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Evaluation of Groundwater Quality and Discharge Conditions at the Confluence of Deep Creek with the Spokane River



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Cover photo: Deep Creek, just above its confluence with the Spokane River, during an unusually robust spring runoff event, March 22, 2017. Photo taken, looking upstream, from the footbridge shown in Figure 3 (Brian Gallagher).

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Evaluation of Groundwater Quality and Discharge Conditions at the Confluence of Deep Creek with the Spokane River

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Abstract

The Spokane River and Lake Spokane are on Washington's 303D list of impaired waters for periodic violations of surface water quality standards – notably, dissolved oxygen. Parts of these waterbodies experience significant nutrient-driven algal blooms during the summer months, which contribute to these violations. Reducing the nutrient inputs from point and non-point sources that fuel algal growth (e.g., nitrogen and phosphorus) is key to improving water quality conditions in the Spokane River.

In August 2016, the Washington State Department of Ecology undertook a study to better understand the dissolved nutrient load that potentially enters the Spokane River as direct groundwater discharge from the Deep and Coulee Creek watersheds. For this study, we used a number of instream piezometer-based field methods to evaluate the timing, magnitude, and spatial distribution of surface water/groundwater interactions at the confluence of Deep Creek with the Spokane River. Piezometers were used to:

- Measure hydraulic gradients between the creek/river and near-surface groundwater.
- Measure continuous streambed thermal profiles.
- Sample shallow groundwater just before its discharge into the creek/river.

These evaluations indicated that upwelling groundwater from the Deep and Coulee Creek watersheds discharges year round to lower Deep Creek and the Spokane River across a narrow discharge zone centered at the point where the Deep Creek channel enters the Spokane River. A Darcy flow analysis, conducted using information collected from the project instream piezometers, suggests that groundwater discharge volumes and daily mass loads of Ortho-Phosphate (OP), Dissolved Total Phosphorus (DTP), nitrate+nitrite-N and Total Persulfate Nitrogen (TPN) to the Spokane River were greatest from spring to early summer when positive streambed vertical hydraulic gradients were most pronounced.

The estimated lower and upper-bound groundwater fluxes to the Spokane River/lower Deep Creek varied seasonally and ranged from approximately 0.14 to 4.6+ ft³/s during the study period. The estimated lower and upper-bound daily mass loads to the river for OP and DTP followed a similar pattern and ranged from approximately 0.03 to 1 kg/d. The estimated lower and upper-bound daily mass loads for dissolved nitrate+nitrite-N and TPN ranged from approximately 0.5 to 17.5 and 0.4 to 13.6 kg/d, respectively.

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Many people contributed their time and effort to this study. We thank:

- Amy Walker (Washington State Parks) for arranging and providing ongoing access to the Deep Creek study site.
- Karin Baldwin (the project client), Pam Marti, Jessica Archer, and Andy Albrecht of the Washington State Department of Ecology assisted with the initial deployment of field instrumentation and subsequent data collection.
- The staff at Manchester Environmental Laboratory who provided courier and analytical laboratory support for this project.

Introduction

Over the past 20 years, the Washington State Department of Ecology (Ecology) has partnered with other government agencies, tribes, industries, and local communities to help improve dissolved oxygen conditions in the Spokane River and Lake Spokane in northeast Washington. Portions of these waterbodies experience significant algal blooms during the summer months. Left unchecked, such growth can contribute to increased biological and chemical oxygen demand, and ultimately to reductions in the amount of oxygen available to support fish and other aquatic life.

Reducing the nutrient inputs that fuel algal growth (e.g., nitrogen and phosphorus) is key to improving water quality conditions in the Spokane River. To this end, Ecology's 2010 Spokane River Dissolved Oxygen Total Maximum Daily Load (DO TMDL) report requires the following water quality improvements:

- Remove 90+ percent of total phosphorus from Washington's point source discharges to the river.
- Reduce up to half of the nutrients from nonpoint sources in Hangman and Coulee Creeks, the Little Spokane River, and surrounding Lake Spokane.

During development of the water quality model that supported the Spokane River DO TMDL, Ecology modelers assumed the water quality of Deep and Coulee Creeks was similar to Hangman Creek, which joins the Spokane River a few miles upstream of Deep Creek (Figure 1). However, data collected since the model was developed indicates this assumption was incorrect. Another confounding factor is that unlike Hangman Creek, both Deep and Coulee Creek typically infiltrate into the ground (i.e., dry up) a few miles above their confluence with the Spokane River. Accordingly, they provide measurable surface flow to the Spokane River only during periods of significant snowmelt or infrequent rain-on-frozen-ground events.

To better understand the dissolved nutrient load that potentially enters the Spokane River from the Deep and Coulee Creek watershed, Ecology undertook a study in August 2016 to characterize groundwater discharge conditions at the mouth of Deep Creek and to sample discharging groundwater for selected nutrients. This report describes the approach and results of this investigation.

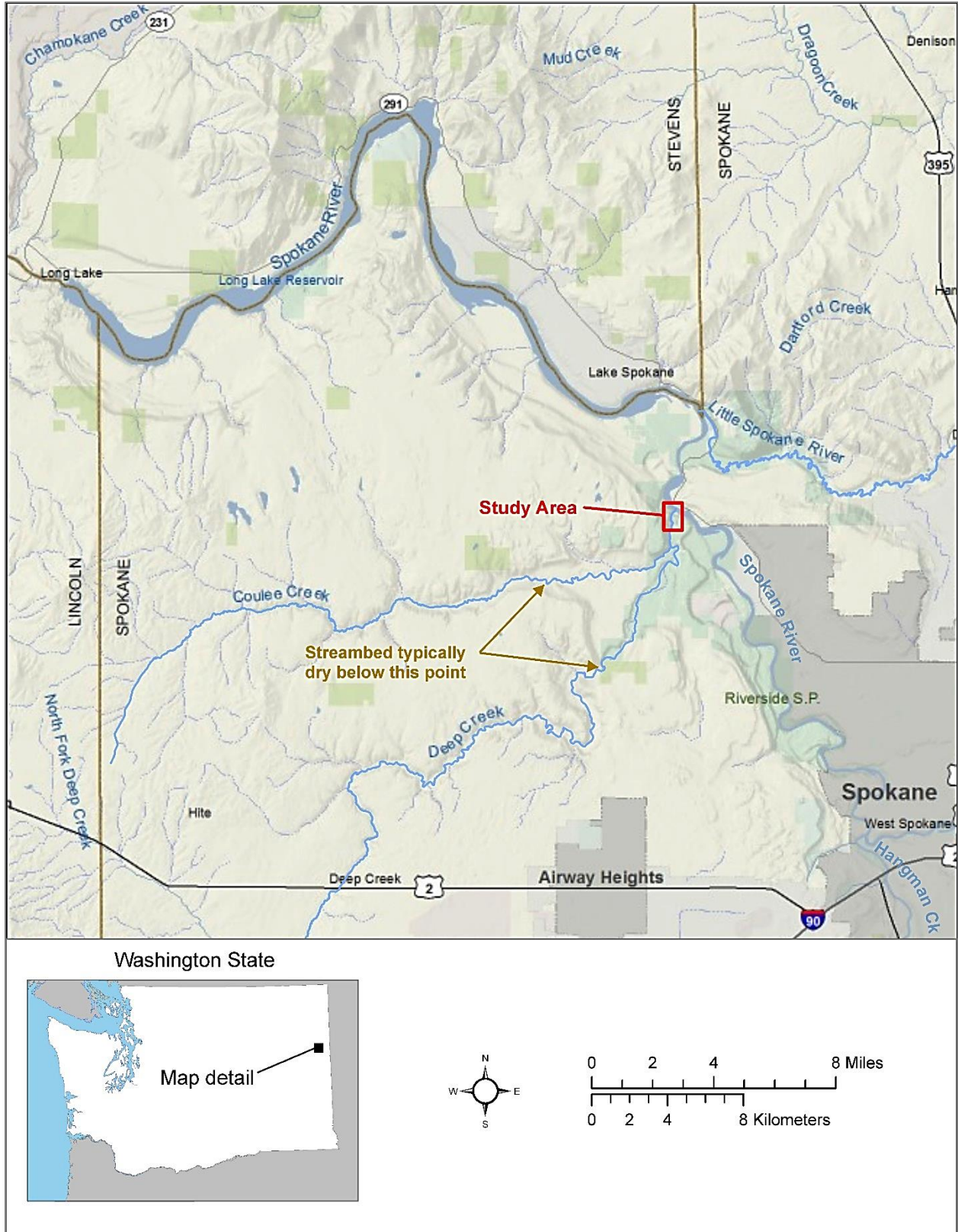


Figure 1: Study area location.

Study Area Description and Hydrogeologic Setting

The greater Deep and Coulee Creek watersheds encompass approximately 173 square miles (mi²) of mostly agricultural and rural residential land west of the City of Spokane. The creeks originate on buttes west of Spokane and flow northeast for several miles across a rolling basalt plain that spans the region between their headwaters and the Spokane River. Coulee Creek merges with Deep Creek approximately one mile above Deep Creek's confluence with the Spokane River (Figure 2).

Previous investigations by GeoEngineers (2011) and Spokane County (2013) suggest that Deep Creek and Coulee Creek share a complex hydrology. The upper reaches of both creeks are comprised of interspersed gaining and losing stream segments but are largely perineal due to groundwater that enters the creeks from aquifers contained within the adjacent and underlying Wanapum Basalts. Streamflow gains are most pronounced where groundwater levels in the Wanapum basalt aquifers typically exceed (i.e., are higher than) the elevation of the streambed.

Both Deep Creek and Coulee Creek tend to lose flow in their mid-to-lower reaches, where groundwater levels in the underlying Grande Ronde formation basalts generally lie below the elevation of the creek bed. Both creeks eventually go dry, during most years, where they flow across a thick sequence of flood deposits that fill the creek channel a few miles above their confluence with the Spokane River (Figure 2). Direct surface flow to the Spokane River from the Deep and Coulee Creek watersheds is minimal and is often restricted to the spring snowmelt period or infrequent rain-on-snow/frozen-ground events.

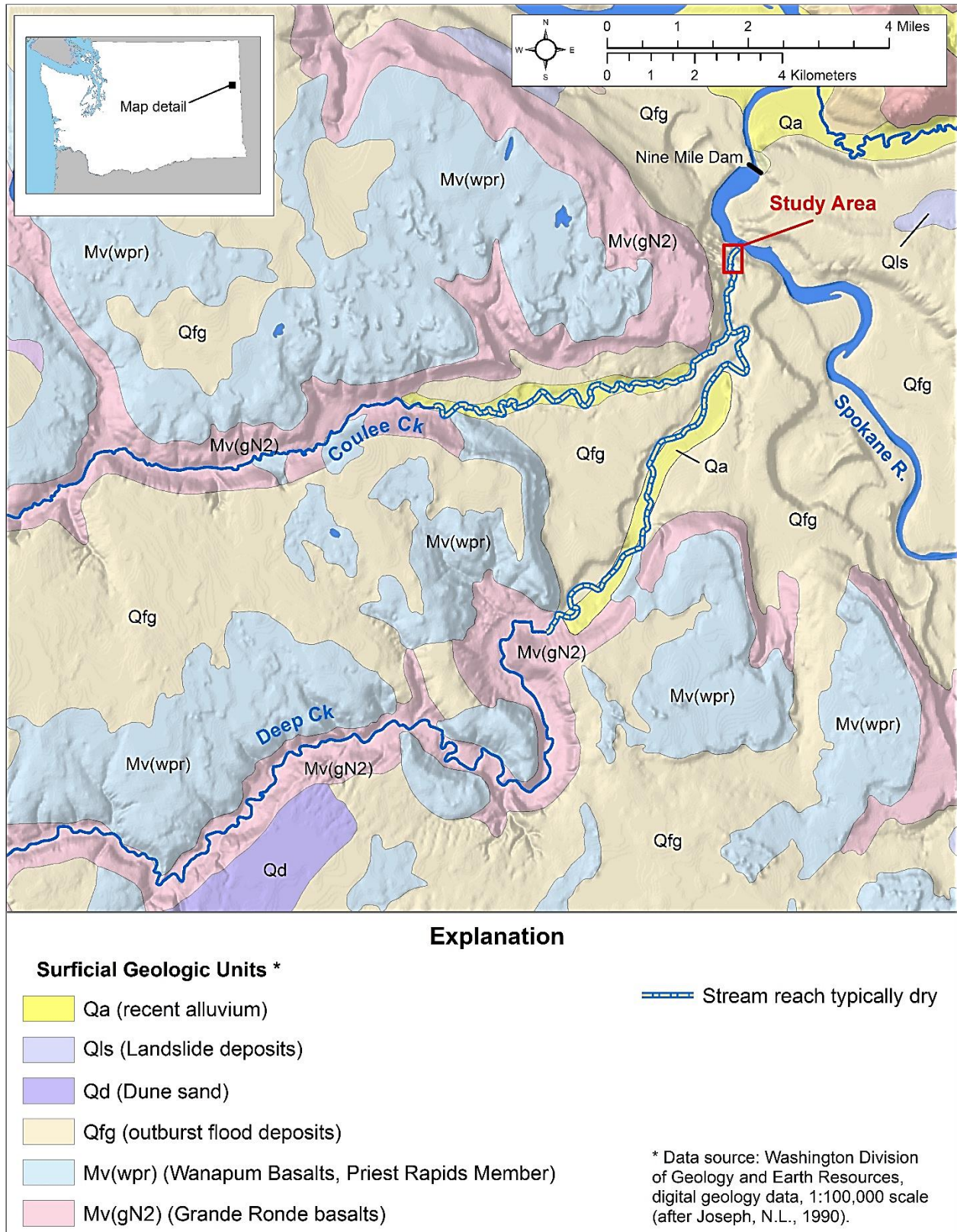


Figure 2: Surficial geology of the lower Deep and Coulee Creek drainages.

