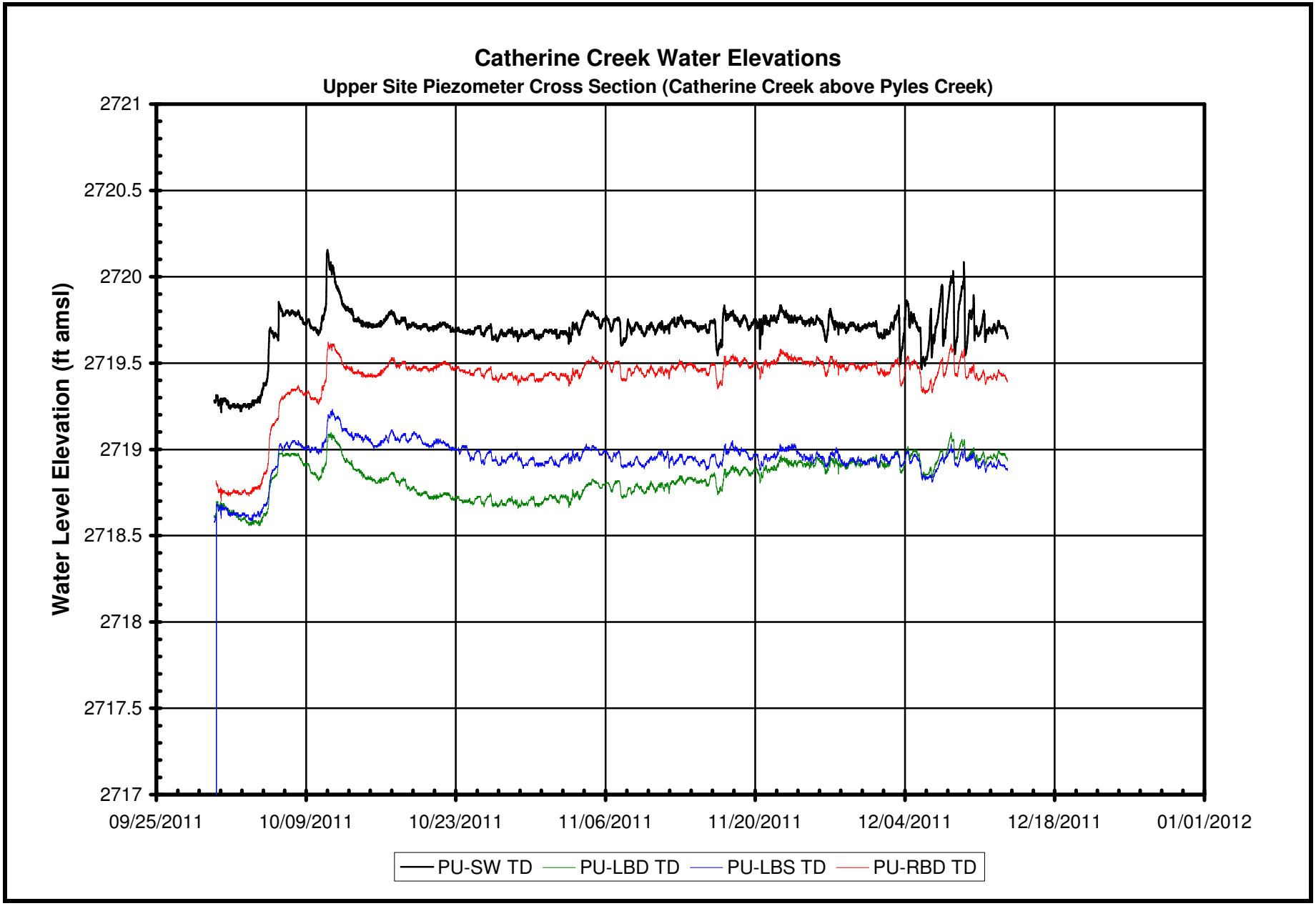


**Figure 18**: Water elevation for upper piezometer cross section (PU); SW = surface water; LBD = piezometer, left bank deep; LBS = piezometer, left bank shallow; RBD = piezometer, right bank deep.

