Groundwater and Surface Water Exchanges in the Catherine Creek Watershed, Oregon

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Abstract

In the fall of 2011, the Oregon Water Resources Department (OWRD), in collaboration with local and regional partners, initiated a study of groundwater / surface water (GW / SW) exchanges in the Catherine Creek watershed of the upper Grande Ronde Basin near Union, Oregon. Stream stage gages were installed at three monitoring sites along the creek and nested piezometers were installed on adjacent banks at each site to evaluate hydraulic head gradients between the stream and the underlying alluvial aquifer. Stream gains and losses were evaluated by a series of stream discharge measurements during a two day period in October of 2011. Analysis of the fall 2011 dataset, presented in OWRD Open File Report SW 2012-001, showed relatively minor groundwater exchanges with Catherine Creek in the mid and upper reaches of the valley—generally less than discharge measurement uncertainty. In the lower reaches of the study area, north of Cove, the fall 2011 dataset showed persistent discharge from the aquifer to the stream. This report examines a longer set of data, collected throughout 2012, to determine the seasonal variability of GW / SW exchanges in the study area.

The 2012 dataset shows seasonal changes in GW / SW interactions at the upper and middle monitoring sites. At the upper site, near Union, downward vertical head gradients occur during most of the year. Abrupt, short–lived increases in groundwater elevations in July and August temporarily reverse the vertical gradient. These temporary reversals are probably caused by flood irrigation of adjacent fields with surface water, which increases the groundwater elevation above that of the creek at the monitoring site. However, stream discharge measurements and gage data demonstrate that Catherine Creek gained ~1–5 cubic feet per second (cfs) above this monitoring site throughout 2012 despite downward head gradients during most of the same time period. This implies a positive head gradient to the stream and net discharge of groundwater to the creek upstream of the monitoring site throughout most of the spring and summer, and into the fall. Much of this discharge is probably due to a rise in the elevation of the water table above stream levels caused by losses from an extensive canal system and wide-spread surface water irrigation near Union.

At the middle monitoring site, east of Hot Lake, the vertical head gradients were downward throughout most of 2012. The deep piezometers show several direct drawdown and recovery responses from nearby groundwater pumping during the summer. The shallow piezometers did not show this response, which likely reflects both local recharge from stream losses and low vertical conductivity in the fine grain sediments between the shallow and deep piezometers. Streamflow losses on the order of 0.5 cfs, observed near the middle piezometer site when streamflow was extremely low (< 2 cfs), agree with the observed downward head gradients. This relatively small loss, despite the observed head differences, is consistent with low vertical permeability of the streambed sediments which are mostly silt, fine sand, and clay in this reach. The shallow and deep piezometers also show a broad summer drawdown which corresponds to general groundwater pumping patterns in the surrounding area. Head differences between the shallow aquifer and the stream during much of July and August were equal to or greater than 2 feet.

Generally speaking, downward vertical head gradients at the upper (0.04 – 0.05 ft. / ft.) and middle (0.14 - 0.18 ft. / ft.) monitoring sites during the 2012 irrigation season were similar to gradients during the fall and winter of 2011. This leads to the conclusion that GW / SW exchanges in the creek are not expected to differ significantly from what was observed during the 2011 seepage run in the middle and upper portions of the study area. The lower monitoring site shows an upward head gradient until July, 2012 when stream stage was artificially raised by check boards in the dam located just downstream. The pre–July upward head gradient is consistent with the upward gradient seen in the last quarter of 2011. After July, groundwater elevations are coincident with, or slightly lower than, creek water elevations. However, this downward gradient is unlikely to result in significant stream losses because the streambed is composed of clays and silts that probably have very low vertical permeability.

Introduction

In 2011, OWRD in cooperation with federal, state, and local partners undertook a study of groundwater / surface water exchanges in Catherine Creek; a critical salmonid stream in the upper Grande Ronde basin where historic anadromous fish runs have undergone marked declines (Bach and others, 1995; Nowak and Kuchenbecker, 2004). Low or non–existent streamflow occurs in reaches of Catherine Creek due to summer irrigation diversions, exacerbating poor habitat conditions in the stream. One proposal to enhance Catherine Creek flows through the Grande Ronde Valley (GRV) during the summer months is to pump groundwater into the creek from a small valley located about 10 miles above the GRV (fig. 1). The proposed wells would be completed in confined Columbia River Basalt Group aquifers at depth to reduce the likelihood of an efficient hydraulic connection to Catherine Creek and would include a recharge component (i.e., an aquifer storage and recovery or ASR project) during the winter.

OWRD manages streamflow and water distribution in Catherine Creek. Therefore, the OWRD watermaster will be responsible for managing any augmented streamflow through the GRV. Effective management of this water is not possible without a good understanding of the watershed hydrology, especially knowledge of any water exchanges between the underlying aquifer system and the stream. The 2011 data collection and analysis resulted in an OWRD open file report describing the GW / SW exchanges in the valley during the fall of 2011, a fairly wet climate year. The 2012 data collection was focused on understanding any seasonal variations in these exchanges during a more normal precipitation year (fig. 2). This report describes the results from the follow–up data collection effort.

Background

The geographic, physiographic, geologic, and hydrologic setting for Catherine Creek was described in detail in the 2011 report on groundwater / surface water (GW / SW) interactions in the watershed (OWRD Open File Report SW 2012-001). Only a brief summary of this background is presented in this report.

Catherine Creek is a tributary of the Grande Ronde River in northeastern Oregon (fig. 1) and is located in the Blue Mountains physiographic province of Northeastern Oregon (Baldwin, 1981). Catherine Creek originates 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 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 it meets the Grande Ronde River about eight miles northwest of Union. Prior to the late 1800s, the confluence with the Grande Ronde River 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 upstream of the historic confluence with Catherine Creek eventually capturing the entire flow of the river. In essence, the State Ditch moved the mouth of Catherine Creek 23 miles downstream (fig. 1).

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. In some areas between Union and Cove, the creek channel has been straightened to eliminate flooding in the historic floodplain. This straightening is obvious in the town of Union and near Woodruff lane. 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. Precipitation increases with elevation with nearly 60 inches per year on average falling in the headwaters of Catherine Creek as snow, but only 13 inches per year fall in the GRV. Most precipitation falls between November and April, with significant snow accumulations in the mountainous areas. 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 as it pertains to the hydrologic characteristics of the watershed is described in detail in the earlier 2011 report based on reports by Hampton and Brown (1964), Baldwin (1981), Orr and others (1992), Ferns and others (2002), and Ferns and others (2010). A summary of the hydrogeology of the basin, based in large part on these reports, is presented in the following paragraphs.

The Grande Ronde Valley (GRV) is a fault-bounded basin with a sedimentary fill that ranges up to 2000 feet in thickness (fig. 3 and fig 4.). The basin is bounded by steep-walled uplands composed of Columbia River Basalt Group (CRBG) lavas which are overlain by younger lavas of the Powder River Volcanic Field (PRVF). Lavas from both units are exposed as bedrock in the upper portions of the basin and occur at depth beneath the sedimentary fill in the lower valley (fig. 4). Because both bedrock units have low vertical permeability, groundwater recharge in the uplands is limited and most rainfall and snowmelt runs off directly to streams. However, local groundwater discharge from bedrock units to stream channels in the uplands supports a baseflow of about 20 cfs in Catherine Creek above Union during the summer 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 main GRV and Catherine Creek canyon upstream of Union (fig. 3, fig. 5 and fig. 6). 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 (fig. 3 and fig. 6). 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 formed at the margin of the valley where the stream gradient decreases abruptly at the margin of the GRV. 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 (fig. 3 and fig. 6). 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 losses to the underlying aquifer 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 (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 artesian wells that seasonally flow at land surface indicate upward gradients from the aquifer to the stream during some portions of the year. Stream gains are likely to be small, however, since vertical groundwater flow is likely to be impeded by silt and clay beds. Farther to the north, streambed sediments transition to sand and then to silt and clay and are underlain by a thick sequence 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

Data collection in 2011 consisted of a seepage run from the proposed ASR project to the mouth of Catherine Creek performed in the fall, specific conductance sampling along the creek during the seepage run, examination of water temperature data from a previous study (Watershed Sciences, 2000), and the installation of temporary stream gages and nested piezometers on adjacent creek banks at three locations (fig. 7). The methods associated with these data collections were described in the 2012 report on GW / SW interactions in Catherine Creek (OWRD Open File Report SW 2012-001).

