Review of Previously Collected Source Water and Groundwater Quality Data from Alluvial Aquifer Recharge Projects in the Walla Walla Basin, Washington and Oregon

Prepared by GSI Water Solutions

Contents

Introduction

Present and future alluvial aquifer recharge (AR) projects in the Walla Walla Basin (the Basin) must proceed with the assurance that these projects not only provide recharge to the alluvial aquifer but also that the additional recharge does not degrade native, or background, groundwater quality. Traditionally water quality monitoring focuses on project-by-project and/or site specific up-gradient and down-gradient sampling. For Walla Walla Basin AR projects this has resulted in each individual AR site having a water quality monitoring program specific to that site, and independent of other AR sites.

In reviewing water quality data collected at multiple AR sites in the Basin, Walla Walla Basin Watershed Council (WWBWC) staff and consultants have made a preliminary observation that AR in the Walla Walla Basin has not resulted in detectable degradation of native groundwater quality. Given this preliminary observation and the desire to streamline water quality monitoring associated with multiple, but inter-related AR sites, the WWBWC decided to do a more comprehensive review of the historical water quality monitoring data collected at the four AR sites it has worked on since AR began in the Walla Walla Basin in 2004. Two of these sites, Hall-Wentland and Hulette Johnson (formerly referred to as the Hudson Bay site) are located in Oregon. The other two, Locher Road and Stiller Pond, are located in Washington (Figure 1). Based on that effort the WWBWC, would like to eliminate synthetic organic compounds (SOC's) from the analyte list for the proposed multi-site AR monitoring program.

This report presents the results of this review of available AR water quality monitoring data, and WWBWC's recommendations for a single, multi-site water quality monitoring program to be used in lieu of a series of independent site-specific monitoring efforts, including the elimination of SOC sampling from normal AR monitoring for the proposed multi-site AR project.

To that end, the purpose of the analysis is twofold:

1. Evaluate water quality data collected before, during, and following various AR events at the four AR sites in an effort to identify analyte trends that may indicate any possible negative or positive effects with respect to water quality on the alluvial aquifer from AR operations.
2. Using that evaluation, propose removing synthetic organic compounds (SOC's) from the list of sampled parameters is plausible.

The remainder of this report focuses on a review of water quality data collected to-date at each of the four AR sites, the evaluation of the impacts of AR on groundwater quality, and recommendations for the scope of a potential future multi-site AR monitoring effort that eliminates expensive and time consuming SOC sampling. Details of AR operations at the four sites are found in Kennedy/Jenks (2006), GSI (2007a, 2007b, 2008a, 2008b, 2009, 2012), and WBWC and GSI (2010). Alluvial aquifer geology and hydrogeology are discussed in detail in Newcomb (1965), Barker and McNish (1976), and GSI (2007c).

Alluvial Aquifer Water Quality

Alluvial aquifer water quality data collected from the various AR sites and evaluated for this effort varies from site-to-site. However, they generally included field parameters, major ions, nutrients (nitrate-N, total Kjeldahl nitrogen (TKN) and ortho-phosphate), PCB's, bisphenol-A (BPA), and agricultural synthetic organic compounds (SOC's).

AR Site Water Quality Findings

Hulette Johnson

The Hulette Johnson site (Figures 1 and 2) is a fully developed AR site that has been in operations since 2004. Both recharge basins and infiltration galleries are used at this site. It is the most up-gradient of all the sites evaluated herein (WWBWC, 2012) and is located about 2 miles northwest of Milton-Freewater, Oregon. Water quality data used in this evaluation come from two monitoring wells (HJ-1 and HJ-2) and from the source water intake at the site. The source water is Walla Walla River water delivered to the site via the White Ditch operated by HBDIC. This site has been operated under a Limited License issued to the HBDIC.

The samples evaluated herein were collected periodically between 2006 and 2012. Water quality parameters evaluated from the Hulette Johnson site include nitrate-N, total Kjeldahl nitrogen (TKN), ortho-phosphate, chloride, total organic carbon (TOC), total suspended solids (TSS), total dissolved solids (TDS), hardness, and a suite of synthetic organic compounds (SOC's). Field parameter data, consisting of pH and electrical conductance (EC), where only collected at this site during its early years of operation. Plots for many of the parameters collected at this site are provided in Appendix A.

A range of source water and groundwater quality relationships are found in the Hulette Johnson site data. Some parameters display higher values in groundwater, while others display higher values in the source water. In other data sets groundwater quality parameter values are similar to those from source water samples. Specific observations are as follows.

Ortho-phosphate, nitrate-N (nutrient type parameters) and TDS generally are lower in source water during the same sampling events as compared to local groundwater. Slightly negative correlations (Table 1) between both source and alluvial groundwater ortho-phosphate data with sampling dates over time suggest that with respect to this parameter groundwater quality is not degraded but improved during AR operations. Groundwater nitrate-N concentrations have a slightly positive (0.02) correlation to sampling date but source water nitrate-N has a negative correlation (-0.45). The slightly increasing nitrate correlation in groundwater with sampling date over time, as compared to decreasing correlation in surface water, is interpreted to show that surface water introduced via AR is not degrading groundwater quality.

Chemical oxygen demand (COD) data exhibit no trends in groundwater and surface water, but do show generally values with the range of concentrations measured to-date in both systems overlapping (Appendix A Figure A-12). A slightly negative correlation between the data from each sampling location at this site and the sampling date suggests that groundwater quality at this site is not degraded but improved with respect to organic constituents.

TKN and TOC in groundwater and surface water generally show similar values with the range of concentrations measured to-date in both systems overlapping (Appendix A Figures A-17 and A-19). A slightly negative correlation (TKN = -0.31, TOC = -0.52) between the data from each sampling location at this site and the sampling date suggests that groundwater quality at this site is not degraded but improved with respect to TKN and TOC.

Chloride and TSS in source water generally is the same as, or higher than is seen in local groundwater (Appendix A Figures A-15 and A-13). The parameter concentrations measured to-date are low in general and suggest no contamination issues related to TSS and chloride. A positive correlation of chloride data to sampling date (0.54) suggests that chloride in groundwater may be increasing slightly over time. TSS source water data also has a positive correlation to sampling date (0.11), also suggesting that it could be slightly increasing over time. For both parameters though negative correlation in groundwater of -0.03 for chloride and -0.54 for TSS is interpreted to show that AR is not degrading local groundwater quality with respect to these two parameters.

Bisphenol-A (BPA) is the only ***SOC*** at this site with repeat detections, being detected intermittently in site groundwater between 2008 and 2012. BPA has not been detected at this site in source water. To-date, these measured BPA concentrations are two orders of magnitude lower than EPA toxic levels for aquatic organisms. EPA toxic levels for aquatics are between 1100 and 10,200 µg/L for aquatic organisms (EPA, 1988). Insufficient data is available for statistical and long term trend evaluation of BPA at this site.

In summary, these data are interpreted to show that to-date, AR operations at the Hulette Johnson site generally have not lead to degradation of local groundwater. Nutrients in source water are lower than seen in groundwater; therefore if they have any influence on groundwater, they decrease down gradient concentrations. Although Chloride and TSS are higher in source water, the relatively low concentrations seen in local groundwater are interpreted to reflect a minimal impact on local groundwater quality by AR operations. With respect to other parameters TDS, TKN, and TOC in both groundwater and surface water overlap to such a degree that they are interpreted to reflect a similar origin and AR operations has a minimal influence on them. SOC data collected to-date do not show any impact to groundwater by AR activities. BPA when found in groundwater is not detected in source water, suggesting its introduction to groundwater via other means than AR activity at this location.

Hall-Wentland

The Hall-Wentland site (Figures 1 and 3) hosted AR activity between 2006 and 2009. This site is located 4 miles southwest of Walla Walla, WA and about 6 miles northeast of the Hulette Johnson site. The Hall-Wentland site is on irrigated pasture and adjacent cropped ground which was flooded for AR operations. Water was delivered to the Hall-Wentland site via a small canal, the Wells ditch. Wells ditch is sourced from a weir structure on the East Branch of the Little Walla Walla River less than one mile south-southeast of the site. When operated, this AR project was operated under a Limited License issued to the WWRID, but operated by a local land owner.

WQ samples were collected in 2006, 2007, 2008, and 2009 from one up-gradient monitoring well (HW-2), two down-gradient monitoring wells (HW-1 and HW-3), and from source water before, during, and after AR operations. Parameters used in this evaluation of AR influences on groundwater at the Hall-Wentland site include pH, EC, turbidity, nitrate-N, hardness, TDS, chloride, and SOC's. Plots for these data are provided in Appendix B. As with the Hulette Johnson site, water quality data from the Hall-Wentland site shows that for some constituents source water and groundwater geochemistry are similar, while for others they differ, but without a significant change, or degradation, in groundwater conditions resulting from AR operations.

With respect to the ***field parameters (pH and EC)*** source water pH generally is higher than groundwater pH, and while there is a slight increase in down-gradient pH the differences between the two are small (Appendix B Figures B-13 and B-14), and up-gradient to down-gradient changes are not consistent. Source water EC generally is lower than groundwater EC, and groundwater EC does not show any clear up-gradient to down-gradient changes that are interpreted as indicative of AR influences on groundwater quality (Appendix B Figure B-14). These trends are exemplified with a positive correlation (0.23) between pH and sampling date over time in source water and slightly negative correlations between groundwater data sets (-0.05, -0.23 and -0.23 for HW-1, HW-2 and HW-3 respectively).

Turbidity also appears to be generally higher in source water when compared to groundwater. With that though, there is no readily apparent increase in groundwater turbidity from up-gradient to down-gradient at the Hall-Wentland site (Appendix B Figure B-15). This likely reflects the filtration of fines from the source water as it migrates through the vadose zone to the water table.

Source water generally displays lower values for ***hardness, TDS, and nitrate-N*** than groundwater (Appendix B Figures B-16 and B-19). Given that, if there were significant changes in groundwater quality caused by AR operations at the Hall-Wentland site one should expect to see up-gradient to down-gradient decreases in these parameters. Such trends are not readily apparent in the data collected to-date. Negative correlations (see Table 1) between source and groundwater samples at this site for all but one sampling location (HW-3, which is the furthest down-gradient) indicate that groundwater quality with respect to TDS could have improved due to AR at this site. All sampling locations at this site exhibited positive correlations between nitrate values and sampling dates over time (See Table 1). Being that groundwater values are higher than source water values (Appendix B Figure B-19), it is most likely that nitrate-N levels in groundwater are influenced by other activities than AR.

Ortho-phosphate in groundwater and surface water generally show similar values with the range of concentrations measured to-date in both systems overlapping (Appendix B Figure B-20). Positive correlations between ortho-phosphate values and sampling times (See Table 1) showed that values increased over the time of sampling at this site.

The ***chloride*** data collected during Hall-Wentland operations contains some anomalously high values which may mask a trend indicative of AR influences on groundwater quality (Appendix B Figure B-18). Although chloride concentrations generally are low in both groundwater and source water (<5 mg/L) high and low source water values do seem to generally be reflected in down-gradient increases and decreases. Given that though, negative correlations between chloride data and sampling dates over time for all sampling locations at this this site suggest that chloride over time could be decreasing.

Three ***SOC's, di(ethylhexyl)-phthalate, diethyl phthalate, and Malathion***, were detected in 4 different sampling events. However, in only one sampling event were SOC's (di(ethylhexyl)-phthalate and diethyl phthalate) detected in the source water. In all cases, the detected concentrations were below EPA drinking water standards, as follows:

- Di(ethylhexyl)-phthalate values ranged from 1.6 to 4.1 µg/L. The EPA drinking water standard is 6.0 µg/L.
- Diethyl phthalate values ranged from 0.5 to 2.2 µg/L. The EPA drinking water standard for diethyl phthalate is 5000 µg/L.
- Malathion was detected only for the 04/11/07 sampling event in the three wells and not in the source water. Malathion levels ranged 0.3 to 0.4 µg/L. This is far below the EPA drinking water standard of 500 µg/L.

Insufficient data is available for statistical and long term trend evaluation of SOC's at this site.

In summary data from the Hall-Wentland site are interpreted to show that AR operations generally had little or no significant influence on local groundwater quality. There are likely several reasons for this, including:

- The general similarity of the source water and the groundwater at the Hall-Wentland site may be related to the location and leaky nature of the Wells ditch with respect to the monitoring wells and the AR site. Wells ditch was shown during work on the AR project to be a leaking ditch, supplying recharge to local groundwater. The ditch is in-turn located up gradient of the up gradient well, HW-2. Given this relationship, water leaking from the canal to the aquifer has already influenced local groundwater up gradient of the AR site, masking any potential AR site influence on local groundwater. This relationship is one we have come to expect across much of the Basin, the surface water system contributes significant recharge to the alluvial aquifer, and as such, exerts a strong influence on local groundwater quality quite independently of any AR activity.
- For some constituents the soil column (vadose zone) acts as a filter and these constituents are held up, or filtered, by the soil column as water infiltrates from the surface to the underlying alluvial aquifer.
- In other cases, where constituents are present in groundwater but not in source water, such as is usually the case with SOC's, we infer that these entered the groundwater system at a location(s) other than the AR site.

Based on what was seen at the Hall-Wentland site when it was operated, AR activity may have influenced down-gradient water quality, but the changes from up to down-gradient are relatively small, with the total potential change caused by AR less than variation occurring independent of AR resulting from natural (or normal) canal and ditch operations. With that though, even normal operation generally appears to not cause degradation of the underlying alluvial aquifer.

Locher Road

The Locher Road site is an excavated basin specifically designed for AR located within a larger, inactive gravel pit. It is cross gradient of the Hall-Wentland site and down gradient from the Hulette Johnson site. It is located about 5 miles southwest of College Place, WA (Figures 1 and 4). AR operations occurred seasonally at the site in 2006, 2007, 2008, 2009, 2011, and 2012. The Locher Road site is operated by GFID#13 under an agreement with the owner of the site.

Water quality samples have been collected from one up gradient monitoring well (L-1), two down gradient monitoring wells (L-2 and L-3), and from the source water diversion on GFID's Burlingame Canal. Parameters used in this evaluation of potential AR influences on the alluvial aquifer include the field parameters pH and EC, turbidity, nitrate-N, hardness, TDS, chloride, and SOC's. Plots for these data are provided in Appendix C.