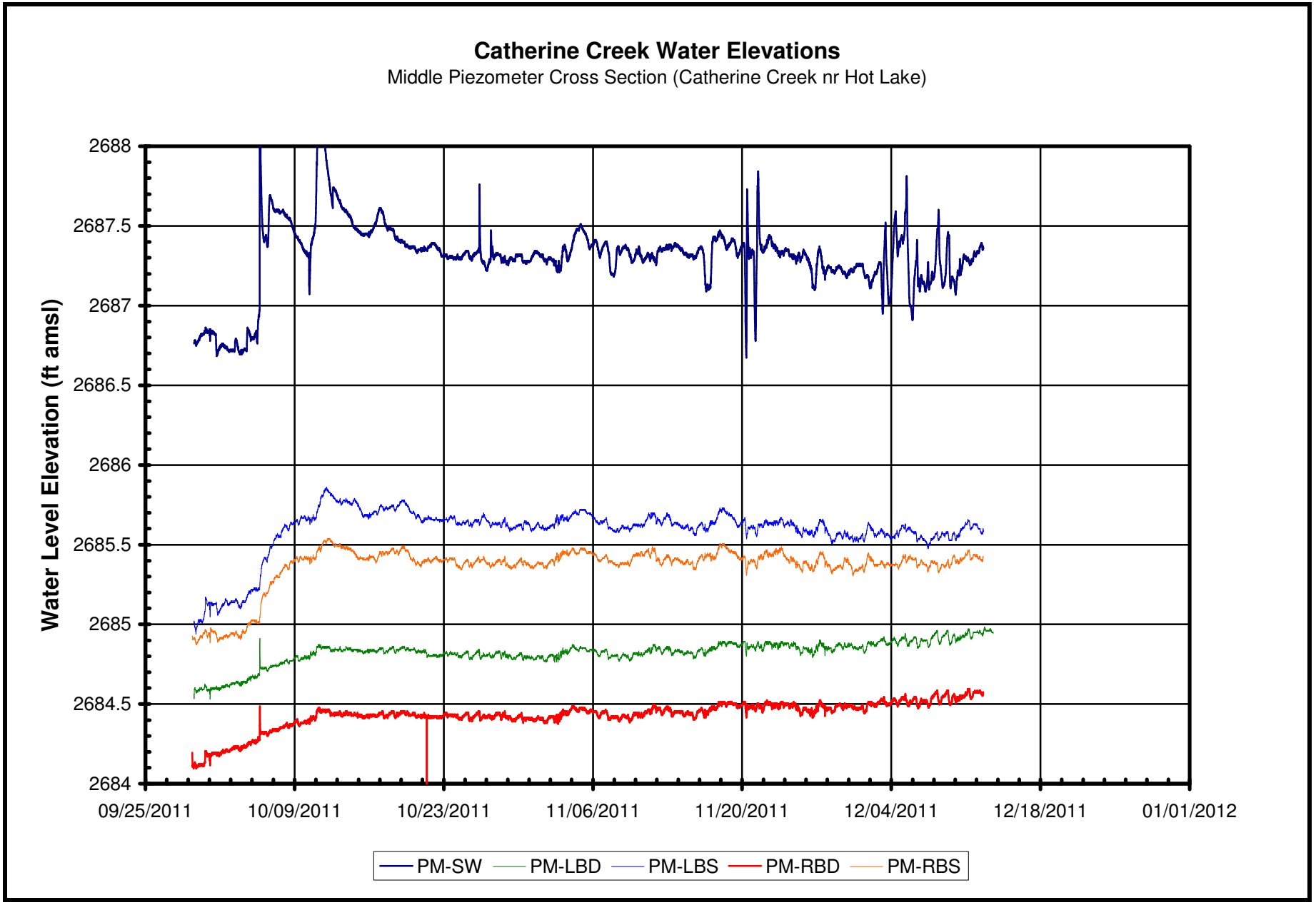


**Figure 19**: Water elevation for middle Piezometer site (PM); SW = surface water; LBD = piezometer, left bank deep; LBS = piezometer, left bank shallow; RBD = piezometer, right bank deep; RBS = piezometer, right bank shallow.