Study Methods

For this study, we used a number of instream piezometer-based field methods to evaluate the timing, magnitude, and spatial distribution of surface water/groundwater interactions at the confluence of Deep Creek with the Spokane River. Piezometers were used to:

- Measure hydraulic gradients between the creek/river and near-surface groundwater.
- Measure continuous streambed thermal profiles.
- Sample shallow groundwater just prior to its discharge into the creek/river.

Each of these field methods and analytical techniques are described in detail below.

Instream Piezometers

In mid-August 2016, we installed three shallow instream piezometers near the confluence of Deep Creek and the Spokane River using methods described by Sinclair and Pitz (2009) (Figure 3). The piezometers consisted of a lower 5-foot section of 1.5-inch diameter galvanized steel pipe and an upper removable 2-foot extension (Figure 4 and Appendix B, Table B-1). They were installed into the streambed to a maximum depth of about 5 feet. These piezometers were used to monitor:

- Surface water/groundwater head relationships.
- Streambed water temperatures.
- Near-stream groundwater quality.

After installation, the piezometers were developed with a manual bladder pump to ensure good hydraulic connection with the streambed sediments. Piezometers were accessed approximately monthly, when flows permitted, to make comparative stream and groundwater hydraulic head measurements. The stream stage (hydraulic head) was measured by aligning an engineer's tape parallel to the piezometer pipe and measuring the distance from the stream water surface to the top of the piezometer casing. The groundwater level inside the piezometer was measured from the same reference point, using a calibrated low-displacement E-tape or steel hand tape (Marti, 2018). For angled (off-vertical) piezometers, these "raw" field values were corrected using simple trigonometric relationships to obtain true (angle normalized) depth-to-water measurements.

The water level difference, represented by the inside and outside of pipe measurements, indicates the direction and magnitude of the local hydraulic potential between the stream and underlying groundwater. When the piezometer head exceeds (is higher than) the stream stage, groundwater flow into the stream can be inferred. Similarly, when the stream stage is higher than the groundwater level in the piezometer, loss of water from the stream to groundwater can be inferred.



Figure 3: Study area detail and sampling locations.

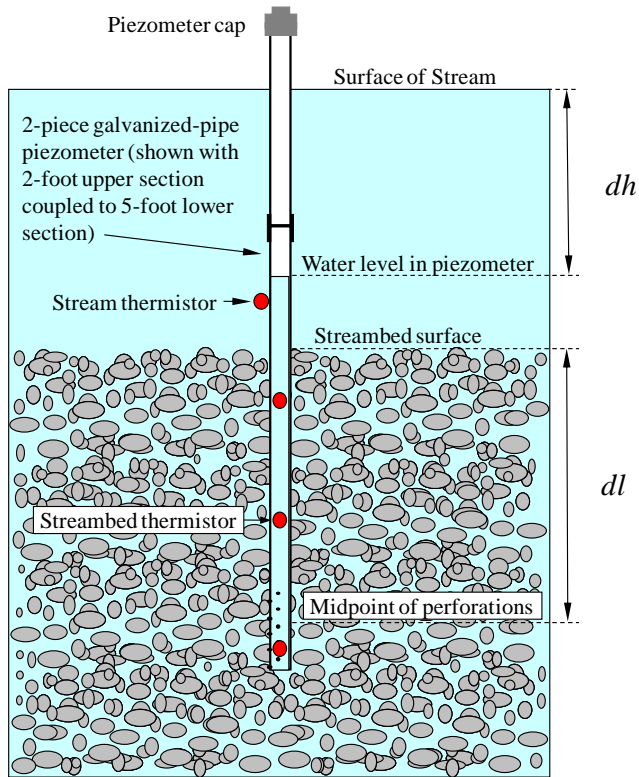


Figure 4: Schematic of a typical instream piezometer and thermistor array.

Equation 1 (below) was used to derive vertical hydraulic gradients for each piezometer, from the paired groundwater level and stream stage measurements that were made during monthly site visits. Converting the field-measured water levels to hydraulic gradients normalizes for differences in piezometer depth and screen interval between sites, thereby enabling direct comparisons to be drawn between piezometers.

$$i_v = \frac{dh}{dl} \quad \text{(Equation 1)}$$

Where:

i_v is vertical hydraulic gradient (dimensionless),

dh is the difference in head between the stream stage and instream piezometer water level (L),

dl is the distance from the streambed surface to the mid-point of the piezometer perforations (L), and

where (L) represents units of length.

By convention, negative hydraulic gradient values indicate potential loss of water from the creek to groundwater, while positive values indicate probable groundwater discharge into the creek.

In addition to measuring water levels, the piezometers were also used to conduct constant head injection tests (CHIT) to estimate the vertical hydraulic conductivity of the streambed sediments at each piezometer site¹. To perform the tests, a constant head chamber was attached to the piezometer casing using a standard pipe coupler (Figure 5).

Water was then added to the chamber from an adjacent graduated reservoir at a rate equal to or slightly greater than the piezometer's ability to take water. Field measurements of the operating head (y), the net injection rate (Q), and piezometer construction information were used as inputs to a spreadsheet model that solves Equation 2 (below) (Pitz, 2006; Cardenas and Zlotnik, 2003).

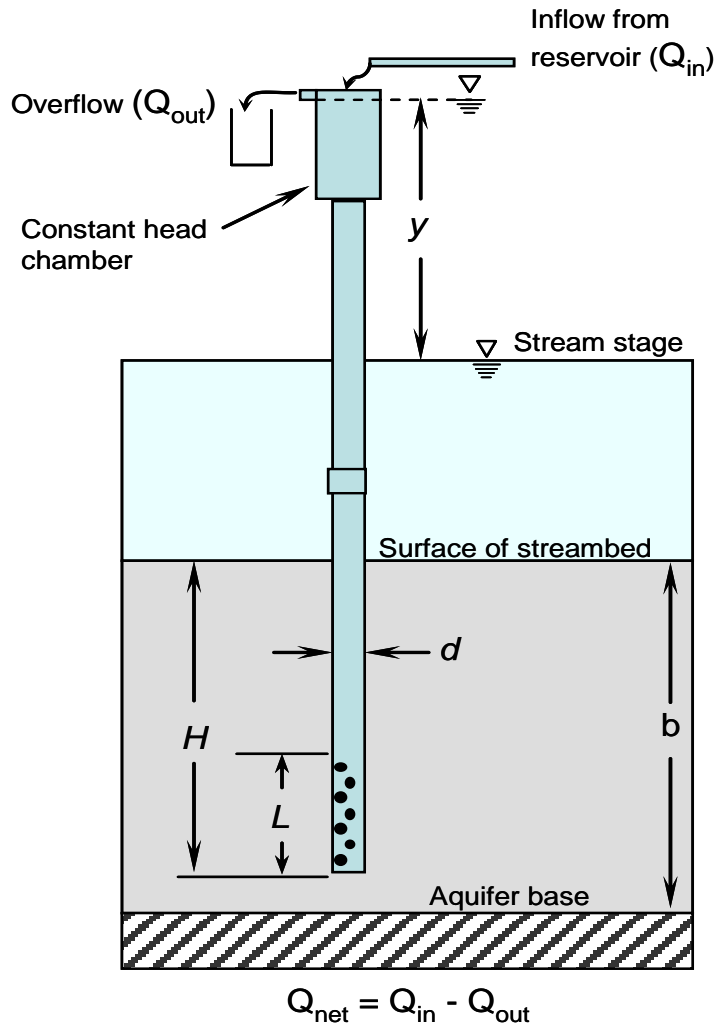


Figure 5: Schematic of the constant head injection test (CHIT) apparatus and field measurements (adapted from Pitz, 2006).

¹ See Cardenas and Zlotnik (2003) for a detailed discussion of the CHIT method and its limiting assumptions.

$$K = \frac{Q}{2\pi LPy} \quad \text{(Equation 2)}$$

Where:

- K is the isotropic hydraulic conductivity of the streambed sediments adjacent to the piezometer open interval (L/t),
- Q is the net injection rate required to maintain a constant head within the piezometer (L³/t),
- L is the length of the piezometer open interval (L),
- P is the well shape factor (see Cardenas and Zlotnik, 2003 for the derivation of this term),
- y is the height of the constant head above the stream surface (L), and

where (L) represents units of length and (t) represents units of time.

The CHIT test results are shown in Appendix B, Table B-2 by piezometer.

Thermal Profiling of Streambed Sediments

Streams and rivers commonly experience pronounced (several degree) daily fluctuations in water temperature due to variations in atmospheric and solar heating over the course of a day. In contrast, groundwater generally shows little if any diurnal temperature variability since it is typically insulated from the sun and atmosphere by overlying rock or sediment. These differences in daily temperature pattern, between a stream and near-surface groundwater, can be monitored to provide secondary confirmation of the surface water/groundwater interactions inferred from periodic hydraulic gradient measurements.

For this project, we instrumented each instream piezometer with three recording thermistors to monitor groundwater temperatures within the upper 4 to 5 feet of the streambed sediments. Thermistors were placed so that:

1. One lay near the piezometer bottom within the perforated interval of the pipe.
2. One was approximately 0.5 to 1 foot below the streambed, and.
3. One roughly equidistant between the upper and lower thermistors.

A fourth thermistor was mounted to the outside of the piezometer to monitor the stream temperature (Figure 4).

At piezometer sites where streambed water temperatures are highly dampened relative to instream temperatures, one can infer that groundwater is moving upward through the streambed and discharging to the stream (a gaining stream reach) (Figure 6A). Conversely, at sites where streambed water temperatures closely mimic those of the stream, one can infer that water is

leaving the stream and moving down into the streambed at that location (a connected losing reach) (Stonestrom and Constantz, 2003) (Figure 6B).

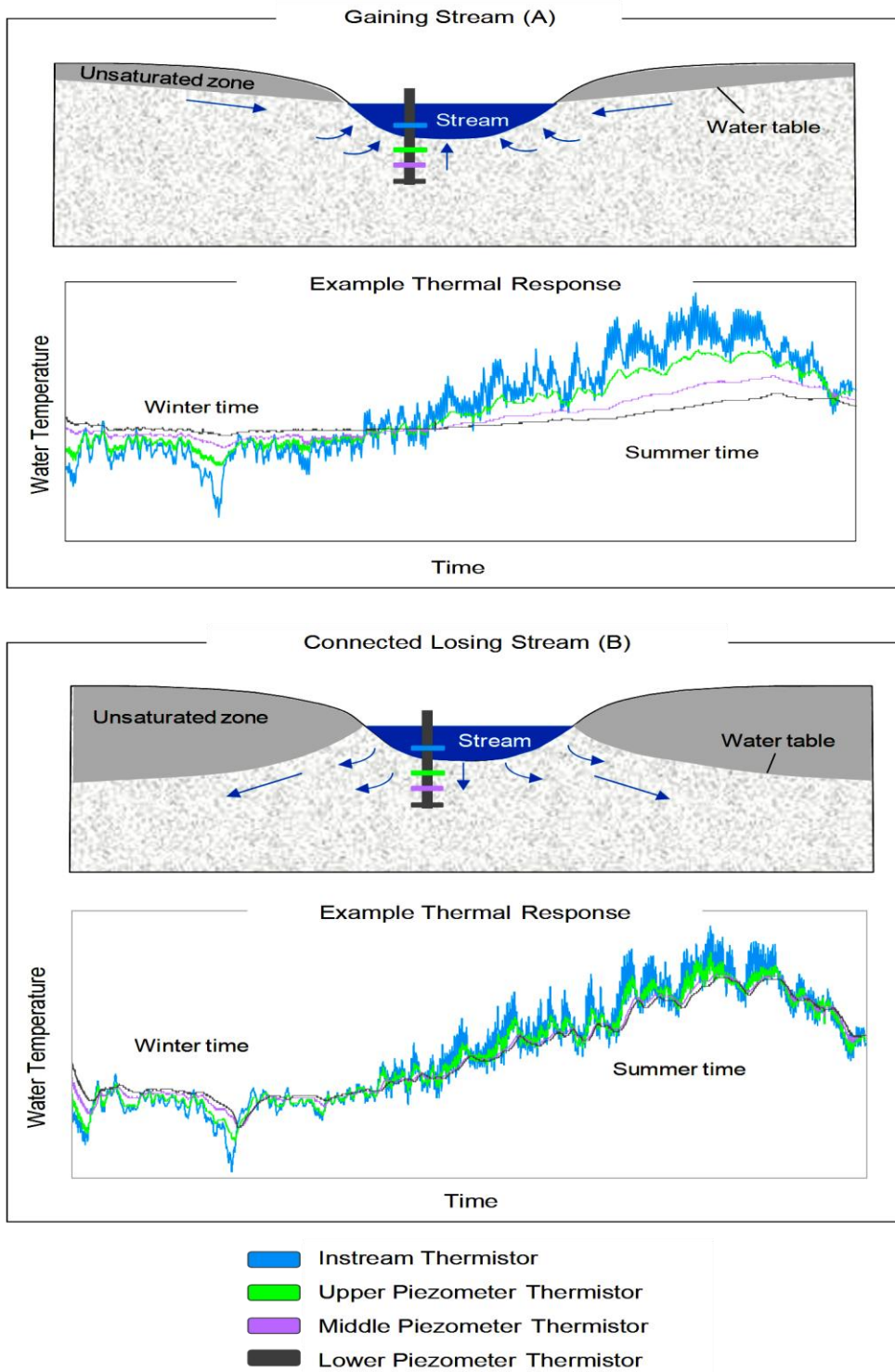


Figure 6: Example streambed thermal response for a perennial gaining (A) and losing (B) stream.