Locher Road groundwater monitoring data is interpreted to show that AR at this site does influence groundwater quality. In addition, some of the data may show the influence of local land uses.

TDS, hardness, and EC data are interpreted to show up gradient to down gradient decreases directly related to AR. Generally source water values are lower than down gradient groundwater, and down gradient groundwater values are lower than up gradient (Appendix C Figures C-15, C-16 and C-12). Scatter plot trends and positive correlations between TDS data and sampling dates over time for all site source and all groundwater datasets indicates a slight increasing trend over time. However, this trend appears to be slight enough as to not be indicative of any groundwater degradation by AR operations at the site (Appendix C Figures C-5, C-15 and Table 1). EC at this site exhibits slightly increasing trends on scatter plots and positive correlations between EC values and sampling dates over time in source water and all monitoring wells except the up-gradient well LR-1 which exhibits a slightly negative trend and negative correlation (Appendix C Figures C-2, C-12 and Table 1). However actual values of EC from LR-1 average higher than all other locations and source water at this site which is typical for up-gradient conditions. LR-1 is very close to the recharge basin and the decreasing trend and negative correlation with sampling date over time could be due to some groundwater dilution caused by possible groundwater mounding from AR.

Chemical oxygen demand (COD) show concentration ranges where both source water and groundwater overlap (Appendix C Figure C-14 and Table 1). These data are interpreted to show that there are no trends in groundwater and surface water.

Locher Road site ***nitrate- N*** data is interpreted to in part reflect groundwater impacts unrelated to AR operations. Source water nitrate-N is very low and prior to 2009 there was an up gradient to down gradient decrease in constituent concentration that is interpreted to result from source water dilution of groundwater nitrate -N. In the 2009, 2011, and 2012 there is elevated nitrate-N in the most down gradient well, L-2, while source nitrate-N is extremely low, less than 1 mg/L. Elevated nitrate-N in well L-2 is interpreted to be because the well is down gradient of an actively farmed field and results from fertilizer application on that field, and not AR operations. Box-plot analysis and positive correlation coefficient comparisons between sampling location datasets at this site indicate dilution of groundwater with respect to nitrate-N in a down gradient direction (Appendix C Figure C-18 and Table 1). This is interpreted to show no alluvial groundwater quality degradation, but possibly improvement, because of AR operations with respect nitrate-N.

Source water generally displays lower values for ***ortho-phosphate*** than groundwater. These values do trend together and are relatively close suggesting a common source of ortho-phosphate for both systems. These observations can be seen in box-plots comparing sampling location datasets for this site (Appendix C Figure C-19). Source water ortho-phosphate correlation with sampling date over time is slightly positive but moderately negative for all monitoring wells. This suggests that AR operation at Locher Road does not degrade alluvial groundwater quality with respect to ortho-phosphate.

Chloride, pH, and turbidity data are less clear, and at this time are interpreted to show that source water and local groundwater have many similarities. With that general interpretation groundwater chloride generally is higher than source water, groundwater pH generally is lower, and turbidity does not seem to show a clear trend because of intermittent elevated levels in L-1. On box-plots, source and groundwater chloride ranges overlap, further illustrating the similarity between them (Appendix C Figure C-17). Turbidity does exhibit slightly negative correlations with sampling dates over time suggesting some possible flushing of fine materials from the alluvial aquifer in the vicinity of Locher Road due to AR (Table 1).

With respect to ***SOC's***, the Locher Road SOC data collected in 2007 and 2008 is similar to the other SOC data sets, showing intermittent low concentration detections of just a few parameters ***(Bromacil, Malathion, Di-N-Butyl-Phthalate)***, although these parameters differ somewhat from the other sites. Bromacil is detected in some of the up gradient groundwater samples, but not in the down gradient samples, suggesting potential down gradient dilution from AR activities. The other low concentration SOC detections for Malathion (detected once in all three wells) and Di-N-Butyl-Phthalate (detected in 2 sampling events in 2007) are sporadic, low concentration in nature, and show down gradient reduction in concentrations when seen. These are interpreted to show that Locher Road AR activities are not causing degradation of local groundwater by introducing SOC's to the alluvial aquifer system. Insufficient data is available for statistical and long term trend evaluation of SOC's at this site.

Stiller Pond

The Stiller Pond AR site is an artificial pond that has been used historically as an irrigation water storage impoundment. Unlike the other three sites it is located north of the Walla Walla River and several miles west of Walla Walla (Figure 1 and 5). The source of water for the Stiller Pond site is Mill Creek, and water is delivered via a pipeline that extends from the creek to the site. The Stiller Pond site was operated by the WWCCD, under an agreement with the land owner.

AR operations first began at Stiller Pond in the spring of 2012 and lasted approximately 3 weeks. During this AR event water quality samples were collected at one down gradient well and from the source water. Parameters used in this evaluation of potential AR influences on the alluvial aquifer include the field parameters pH, EC, dissolved oxygen (DO), and oxidation-reduction potential (ORP) and hardness, chloride, magnesium, TDS, nitrate-N, phosphate, and TKN.

SOC’s were not collected at the Stiller Pond site. Comparative histograms for the data collected are provided in Appendix D.

Like the other AR sites described herein, at Stiller Pond, the influence of AR operations on local groundwater is apparent but impacts are not major and do not appear to lead to degradation of local groundwater quality. Specifically:

- Pre- and post-test groundwater and source water ***pH*** remained relatively consistent.
- ***EC and ORP*** appear to have decreased as a result of AR activities, with the down gradient well dropping soon after the start of AR operations and infiltration of low EC and anion source water.
- ***Chloride, hardness, magnesium, and TDS*** were all lower following the AR event. This is again inferred to result from dilution of groundwater constituents as low concentration source water infiltrated to and recharge the local alluvial aquifer.
- Nutrient concentrations, which include ***nitrate-N, phosphate, and TKN*** are interpreted to show that AR at this site did not degrade groundwater quality. TKN was elevated slightly in the post-recharge sample, but this was expected due to the introduction of additional organic nitrogen, ammonia and ammonium to the groundwater via recharge through the biomass on the surface of the Pond in the form of decaying plant matter. This slight rise in TKN is not interpreted to reflect groundwater degradation because the slight increase in TKN did not correspond to a matching increase in nitrate-N. In fact, nitrate-N decreased in groundwater following the AR event.

Basic water quality parameters summarized above are interpreted to show that AR activities at the Site did not degrade groundwater quality during the 2012 AR season. This data, especially the fact that pre-test groundwater concentrations in most parameters are higher than post-test groundwater concentrations and source water, suggests AR operations at the Site may lead to reductions in parameter concentrations as recharge water is added to the alluvial aquifer underlying the Site.

Summary

Review of the groundwater quality monitoring data collected to-date at the three active AR sites, Hulette Johnson, Locher Road, and Stiller Pond and at the inactive Hall-Wentland site we conclude that while AR operations conducted in the Walla Walla Basin does influence local groundwater quality, this influence should not be construed as degradation. Based on the data reviewed here the basic changes seen include the following:

- With respect to nutrient type constituents, including nitrate-N, TKN, phosphate, and ortho-phosphate the groundwater changes we see generally show down gradient declines in constituent concentrations, which we interpret to reflect dilution of groundwater concentrations by AR water.
- Other parameters, such as TDS, chloride, and EC also commonly show evidence of down gradient reductions through AR sites that we again interpret as evidence of dilution of these parameters in groundwater by AR water.
- The SOC data available for these sites is interpreted to show that AR operations have essentially no influence on SOC’s present in groundwater. Based on what we reviewed

SOC detections are sporadic, not systematic, and at very low concentrations. With that observation, we interpret the few detections to result from background conditions reflective of activities other than AR operations.

- In addition to these observations, the Hall-Wentland data is instructive as it shows the importance of natural leakage from surface waters (which typically are the same waters these AR sites use for source water) influencing local groundwater chemistry.

The water quality data collected over several AR seasons from four different sites are interpreted to have not resulted in alluvial aquifer water quality degradation. Field parameters and major ion hydrochemical trends seen in monitoring well data commonly show reduced concentrations, indicating dilution of groundwater concentrations by AR operations. A few anomalies did occur in these trends, but low source water concentrations versus high monitoring well concentrations strongly suggest that AR operations were not the cause of these anomalies. There were no significant SOC detections from any site. Of the SOC detections seen in the data sets, SOC concentrations are low enough to be considered background levels and/or these detections were instances of localized transient introduction to the water table from an unaltered ground surface AR site (specifically HW).

Recommendations

Based on our interpretation that AR has led to little to no degradation of groundwater quality in the Walla Walla Basin, we recommend that future monitoring of AR projects exclude extensive sampling and testing for SOC’s. The data collected to-date is interpreted to show very low, and sporadic background SOC concentrations not related to AR activities. Rather SOC detections are likely related to transient events originating at sites other than the AR sites. Thus it is unlikely that SOC’s have been or would be introduced to the alluvial groundwater by AR source water.

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Table 1. Correlation Coefficients between Water Quality Parameters and Sampling Dates over Time. EC =electrical conductivity, COD = chemical oxygen demand, TDS = total dissolved solids, TSS = total suspended solids, TKN = total Kjeldahl nitrogen and TOC = total organic carbon.

Site/ Well	**Correlation Coefficient**											
	pH	**EC**	**Turb.**	**COD**	**TDS**	**TSS**	**HCO3**	**Cl-**	**NO3-**	**TKN**	**Ortho-phos.**	**TOC**
Hall-Wentland												
Source	0.23	0.34	0.16	-0.33	-0.23	N/A	-0.15	-0.44	0.07	N/A	0.42	N/A
HW-1	-0.05	0.66	0.61	-0.28	-0.06	N/A	-0.08	-0.36	0.52	N/A	0.61	N/A
HW-2	-0.23	0.57	0.18	-0.28	-0.02	N/A	-0.36	-0.27	0.32	N/A	0.59	N/A
HW-3	-0.23	0.86	0.12	-0.25	0.21	N/A	0.05	-0.37	0.64	N/A	0.71	N/A
Hulette-Johnson												
Source	N/A	N/A	N/A	-0.89	0.33	0.11	N/A	-0.03	-0.45	-0.31	-0.15	-0.52
HJ-1	N/A	N/A	N/A	-0.57	0.30	-0.54	N/A	0.54	0.02	-0.25	-0.20	-0.35
Locher Road												
Source	-0.50	0.01	0.76	0.31	0.14	N/A	0.00	-0.57	-0.25	N/A	0.14	N/A
LR-1	-0.43	-0.16	-0.11	0.03	0.44	N/A	-0.37	0.40	0.28	N/A	-0.40	N/A
LR-2	-0.69	0.54	-0.03	-0.05	0.68	N/A	0.42	0.55	0.63	N/A	-0.42	N/A
LR-3	-0.65	0.12	-0.22	-0.09	0.33	N/A	0.07	-0.27	0.43	N/A	-0.39	N/A

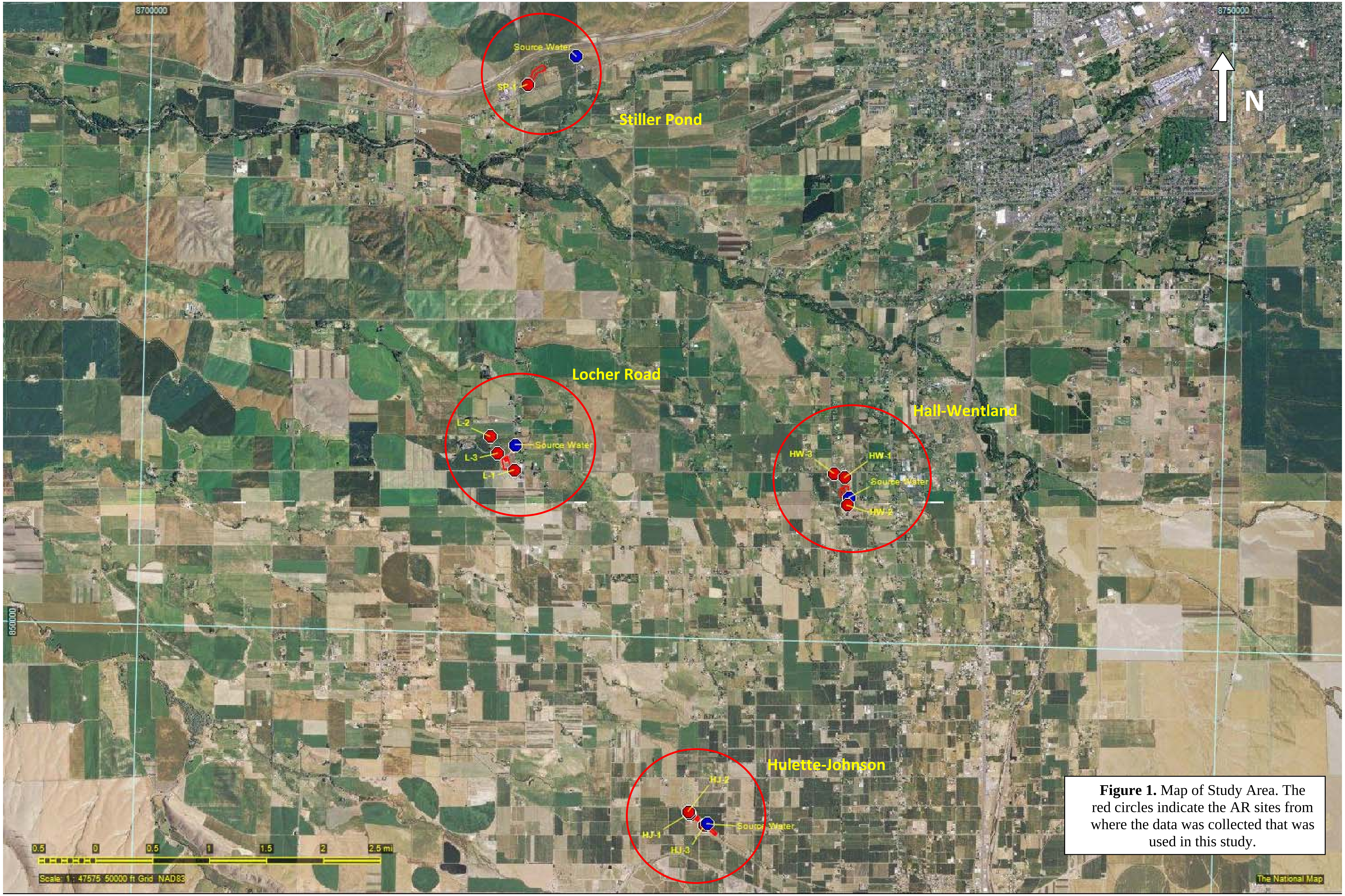

Figure 1. Map of Study Area. The red circles indicate the AR sites from where the data was collected that was used in this study.