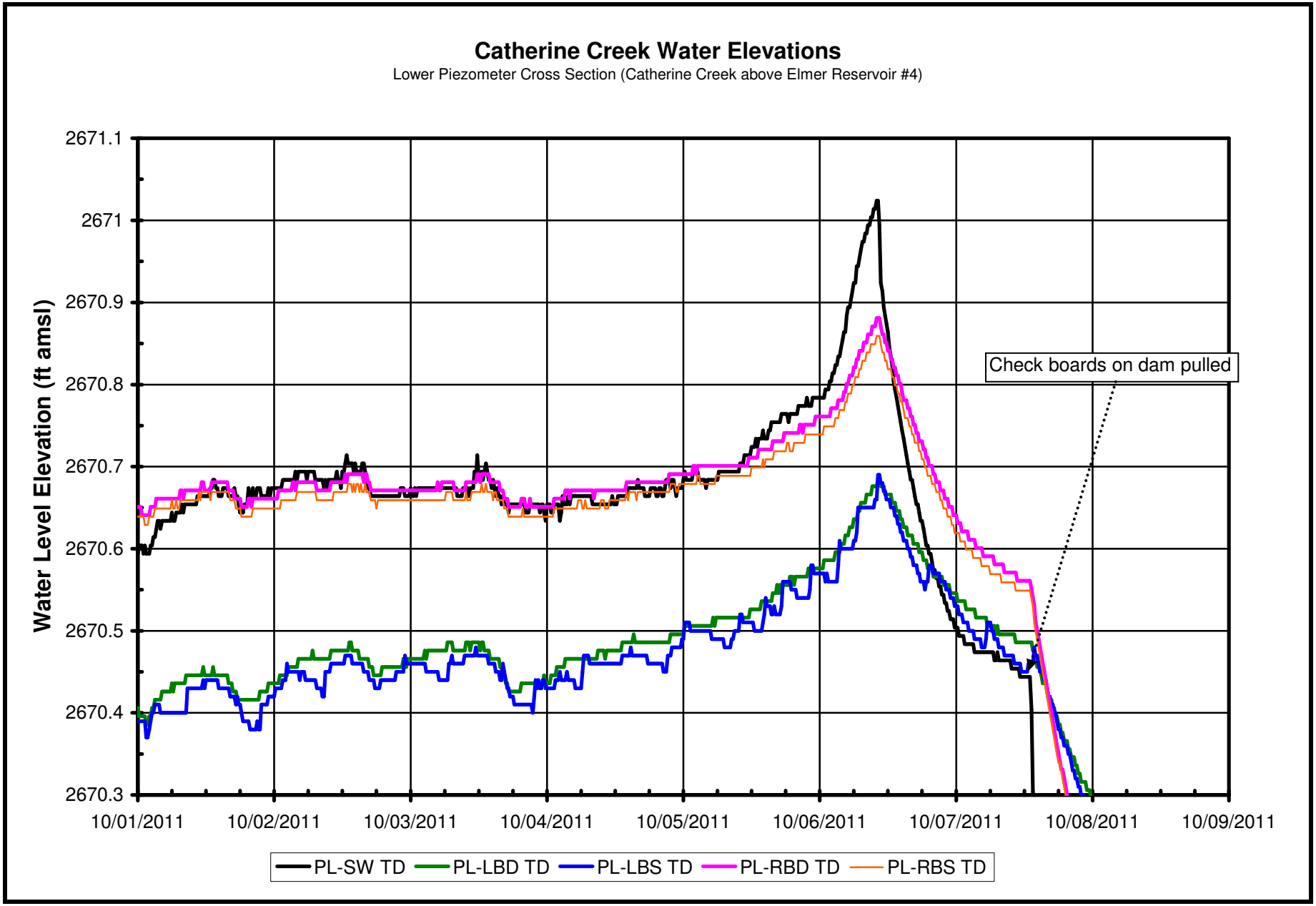


**Figure 20**: Water elevation for lower Piezometer site (PL) in the first week of October; SW = surface water; LBD = piezometer, left bank deep; LBS = piezometer, left bank shallow; RBD = piezometer, right bank deep; RBS = piezometer, right bank shallow.