Collection of groundwater and stream–stage elevation data continued through 2012 at the three nested piezometer sites and followed the same methods outlined in the 2011 report. For the piezometers and stream stage, data loggers recorded water elevation data at 15 minute intervals. Temporary piezometers were installed by hand in the streambed at the upper and middle piezometer sites to measure the instantaneous head gradient directly under the stream.

In addition to water level measurements, concurrent streamflow measurements were made at the upper piezometer site (i.e., Catherine Creek above Pyles Creek, #13320310) and the stream gage at the 10th street bridge (i.e., Catherine Creek at Union, #13320300). Since there are no diversions between these two stream gaging sites, a water balance was calculated for the reach to assess GW / SW exchanges. In addition, a rating curve was developed for the upper piezometer site to evaluate transient exchanges between the stream and the aquifer.

Streamflow was also estimated at the middle piezometer site (at Woodruff Lane) and the next downstream bridge crossing; Wilkinson Lane. Flow conditions were too low (stream depth was too shallow) to make discharge measurements using standard OWRD / USGS protocols or equipment. There are no diversions on inflows between the two locations so any difference in streamflow may be attributed to GW / SW exchanges.

Results

Streamflow Data

Streamflow measurements at the 10th street gage in Union and the upper piezometer site demonstrate that this reach of Catherine Creek consistently gains water from the underlying aquifer during the summer despite persistent downward gradients between the stream and the piezometers at the bottom of the reach (table 1). This suggests that although the stream may be losing water to the groundwater locally at the piezometer site, net gains are occurring over much of the reach between the piezometers and the 10th street gage. A mechanism for these gains is suggested by abrupt but temporary gradient reversals that occur at the piezometer site in July and August which correlate with short intervals of flood irrigation on local fields adjacent to the piezometer site (personal communication by Shad Hattan). Much of this discharge is probably due to a rise in the elevation of the water table above stream levels caused by infiltration losses from an extensive canal system and wide-spread flood irrigation using surface water in the area around Union.

Comparison of the daily flow record between the upper piezometer stream gage (# 13320310) and Union stream gage (# 13320300) indicates a gaining reach, where the magnitude of the gain coincides with a general increase in groundwater elevations from the end of August through mid–October (fig. 8). Irrigation activities are diminishing during this time of year, so the increase in GW levels at the piezometer site could be related to an increase in regional groundwater elevations that accompany cessation of GRV groundwater irrigation. This fact also implies a seasonal change in the magnitude of GW / SW interactions near Union, probably associated with up gradient irrigation practices and down gradient groundwater pumping. For water management purposes the bottom line is that during the 2012 irrigation season and during the 2011 seepage run (when similar head gradients to the 2012 irrigation season were observed), no streamflow losses were measured in a reach where conditions are conducive for them to occur.

Discharge measurements could not be made at the middle piezometer site at Woodruff Lane (gage #13321150) and at Wilkinson Road (approximately 1.8 miles downstream) due to low flow conditions. Water depths at both locations were less than 0.10 feet. Visual estimates of flow at Woodruff Lane on August 28th and 29th were roughly 1.0 to 1.5 cfs, while the estimate of flow at Wilkinson Road was less than half of that amount. The decrease in flow was visually very obvious between the two sites and is estimated to be on the order of 0.5 to 0.75 cfs.

Piezometer Data

As described in the previous report (OWRD Open File Report SW 2012-001), vertical head gradient and streambed conductivity are the parameters that primarily control water losses or gains to the stream. A downward head gradient (i.e., creek water elevation higher than the groundwater elevation) is required for stream losses to occur through the channel bed, and the reverse is true for gains to occur. However, the rate of GW / SW exchange is also dependent on the hydraulic conductivity of the streambed and the exchange can be un–measurable for low conductivity sediments even when the head gradients are substantial.

Piezometer data collected during the seepage run in 2011 indicated a downward head gradient from the stream to the aquifer at the upper and middle monitoring sites, and an upward head gradient from the aquifer to the stream at the lower site. The results at the lower site near Elmer Reservoir #4 were consistent with streamflow increases measured during the fall 2011 seepage run. However, no streamflow losses were found for reaches near the middle (near Hot Lake) and upper (near Union) piezometer sites, despite the presence of downward head gradients between the stream and the aquifer. The results implied that streambed conductivity was controlling GW / SW exchanges in stream reaches near both monitoring locations, despite the presence of coarse grain streambed material near the town of Union.

In general, groundwater and stream stage water elevations at all three monitoring sites during 2012 were consistent with trends and gradients observed from the 2011 fall data.

The 2012 data show that the variations in groundwater elevations closely follow variations in creek stage at all sites (fig. 9, fig. 10, and fig. 11). The 2012 data also revealed seasonal variations in the hydraulic head gradient between the alluvial aquifer and the stream, some of which are likely related to groundwater pumping and surface water irrigation.

At the upper and middle sites the head gradient in 2012 was generally downward from the stream to the alluvial aquifer (fig. 9 and fig. 10), similar to the fall of 2011. This downward gradient was largest in the summer at both these sites, which is indicative of a summer regional groundwater decline perhaps in response to irrigation pumping as previously mentioned. At the upper site, a localized groundwater response to summer irrigation pumping was not readily apparent. In contrast, the groundwater elevations of the deep piezometers at the middle site show clear pump and recovery signs from nearby wells (see last week in August in fig. 10). However, the shallow piezometers at the same site do not reflect pumping effects; an indication of both local recharge from stream losses and low vertical hydraulic conductivity in the fine grain sediments between the shallow and deep piezometers.

At the lower monitoring location, irrigation pumping effects on local groundwater elevations were not readily apparent (fig. 11). In addition, although the largest downward head gradient from the creek to the aquifer is during the summer, a regional decline in groundwater elevations is also not readily apparent. As with the middle site, groundwater elevations at the lower site follow changes in creek stage, but are muted compared to the upper site.

Surface water irrigation also caused variations in the head gradient at the upper and middle monitoring locations. Although the head gradient at both locations is generally downward, there are a few instances where the head gradient reversed (i.e., groundwater elevation higher than stream stage). Multiple, short–duration, head gradient reversals occurred during the summer at the upper site; likely the result of flood irrigation in fields west of the river in July and August (fig. 8). A significant, longer duration head reversal occurred in the fall at the middle site, which was also thought to be caused by water management practices; mainly longer duration (> 1 month) land flooding (including Ladd Marsh) to saturate soils and prevent wind erosion (fig. 10). The middle site also had two short–duration head gradient reversals along the east (right) bank in the spring that likely coincided with springtime flooding of fields east of the creek.

At the lower site, the manipulation of stream stage via check boards on the dam immediately downstream of the piezometers affects the head gradient between the stream and aquifer, and also the head gradient between the west and east banks (fig. 11). Seasonally, the head gradient was predominately from the aquifer towards the creek until the check boards on the dam located downstream of the monitoring site were installed the first week in July. At that time, the head gradient reversed back to what was observed in late September of 2011, with the stream stage coincident or above that of the groundwater levels. Stream stage above the groundwater elevations also occurred occasionally during runoff events (~1 day) and during the snowmelt driven spring freshet (~ 2–3 weeks).

Collectively this data indicates that both groundwater and surface water irrigation practices influence the head gradient between the aquifer and Catherine Creek. Periodic surface water irrigation temporarily reversed the head gradient at the upper and middle monitoring sites so that groundwater levels exceeded creek stage. During these times, conditions are conducive for groundwater to contribute to streamflow. Outside of these times, however, groundwater pumping appears to increase the downward head gradient from the creek to the shallow aquifer. At the middle monitoring site, fine grain sediments help limit channel losses to roughly 0.5 cfs in the summer of 2012 in the presence of a downward head gradient. This amount of loss was below the measurement uncertainty in the 2011 seepage run. The fine–grained sediments and muted groundwater response to changes in stage at the lower site indicates that changes in the vertical head gradient in the lower reaches of Catherine Creek probably have minimal effect on the GW / SW exchange. At the upper site, the GW / SW connection appears to be more robust (fig. 9).

Temporary streambed piezometers were installed at the upper and middle piezometer sites to determine the head gradient directly under the streambed. At the upper site, only one piezometer was installed roughly 4 feet below the streambed due to difficulties in hand driving the open pipe into the coarse grain substrate of gravels and cobbles. The measured head gradient was upwards (+0.08 ft) towards the creek on August 30th, which is in agreement with the head gradient direction measured by the stream bank piezometers. This positive head gradient also agrees with gains measured by concurrent streamflow measurements the day before (table 1). At the middle site two streambed piezometers were driven through the streambed. The shallow piezometer was driven five feet below the channel bottom, while the deep piezometer was driven 10 feet below the channel bottom. The head gradient directly below the stream was downward from the stream to the shallow (-0.22 ft) and deep piezometers (-1.83 ft) on August 30th, again in agreement with the head gradient shown by the stream bank nested piezometers.