Water Quality Sampling

We collected groundwater samples from the project piezometers on four occasions between September 2016 and August 2017. Samples were collected to determine concentrations of phosphorous and nitrogen-based nutrients in upwelling groundwater and to estimate nutrient loading to lower Deep Creek and the Spokane River. We also collected surface water samples from Deep Creek on five occasions (at the point where defined surface flow was first evident above the upper-most piezometer) and from the Spokane River just upstream of Deep Creek, on three occasions (Figure 3). All sampled sites were evaluated for field parameters and a small suite of laboratory-analyzed constituents (Table 1).

Table 1: Target analytes, test methods, and method detection limits.

<i>Field-measured parameter</i>	<i>Test method</i>	<i>Reporting limit</i>
Water level	Calibrated E-tape	0.1 foot
Temperature	Alcohol Thermometer	0.1°C
Specific Conductance	Hydrolab MS-5	1 µS/cm
pH	Hydrolab MS-5	0.1 SU
Dissolved Oxygen	Hydrolab MS-5	0.1 mg/L
<i>Laboratory-measured parameter</i>	<i>Test method</i>	<i>Reporting limit</i>
Alkalinity¹	SM2320B	5 mg/L
Chloride¹	EPA300.0	0.1 mg/L
Orthophosphate¹	SM4500PG	0.003 mg/L
Total phosphorus¹	SM4500PH	0.005 mg/L
Nitrate+nitrite-N¹	SM4500NO3I	0.01 mg/L
Ammonia¹	SM4500NH3H	0.01 mg/L
Total persulfate nitrogen-N¹	SM4500NB	0.025 mg/L
Dissolved organic carbon¹	SM5310B	1 mg/L

¹ Dissolved fraction
SU – Standard units

Both the piezometer and surface water sites were sampled using a peristaltic pump and a length of new ¼-inch high-density polyethylene (HDPE) tubing. When sampling piezometers, the installed thermistor string was first removed and set aside. One end of the HDPE tubing was inserted into the piezometer until it abutted the casing perforations. The other end of the tubing was connected to a peristaltic pump via a short length of clean silastic tubing. The pump discharge was routed through a closed-atmosphere flow cell connected to a Hydrolab® model MS-5 multimeter to enable field parameters to be evaluated.

Piezometers were purged at a maximum rate of 0.3 to 0.5 L/min. To ensure fresh formation water was being sampled, purging continued until the difference in measured field parameter values for 2 successive 3-minute measurement periods differed by less than 5 percent. At the completion of purging, the pump discharge line was disconnected from the flow cell and attached to a 0.45 micron in-line-capsule filter. An additional 500 milliliters (ml) of water was

purged through the filter before commencing with sample collection. The surface water samples from Deep Creek and the Spokane River were collected and filtered in similar fashion to the piezometer samples, to ensure consistency in data collection across sites. Filled sample bottles were tagged and stored on ice pending their arrival at the laboratory.

Study Results

Surface Water/Groundwater Interactions

Figure 7 provides a visual summary of the vertical hydraulic gradients and streambed thermal profiles measured at the three instream piezometers installed for this project. The two Deep Creek piezometers showed a persistent pattern of positive hydraulic gradients² (Figures 7B and 7C), suggesting that groundwater from the greater Deep and Coulee Creek watersheds discharged as baseflow to the lowermost reach of Deep Creek throughout the study period. Gradients in the two piezometers were quite similar in both pattern and magnitude. Gradients at the upper piezometer (AHL155) ranged from 0.002 to 0.037 and averaged 0.017 ft/ft, while gradients in the lower piezometer (AHL154) ranged from 0.0 to 0.055 and averaged 0.015 ft/ft. The streambed thermal profiles at these sites exhibited stable and essentially flat signatures during most of the study period³, which is consistent with groundwater discharge conditions. Viewed together, the thermal profiles and hydraulic gradients at these sites indicate that Deep Creek consistently gained flow from groundwater discharge near (or at) its confluence with the Spokane River during the study period.

In contrast, the vertical hydraulic gradients in the Spokane River piezometer (AHL153, Figure 7A) were more varied and ranged from -0.008 to 0.007 and averaged 0.0 ft/ft. The piezometer exhibited mostly neutral-to-negative gradients between August 2016 and early February 2017 before transitioning to mostly positive gradients following a late February 2017 runoff event that resulted in significant surface discharge from Deep Creek to the Spokane River for several weeks. There was a tandem increase in the hydraulic gradients for the two Deep Creek piezometers during the spring 2017 runoff event, as well, indicating an increase in groundwater discharge to lower Deep Creek during this period. The streambed thermal profile at the Spokane River piezometer exhibits characteristics of both gaining and losing conditions; supporting the dynamic nature of water exchanges inferred from periodic hydraulic gradient measurements at this site.

² Positive hydraulic gradients (indicating discharge conditions) are indicated by green symbols on Figure 7. Negative gradients (indicating loss of streamflow to groundwater) are represented by red symbols. Neutral gradients (indicating no net exchange of water between the creek and groundwater) are represented by orange/yellow symbols.

³ Beginning in late February 2017, the thermal profiles at all of the project piezometers show a marked shift and muting of signals due to an unusual runoff event in Deep Creek that resulted in burial of the instream thermistors and an effective deepening of the in-piezometer thermistors relative to their initial placement depths.

Figure 7A: Instream Piezometer AHL153 (Spokane R. at Deep Ck Terminus)

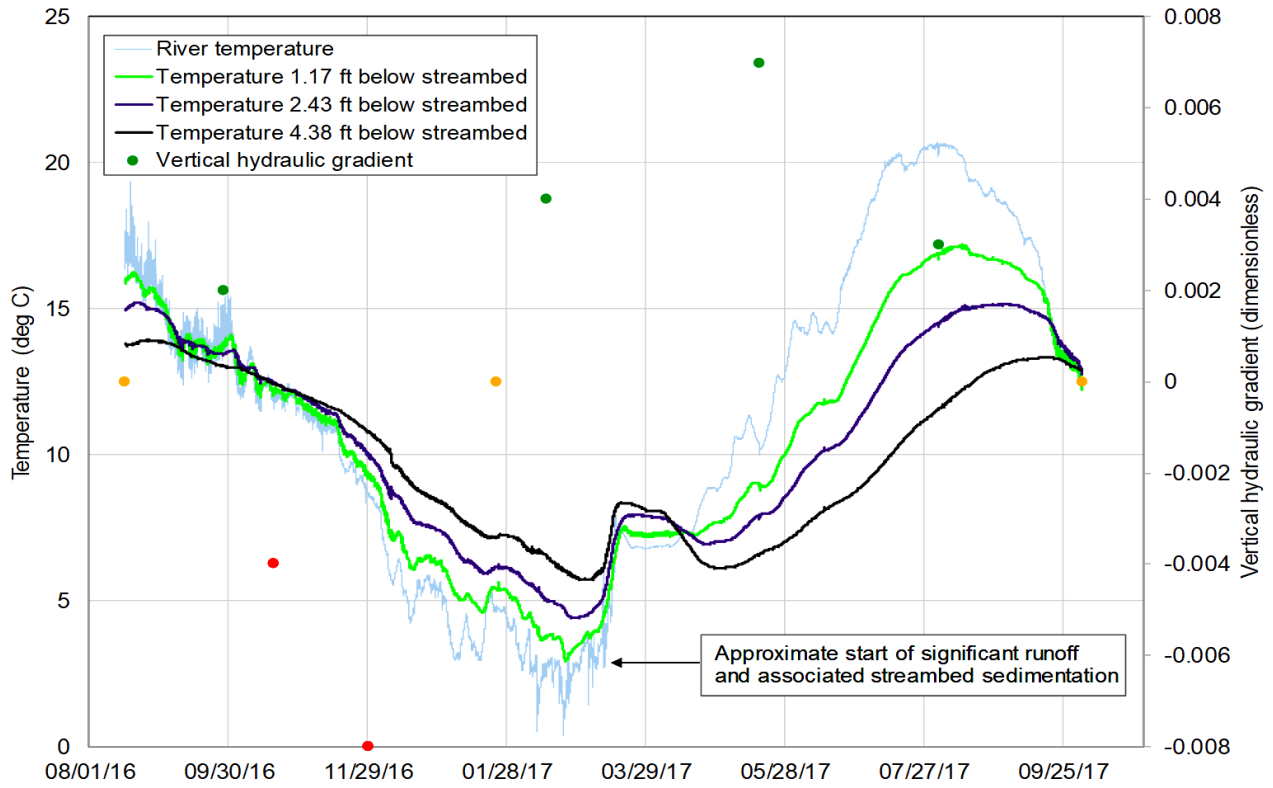


Figure 7B: Instream Piezometer AHL154 (Deep Ck Lowermost)

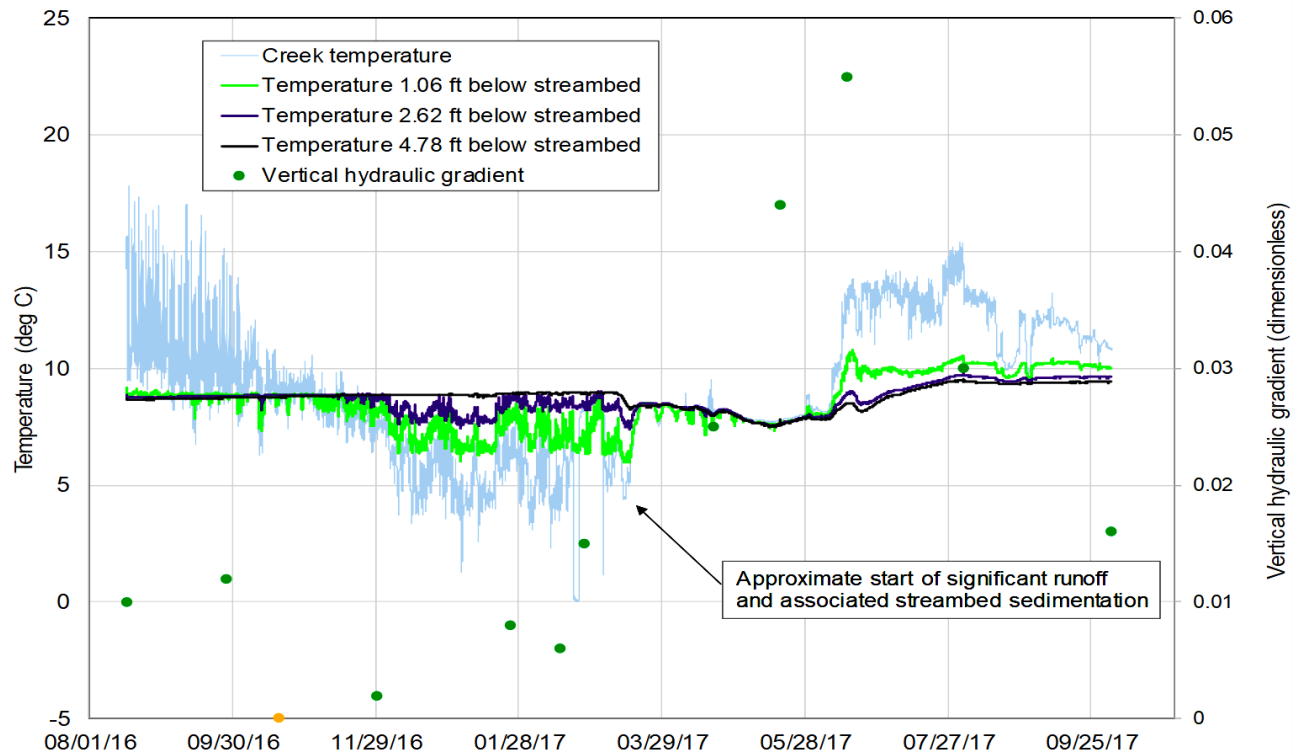


Figure 7C: Instream Piezometer AHL155 (Deep Ck Uppermost)