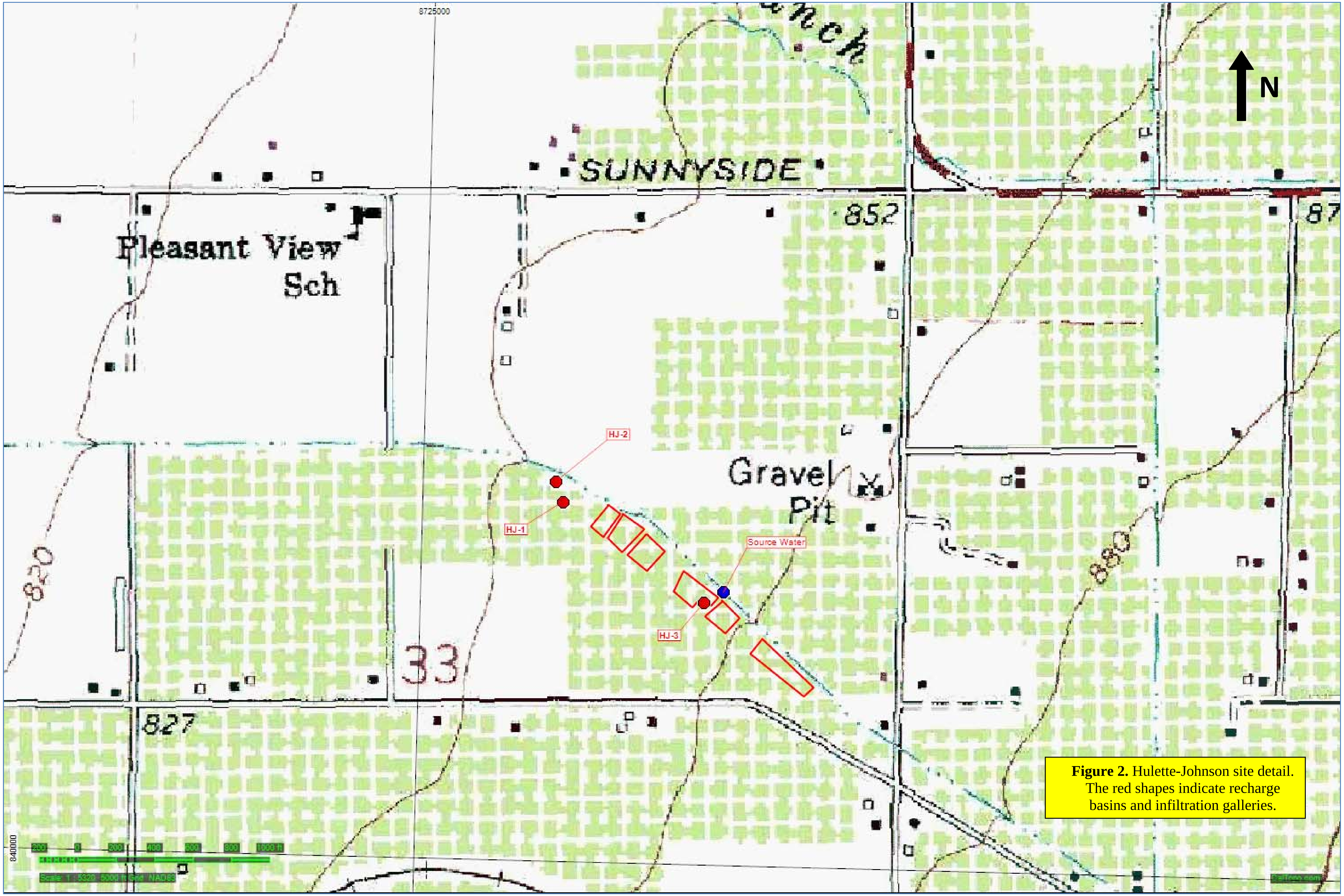

Figure 2. Hulette-Johnson site detail. The red shapes indicate recharge basins and infiltration galleries.

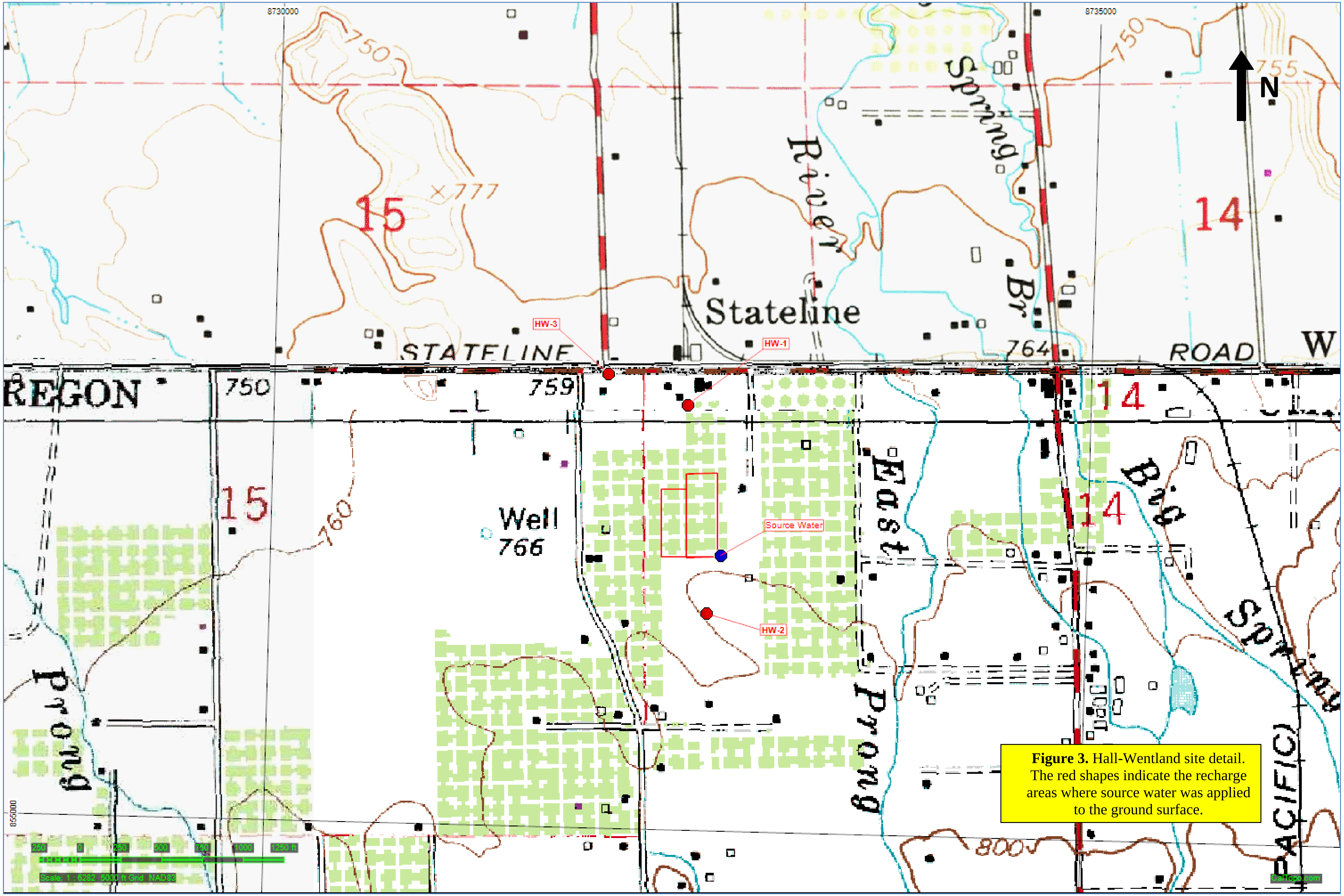

Figure 3. Hall-Wentland site detail. The red shapes indicate the recharge areas where source water was applied to the ground surface.

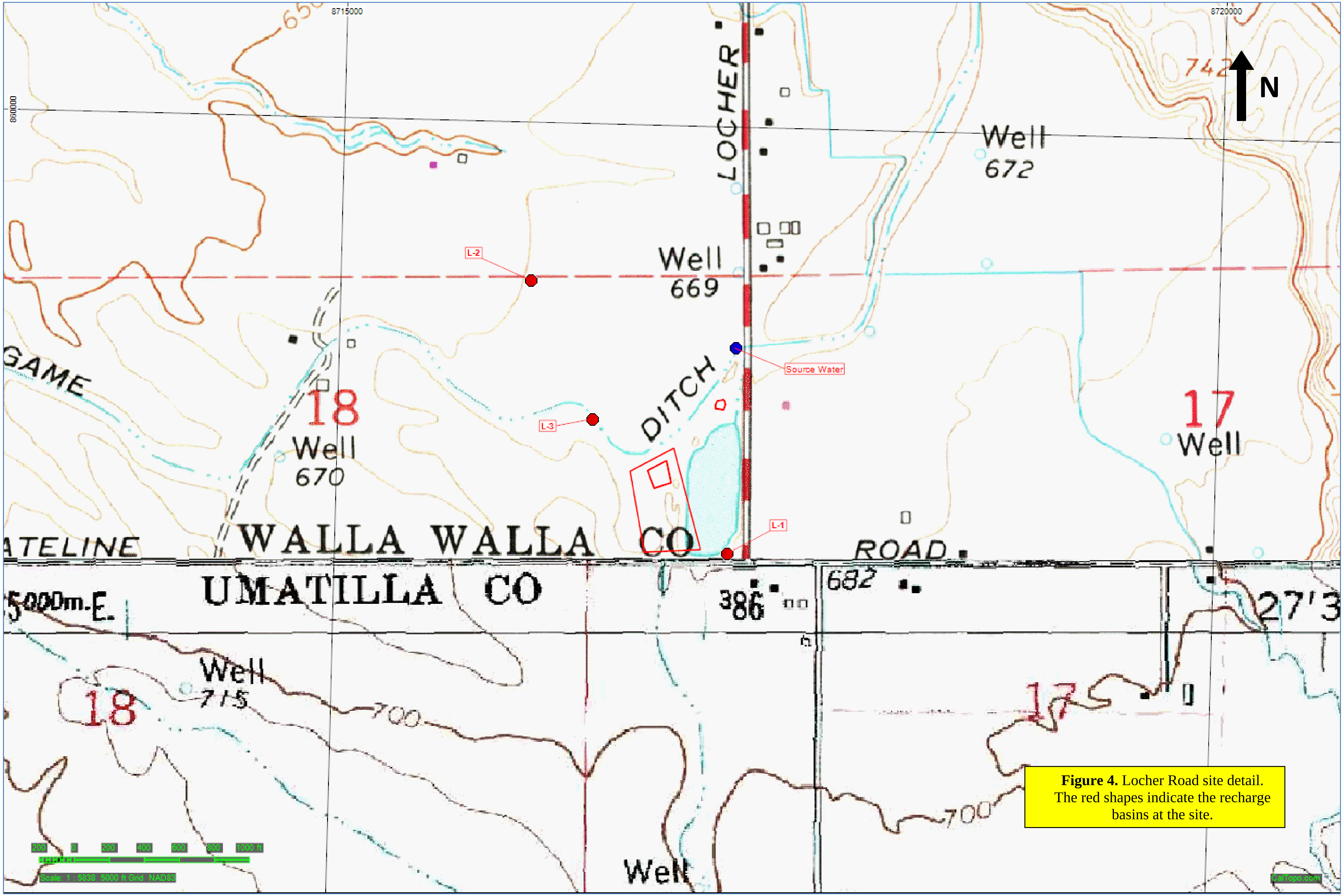

Figure 4. Locher Road site detail. The red shapes indicate the recharge basins at the site.

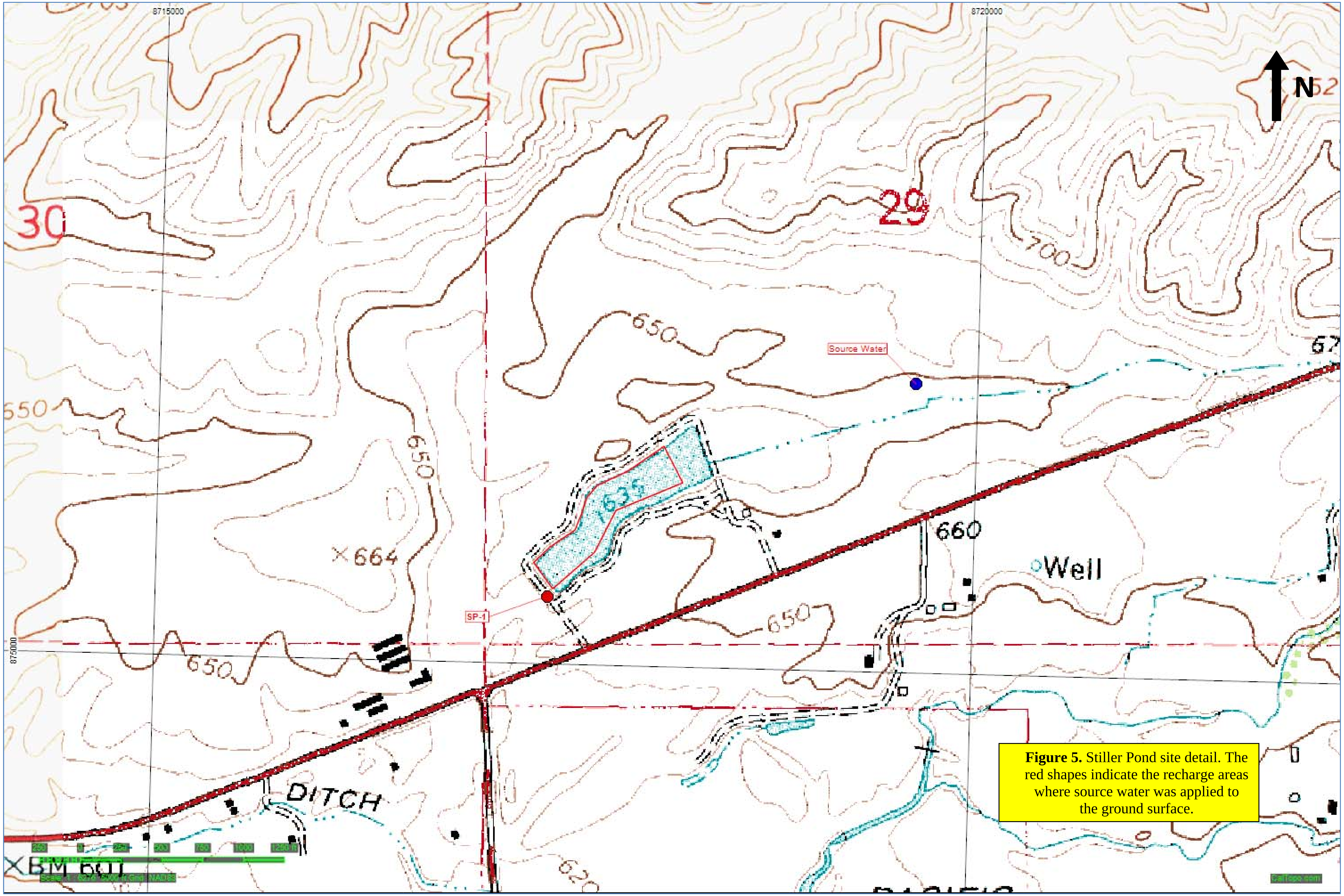

Figure 5. Stiller Pond site detail. The red shapes indicate the recharge areas where source water was applied to the ground surface.