Conclusion

Piezometer and stream stage data collected through 2012 demonstrate seasonal changes in vertical head gradient between the creek and shallow groundwater occur in the Grande Ronde Valley. These changes are caused by both surface water irrigation activities and by a regional decline in groundwater levels from groundwater pumping.

Downward head gradients were predominately present at the upper piezometer site and Catherine Creek was expected to lose water to the shallow aquifer through a relatively 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. Despite this hydrogeolologic setting, discharge measurements and stream gage data demonstrate that groundwater discharges to the stream near Union. This indicates that groundwater elevations are generally above that of the creek between the 10th street bridge and the upper piezometer site

A general downward head gradient at the middle site near Hot Lake was also observed. The deep piezometers show groundwater elevations that clearly reflect pump and recovery signals from nearby wells. The shallow piezometers do no show these signals, an indication of both local recharge from stream channel losses and low vertical hydraulic conductivity in the fine grain sediments between the shallow and deep piezometers. Losses on the order of 0.5 cfs from the stream to the shallow aquifer were observed in late August for the roughly two mile reach below the middle piezometer site when streamflow was extremely low (< 2 cfs). Synoptic measurements made in 2011 showed no losses greater than the measurement uncertainty in this reach when streamflow was much higher (~35 cfs). The vertical head gradient during the 2011 seepage run were similar to those in August when losses were observed. Groundwater pumping is clearly affecting the head gradient in this reach, but the fine grain sediments help to limit the impact on the stream.

North of Cove at the lower piezometer site, the head gradient between the deep and shallow piezometers was essentially non–existent. However, there was an upward gradient from the alluvial aquifer to the creek until early July when check boards were installed in the dam just downstream of the piezometers. Local aquifer recharge occurs east of the creek from tributary streams draining Gassett Bluff during times of runoff and the spring–freshet. These tributaries lose water to the shallow aquifer as they cross their alluvial fans, which subsequently migrates as groundwater to Catherine Creek. However, flooded fields and oxbows to the west also appear to be a source of drainage to the creek from the fall through the spring. Based on the observed head gradient and results from the 2011 seepage run, groundwater inflows are generally expected in this area until the check boards on the dam just downstream of the piezometer site are installed. These check boards, installed in July, create an in–channel reservoir for several miles upstream and reverse the head gradient so that the creek stage is higher than the groundwater to the west and coincident with groundwater to the east. The piezometer data in the area do not show any obvious effects from groundwater pumping or surface water irrigation. Due to the geologic setting and streambed materials, it is unlikely this area would lose significant quantities of water when the head gradient reverses.

References

Bach, Leslie B., 1995, River Basin Assessment – Upper/Middle Grande Ronde River and Catherine Creek, Oregon Department of Environmental Quality, Portland, OR. 92p

Bailey, D. E., 1990, Geochemistry and petrogenesis of Miocene volcanic rocks in the Powder River volcanic field, northeastern Oregon: Pullman, Wash., Washington State University, doctoral dissertation, 341 p.

Baldwin, E. M., 1981, Geology of Oregon (3rd Ed): Dubuque, Iowa, Kendall/Hunt Publishing Co. 170p

Bartholomew, W.S., 1975, Ground–water conditions and declining water levels in the Butter Creek area, Morrow and Umatilla counties, Oregon: Oregon Water Resources Department Ground Water Report no. 24, 101p

Daly, C., R.P. Neilson, and D.L. Phillips. 1994. A statistical–topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology 33: 140–158.

Daly, C., W. P. Gibson, G.H. Taylor, G. L. Johnson, P. Pasteris. 2002. A knowledge–based approach to the statistical mapping of climate. *Climate Research*, **22**: 99–113.

Ferns, M. L., Madin, I. P., McConnell, V. S., and Johnson, J. J., 2001, Geology of the surface and subsurface of the southern Grande Ronde Valley and Lower Catherine Creek drainage, Union County Oregon. A Preliminary Release. Oregon Department of Geology and Mineral Industries Open–File Report O–02–02, 54 p., 3 pls

Ferns, M. L., McConnell, V. S., Madin, I. P., and Johnson, J. A., 2010, Geology of the upper Grande Ronde River basin, Union County, Oregon; Oregon Department of Geology and Mineral Industries Bulletin 107, scale 1:100,000, 65 p.

Gannett, M.W., Lite, K.E. Jr., La Marche, J.L., Fisher, B.J., and Polette, D.J., 2007, Ground–water hydrology of the upper Klamath Basin, Oregon and California: U.S. Geological Survey Scientific Investigations Report 2007–5050, 84 p.

Hampton, E.R., and Brown, S.G., 1964, Geology and ground–water resources of the Upper Grande Ronde River Basin Union County, Oregon: U.S. Geological Survey Water–Supply Paper 1597, 99 p., 6 pls.

La Marche, J. L., Wozniak, K., Hattan, S., and Hackett, J. 2012, Groundwater and Surface Water Interactions in the Catherine Creek Watershed, Oregon – Results and Analysis from the 2011 Seepage Run. Open File Report SW 2012-001, Salem, Oregon 58 p

Lite, Kenneth E. Jr., and Gannett, M. W. 2002, Geologic Framework of the Regional Ground–Water Flow System in the Upper Deschutes Basin, Oregon. U.S. Geological Survey, Water–Resources Investigations Report 02–4015, Portland, Oregon. P.44.

Lite, Kenneth E. Jr., and Gerald H. Grondin. 1988, Hydrogeology of the Basalt Aquifers Near Mosier, Oregon: A Ground Water Resource Assessment. Salem, Oregon: State of Oregon Water Resources Department Ground Water Report No. 33, 119 p.

Nowak, M.C., and Kuchenbecker, L. 2004, Grande Ronde Subbasin Plan, 222p

Miller, D. W., Gates, S. M., Brodersen, B.T., and Zwart, M.J., 1993, Groundwater Conditions of the Basalt Aquifers, Parrett Mountain, Northern Willamette Valley, Oregon. Salem, Oregon: State of Oregon Water Resources Department Ground Water Report No 40, 144.

Norton, M. A., and Batholomew, W.S., 1984, Update of Ground Water Conditions and Declining Water Levels in the Butter Creek Area, Morrow and Umatilla Counties, Oregon. Salem, Oregon: Oregon Water Resources Department Groundwater report No. 30, 203p

Orr, E.L., Orr W.N., and Baldwin, E.M., 1992, Geology of Oregon (4th Ed): Dubuque, Iowa, Kendall/Hunt Publishing Co, 254p

PRISM Group, 2010, Precipitation (normals): PRISM Climate Group, Oregon State University, accessed December 1, 2011, at http://prism.oregonstate.edu/products/viewer.phtml?file=/pub/prism/us_30s/grids/ppt/Normals/us_ppt_1971_2000.14.gz&yr=1971_2000&vartype=ppt&month=14&status=final.

Sceva, J. E., 1966, A brief description of the ground–water conditions in the Ordnance area, Morrow and Umatilla counties, Oregon; Oregon Water Resources Department Ground Water Report no. 11, 43p

Tolan, T.L., Martin, B.S., Reidel, S.P., Anderson, J.L., Lindsey, K.A., and Burt, Walter, 2009, An introduction to the stratigraphy, structural geology and hydrogeology of the Columbia River Flood–Basalt Province—A primer for the GSA Columbia River Basalt Group field trips, *in* O'Connor, J.E., Dorsey, R.J., and Madin, I.P., eds., Volcanoes to vineyards—Geologic field trips through the dynamic landscape of the Pacific Northwest: Geological Society of America Field Guide 15, p. 599–643, doi:10.1130/2009.fld015(28).

U.S. Bureau of Reclamation, 2011, *Catherine Creek Seepage Run Discharge Measurements– Grande Ronde Subbasin, Oregon*. Pacific Northwest Region, Boise, Idaho, p. 41

U.S. Bureau of Reclamation. 2012. *The Catherine Creek Tributary Assessment, Appendix E – Hydrogeology. Grande Ronde River Basin. Tributary Habitat Program, Oregon*. Pacific Northwest Region. Boise, Idaho.

Watershed Sciences, LLC, 2000. *Remote Sensing Survey of the Grande Ronde River Basin Thermal InFared and Color Videography.* Final Report for the Oregon Department of Environmental Quality, Corvallis OR, p. 25.