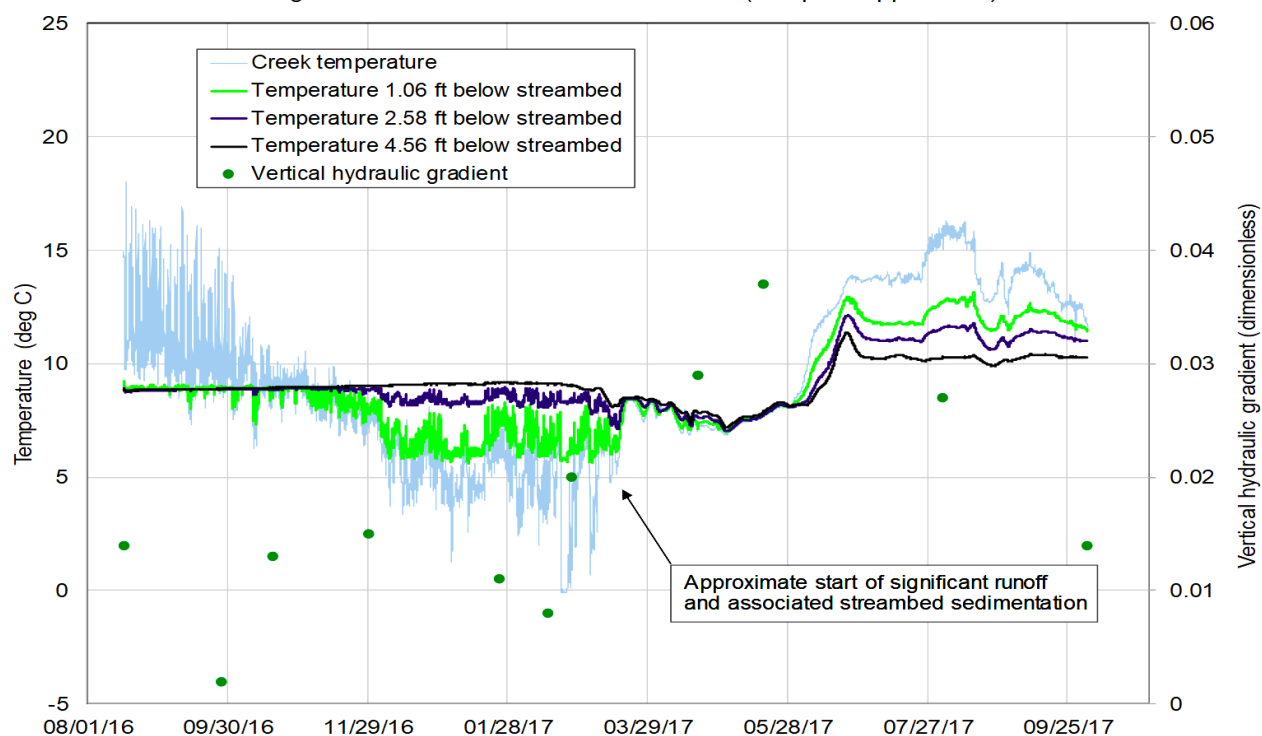


Figure 7: Chart of streambed vertical hydraulic gradients and thermal profiles at instream piezometers AHL153, AHL154, and AHL155.

Viewed together, these results suggest that groundwater from the Deep and Coulee Creek watersheds discharges, year round, as baseflow to the lowermost reach of Deep Creek just above its confluence with the Spokane River. The discharge is greatest along the lower few hundred feet of Deep Creek proper and diminishes with proximity to the Spokane River.

Water Quality

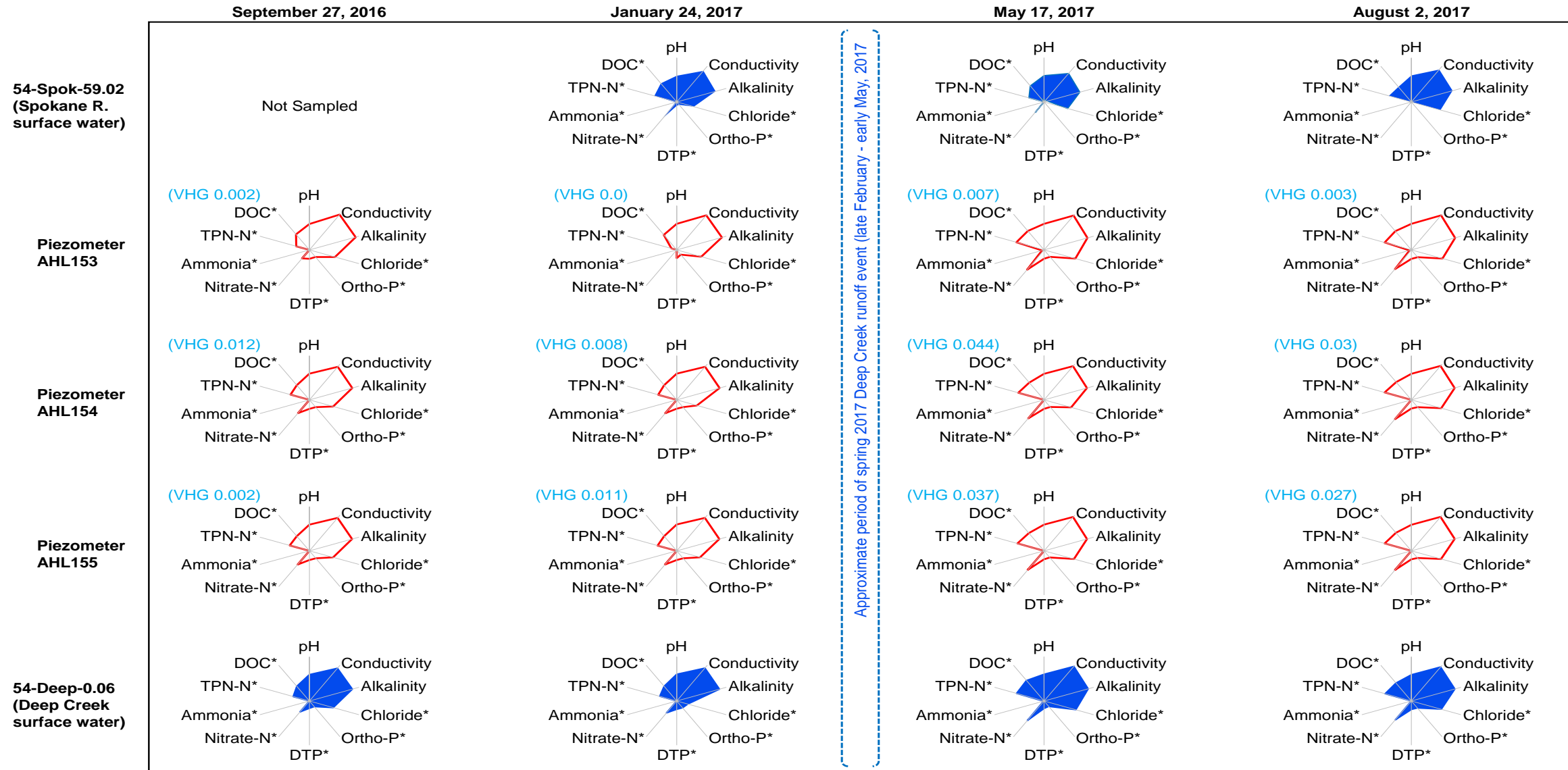
We collected groundwater samples from the project instream piezometers on four occasions, between September 2016 and August 2017, to characterize groundwater quality just prior to its discharge into Deep Creek and the Spokane River. We also collected surface water samples from Deep Creek and the Spokane River for comparison purposes. The results of this sampling effort are summarized in Figure 8 and Appendix B, Table B-3. The associated data quality assessment is presented in Appendix A.

Radar plots such as those shown in Figure 8 provide a convenient visual framework for evaluating general similarities or differences in the water quality profiles of individual samples. Samples from sites that share a common water source typically exhibit comparably shaped data plots, while differences in the plot area (i.e., overall plot size) indicate differences in analyte concentrations between samples.

Evaluation of the radar plots in Figure 8 indicates generally good correspondence between the Deep Creek surface water samples (site 54-Deep-0.06) and the two Deep Creek piezometer samples (sites AHL154 and AHL155) during all four sampling events. This suggests that lower Deep Creek and the two Deep Creek piezometers share a common water source. This is consistent with the persistent pattern of positive vertical hydraulic gradients measured at these sites.

Water samples from the Spokane River (site 54-Spok-59.02) showed a deficit of nitrate, DTP, Ortho-P, TPN, alkalinity, and conductivity/specific conductance relative to Deep Creek and the Deep Creek piezometers. Ammonia was present at detectable levels in only a few samples collected from the Spokane River piezometer, Deep Creek, and the Spokane River.

The Deep Creek runoff event in spring 2017 resulted in increases in piezometer vertical hydraulic gradients in May and August 2017 as well as in the corresponding chemical concentrations (e.g., conductivity, chloride, nitrate+nitrite-N, TPN-N, and DOC) for samples collected from Deep Creek and the two Deep Creek piezometers (Figure 8 and Table B-3). The Spokane River piezometer (site AHL153) showed comparable increases in hydraulic gradients and chemical concentrations during this period – suggesting the zone of active groundwater discharge from the Deep Creek channel extended into and beneath the Spokane River for a period of several months following the runoff event.



- Surface water sampling site
- Groundwater sampling site
- Direction of surface water flow

Notes:
 Analytes denoted with an asterisk at left represent dissolved sample fractions. (See the report glossary for an explanation of the analyte abbreviations used here).
 VHG – Vertical Hydraulic Gradient measured in instream piezometer prior to sampling (dimensionless)

See Table B-3 for a tabular summary of the data depicted here.

Site Number	Field Parameters					Laboratory Analyses ¹							
	Vertical hydraulic gradient ⁴ (dimensionless)	Water temperature (deg C)	pH (standard units)	Specific conductance (µS/cm @ 25 °C)	Dissolved oxygen (mg/L)	Dissolved total alkalinity (mg/L)	Dissolved total chloride (mg/L)	Dissolved Ortho-phosphate (mg/L)	Dissolved total phosphorus (mg/L)	Dissolved nitrate+nitrite-N (mg/L)	Dissolved ammonia (mg/L)	Dissolved TPN-N (mg/L)	Dissolved organic carbon (mg/L)
54-Spok-59.02 ³	NA	10.88	7.98	165	9.44	67	3.19	0.0123	0.0150	1.11	0.011	1.15	2.05
AHL153 ²	0.000	10.15	7.15	503	0.93	238	6.39	0.0796	0.0905	2.26	0.013	2.37	2.43
AHL154 ²	0.019	9.17	7.41	346	3.93	158	4.73	0.0946	0.0943	2.16	0.01U	2.22	169
AHL155 ²	0.017	9.57	7.52	342	5.60	155	5.11	0.0947	0.0943	2.30	0.01U	2.43	175
54-Deep-0.06 ²	NA	9.77	8.00	361	8.48	170	5.74	0.0715	0.0740	2.14	0.01	2.35	2.70

¹ - Laboratory reported non-detect values were included as reported, when calculating sample averages. See Table B-3 for a summary of individual sample results by site and sample date.
² - The average analyte concentrations for these sites are based on the four samples collected in Sep 2016 and Jan, May, and Aug 2017.
³ - The average analyte concentrations for this site are based on the three samples collected in Jan, May, and Aug 2017.
⁴ - The average VHG values reported here are based on each sites full period of record. See Table B-3 for a summary of individual measurements.

Figure 8: Radar plots and table of average concentrations for samples collected from Deep Creek, the Spokane River, and the three project instream piezometers between September 2016 and August 2017.

Site Conceptual Model and Evaluation of Groundwater Nutrient Loading to Lower Deep Creek and the Spokane River

The field observations and streambed vertical hydraulic gradient measurements made during this study indicate that upwelling groundwater from the Deep and Coulee Creek watersheds enters the Spokane River across a narrow discharge zone centered at the point where the Deep Creek channel enters the Spokane River (Figure 9). Groundwater contained within the saturated flood deposits and sediments that comprise the lower Deep Creek channel flows down gradient toward natural points of discharge along the creek and river. Most of this discharge occurs along the Deep Creek channel proper and diminishes with proximity to the Spokane River. As suggested by the groundwater flow lines depicted in Figure 9, the principal direction of groundwater flow is inferred to be essentially perpendicular to the creek/river bed at the actual point of discharge to surface water.