Appendix A

Hewlett-Johnson Data Plots

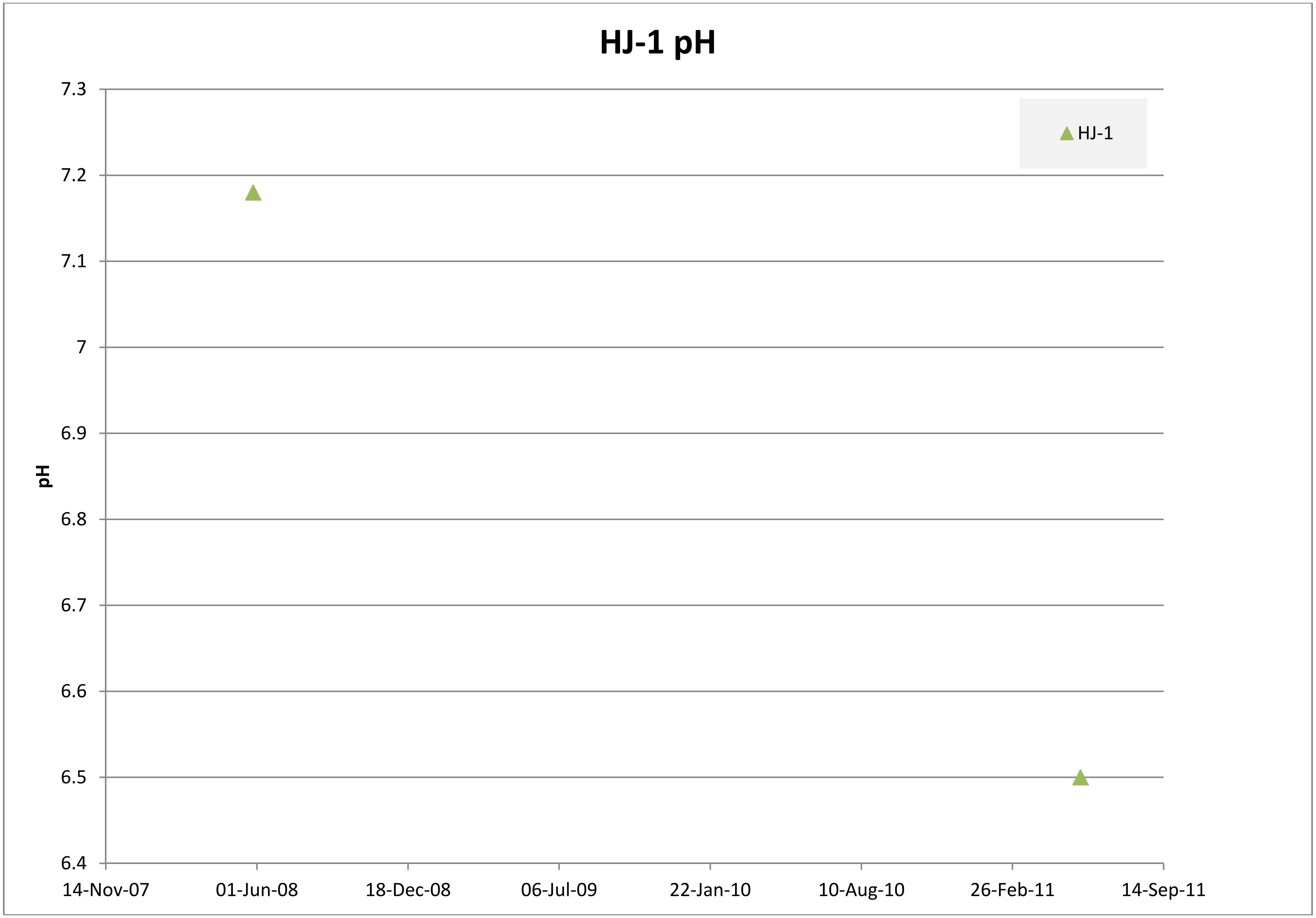

Figure A-1. Hewlett-Johnson pH. HJ-1 = Hewlett-Johnson monitoring well 1.

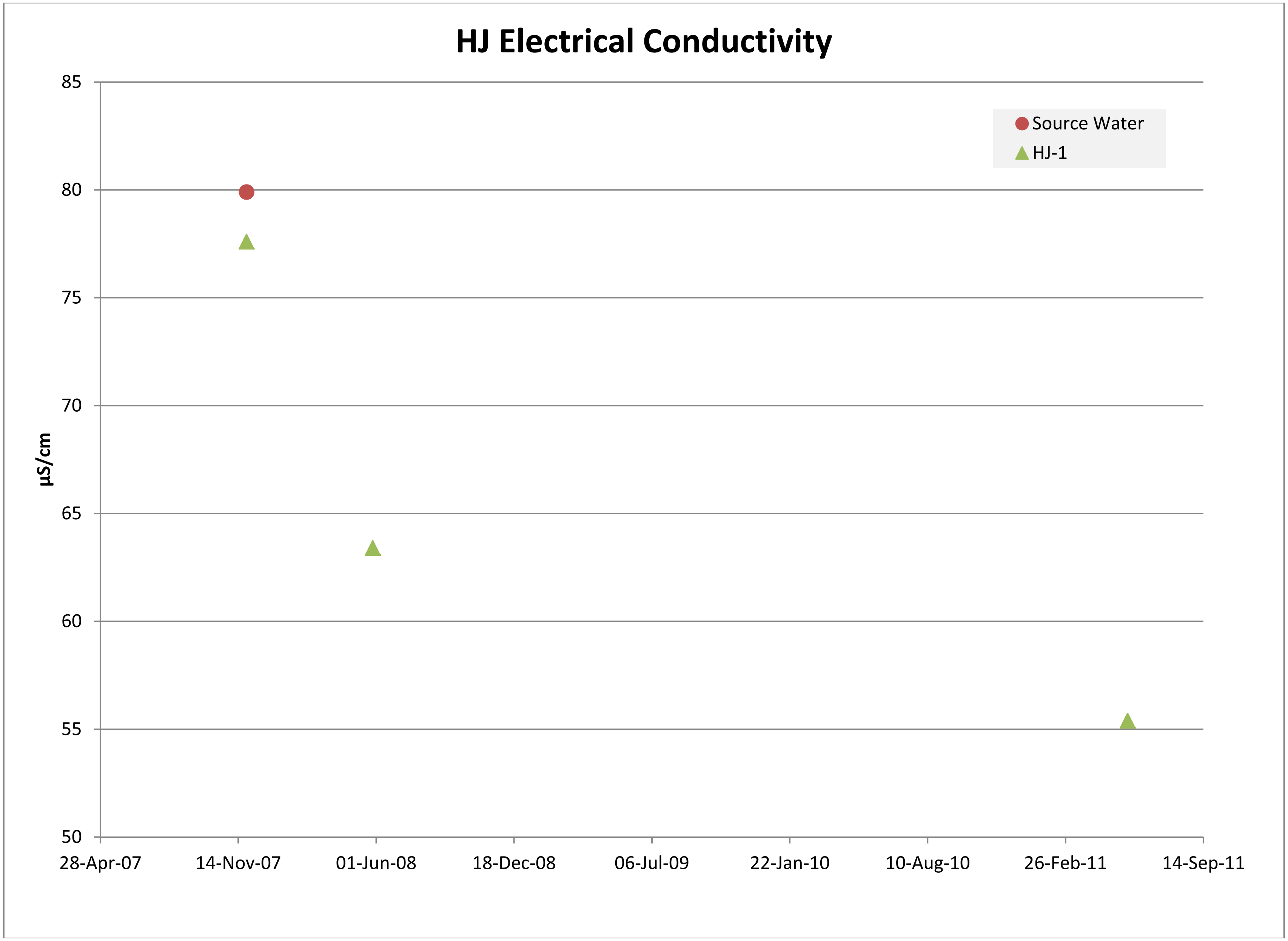

Figure A-2.Hewlett-Johnson electrical conductivity (EC). HJ-1 = Hewlett-Johnson monitoring well 1.

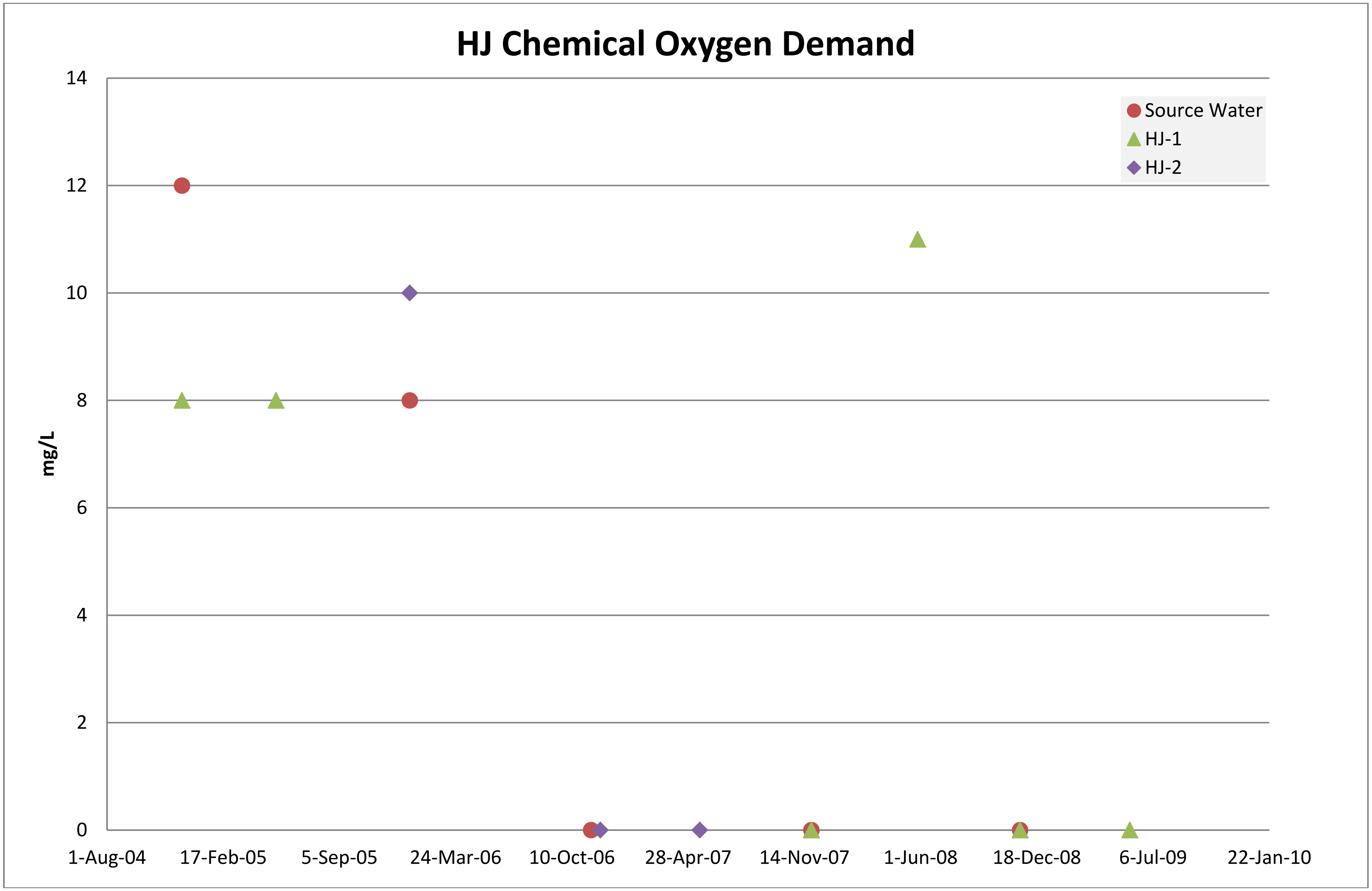

Figure A-3. Hewlett-Johnson chemical oxygen demand (COD). HJ-1 = Hewlett-Johnson monitoring well 1. HJ-2 = Hewlett-Johnson monitoring well 2.