FIGURES and TABLES

Table 1: Streamflow changes attributed to groundwater exchange: 10th street bridge to upper monitoring site.

mmt #	Catherine @ Union #13320300 (10th street gage)			Catherine abv Pyles Cr #13320310 (upper monitoring site)			Return Ditch	Reach Gain (+) or Loss (-)		Approx Head Gradient (+ = positive to stream)		Notes
	Date/Time	GH (ft)	Q (cfs)	Date/Time	GH (ft)	Q (cfs)	Q (cfs)	Absolute Change (cfs)	% Change	Left Bank	Right Bank	
1	11/16/2012 13:00	1.19	25.3	11/16/2012 12:15	1.36	27.5	0.4	1.8	7%	0.2	0.0	Heads and stage measured just after apparent irrigation event along the left bank. Gradient was 0.4ft higher the night before mmt.
2	10/25/2012 9:30	1.13	20.1	10/25/2012 10:45	1.26	22.2	0.0	2.1	10%	-0.8	-0.4	
3	10/2/2012 13:30	0.86	5.1	10/2/2012 13:30	1.10	8.4	0.0	3.3	63%	-0.8	-0.4	
4	8/29/2012 15:06	0.67	1.7	8/29/2012 15:00	0.96	2.3	0.0	0.6	36%	-0.2	0.0	Piezometer head rising, starting on R. Bank Side. By 4:30 pm (2hrs after mmt) GW heads above surface water)
5	8/28/2012 12:40	0.74	2.7	8/28/2012 11:00	1.01	3.7	0.0	1.0	37%	-0.6	-0.3	
6	8/23/2012 9:20	0.71	2.2	8/23/2012 11:00	0.99	2.8	0.0	0.6	28%	0.3	0.0	irrigation and GW was abv SW for 2 days prior to visit and just after mmt rose again. Prior to mmt LB gradient was +1.7 ft and RB gradient was + 0.336
7	7/11/2012 9:20	1.28	41.6	7/11/2012 10:30	1.46	45.2	0.0	3.6	9%	-1.0	-0.3	
8	6/20/2012 12:55	1.81	154.0	6/20/2012 13:15	2.08	165.4	0.0	11.4	7%	0.4	0.0	irrigation event just before measurement

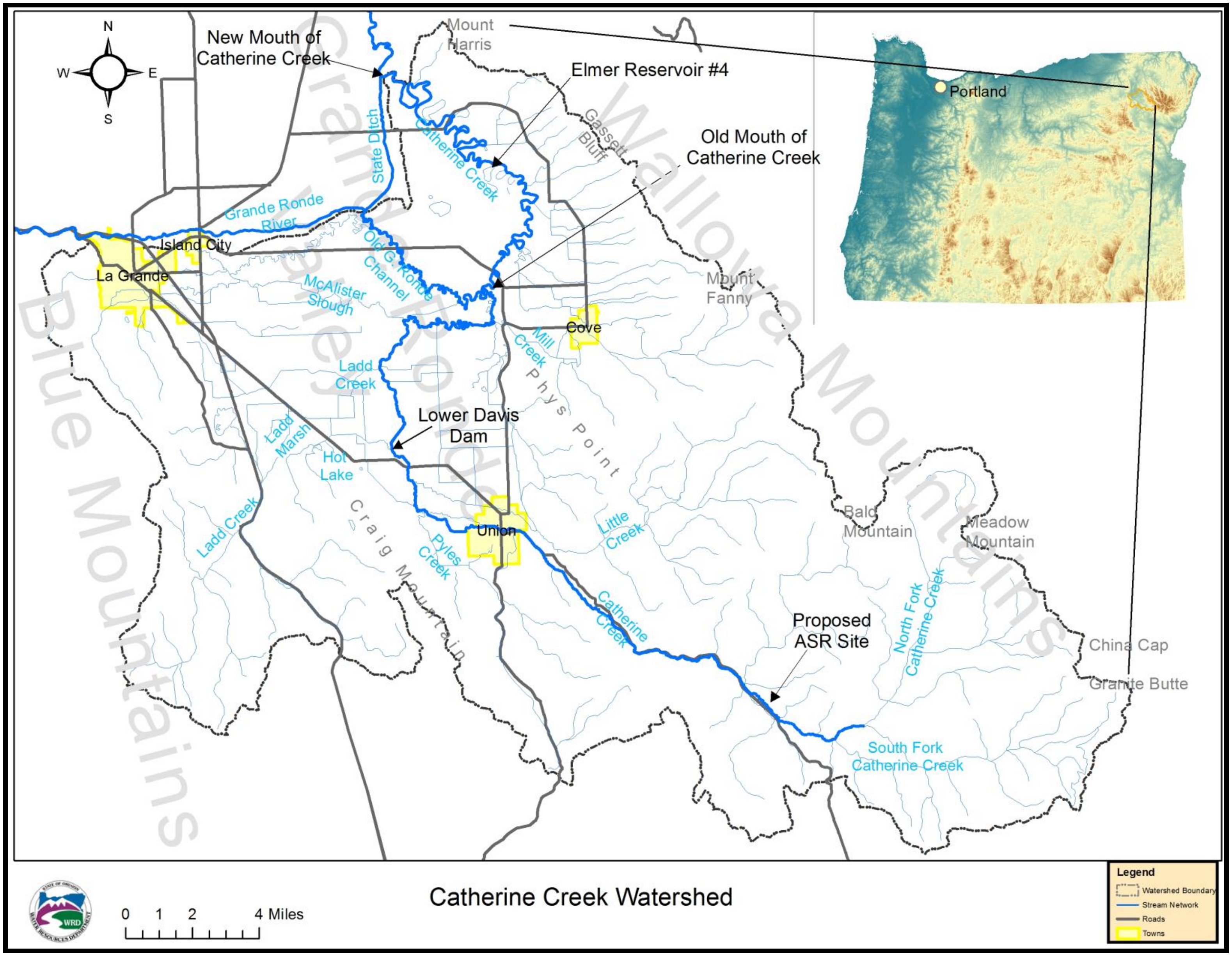

Figure 1: Catherine Creek watershed location and topographic features.