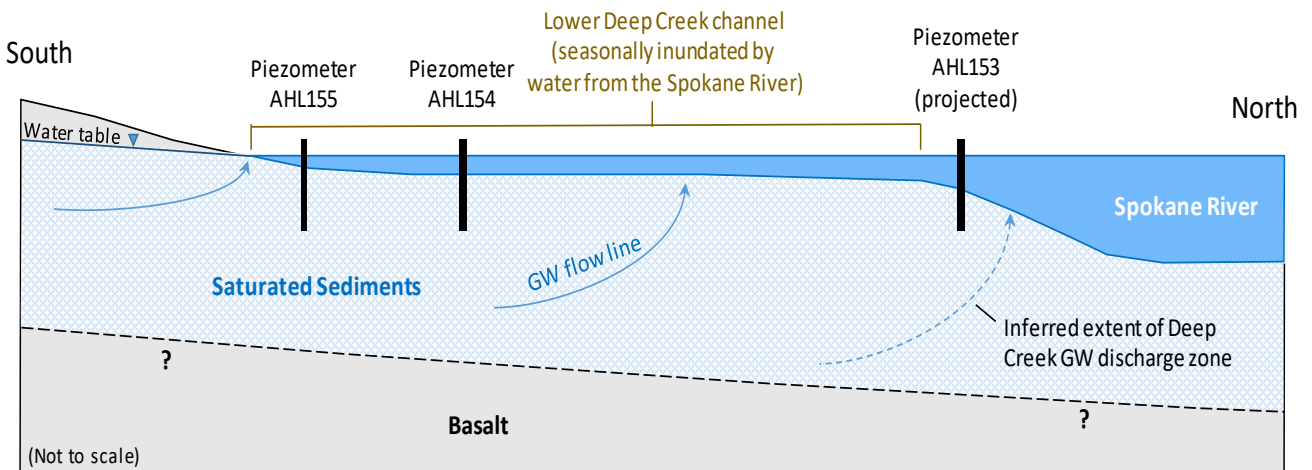


Figure 9: Conceptual cross-section depicting inferred groundwater discharge conditions at Deep Creek's confluence with the Spokane River.

Based on the above conceptual model, we conducted a simple Darcy flow analysis using information collected from the project instream piezometers to estimate groundwater discharge volumes and timing to lower Deep Creek and adjacent Spokane River. These discharge estimates were combined with water quality data collected from the piezometers to derive groundwater nutrient mass flux estimates for the modeled discharge zone. The procedures, methods, and assumptions required to perform the evaluation are described below by principal task.

Groundwater Flux

To estimate the rate of groundwater discharge from the Deep Creek Channel to the Spokane River, the approximate area of the discharge zone had to be determined. Based on field observations of groundwater seepage presence (or absence) along lower Deep Creek and the

vertical hydraulic gradients measured in the study instream piezometers, the discharge zone was inferred to be approximately 120 meters long and approximately 100 meters wide (Figure 10). The upper extent of the groundwater discharge zone was set to correspond with the first observed presence of surficial groundwater discharge/seepage into the Deep Creek Channel. The lower extent of the discharge zone was inferred to lie within (or just up gradient of) the Spokane River and corresponded with the location of a neutral (i.e., zero) value for vertical hydraulic gradient. The discharge zone width was assumed to be approximately 100 meters, which encompasses the portion of the lower Deep Creek channel that is underlain by unconsolidated sediments and bounded by basalt outcroppings.

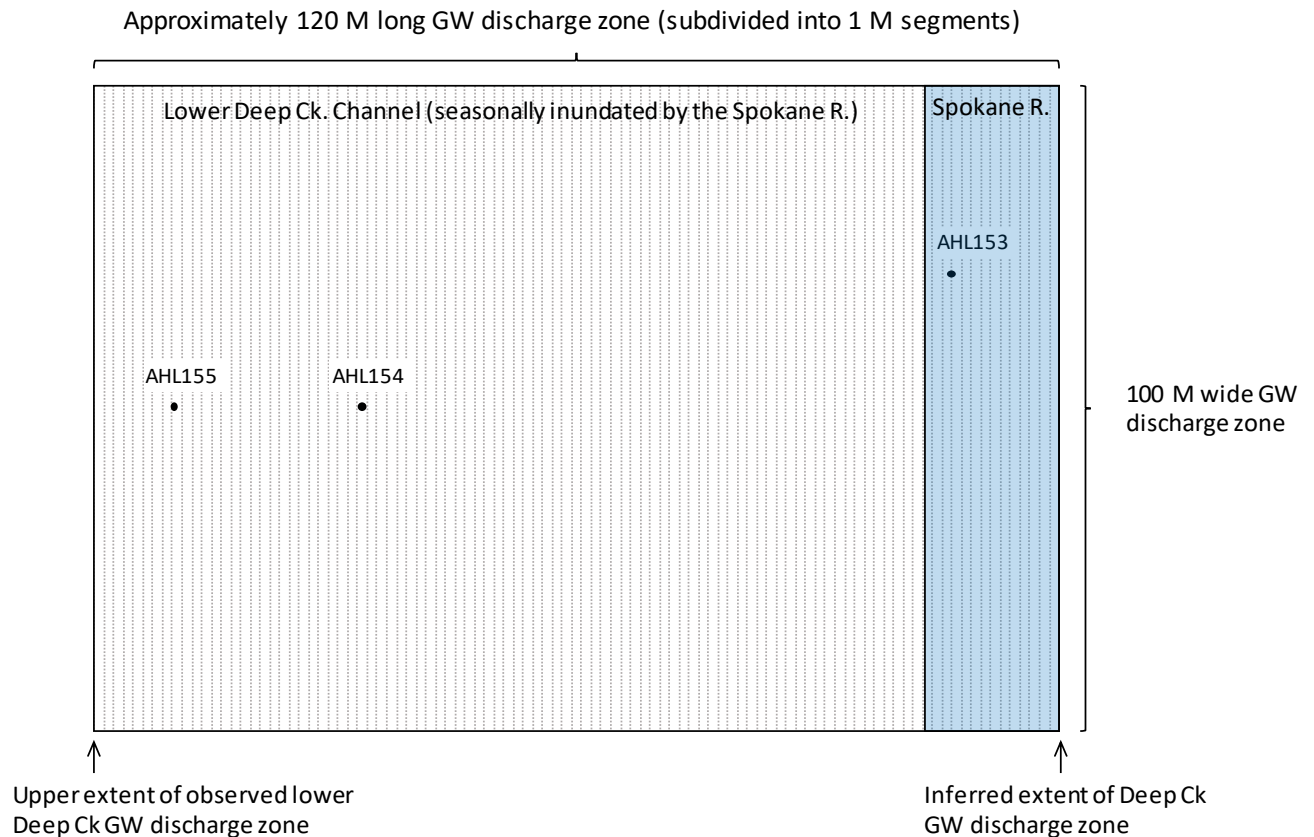


Figure 10: Conceptual model of lower Deep Creek groundwater discharge zone (plan view).

Total groundwater flux across the modeled discharge zone was estimated using Equation 3 and the vertical hydraulic gradients and streambed hydraulic conductivity estimates from the instream piezometers.

$$Q = -K_v I_v A \quad \text{(Equation 3)}$$

Where:

- Q is the total estimated volume of groundwater discharged across the discharge zone (L^3/t),
- K_v is the geometric mean of the individual vertical hydraulic conductivity values determined for the streambed sediments at each of the three piezometer sites within the discharge zone (L/t),
- I_v is the vertical hydraulic gradient between the creek and groundwater as measured at or interpolated from the piezometers installed within the discharge zone (dimensionless),
- A is the streambed cross-sectional area across which water exchange occurs (L^2),

where (L) represents units of length and (t) units of time.

To better account for observed differences in streambed vertical hydraulic gradient at the individual piezometers, we chose to subdivide the overall discharge zone into 120 segments, with each segment measuring 1 meter long by 100 meters wide. The area of each segment (A) was calculated by multiplying the segment length by the segment width. The vertical hydraulic gradient (I_v) for each segment was derived by linear interpolation using the piezometer measured gradients as inputs.

The vertical hydraulic conductivity (K_v) value for each segment was defined as the geometric mean of the hydraulic conductivity values derived from the CHIT tests conducted at the three piezometers. The CHIT test method is highly sensitive to the total saturated thickness of the streambed sediments (see variable b , Appendix B, Table B-2). Since we did not have a measured value for this variable, we used an assumed streambed thickness to perform the CHIT analysis on the three instream piezometers installed for this study. To evaluate the potential impact streambed thickness has on the CHIT result, we ran three test scenarios for each piezometer using assumed streambed thickness values ranging from approximately 5 to 20 feet (Appendix B, Table B-2). We used the geometric mean of the individual piezometer CHIT results to define a representative bulk K_v value for each scenario. This resulted in three bulk K_v values (20, 24, and 39 meters/day) that were subsequently used in Equation 3 to calculate estimated groundwater discharge volumes to the individual model segments/domain for each of the three test scenarios.

The resulting values for A , I_v , and K_v for each one-meter segment were then multiplied to define the estimated groundwater discharge volume for the segment and measurement period. Finally, the total estimated groundwater discharge (Q) across the entire discharge zone was estimated by summing the calculated gains for the 120 one-meter segments comprising the modeled discharge zone.

Mass Flux

To estimate the mass flux of nutrients carried into the lower reach of Deep Creek and the Spokane River by discharging groundwater, the estimated groundwater discharge (Q) for the discharge zone was combined with water quality information collected from the instream piezometers using Equation 4:

$$F = QC \quad \text{(Equation 4)}$$

Where:

- F is the total mass flux rate across the discharge zone for the parameter of interest (M/t)
- Q is the total volume of groundwater discharged across the modeled discharge zone (L³/t)
- C is the groundwater nutrient concentration of interest (M/V),

where (L) represents units of length, (t) represents units of time, and (M) represents units of mass.

The groundwater nutrient concentrations used as inputs to Equation 4 represent the geometric mean of the dissolved total phosphorus (DTP), orthophosphate (OP), total persulfate nitrogen-N (TPN-N), and nitrate+nitrite-N concentrations measured in groundwater collected from the piezometers during periods when measured vertical hydraulic gradients were positive (e.g., during periods of inferred groundwater discharge) (Appendix B, Table B-3).

Method Assumptions and Limitations

To perform this evaluation, we made a number of simplifying assumptions regarding the site hydrogeology and the assignment of appropriate input values for the variables used in the instream piezometer CHIT tests and Equations 3 and 4 above. The principal assumptions and limitations for this work are described below.

- The CHIT test method assumes the streambed sediments are hydraulically isotropic (i.e., horizontal and vertical hydraulic conductivity are equal) at a sub-meter scale. However, in most alluvial environments sediments exhibit some degree of anisotropy (i.e., their hydraulic properties are not equal in all flow directions) due to the preferential orientation of grains and clay minerals or to local-scale inter-fingering or layering of fine and coarse grained materials (Freeze and Cherry, 1979). For this evaluation, we did not attempt to adjust or account for streambed sediment anisotropy and its potential influence on estimated groundwater flux volumes and mass loads. Significant anisotropy, if present, would result in lower estimates of volumetric flux and dissolved mass loading than reported here.

- The vertical hydraulic gradients assigned to each of the 120 model segments comprising the model domain were derived by linear interpolation, using the measured vertical hydraulic gradients (VHG's) from the project instream piezometers as initial starting values. This approach assumes the streambed VHG values in the field follow a similar linear trend.
- The groundwater nutrient loading estimates provided here are reported in terms of the dissolved mass that is carried into Deep Creek and the Spokane River within the modeled discharge zone by upwelling groundwater. We did not attempt to adjust the values to account for biological or geochemical processes (e.g., sorption/desorption, dilution, etc.) that can potentially attenuate nutrient concentrations in groundwater as it flows through the final few feet of stream bed sediments. This is particularly true for phosphorus, which can rapidly sorb/bond to sediment with changes in geochemical environment – such as the transition from groundwater to surface water conditions.
- The modeled groundwater discharge zone at the mouth of Deep Creek was assumed to be 100 meters wide and approximately 120 meters long with the final 20 meters extending out beneath the Spokane River. As described earlier, the extent of the discharge zone was defined based on:
 - The streambed vertical hydraulic gradients measured in instream piezometers.
 - The observed upper extent of surficial groundwater seepage into the lower creek channel from the unconsolidated sediments that comprise the streambed in this area.
 - The presence of bounding basalt outcrops along the sides of the lower creek channel.

Significant deviations between the inferred discharge area/model domain and actual site conditions (e.g., modeled discharge area significantly greater or smaller than the actual discharge zone) will result in over or under predictions of groundwater fluxes and mass loads, respectively.

Evaluation Results

Table 2 summarizes estimated daily groundwater flux and dissolved mass load estimates based on assumed input values of 20, 24, and 39 meters/day for the streambed sediment K_v (Equation 3). This represents the probable upper and lower range of values for this parameter and thus the likely range of estimated flux and dissolved mass loads to the river from the Deep Creek channel.

The analysis results indicate the estimated lower- and upper-bound groundwater fluxes to the Spokane River/lower Deep Creek varied seasonally during the study period in response to differences in streambed vertical hydraulic gradient and ranged from approximately 0.14 to 4.6 ft^3/s (Table 2). The estimated lower- and upper-bound daily mass loads to the river for OP and dissolved TP followed a similar pattern and ranged from approximately 0.03 to 1 kg/d. The estimated lower- and upper-bound daily mass loads for nitrate+nitrite-N and TPN ranged from approximately 0.5 to 17.5 and 0.4 to 13.6 kg/d, respectively (Table 2).

Based on observed field conditions, the most likely range of groundwater fluxes and mass loads to the river/lower Deep Creek were derived using an estimated streambed K_v value of 24 meters/day. These values are highlighted in gray, in Table 2.

Table 2: Estimated total daily groundwater flux and dissolved nutrient mass loading to the Spokane River from the Deep and Coulee Creek drainage (grey highlighted values are thought to represent best estimate of field conditions).