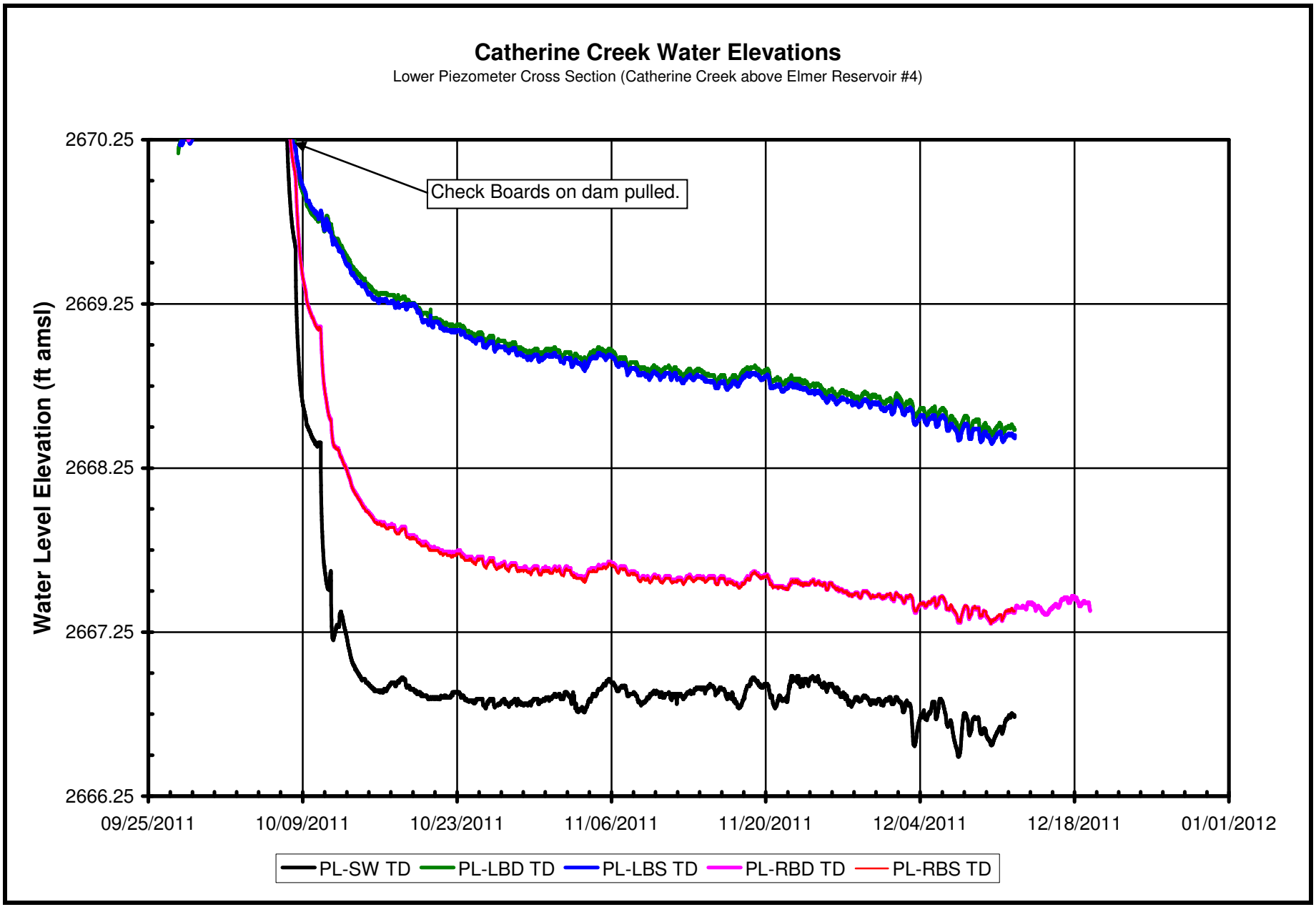


**Figure 21**: Water elevation for lower Piezometer site (PL); SW = surface water; LBD = piezometer, left bank deep; LBS = piezometer, left bank shallow; RBD = piezometer, right bank deep; RBS = piezometer, right bank shallow. Note scale change between figure 21 and 22.