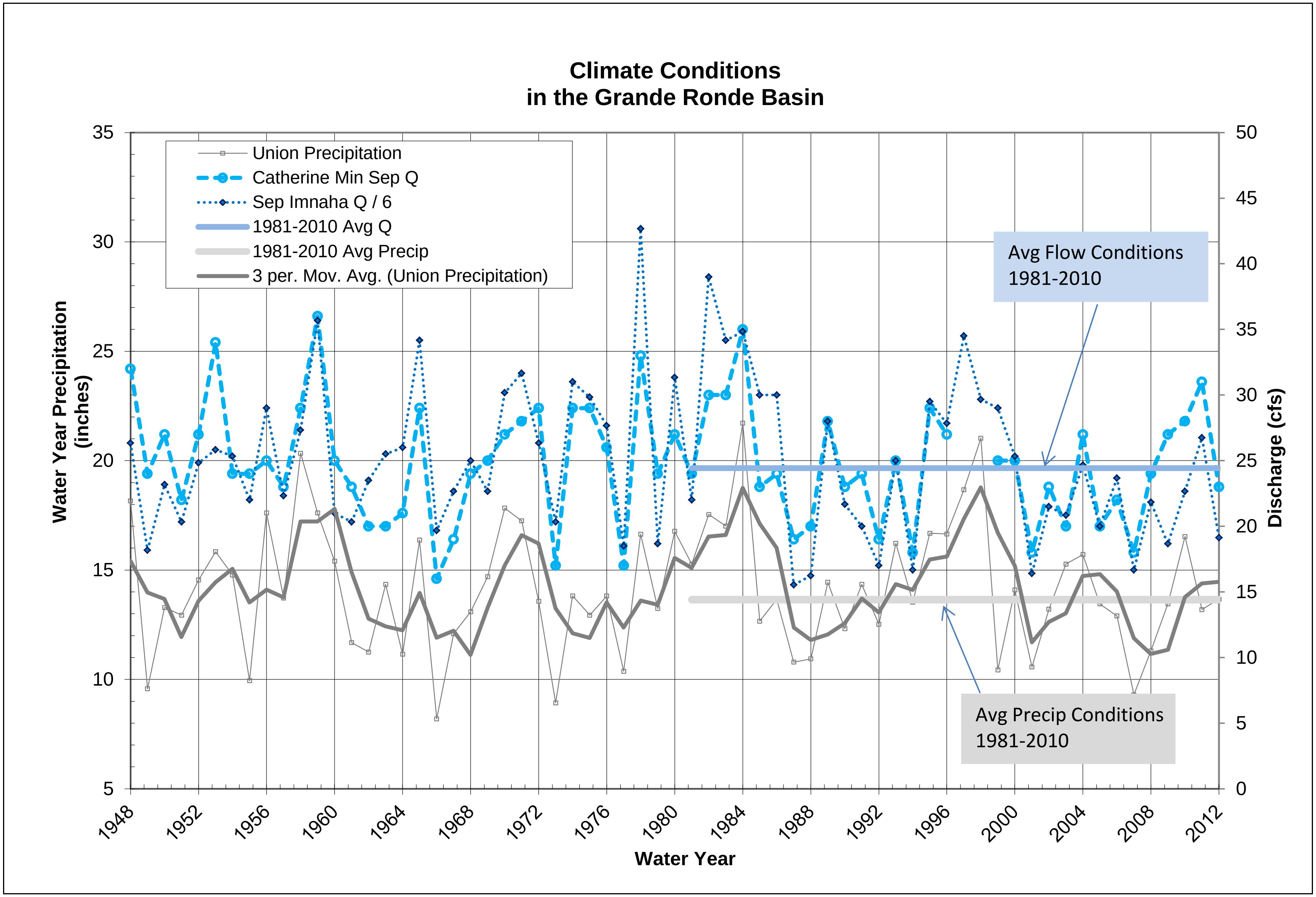

Figure 2: Climate conditions in the Grande Ronde area as depicted by Catherine Creek and Imnaha River September minimum flows (baseflows) and precipitation values and trends at Union Oregon.

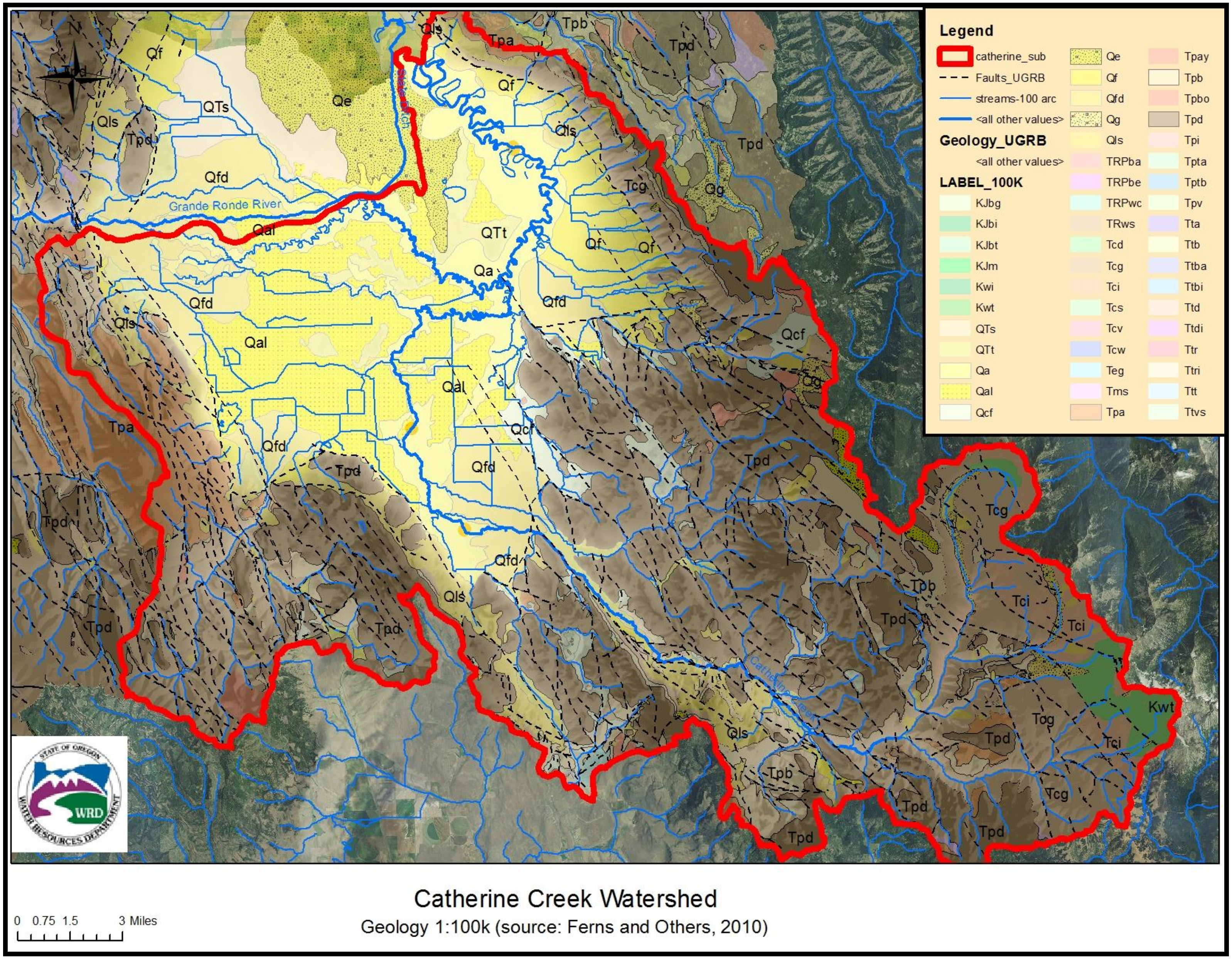

Figure 3: 1:100k Catherine Creek Watershed Geologic Map (from Ferns and Others, 2010)

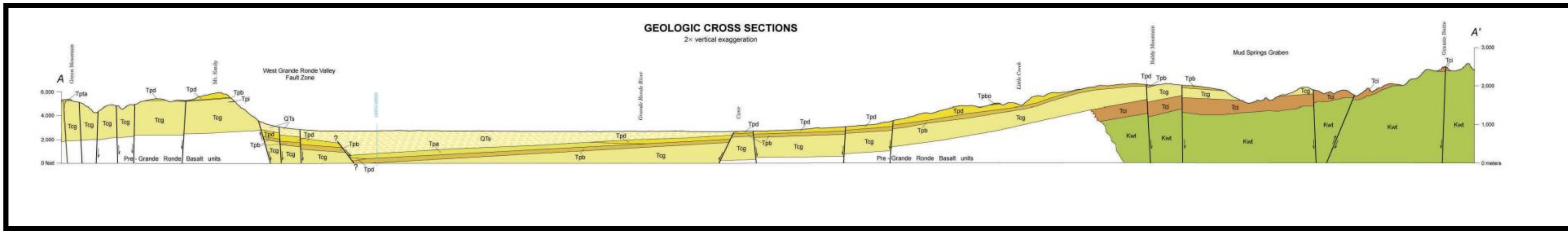

Figure 4: Geologic Cross section of upper Grande Ronde Basin (from Ferns and Others, 2010).