Sample date	Julian date	Total daily estimated groundwater flux (ft ³ /s)	Total estimated daily OP mass flux (kg/d)	Total estimated daily TP mass flux (kg/d)	Total estimated daily nitrate +nitrate-N mass flux (kg/d)	Total estimated daily TPN mass flux (kg/d)
1/24/2017	24	0.83	0.178	0.188	3.13	2.44
2/14/2017	45	0.93	0.200	0.211	3.52	2.74
2/24/2017	55	1.85	0.398	0.421	7.01	5.46
4/19/2017	109	2.91	0.624	0.660	11.00	8.56
5/17/2017	137	4.62	0.991	1.048	17.46	13.59
8/2/2017	214	3.04	0.653	0.691	11.51	8.96
8/16/2016	228	1.04	0.223	0.236	3.93	3.06
9/27/2016	270	1.10	0.236	0.249	4.15	3.23
10/3/2017	276	1.49	0.320	0.338	5.63	4.38
10/19/2016	292	0.27	0.058	0.061	1.02	0.79
11/29/2016	333	0.36	0.077	0.082	1.27	0.99
The above groundwater flux and mass flux estimates assume a streambed K_v value of 39 meters/day.						
1/24/2017	24	0.51	0.109	0.116	1.93	1.50
2/14/2017	45	0.57	0.123	0.130	2.17	1.69
2/24/2017	55	1.14	0.245	0.259	4.32	3.36
4/19/2017	109	1.79	0.384	0.406	6.77	5.27
5/17/2017	137	2.84	0.610	0.645	10.74	8.36
8/2/2017	214	1.87	0.402	0.425	7.09	5.51
8/16/2016	228	0.64	0.137	0.145	2.42	1.88
9/27/2016	270	0.68	0.145	0.153	2.56	1.99
10/3/2017	276	0.92	0.197	0.208	3.47	2.70
10/19/2016	292	0.17	0.036	0.038	0.63	0.49
11/29/2016	333	0.22	0.048	0.050	0.78	0.61
The above groundwater flux and mass flux estimates assume a streambed K_v value of 24 meters/day.						
1/24/2017	24	0.42	0.091	0.096	1.60	1.25
2/14/2017	45	0.48	0.102	0.108	1.81	1.41
2/24/2017	55	0.95	0.204	0.216	3.60	2.80
4/19/2017	109	1.49	0.320	0.339	5.64	4.39
5/17/2017	137	2.37	0.508	0.537	8.95	6.97
8/2/2017	214	1.56	0.335	0.354	5.90	4.60
8/16/2016	228	0.53	0.114	0.121	2.02	1.57
9/27/2016	270	0.56	0.121	0.128	2.13	1.66
10/3/2017	276	0.76	0.164	0.173	2.89	2.25
10/19/2016	292	0.14	0.030	0.031	0.52	0.41
11/29/2016	333	0.18	0.040	0.042	0.65	0.51
The above groundwater flux and mass flux estimates assume a streambed K_v value of 20 meters/day.						

Discussion

In 2017, Deep Creek contributed unusually large volumes of surface flow to the Spokane River during the spring and early summer snow-melt period. The daily discharge volumes and groundwater-derived mass flux estimates presented in Table 2 do not account for these direct surface water discharges to the Spokane River during this or other periods, nor do they account for groundwater from the Deep and Coulee Creek watersheds that could potentially enter the Spokane River as diffuse seepage upstream or downstream of the Deep Creek/Spokane River confluence. Therefore, these load estimates should be considered minimum values – particularly during the spring snowmelt period when direct surface runoff to the Spokane River may be appreciable, as it was during 2017.

Summary and Conclusions

In August 2016, the Washington State Department of Ecology initiated field studies to better understand and characterize the dissolved nutrient load that groundwater from the Deep and Coulee Creek watersheds potentially contributes to the Spokane River. The study used a number of instream piezometer-based field methods to evaluate the timing, magnitude, and spatial distribution of surface water/groundwater interactions at the confluence of Deep Creek with the Spokane River. The piezometers were used to:

- Measure hydraulic gradients between the creek/river and near-surface groundwater.
- Estimate streambed hydraulic conductivity values.
- Measure continuous streambed thermal profiles.
- Sample shallow groundwater just prior to its discharge into the creek/river.

These evaluations indicate that upwelling groundwater from the Deep and Coulee Creek watersheds discharges year round to lower Deep Creek and the Spokane River across a narrow discharge zone centered at the point where the Deep Creek channel enters the Spokane River. A Darcy flow analysis, conducted using information collected from the project instream piezometers, suggests that groundwater discharge volumes and daily mass loads of OP, TP, nitrate+nitrite-N, and TPN to the Spokane River were greatest from spring to early summer when positive streambed vertical hydraulic gradients were most pronounced. The most likely range of groundwater fluxes and mass loads to the river and lower Deep Creek are highlighted in gray, in Table 2.

Recommendations

As a near-term follow up to this study, we recommend additional field reconnaissance be conducted along the south shore of the Spokane River upstream of Deep Creek. This would help determine whether there are significant springs or seeps that might suggest water from the Deep Creek drainage is entering the river via groundwater discharge upstream of the Deep Creek channel proper.

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Appendices

Appendix A: Data Quality Review

The field and laboratory data from this study were reviewed prior to use to ensure they met the data quality objectives defined in the project study plan (Sinclair, 2016). The evaluation methods are described below by principal data type.

Evaluation of Recording Thermistors and Data

The recording thermistors deployed during this study were tested for accuracy prior to initial use and again at the completion of field studies using methods described by Bilhimer and Stohr (2008). The tests were conducted to confirm that all thermistors met the manufacturer's accuracy specifications for the range of water temperatures that were likely to be encountered during field deployment (Table A-1).

Table A-1: Thermistor model and manufacturer specifications.

Thermistor model	Temperature range	Accuracy	Resolution
Hobo water temp pro (Version 2)	-20°C to +50°C	± 0.2°C at 0 to +50°C	0.02°C

To conduct the tests, a batch of thermistors were pre-programmed to launch at a common start time and to subsequently measure and record temperature every minute thereafter. The programmed thermistors were then submerged in a constantly stirred, room temperature (warm) bath where they were allowed to equilibrate. An NIST⁴-certified thermometer was then used to establish an accurate reference temperature for the warm bath against which the thermistor results could be compared. This was done by manually measuring the warm bath temperature once per minute over a 10-minute period. After completing the warm bath reference measurements, the thermistors were transferred to an adjacent stirred ice bath. There they were again allowed to equilibrate before a second set of 10 manual reference measurements were made for this bath.

Average temperature values were calculated for each thermistor from the 10 paired-reference temperatures measured for each bath. The mean temperature values for each thermistor (one for the ice bath and one for the room temperature bath) were then compared to the mean reference temperatures calculated from the corresponding NIST thermometer measurements. Noted temperature differences were then compared to the reported manufacturer specifications for each thermistor type to assess individual thermistor accuracy.

All tested thermistors met our project acceptance criteria during the pre-deployment and post-deployment calibration checks. Accordingly, the thermistor temperature records were accepted and used here without further qualification.

⁴ National Institute of Standards and Technology

Field Meter Calibration and Verification

Water quality field meters were calibrated in accordance with the manufacturer's instructions at the start of each sampling day (Swanson, 2007). Fresh commercially prepared buffer solutions and reference standards were used for all pH and specific conductance calibrations, respectively. The dissolved oxygen sensor was calibrated against theoretical water-saturated air using the manufacturer-supplied calibration chamber. The initial pH was checked by placing the probes in pH buffer solutions; the specific conductance calibrations were checked by using the reference standards and evaluating the difference between the standard and the meter values (Table A-2). The pH calibration was accepted if the metered values differed by less than ± 0.05 pH units from the buffer value. The specific conductance calibration was accepted if the meter values deviated by no more than $\pm 5\%$ from the specific conductance check standards.

Following each sampling event, the meters were rechecked against reference standards to confirm they had not drifted unacceptably since the initial calibration and were within the post-use acceptance criteria listed in Table A-2. Based on this evaluation, the field water quality results for all four sampling events were deemed acceptable and are reported here without further qualification.

Table A-2: Field meter calibration records.

Date	Status	pH				Specific conductance				Dissolved oxygen		
		Reference standard (pH)	Meter reading (pH)	Difference from standard (pH units)	Accept or reject calibration/ results ¹	Reference standard (µS/cm)	Meter reading (µS/cm)	Deviation from standard (%)	Accept or reject calibration/ results ¹	Meter reading (mg/L)	Saturation (percent)	Accept or reject calibration/ results ¹
9/26/2016	Pre-use	4.01	4.05	0.04	Accept	100.3	100.8	0.5	Accept	8.81	100.1	Accept
		7.01	7.02	0.01	Accept	-	-	-	-	-	-	-
9/28/2016	Post-use	4.01	4.09	0.08	Accept	100.3	100.6	0.3	Accept	8.86	100.4	Accept
		7.01	7.04	0.03	Accept	-	-	-	-	-	-	-
1/23/2017	Pre-use	4.00	4.05	0.05	Accept	100	99.5	-0.5	Accept	8.55	100	Accept
		7.06	7.1	0.04	Accept	-	-	-	-	-	-	-
1/25/2017	Post-use	4.00	4.04	0.04	Accept	100	99.4	-0.6	Accept	8.52	99.8	Accept
		7.06	7.04	-0.02	Accept	-	-	-	-	-	-	-
5/15/2017	Pre-use	4	4.01	0.01	Accept	100.1	101.7	1.6	Accept	8.86	100	Accept
		7.01	7.02	0.01	Accept	-	-	-	-	-	-	-
5/18/2017	Post-use	4.01	3.97	0.04	Accept	100.1	104.6	4.5	Accept	8.8	100	Accept
		7.01	7	-0.01	Accept	-	-	-	-	-	-	-
8/1/2017	Pre-use	4	4.03	0.03	Accept	99	99.7	0.3	Accept	8.6	100	Accept
		7.01	7.01	0	Accept	-	-	-	-	-	-	-
8/3/2017	Post-use	4	4.04	0.04	Accept	99	104	5.0	Accept	8.8	101.4	Accept
		7.01	7.01	0	Accept	-	-	-	-	-	-	-

¹ Pre-use calibration acceptance criteria by parameter

pH

Deviation from check standards following initial calibration:

- ≤ ± 0.05 pH deviation from all standards = accept calibration
- > ± 0.05 pH deviation from any standard = reject calibration

Specific conductance

- ≤ ±5% deviation from all standards = accept calibration
- > ±5% deviation from any standard = reject calibration

Dissolved Oxygen (saturation percent)

- ≥ 99.7 and ≤ 100.3 = accept calibration
- < 99.6 or > 100.4 = reject calibration

¹ Post-use acceptance criteria – deviations from check standards

pH

Deviation from check standards following initial calibration:

- ≤ ±0.15 pH deviation from all standards = accept results
- > ±0.15 and ≤ ±0.5 pH deviation from any standard = qualify results as estimates ("J" code)
- > ±0.5 pH deviation from any standard = reject results

Specific conductance

- ≤ ±5% deviation from all standards = accept results
- > ±5% and ≤ ±10% deviation from any standard = qualify results as estimates ("J" code)
- > ±10% deviation from any standard = reject results

Dissolved oxygen (saturation percent)

- ≥ 99.5 and ≤ 100.5 = accept calibration
- < 99.4 or > 100.6 = qualify results as estimates ("J" code)

Review of Laboratory Water Quality Data

All wells and piezometers were sampled using properly calibrated field meters, dedicated sample tubing, and new in-line cartridge filters, when appropriate. Samples were collected in clean bottles supplied by Manchester Environmental Laboratory (MEL). Pre-acidified bottles were used for preserved samples. Filled sample bottles were labeled, bagged, and then stored in clean, ice-filled coolers pending their arrival at the laboratory. Sample chain-of-custody procedures were followed throughout the project.

Laboratory Quality Assurance

Manchester Laboratory follows strict protocols to ensure and later evaluate the quality of their analytical results (Ecology, 2008). When appropriate, instrument calibration was performed by laboratory staff before each analytical run and checked against initial verification standards and blanks. Calibration standards and blanks were analyzed at a frequency of approximately 10 percent during each analytical run and then again at the end of each run. The laboratory also evaluates procedural blanks, spiked samples, and laboratory control samples (LCS) as additional checks of data quality. The results of these analyses were summarized in a case narrative and submitted to the authors along with each analytical data package.