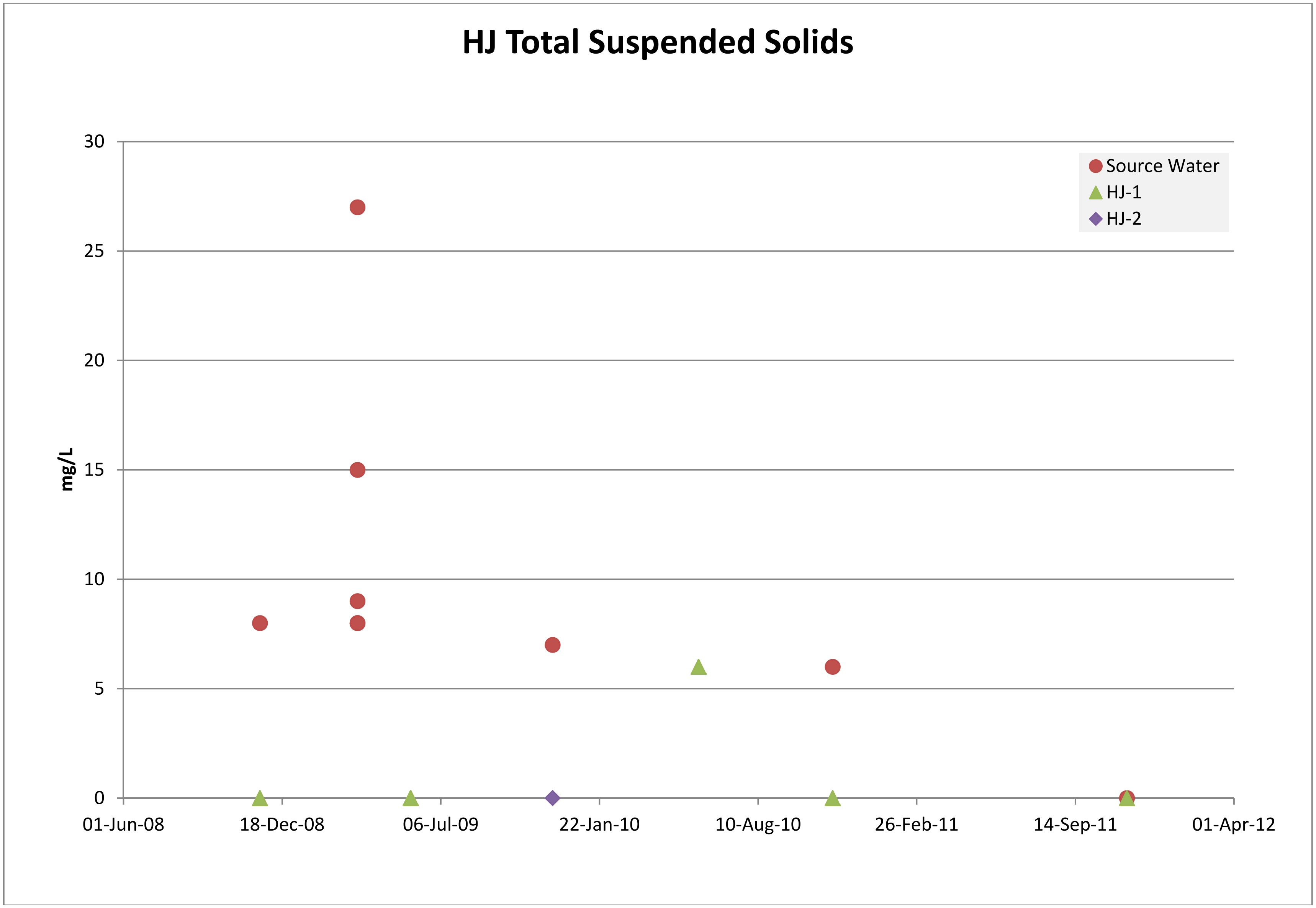

Figure A-4.Hewlett-Johnson total suspended solids (TSS). HJ-1 = Hewlett-Johnson monitoring well 1. HJ-2 = Hewlett-Johnson monitoring well 2.

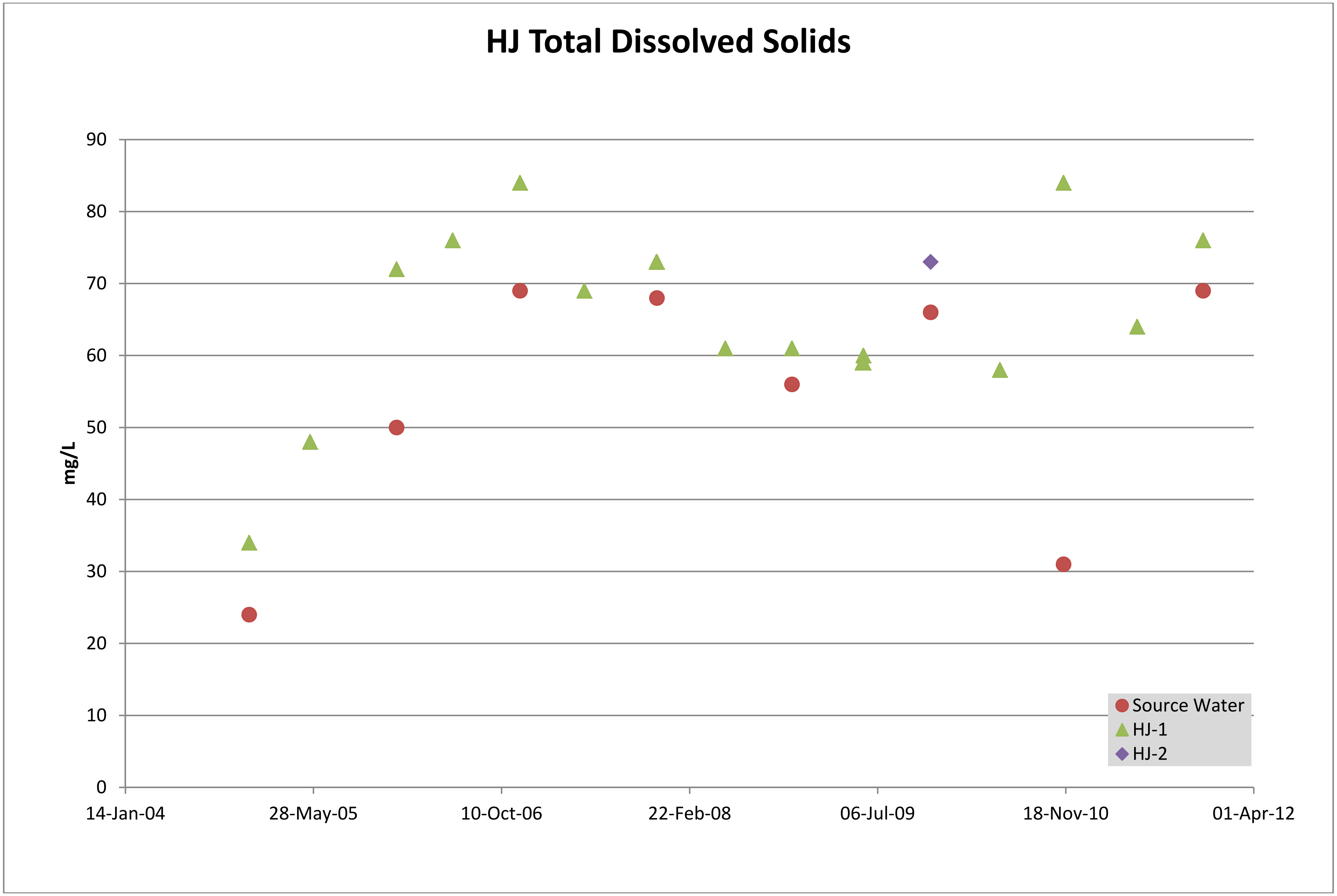

Figure A-5. Hewlett-Johnson total dissolved solids (TDS). HJ-1 = Hewlett-Johnson monitoring well 1. HJ-2 = Hewlett-Johnson monitoring well 2.

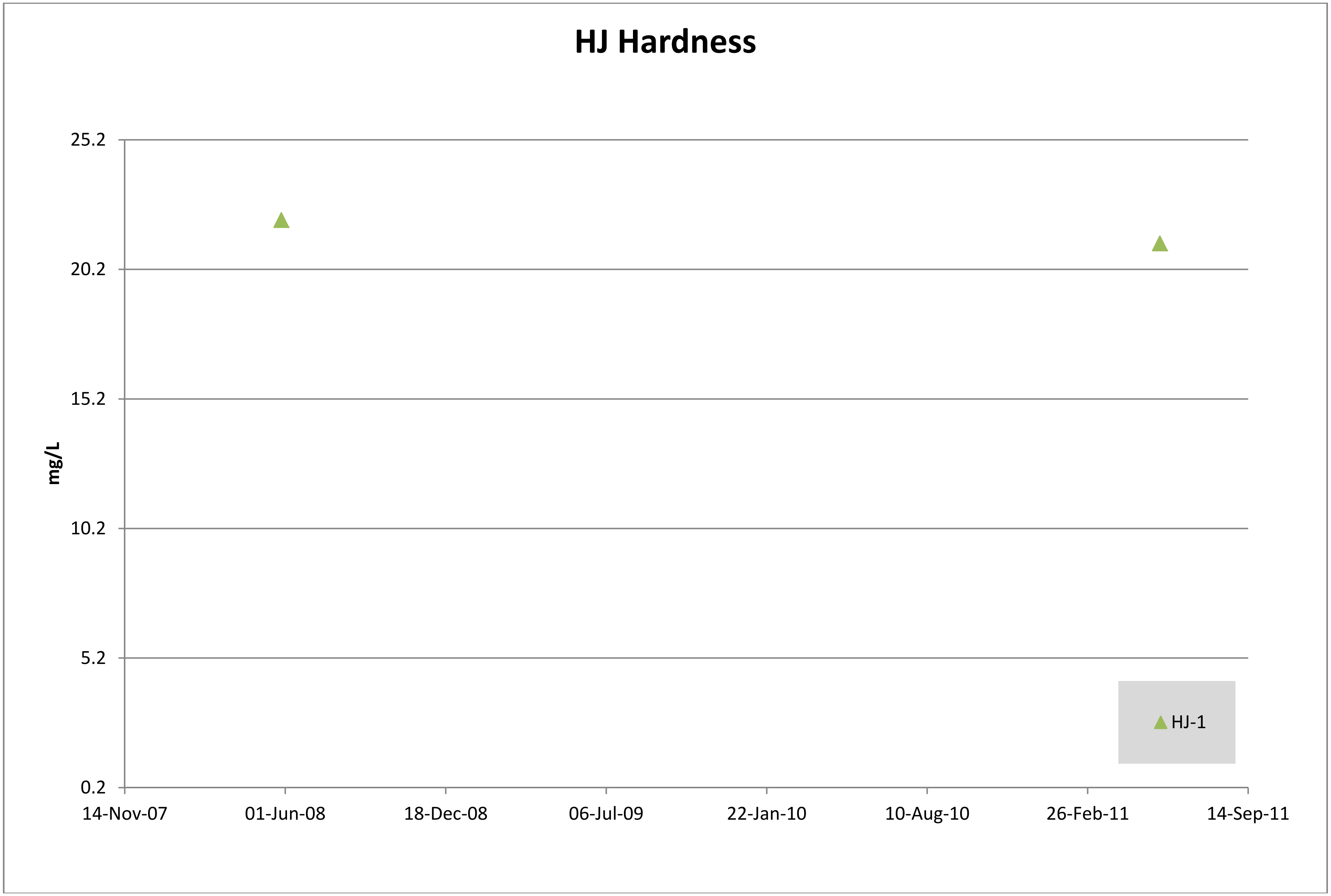

Figure A-6. Hewlett-Johnson hardness. HJ-1 = Hewlett-Johnson monitoring well 1. HJ-2 = Hewlett-Johnson monitoring well 2.

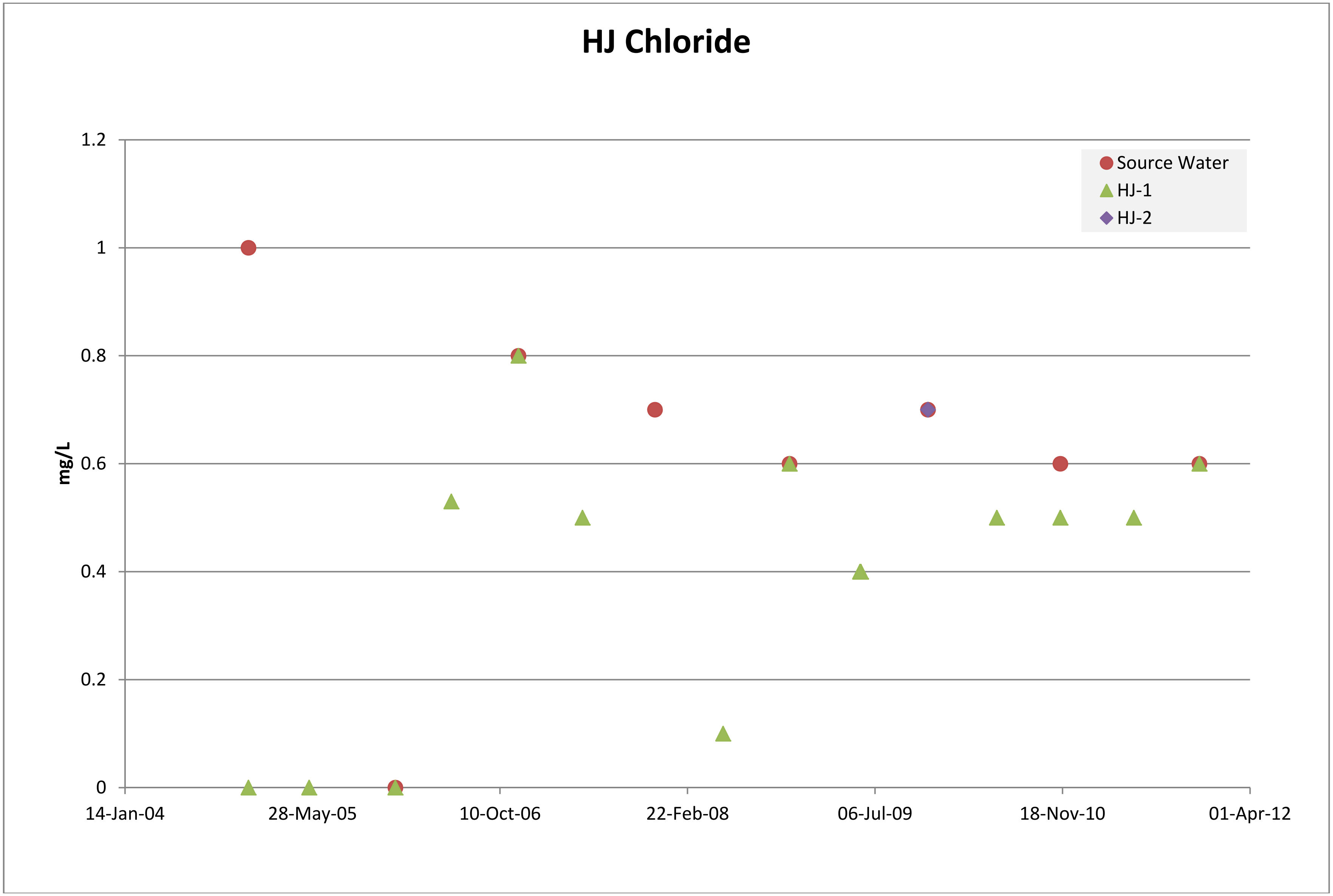

Figure A-7. Hewlett-Johnson chloride. HJ-1 = Hewlett-Johnson monitoring well 1. HJ-2 = Hewlett-Johnson monitoring well 2.