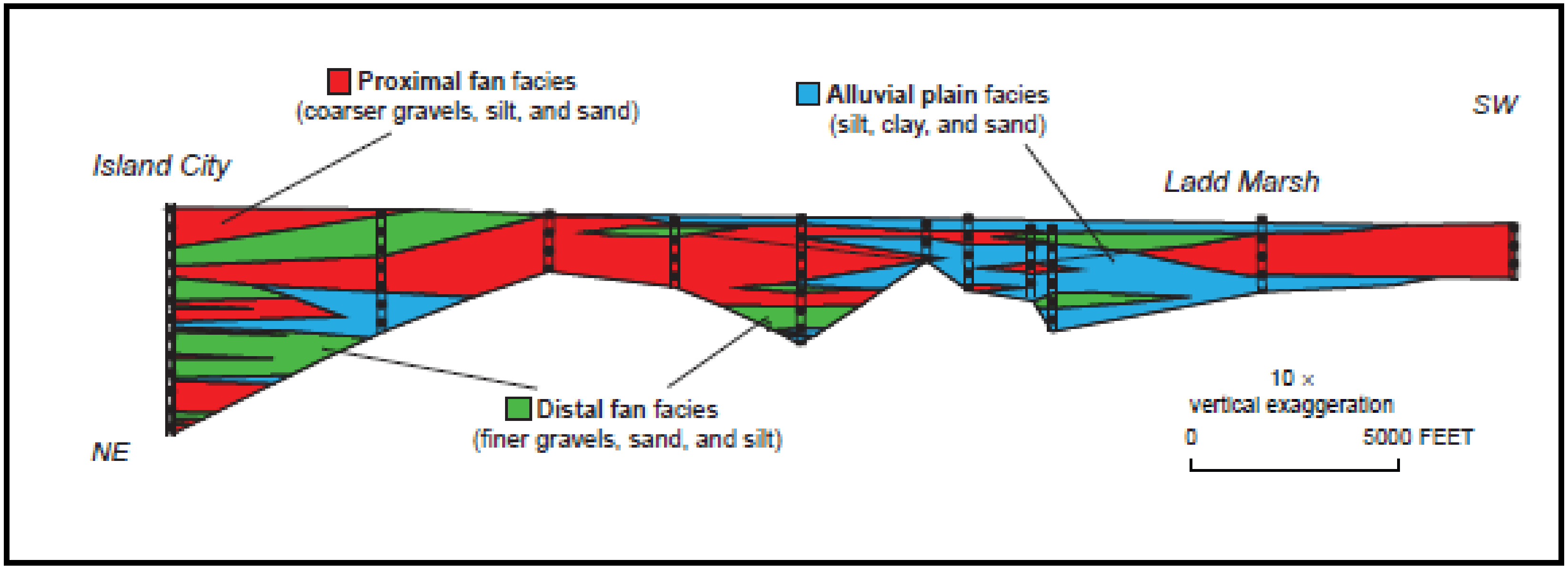

Figure 5: Example of subsurface variability in sediment deposits in the Grande Ronde Valley (from Ferns and Others, 2010).

South North

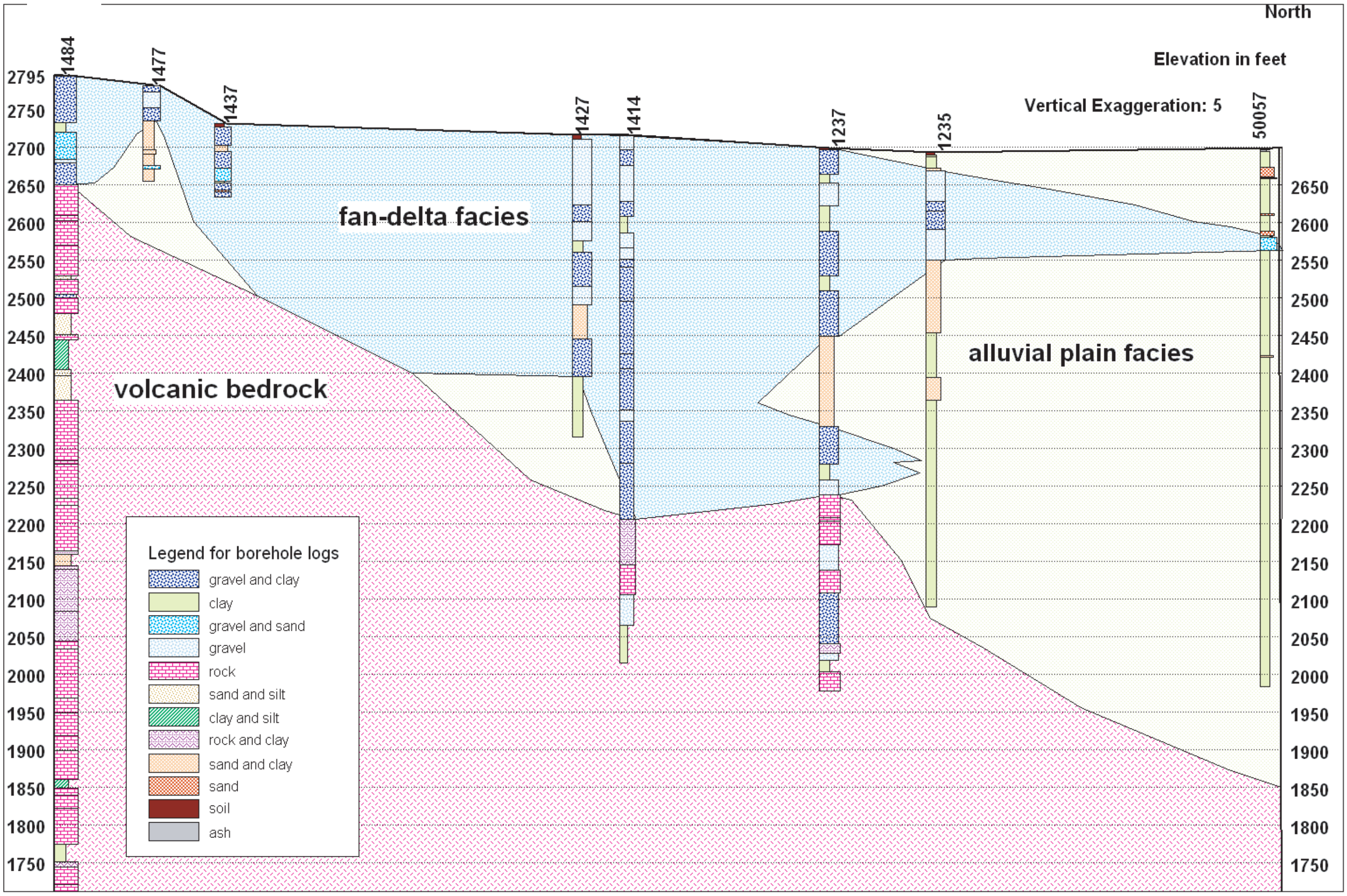

Figure 6: Schematic facies across the Catherine Creek fan delta (from Ferns and others, 2001).

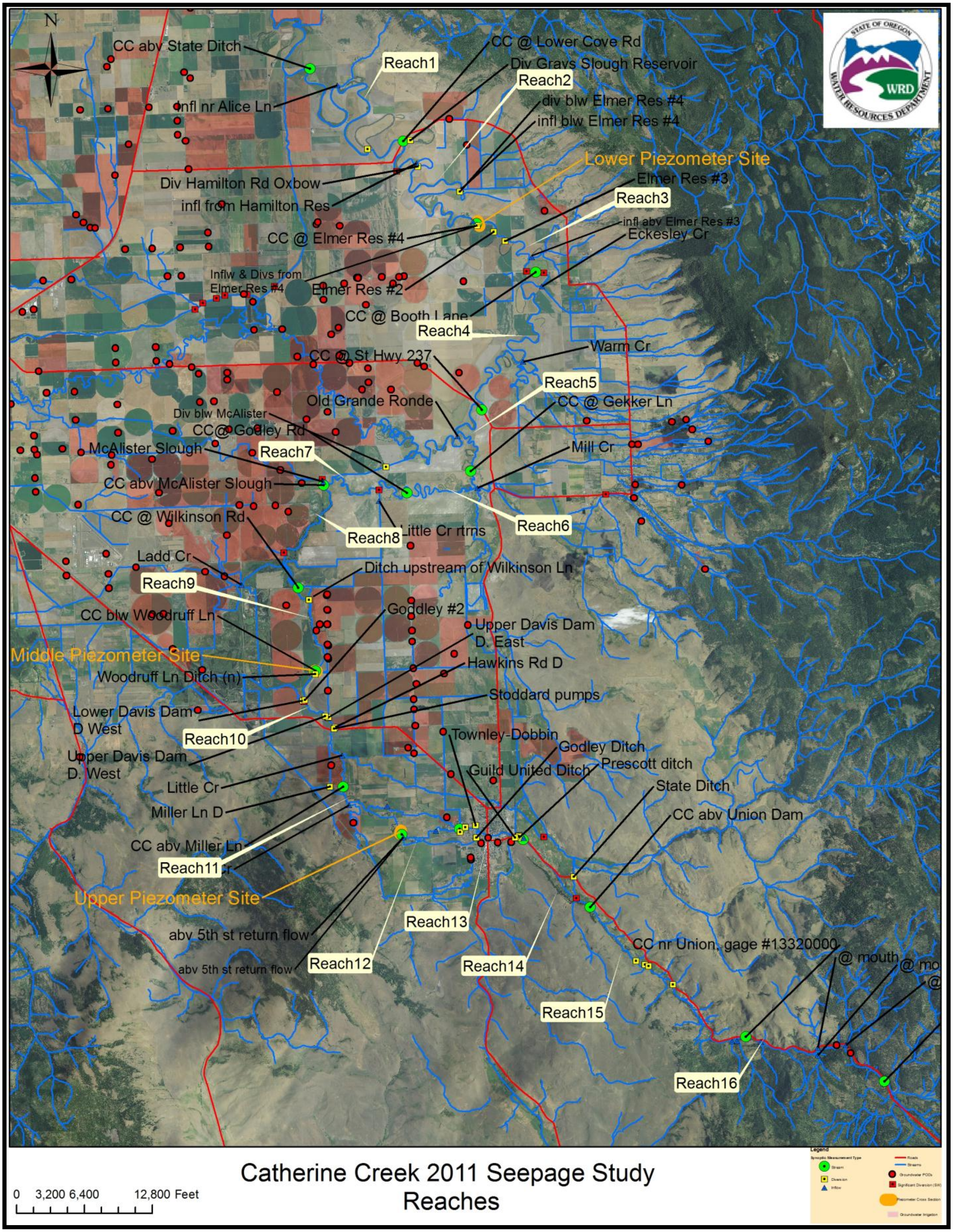

Figure 7: Catherine Creek measurement and piezometer cross section locations.