The laboratory's quality assurance narratives and supporting data for this project indicate that, with a few exceptions, samples arrived at the laboratory in good condition and were processed and analyzed within accepted EPA holding times. Constituent concentrations for laboratory blank samples fell below the analytical detection limit for target analytes on most occasions. In addition, matrix spike samples, laboratory replicate samples, and LCS analyses met applicable acceptance criteria (Table A-3) with few exceptions. Noted laboratory data quality exceptions included:

- The alkalinity samples collected on 1/24/2017 and 8/2/2017 were analyzed outside of accepted holding times and were qualified by the laboratory as estimates (J-coded).
- The 5/17/2017 and 8/2/2017 laboratory blanks contained small but measurable concentrations of dissolved TPN-N. The associated field blanks contained no measurable TPN-N. All field samples with the exception of the 5/17/2017 Spokane River sample exceeded the associated laboratory blank concentration by a factor of 10 or more and are reported here without qualification. The Spokane River TPN-N sample for 5/17/2017 was qualified by the authors as an estimate (J-coded).
- Some of the sample bottles collected on 10/19/2016 for chloride, alkalinity, and dissolved organic carbon analysis contained ice upon arrival at the laboratory. The associated results for these bottles/analytes were qualified by the laboratory as estimates.
- The 1/24/2017 laboratory duplicate for dissolved TP exceeded the acceptable relative percent difference limit of 20 percent. Since the duplicate sample concentrations were less than five times the method reporting limit, this exceedance is not considered significant enough to warrant data qualification.

Table A-3: Data quality objectives for water quality samples.

Parameter	Check standards (% recovery limits)	Field duplicate sample (%RSD)	Matrix spikes (% recovery limits)	Matrix spike duplicates (RPD)	Lowest level of interest (units)
<i>Field Parameters</i>					
pH	± 0.2 SU	± 0.1 SU	NA	NA	NA
Specific conductance	± 10 umhos/cm	± 10 %	NA	NA	10 µmhos/cm
Temperature	± 0.1 C	± 5 %	NA	NA	0.0 C
Dissolved oxygen	± 0.2 mg/L	NA	NA	NA	0.1 mg/L
<i>Laboratory Analyses (dissolved sample fraction)</i>					
Alkalinity	80 – 120 %	± 10 %	75 – 125 %	± 10 %	5.0 mg/L
Ammonia	80 – 120 %	± 10 %	75 – 125 %	± 10 %	0.01 mg/L
Nitrate+Nitrite-N	80 – 120 %	± 10 %	75 – 125 %	± 10 %	0.01 mg/L
TPN-N	80 – 120 %	± 10 %	75 – 125 %	± 10 %	0.025 mg/L
Orthophosphate	80 – 120 %	± 10 %	75 – 125 %	± 10 %	0.003 mg/L
Total phosphorus	80 – 120 %	± 10 %	75 – 125 %	± 10 %	0.005 mg/L
Chloride	90 – 110 %	± 10 %	75 – 125 %	± 10 %	0.10 mg/L
Dissolved organic carbon	80 – 120 %	± 10 %	75 – 125 %	± 10 %	1.0 mg/L

RPD – relative percent difference

%RSD – percent relative standard deviation

Field Quality Assurance

To assess sampling bias and overall analytical precision, field equipment blanks and replicate samples were collected and submitted "blind"⁵ to the laboratory during each sample event. Equipment blanks were prepared using laboratory-supplied de-ionized water and were handled and filtered in the same manner as other samples. Precision for each of the field replicate and laboratory duplicate analyses was quantified by evaluating the percent relative standard deviation⁶ (%RSD) for each duplicate sample pair. The resulting values (Table A-4 and Table A-5) were then tabulated and compared to the project data quality objectives (Table A-3).

Based on this evaluation, the 10/19/2016 and 01/24/2017 field duplicate samples for DOC and Chloride respectively exceeded our target percent relative standard deviation criteria by wide

⁵ The term "blind" refers to "identical" samples that were submitted to the laboratory under different sample numbers, in order to maintain sample anonymity during laboratory analysis.

⁶ Calculated for a pair of results, x_1 and x_2 , as $100 * (S/\text{Average of } x_1 \text{ and } x_2)$ where S is the standard deviation of the sample pair.

margins. The exceedance for DOC is likely related to one of the sample pairs having been obtained from a partially frozen bottle. The result was qualified (J coded) by the laboratory. The cause of the chloride exceedance is not known but was deemed significant enough to warrant qualification (J coding) of all chloride results for the 01/24/2017 sample event.

Except as noted above, the results from the laboratory and field quality assurance reviews indicate that the water quality data generated during this study are of high quality and can be used as intended and reported here without further qualification.

Table A-4: Summary of field duplicate samples and blanks.

Sample date		Dissolved total alkalinity (mg/L)	Dissolved total chloride (mg/L)	Dissolved organic carbon (mg/L)	Dissolved Ortho-phosphate (mg/L)	Dissolved total phosphorus (mg/L)	Dissolved nitrate+ nitrite-N (mg/L)	Dissolved ammonia (mg/L)	Dissolved TPN-N (mg/L)
9/27/2016	Sample	148	2.11	1.0 U	0.101	0.102	0.726	0.01 U	0.84
	Duplicate	146	2.12	1.0 U	0.101	0.102	0.72	0.01 U	0.832
	%RSD	0.96	0.33	0.00	0.00	0.00	0.59	0.00	0.68
	Blank	5 U	0.10 U	1.0 U	0.003 U	0.005 U	0.01 U	0.01 U	0.025 U
10/19/2016	Sample	149 J	2.13 J	3.6 J	0.0627	0.0659	0.275	0.01 U	0.333
	Duplicate	151 J	2.16 J	2.3	0.0602	0.0622	0.266	0.01 U	0.33 J
	%RSD	0.94	0.99	31.16	2.88	4.08	2.35	0.00	0.64
	Blank	5.0 UJ	0.10 UJ	1.4	0.003 UJ	0.005 U	0.01 U	0.01 U	0.025 U
1/24/2017	Sample	259	0.16	1.12	0.0428	0.0801	0.01 U	0.01 U	0.034
	Duplicate	258	2.52	1.13	0.0453	0.0765	0.01 U	0.01 U	0.035
	%RSD	0.27	124.54	0.63	4.01	3.25	0.00	0.00	2.05
	Blank	5.0 UJ	0.10 U	1.0 U	0.003 U	0.005 U	0.01 U	0.01 U	0.025 U
5/17/2017	Sample	173	11.3	3.77	0.0856	0.0926	4.86	0.016	5.12
	Duplicate	174	11.4	3.79	0.0844	0.0907	4.88	0.017	5.28
	%RSD	0.41	0.62	0.37	1.00	1.47	0.29	4.29	2.18
	Blank	5.0 U	0.10 U	0.50 U	0.003 U	0.005 U	0.01 U	0.01 U	0.025 U
8/2/2017	Sample	168	8.38	2.51	0.9520	0.0900	4.12	0.01 U	4.18
	Duplicate	166	8.01	2.47	0.928	0.0859	3.92	0.01 U	4.12
	%RSD	0.85	3.19	1.14	1.81	3.30	3.52	0.00	1.02
	Blank	5.0 UJ	0.10 U	0.50 U	0.003 U	0.005 U	0.01 U	0.01 U	0.025 U
Field: Mean % RSD		0.69	25.94	6.66	1.94	2.42	1.35	0.86	1.31

U – analyte not detected at or above the reported value.

J – analyte positively identified, the numeric result is an estimate.

UJ – analyte not detected at or above the reported estimated value.

Bold values indicate an exceedance of the project quality assurance criteria.

Table A-5: Summary of laboratory replicates and blanks.

Sample date		Dissolved total alkalinity (mg/L)	Dissolved total chloride (mg/L)	Dissolved organic carbon (mg/L)	Dissolved Ortho-phosphate (mg/L)	Dissolved total phosphorus (mg/L)	Dissolved nitrate+nitrite-N (mg/L)	Dissolved ammonia (mg/L)	Dissolved TPN-N (mg/L)
9/27/2016	Sample	39	173	1.2	0.0562	0.098	0.101	0.010 U	0.153
	Duplicate	39	174	1.23	0.0585	0.095	0.105	0.010 U	0.149
	%RSD	0.00	0.41	1.75	2.84	2.20	2.75	0.00	1.87
	Blank	5 U	0.10 U	1 U	0.003 U	0.005 U	0.01 U	0.01 U	0.025 U
10/19/2016	Sample	151	2.12	3.07	0.06	0.0647	2.63	0.01 U	0.025 U
	Duplicate	151	2.13 J	3.11	0.0602	0.0622	2.66	0.01 U	0.025 U
	%RSD	0.00	0.33	0.92	0.24	2.79	0.80	0.00	0.00
	Blank	5.0 U	0.1 U	1 U	0.003 U	0.005 U	0.01 U	0.01 U	0.025 U
1/24/2017	Sample	149 J	0.175	1.12	0.0089	0.011	0.01 U	0.01 U	0.645
	Duplicate	148 J	0.159	1.12	0.0091	0.007	0.01 U	0.01 U	0.653
	%RSD	0.48	6.77	0.00	1.57	31.43	0.00	0.00	0.87
	Blank	5.0 U	0.1 U	1 U	0.003 U	0.005 U	0.01 U	0.01 U	0.025 U
5/17/2017	Sample	205	0.10 U	3.8	0.007	-	4.87	0.01 U	0.535
	Duplicate	202	0.10 U	3.77	0.0071	-	4.86	0.01 U	0.598
	%RSD	1.04	0.00	0.56	1.00	NA	0.15	0.00	7.86
	Blank	5.0 U	0.1 U	0.5 U	0.003 U	0.005 U	0.01 U	0.01 U	0.045
8/2/2017	Sample	166 J	2.29	3.54	0.0092	0.043	4.02	0.018	0.213
	Duplicate	171 J	2.3	3.44	0.0099	0.045	3.95	0.018	0.22
	%RSD	2.10	0.31	2.03	5.18	3.21	1.24	0.00	2.29
	Blank	5.0 U	0.1 U	0.50 U	0.003 U	0.005 U	0.01 U	0.01 U	0.037
Lab: Mean % RSD		0.72	1.56	1.05	2.17	9.91	0.99	0.00	2.58

U – analyte not detected at or above the reported value.

J – analyte positively identified, the numeric result is an estimate.

UJ – analyte not detected at or above the reported estimated value.

Bold values indicate an exceedance of the project quality assurance criteria.

Appendix B: Tabular Data Summaries

Most of the field and laboratory data presented in this report are available in digital format from Ecology's Environmental Information Management (EIM) database. Readers can access the EIM database at: <http://www.ecology.wa.gov/eim/index.htm>

The data for this study are archived in EIM under the following study name and user study ID:

EIM study name:

Evaluation of groundwater conditions at the terminus of Deep and Coulee Creeks
(Spokane County)

EIM user study ID: KSIN0009

Table B-1: Physical description and location of instream piezometers

Site number	Stream name	Approximate river mile location (mile)	Well location	Latitude (decimal degrees)	Longitude (decimal degrees)	Site elevation (feet)	Piezometer stickup (feet above streambed) ¹	Piezometer depth (feet below streambed) ¹	Length of perforated interval (feet)	Depth to midpoint of piezometer perforations (feet below streambed) ¹	Thermistor deployment depths within piezometer (feet below streambed) ¹
AHL153	Spokane R. piezometer	59	26N/42E-07K	47.76368	-117.54784	1609	2.43	4.93	0.5	4.68	1.17 2.43 4.38
AHL154	Deep Ck lowermost piezometer	0.06	26N/42E-07K	47.76299	-117.54790	1606	2	5.35	0.5	5.08	1.06 2.62 4.78
AHL155	Deep Ck uppermost piezometer	0.06	26N/42E-07K	47.76288	-117.54801	1607	2.23	5.09	0.44	4.81	1.06 2.58 4.56

¹ These values are based on measurements made during piezometer installation. Significant snowmelt and associated streambed sedimentation in mid- to late-February 2017 resulted in significant deviations from these initial values.

Table B-2: Summary of CHIT test results.

Piezometer ID	Test scenario number ¹	Piezometer screen length (ft) L*	Real or assumed piezometer diameter (in) D*	Piezometer penetration depth (ft) H*	Assumed total saturated thickness (ft) B*	Operating head (ft) Y*	Total water volume injected during test (liters) VNET*	Time duration of test (min) T*	Net injection rate Vnet/t (L/min) QNET*	Sediment hydraulic conductivity (ft/day) K*	Sediment hydraulic conductivity (m/day) K*
AHL153 (Spokane R).	1	0.35	1.5	4.93	4.93	0.77	1	0.38	2.63	177	54
	2	"	"	"	5.93	"	"	"	"	113	34
	3	"	"	"	20	"	"	"	"	95	29
AHL154 (Deep Creek lower)	1	0.35	1.5	5.33	5.33	0.82	1	0.233	4.29	287	88
	2	"	"	"	6.33	"	"	"	"	182	55
	3	"	"	"	20	"	"	"	"	153	47
AHL155 (Deep Creek upper)	1	0.28	1.5	5.03	5.03	1.02	1	1.5	0.67	38.9	12
	2	"	"	"	6.03	"	"	"	"	23.4	7
	3	"	"	"	20	"	"	"	"	19.5	6
Geometric mean of combined piezometer results for each test scenario										Scenario 1	38.5
(These numbers used in the loading analysis are discussed in Appendix C.)										Scenario 2	23.6
										Scenario 3	20.1

* CHIT test equation variable

¹ The CHIT test method is highly sensitive to the input values used for the assumed total saturated thickness of the streambed sediments (see variable b above and Figure 5). To evaluate the potential impact this assumed variable has on the CHIT results, we ran 4 test scenarios for each piezometer to obtain a likely representative range of model outputs. For test scenario 1: we assumed the piezometer fully penetrated the saturated portion of the streambed and set the streambed thickness equal to the piezometer depth. For test scenario 2: we assumed the saturated portion of the streambed exceeded the piezometer depth by 1 foot. For test scenario 3: we assigned variable b a value of 20, assuming the piezometer penetrated approximately 25 percent of the streambed sediments.