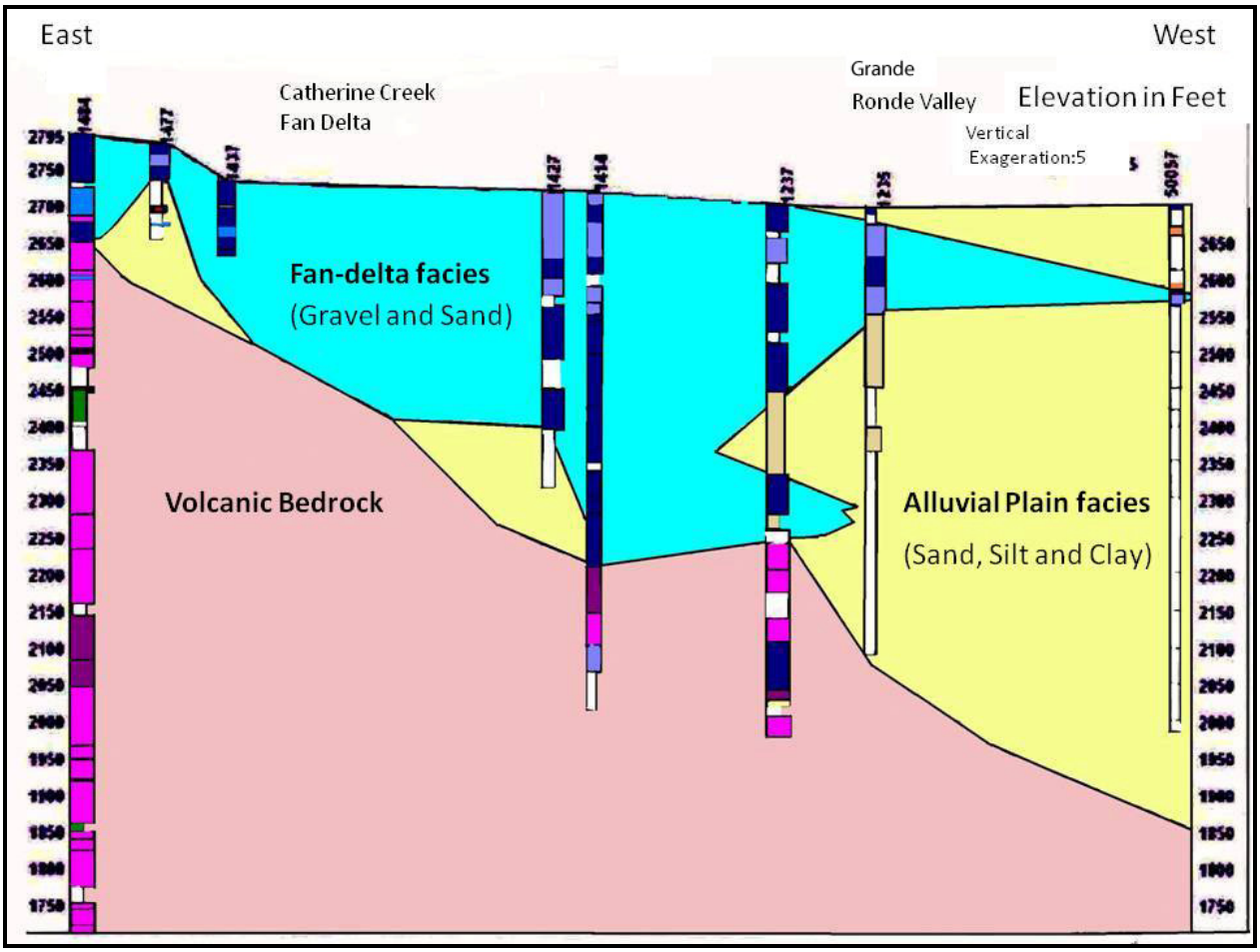


**Figure 22**: Profile from east to west across the Catherine Creek fan delta (Ferns et. al., 2002).