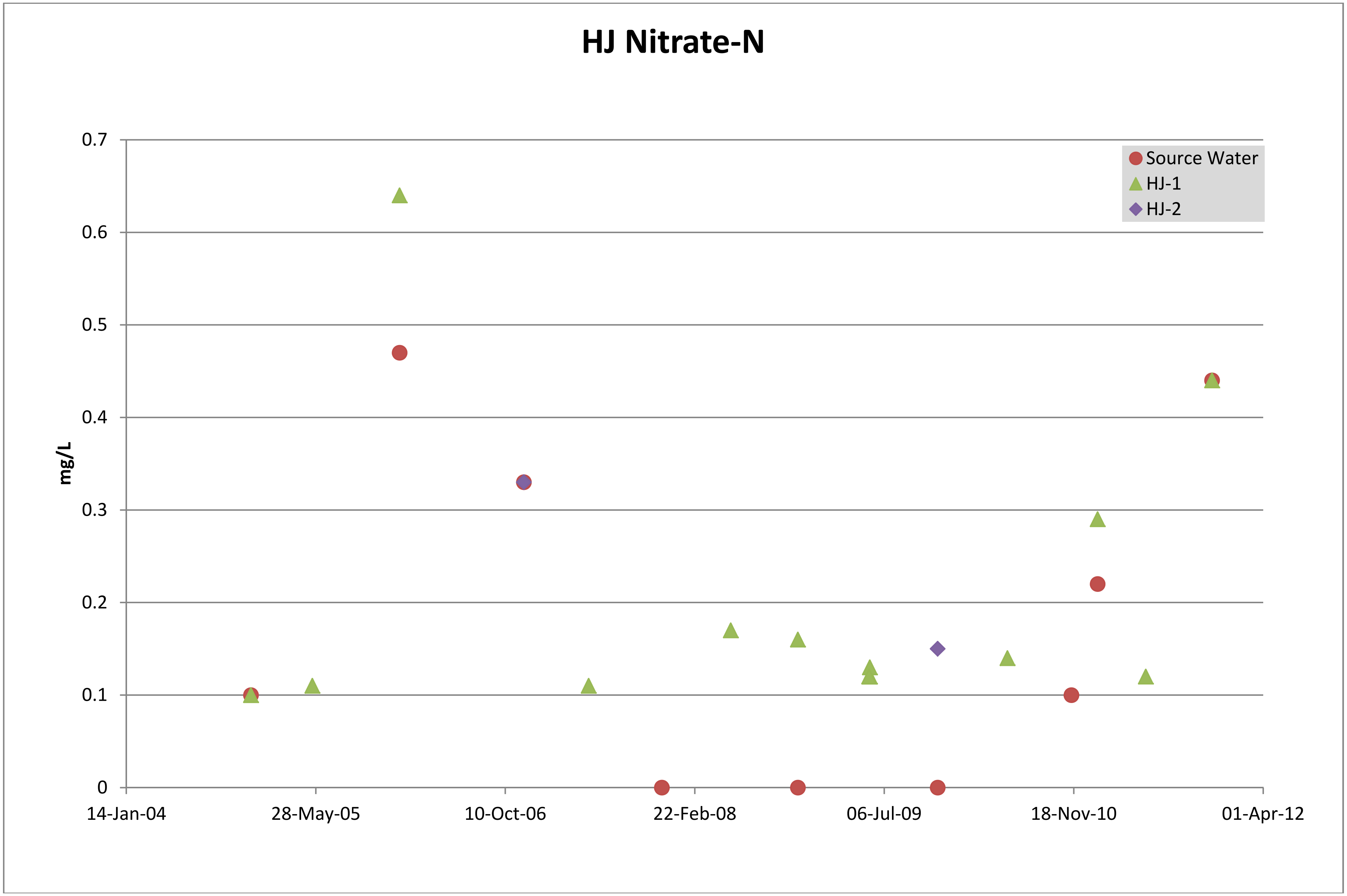

Figure A-8. Hewlett-Johnson nitrate. HJ-1 = Hewlett-Johnson monitoring well 1. HJ-2 = Hewlett-Johnson monitoring well 2.

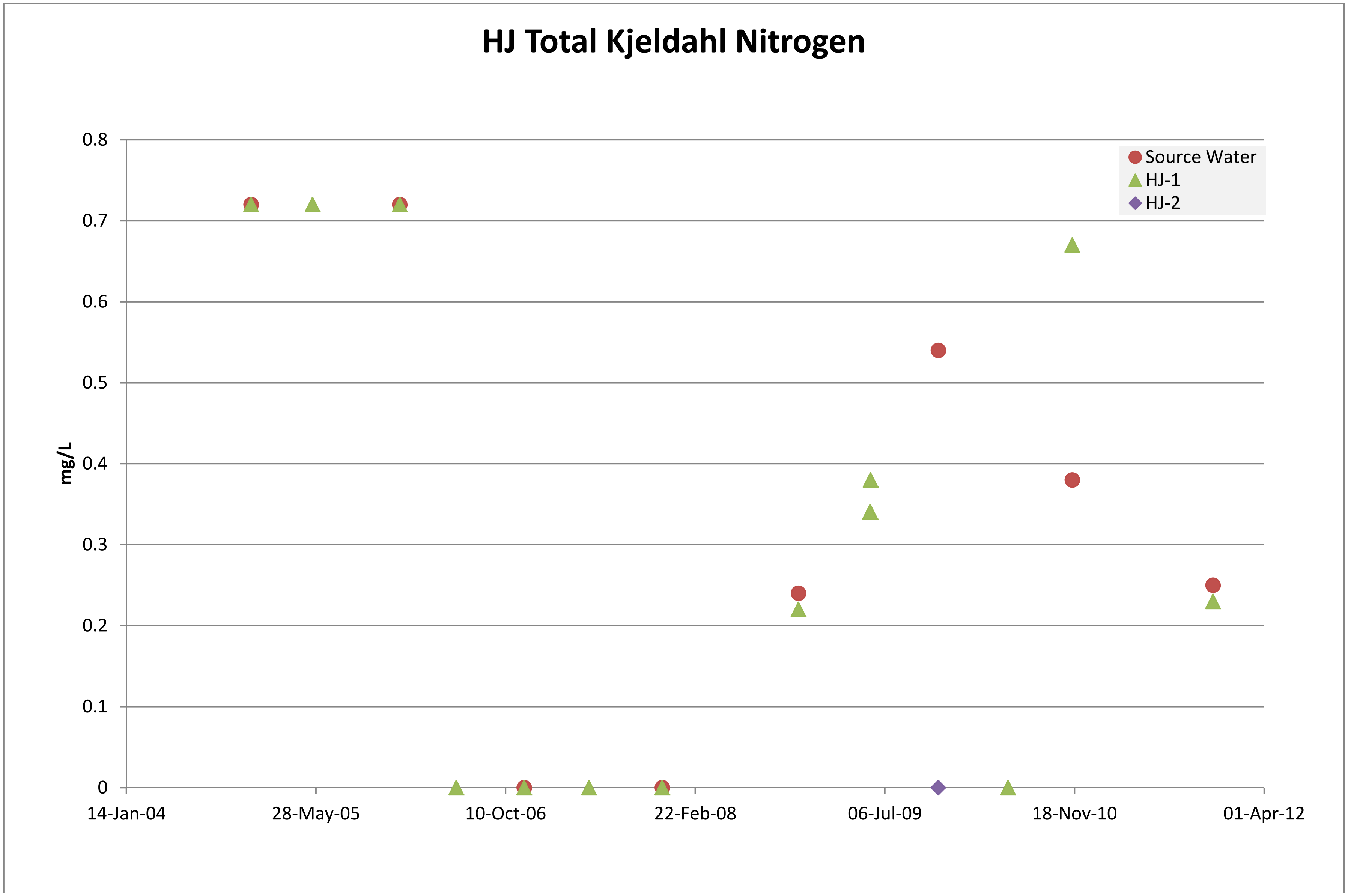

Figure A-9. Hewlett-Johnson total Kjeldahl nitrogen (TKN). HJ-1 = Hewlett-Johnson monitoring well 1. HJ-2 = Hewlett-Johnson monitoring well 2.

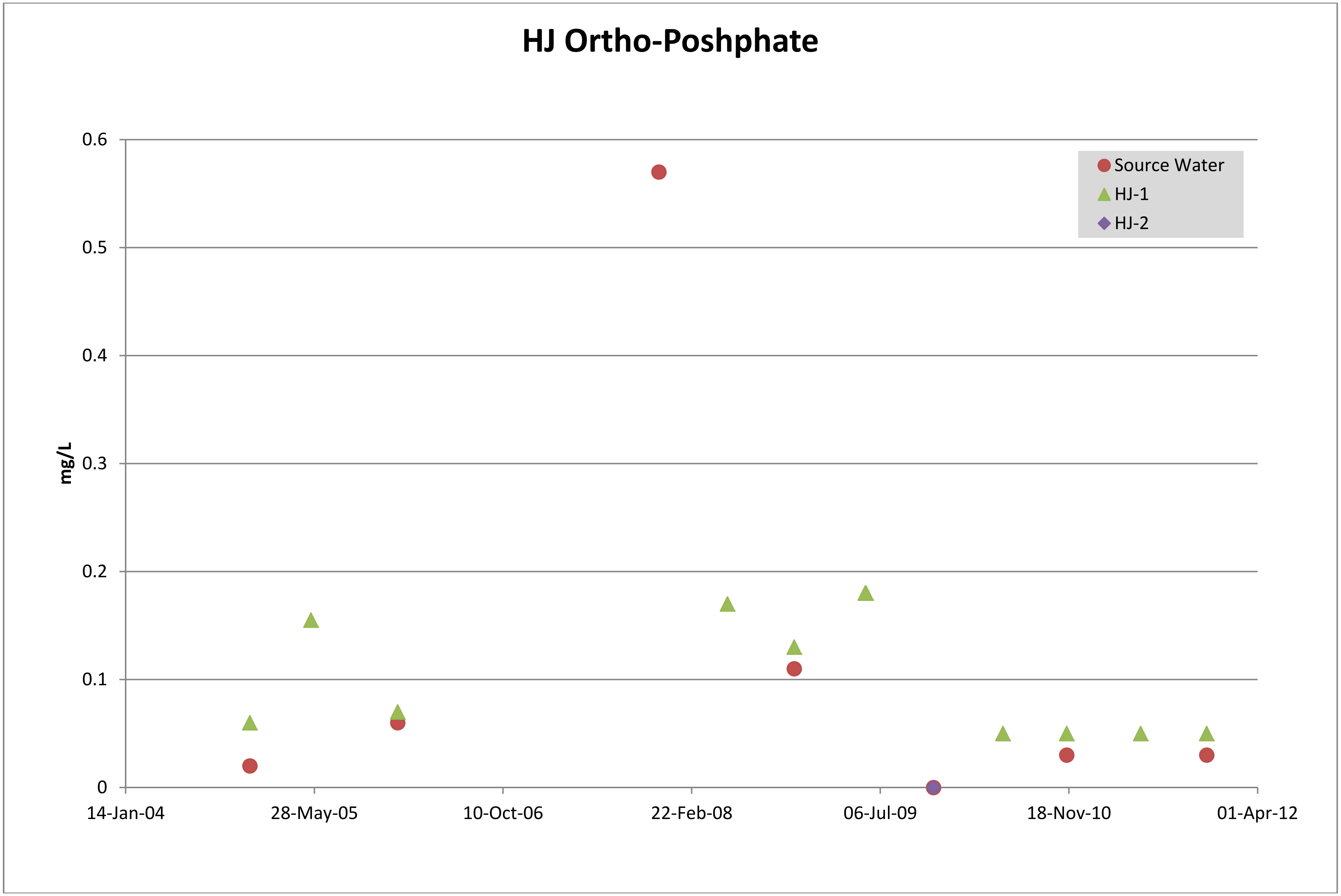

Figure A-10. Hewlett-Johnson ortho-phosphate. HJ-1 = Hewlett-Johnson monitoring well 1. HJ-2 = Hewlett-Johnson monitoring well 2.