Table B-3: Summary of field measurements and water quality results for sampled instream piezometers and surface water sites.

Site number	Sample date	Groundwater Field Parameters ²					Laboratory Analyses ³							
		Vertical hydraulic gradient ¹ (dimensionless)	Water temperature (deg C)	pH (standard units)	Specific conductance (µS/cm @ 25 °C)	Dissolved oxygen (mg/L)	Dissolved total alkalinity (mg/L)	Dissolved total chloride (mg/L)	Dissolved Ortho-phosphate (mg/L)	Dissolved total phosphorus (mg/L)	Dissolved nitrate+ nitrite-N (mg/L)	Dissolved ammonia (mg/L)	Dissolved TPN-N (mg/L)	Dissolved organic carbon (mg/L)
AHL153 (Spokane River piezometer)	08/16/2016 10:40	0.0	-	-	-	-	-	-	-	-	-	-	-	-
	09/27/2016 10:30	0.002	13.24 J	6.94	611.6	1	333	3.23	0.0907	0.0946	0.144	0.010 U	0.191	1.3
	10/19/2016 10:40	-0.004	-	-	-	-	-	-	-	-	-	-	-	-
	11/29/2016 12:15	-0.008	-	-	-	-	-	-	-	-	-	-	-	-
	01/24/2017 10:23	0.0	7.12 J	7.18	487	0	259 J	0.016 J	0.043	0.0801	0.010 U	0.010 U	0.034	1.12
	02/14/2017 12:20	0.004	-	-	-	-	-	-	-	-	-	-	-	-
	05/17/2017 08:55	0.007	7.13 J	7.26	454.8	0	173	11.3	0.0856	0.0926	4.86	0.016	5.12	3.77
	08/02/2017 09:20	0.003	13.09 J	7.22	460	2.71	186 J	11	0.0994	0.0947	4.02	0.015	4.14	3.54
10/03/2017 09:30	0.0	-	-	-	-	-	-	-	-	-	-	-	-	
AHL154 (Deep Ck lower-most piezometer)	08/16/2016 13:30	0.010	-	-	-	-	-	-	-	-	-	-	-	-
	09/27/2016 11:35	0.012	9.32 J	7.47	305.2	2.32	155	2.12	0.0945	0.0974	0.622	0.010 U	0.704	1.0 U
	10/19/2016 10:55	0.0	-	-	-	-	-	-	-	-	-	-	-	-
	11/29/2016 12:35	0.002	-	-	-	-	-	-	-	-	-	-	-	-
	01/24/2017 12:07	0.008	8.72 J	7.54	306	3.22	154 J	0.95 J	0.097	0.0940	0.658	0.010 U	0.653	1.0 U
	02/14/2017 12:35	0.006	-	-	-	-	-	-	-	-	-	-	-	-
	02/24/2017 14:45	0.015	-	-	-	-	-	-	-	-	-	-	-	-
	04/19/2017 10:45	0.025	-	-	-	-	-	-	-	-	-	-	-	-
	05/17/2017 10:06	0.044	8.06 J	7.33	372	3.68	155	7.47	0.0919	0.0956	3.23	0.010 U	3.35	2.24
	06/14/2017 09:45	0.055	-	-	-	-	-	-	-	-	-	-	-	-
08/02/2017 10:45	0.03	10.57 J	7.3	401.5	6.51	168 J	8.38	0.0952	0.0900	4.12	0.010 U	4.18	2.51	
10/03/2017 09:40	0.016	-	-	-	-	-	-	-	-	-	-	-	-	
AHL155 (Deep Ck upper-most piezometer)	08/16/2016 14:00	0.014	-	-	-	-	-	-	-	-	-	-	-	-
	09/27/2016 12:25	0.002	9.6 J	7.6	291.6	5.65	148	2.11	0.101	0.1020	0.726	0.010 U	0.84	1.0 U
	10/19/2016 11:30	0.013	-	-	-	-	-	-	-	-	-	-	-	-
	11/29/2016 12:45	0.015	-	-	-	-	-	-	-	-	-	-	-	-
	01/24/2017 12:48	0.011	8.82 J	7.63	290	6.04	145 J	1.91 J	0.105	0.1030	0.72	0.010 U	0.745	1.0 U
	02/14/2017 12:40	0.008	-	-	-	-	-	-	-	-	-	-	-	-
	02/24/2017 14:55	0.020	-	-	-	-	-	-	-	-	-	-	-	-
	04/19/2017 10:55	0.029	-	-	-	-	-	-	-	-	-	-	-	-
	05/17/2017 10:51	0.037	8.31 J	7.54	387.3	5.09	157	8.4	0.0799	0.0852	3.82	0.010 U	4.02	2.49
	08/02/2017 11:35	0.027	11.54 J	7.3	400.9	5.61	169 J	8.02	0.0927	0.0870	3.94	0.010 U	4.13	2.51
10/03/2017 10:10	0.014	-	-	-	-	-	-	-	-	-	-	-	-	
Geometric mean of piezometer sample concentrations ⁴										0.0877	0.0928	1.546	1.203	
54-Deep-0.06	09/27/2016 11:55	NA	10.17 J	7.69	272.9	7.05	156	2.1	0.0585	0.0622	0.298	0.010 U	0.383	1
	10/19/2016 11:30	NA	9.67 J	7.96	297.3	11.09	149 J	2.13 J	0.0627	0.0659	0.275	0.010 U	0.333	3.6 J/L
	01/24/2017 13:00	NA	7.13 J	8.53	286	11.24	148 J	0.12 J	0.0846	0.0832	0.405	0.010 U	0.449	1.0 U
	05/17/2017 10:51	NA	9.88 J	8.45	481.9	9.06	202	12.5	0.0539	0.0651	4.31	0.011	4.86	6.05
	08/02/2017 10:10	NA	11.91 J	7.34	403.8	6.55	173 J	8.23	0.0891	0.0856	3.53	0.010 U	3.7	2.73
54-Spok-59.02	01/24/2017 10:50	NA	4.84 J	7.78	169	8.89	63.1 J	0.48 J	0.0242	0.0265	1.48	0.013	1.55	3.47
	05/17/2017 11:55	NA	11.04 J	7.96	74.1	10.05	31.2	1.99	0.0036	0.0090	0.257	0.010 U	0.302 J	1.55
	08/02/2017 09:45	NA	16.75 J	8.21	252.6	9.39	106 J	7.1	0.0092	0.0095	1.6	0.010 U	1.61	1.13

¹ Negative gradient values indicate the potential for loss of stream water to groundwater storage. Positive values indicate the potential for groundwater discharge to the stream.

NA-not applicable at this site.

² Water quality field parameters were measured using an inline flow cell. The temperatures reported here are considered estimates (J-coded) since they may not be indicative of true in-situ conditions.

³ Data qualifier codes:

B – Analyte detected in sample and field filter blank. The reported value is the sample concentration without blank correction or associated quantitation limit.

J – The analyte was positively identified. The reported numeric result is an estimate.

JL – The analyte was positively identified. The actual numeric result may be lower than the estimated value reported here.

U – The analyte was not detected at or above the reported value.

UJ – The analyte was not detected at or above the reported estimated value.

⁴ Non detect (U coded) values were excluded when calculating the geometric mean of sample concentrations.

Appendix C: Glossary, Acronyms, Abbreviations, Conversion Factors, and Datums

Glossary

Clean Water Act: A federal act passed in 1972 that contains provisions to restore and maintain the quality of the nation's waters. Section 303(d) of the Clean Water Act establishes the TMDL program.

Conductivity: A measure of water's ability to conduct an electrical current. Conductivity is related to the concentration and charge of dissolved ions in water.

Dissolved oxygen (DO): A measure of the amount of oxygen dissolved in water.

Geometric mean: A mathematical expression of the central tendency (an average) of multiple sample values. A geometric mean, unlike an arithmetic mean, tends to dampen the effect of very high or low values, which might bias the mean if a straight average (arithmetic mean) were calculated. This is helpful when analyzing bacteria concentrations, because levels may vary anywhere from 10 to 10,000 fold over a given period. The calculation is performed by either: (1) taking the nth root of a product of n factors, or (2) taking the antilogarithm of the arithmetic mean of the logarithms of the individual values.

Hyporheic: The area beneath and adjacent to a stream where surface water and groundwater intermix.

National Pollutant Discharge Elimination System (NPDES): National program for issuing, modifying, revoking and reissuing, terminating, monitoring, and enforcing permits, and imposing and enforcing pretreatment requirements under the Clean Water Act. The NPDES program regulates discharges from wastewater treatment plants, large factories, and other facilities that use, process, and discharge water back into lakes, streams, rivers, bays, and oceans.

Nonpoint source: Pollution that enters any waters of the state from any dispersed land-based or water-based activities, including but not limited to atmospheric deposition, surface-water runoff from agricultural lands, urban areas, or forest lands, subsurface or underground sources, or discharges from boats or marine vessels not otherwise regulated under the NPDES program. Generally, any unconfined and diffuse source of contamination. Legally, any source of water pollution that does not meet the legal definition of "point source" in section 502(14) of the Clean Water Act.

Parameter: Water quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

pH: A measure of the acidity or alkalinity of water. A low pH value (0 to 7) indicates that an acidic condition is present, while a high pH (7 to 14) indicates a basic or alkaline condition. A pH of 7 is considered to be neutral. Since the pH scale is logarithmic, a water sample with a pH of 8 is ten times more basic than one with a pH of 7.

Point source: Sources of pollution that discharge at a specific location from pipes, outfalls, and conveyance channels to a surface water. Examples of point source discharges include municipal wastewater treatment plants, municipal stormwater systems, industrial waste treatment facilities, and construction sites where more than 5 acres of land have been cleared.

Riparian: Relating to the banks along a natural course of water.

Salmonid: Fish that belong to the family *Salmonidae*. Species of salmon, trout, or char.

Total Maximum Daily Load (TMDL): Water cleanup plan. A distribution of a substance in a waterbody designed to protect it from not meeting (exceeding) water quality standards. A TMDL is equal to the sum of all of the following: (1) individual wasteload allocations for point sources, (2) the load allocations for nonpoint sources, (3) the contribution of natural sources, and (4) a Margin of Safety to allow for uncertainty in the wasteload determination. A reserve for future growth is also generally provided.

Watershed: A drainage area or basin in which all land and water areas drain or flow toward a central collector such as a stream, river, or lake at a lower elevation.

303(d) list: Section 303(d) of the federal Clean Water Act requires Washington State to periodically prepare a list of all surface waters in the state for which beneficial uses of the water – such as for drinking, recreation, aquatic habitat, and industrial use – are impaired by pollutants. These are water quality-limited estuaries, lakes, and streams that fall short of state surface water quality standards and are not expected to improve within the next two years.

90th percentile: A statistical number obtained from a distribution of a data set, above which 10% of the data exists and below which 90% of the data exists.

Acronyms/Abbreviations

DOC	Dissolved Organic Carbon
DTP	Dissolved total phosphorus
Ecology	Washington State Department of Ecology
EIM	Environmental Information Management database
EPA	U.S. Environmental Protection Agency
GIS	Geographic Information System software
MEL	Manchester Environmental Laboratory
NPDES	(See Glossary above)
Ortho-P	Ortho-Phosphorus
RM	River mile
RPD	Relative percent difference
RSD	Relative standard deviation
SOP	Standard operating procedures
TMDL	(See Glossary above)
TPN-N	Total persulfate nitrogen-N
USGS	U.S. Geological Survey
WAC	Washington Administrative Code
WRIA	Water Resource Inventory Area

Units of Measurement

°C	degrees centigrade
cfs	cubic feet per second
ft	feet
g	gram, a unit of mass
l/s	liters per second (0.03531 cubic foot per second)
m	meter
mg	milligram
mg/L	milligrams per liter (parts per million)
mL	milliliters
s.u.	standard units
umhos/cm	micromhos per centimeter
μS/cm	microsiemens per centimeter, a unit of conductivity

Conversion Factors and Datums

Multiply	By	To Obtain
Length		
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square ft (ft ²)	0.0929	square meter (m ²)
acre	4,047	square meter (m ²)
square mile (mi ²)	2.59	square kilometer (km ²)
Volume		
cubic foot (ft ³)	0.02832	cubic meter (m ³)
cubic foot (ft ³)	28.32	liter (L)
Flow		
cubic foot per second (ft ³ /sec)	0.02832	cubic meter per second (m ³ /sec)
gallon per minute (gal/min)	3.785	liter per minute (L/min)

Temperature

To convert degrees Celsius (°C) to degrees Fahrenheit (°F), use the following equation:
 $^{\circ}\text{F} = (^{\circ}\text{C} \times 1.8) + 32$

To convert degrees Fahrenheit (°F) to degrees Celsius (°C), use the following equation:
 $^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8$

Datums

The horizontal coordinates reported here are referenced to the North American Datum of 1983 (NAD83 HARN).