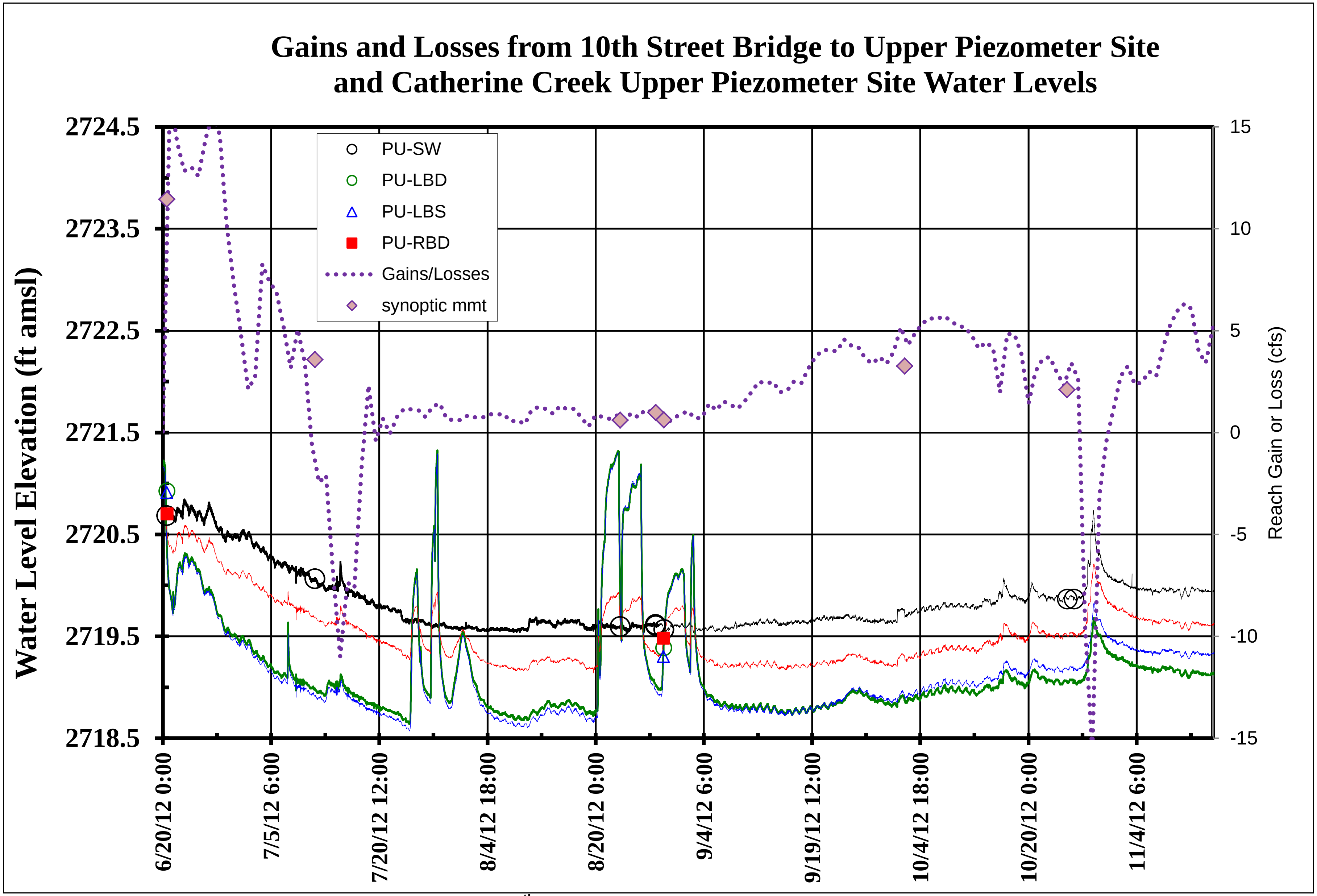

Figure 8: Groundwater exchange between the 10th street gage (#13320300) and upper monitoring site (gage #13320310). Also includes groundwater and stream stage water elevation at the upper piezometer site. LBD = left bank deep piezometer, LBS = left bank shallow piezometer, RBD = right bank piezometer, PU-SW = upper piezometer surface water.

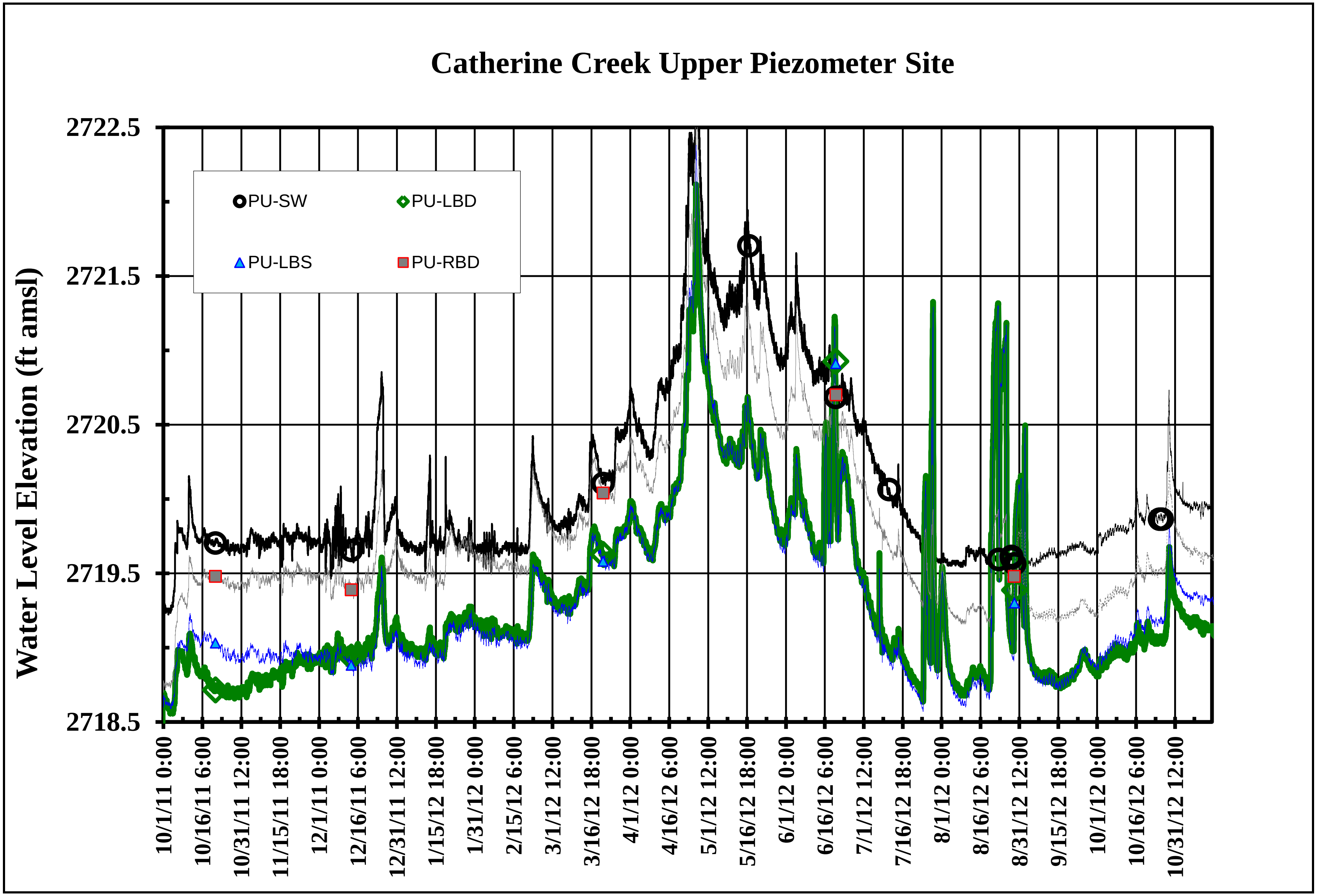

Figure 9: Groundwater elevations and stream stage at the upper piezometer site. LBD = left bank deep piezometer, LBS = left bank shallow piezometer, RBD = right bank piezometer, PU-SW = upper piezometer surface water.