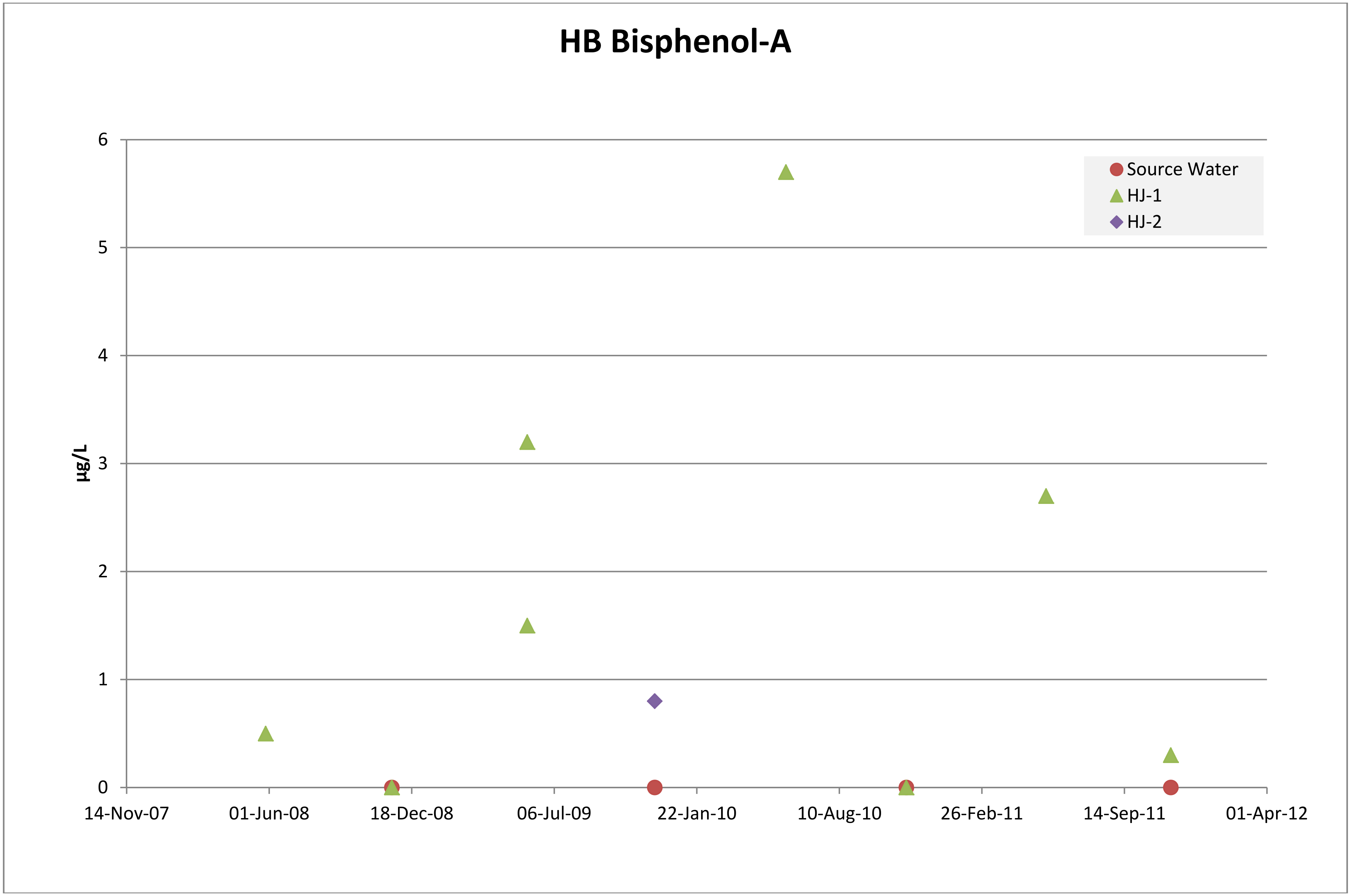

Figure A-11. Hewlett-Johnson bisphenol-A. HJ-1 = Hewlett-Johnson monitoring well 1. HJ-2 = Hewlett-Johnson monitoring well 2.

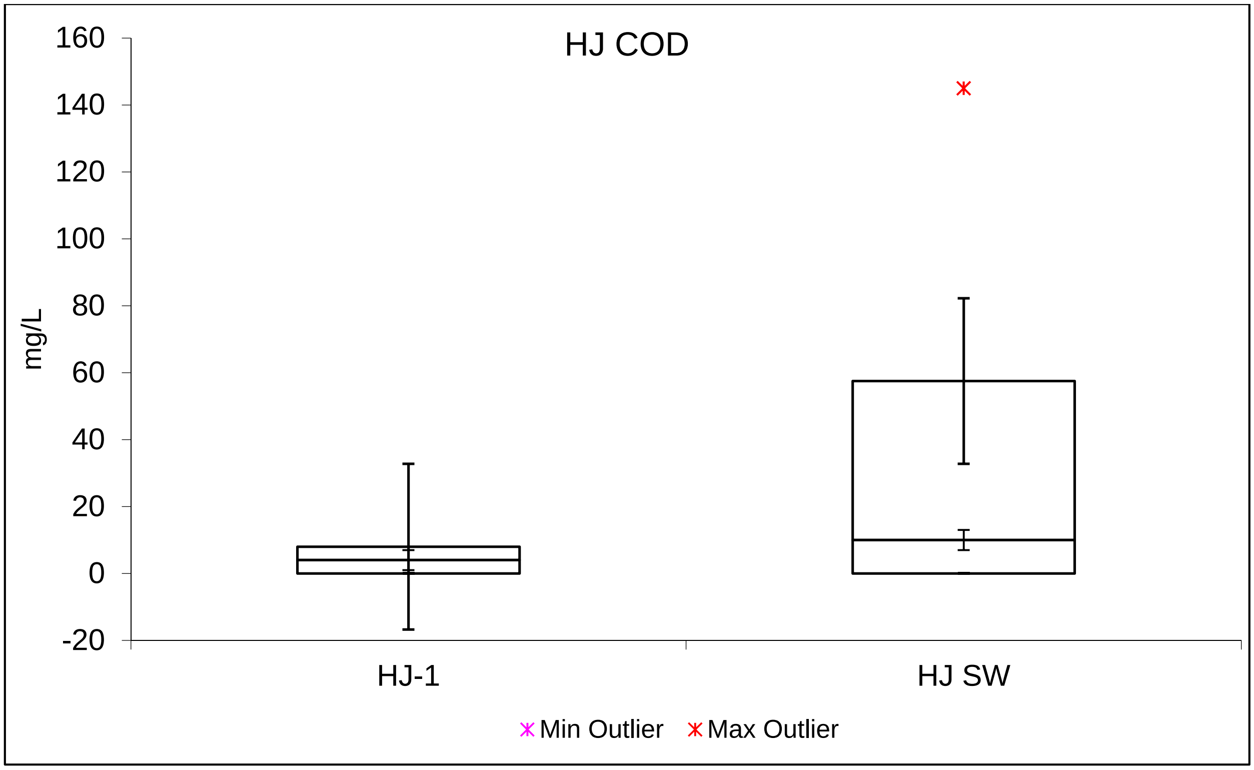

Figure A-12. Hewlett-Johnson pH box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

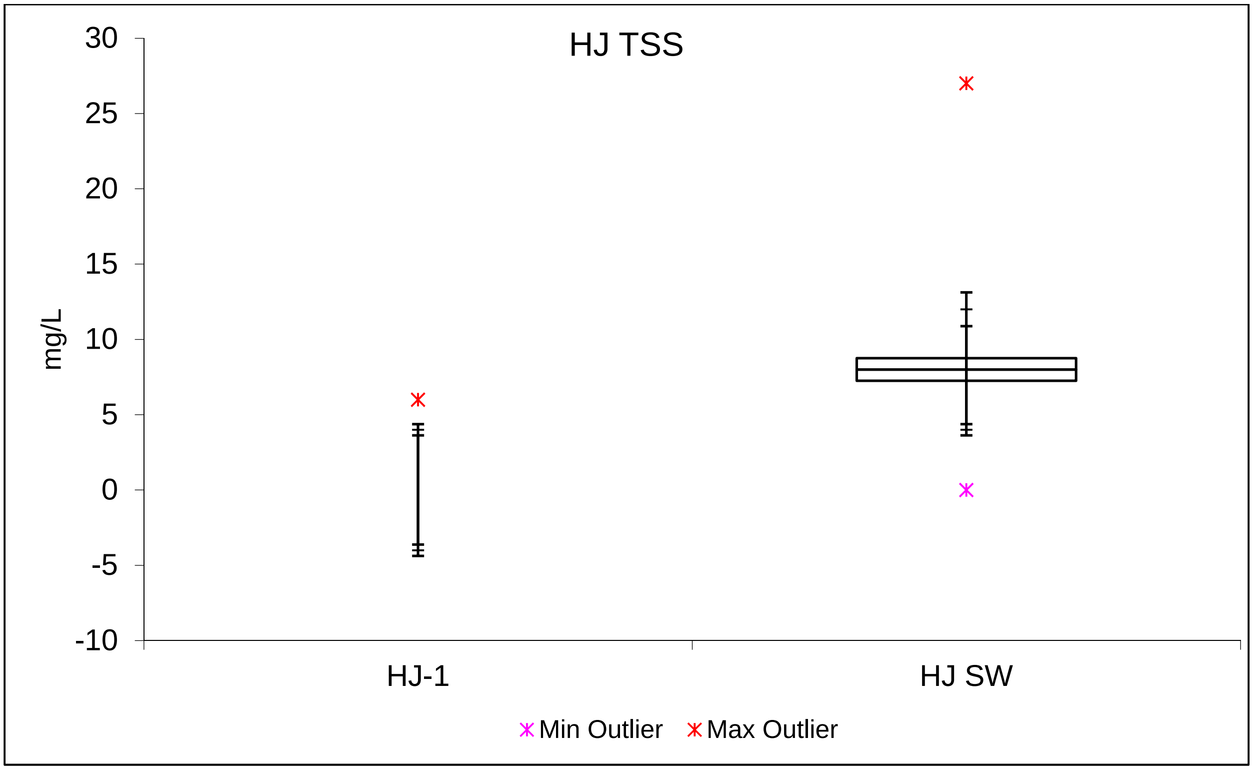

Figure A-13. Hewlett-Johnson TSS box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

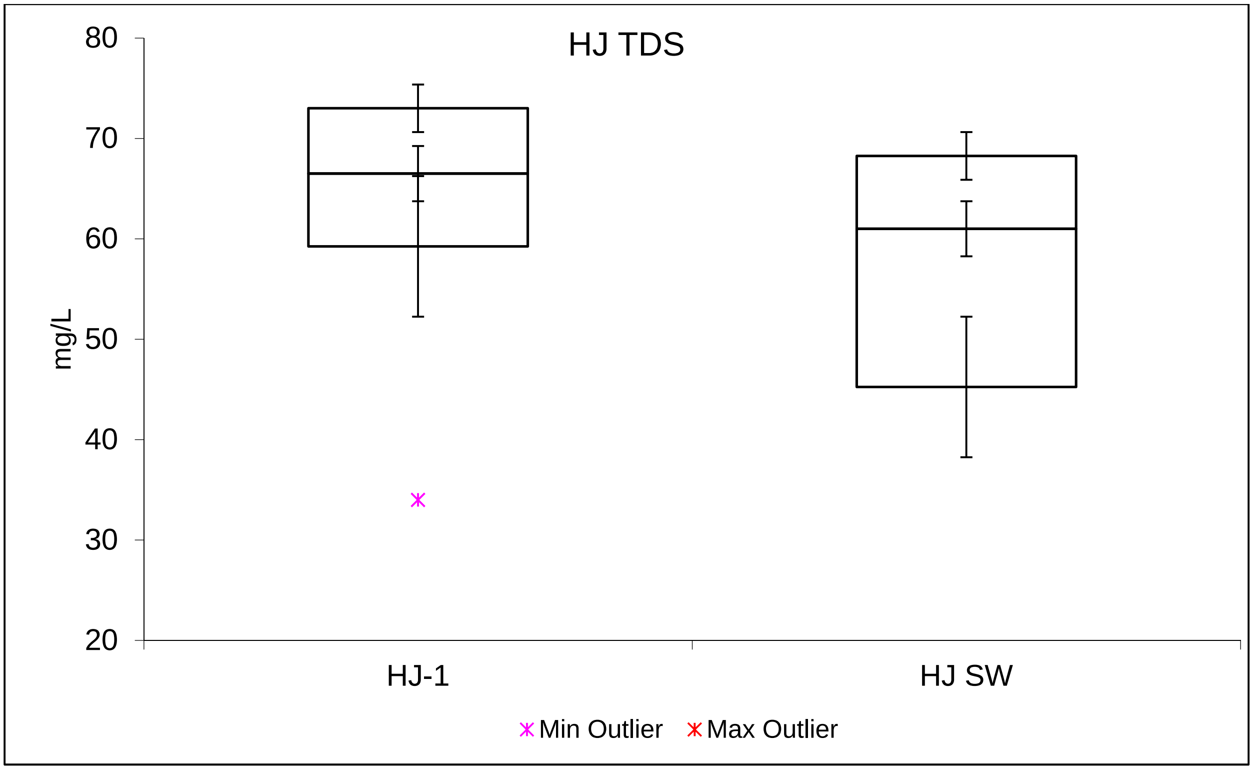

Figure A-14. Hewlett-Johnson TDS box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

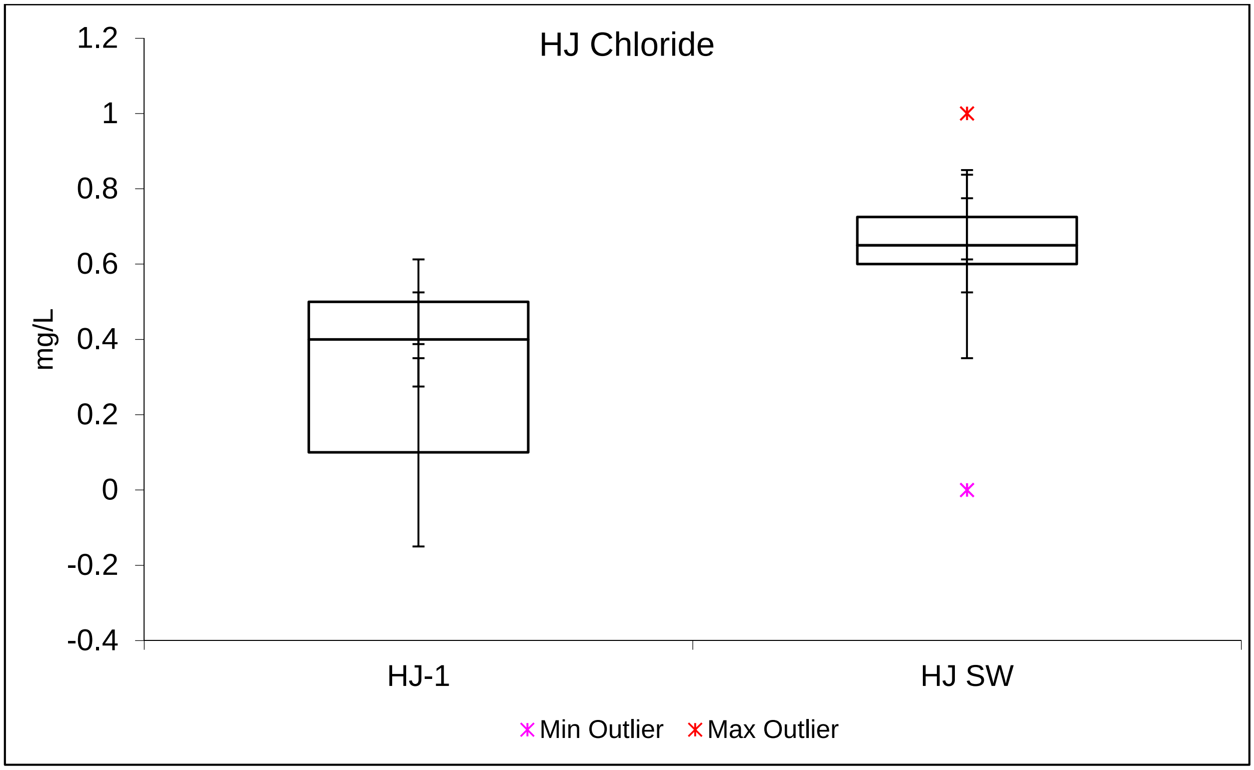

Figure A-15. Hewlett-Johnson chloride box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