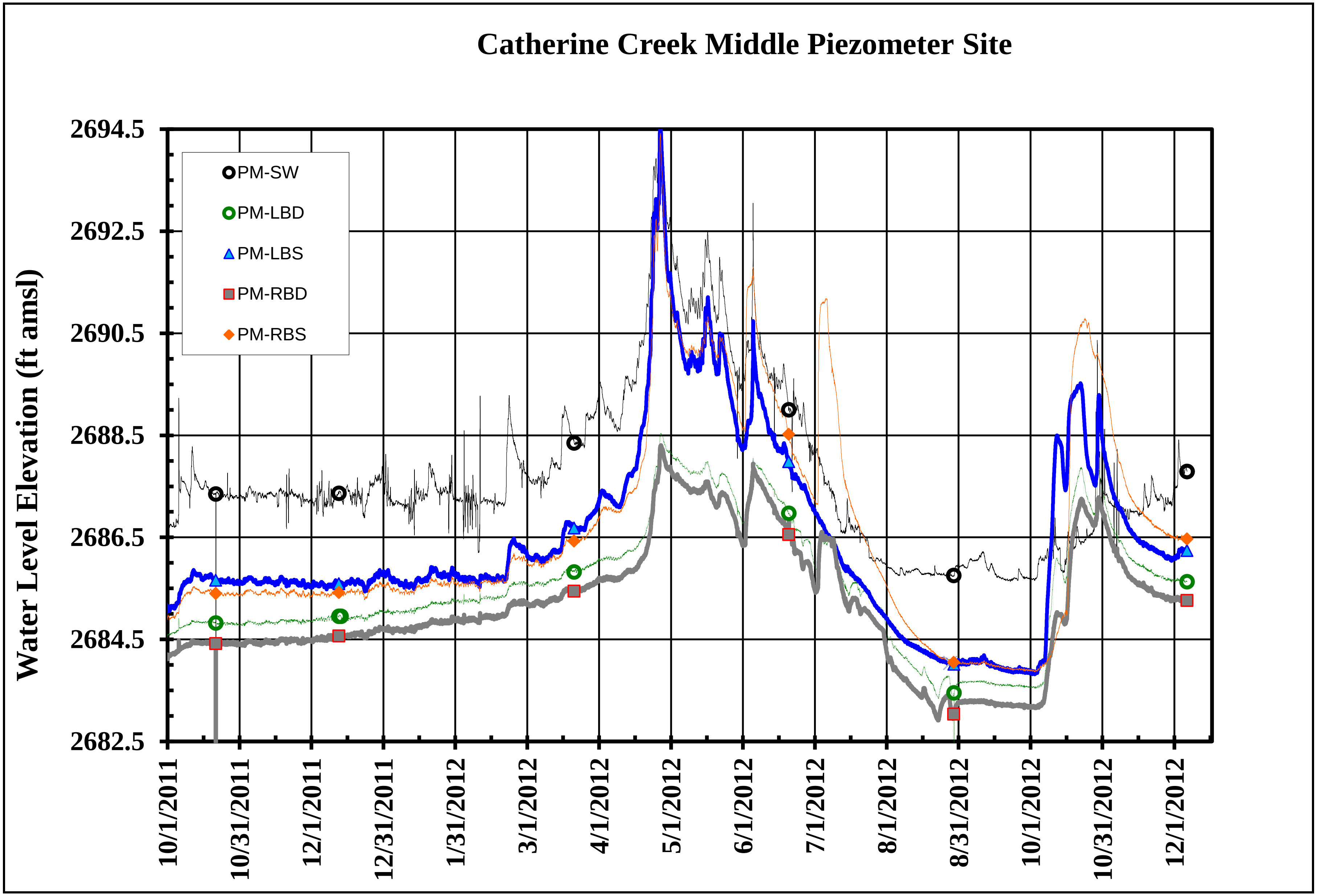

Figure 10: Groundwater elevations and stream stage at the middle piezometer site. LBD = left bank deep piezometer, LBS = left bank shallow piezometer, RBD = right bank piezometer, RBS = right bank shallow, SW = surface water.

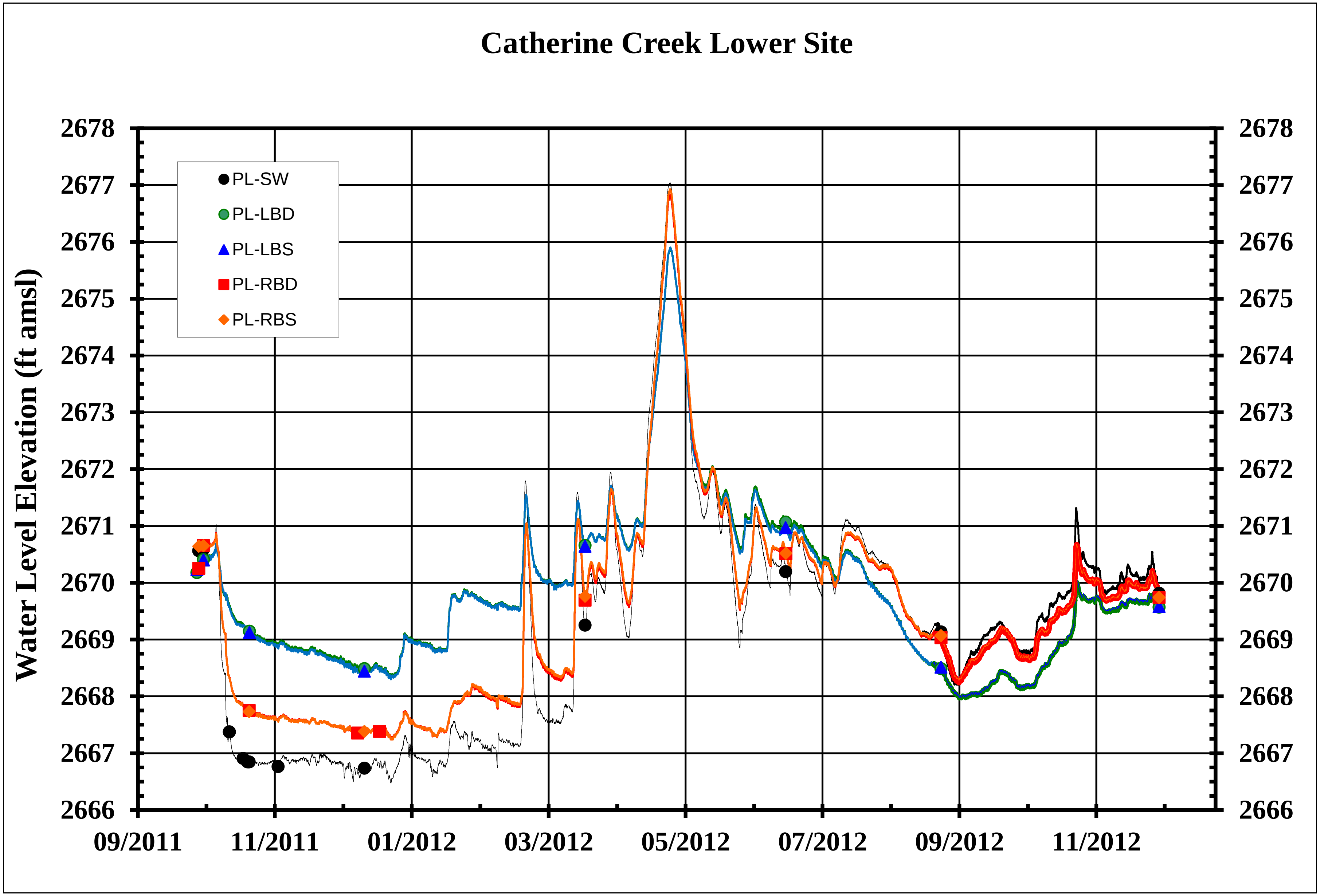

Figure 11: Groundwater elevations and stream stage at the lower piezometer site. LBD = left bank deep piezometer, LBS = left bank shallow piezometer, RBD = right bank piezometer, RBS = right bank shallow piezometer, SW = surface water.