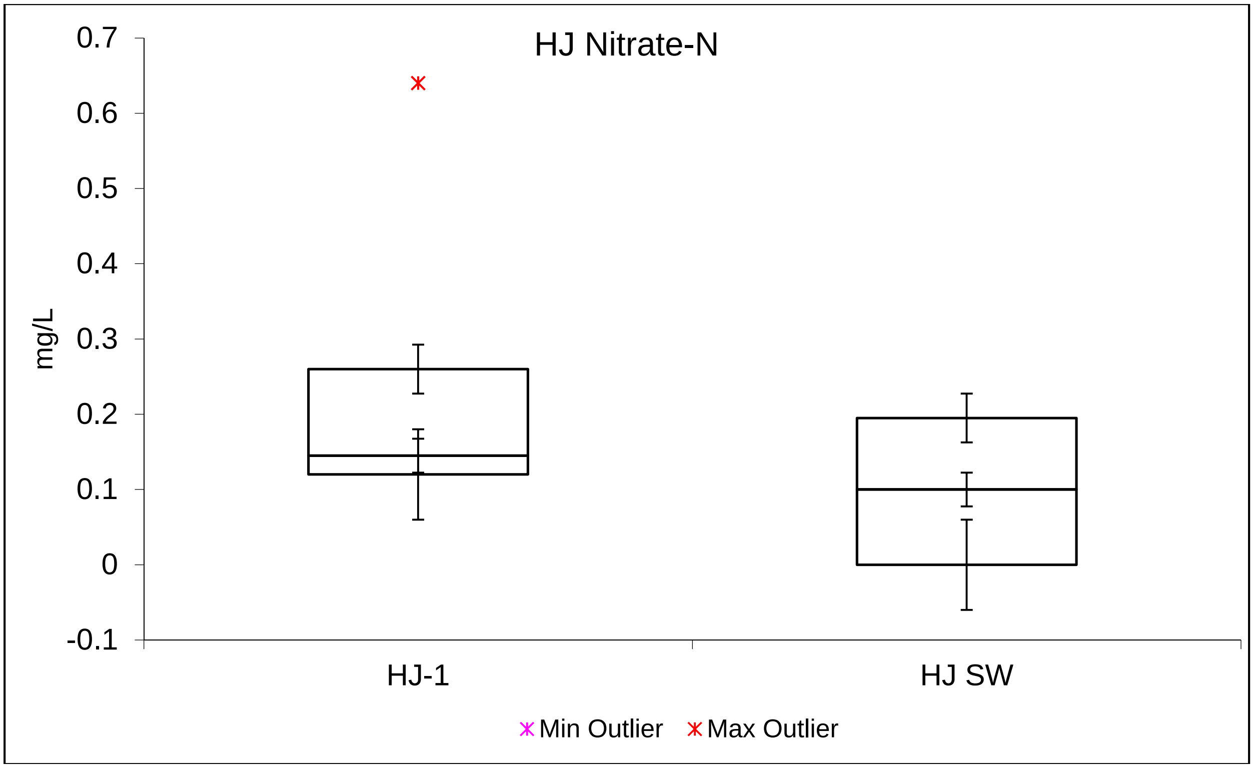

Figure A-16. Hewlett-Johnson nitrate-N box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

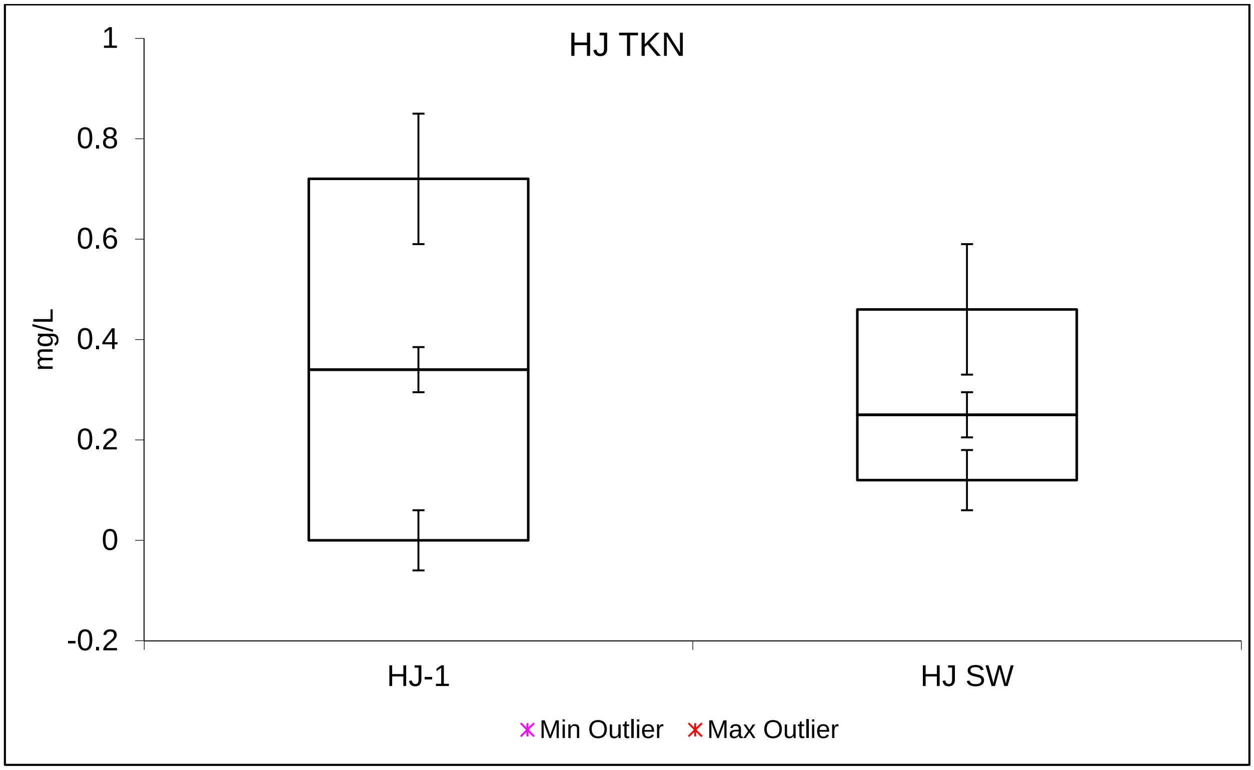

Figure A-17. Hewlett-Johnson TKN box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

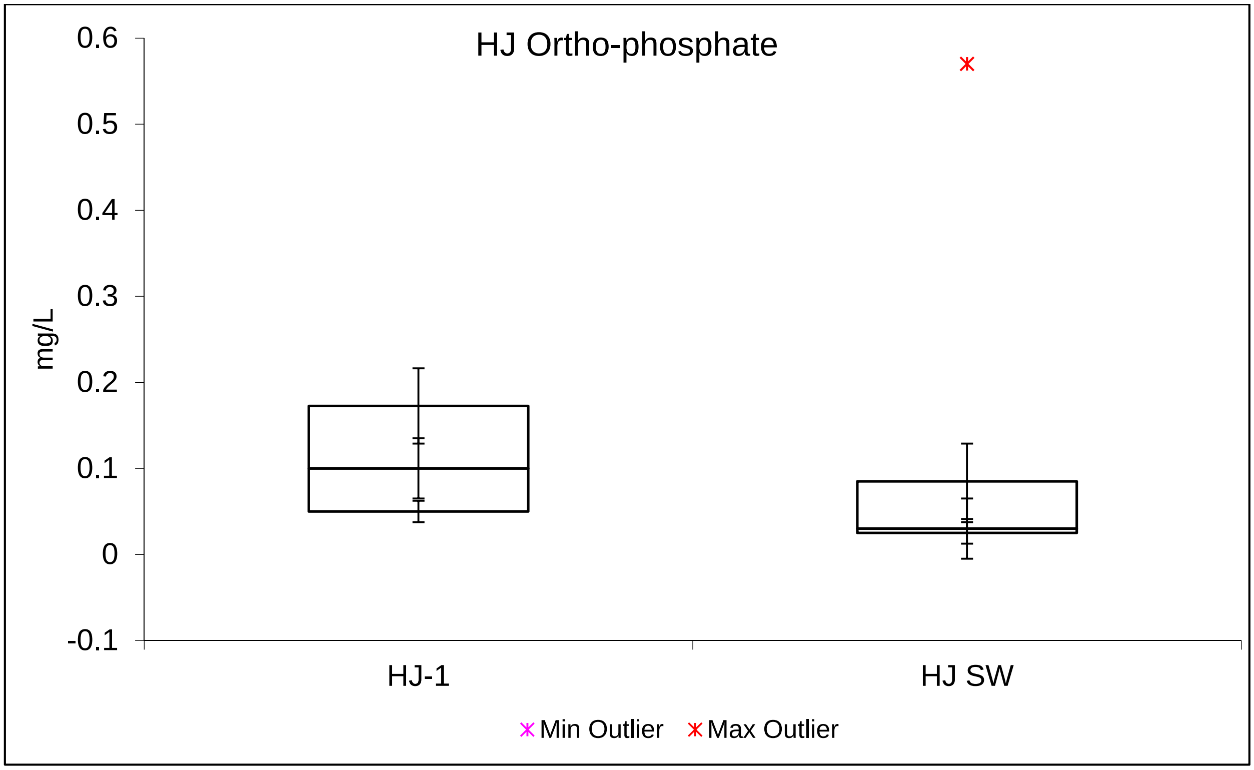

Figure A-18. Hewlett-Johnson ortho-phosphate box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

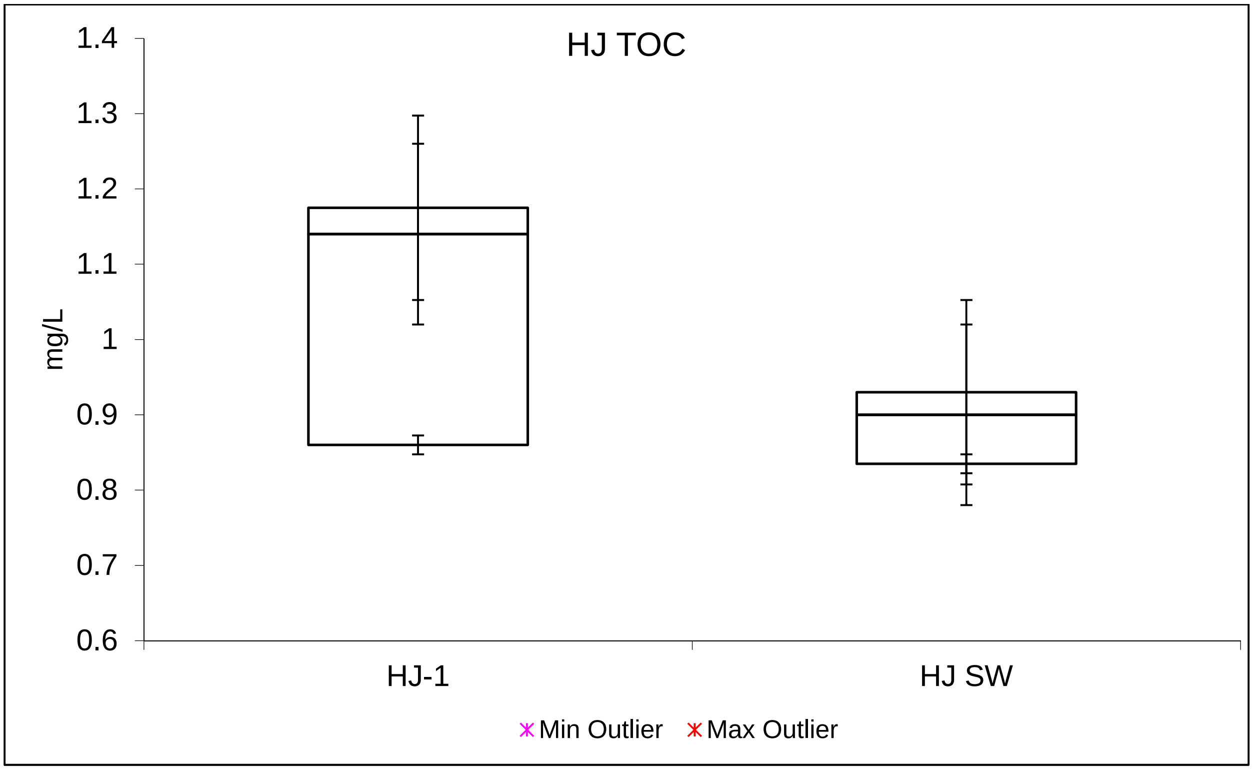

Figure A-19. Hewlett-Johnson TOC box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

Appendix B

Hall-Wentland Data Plots

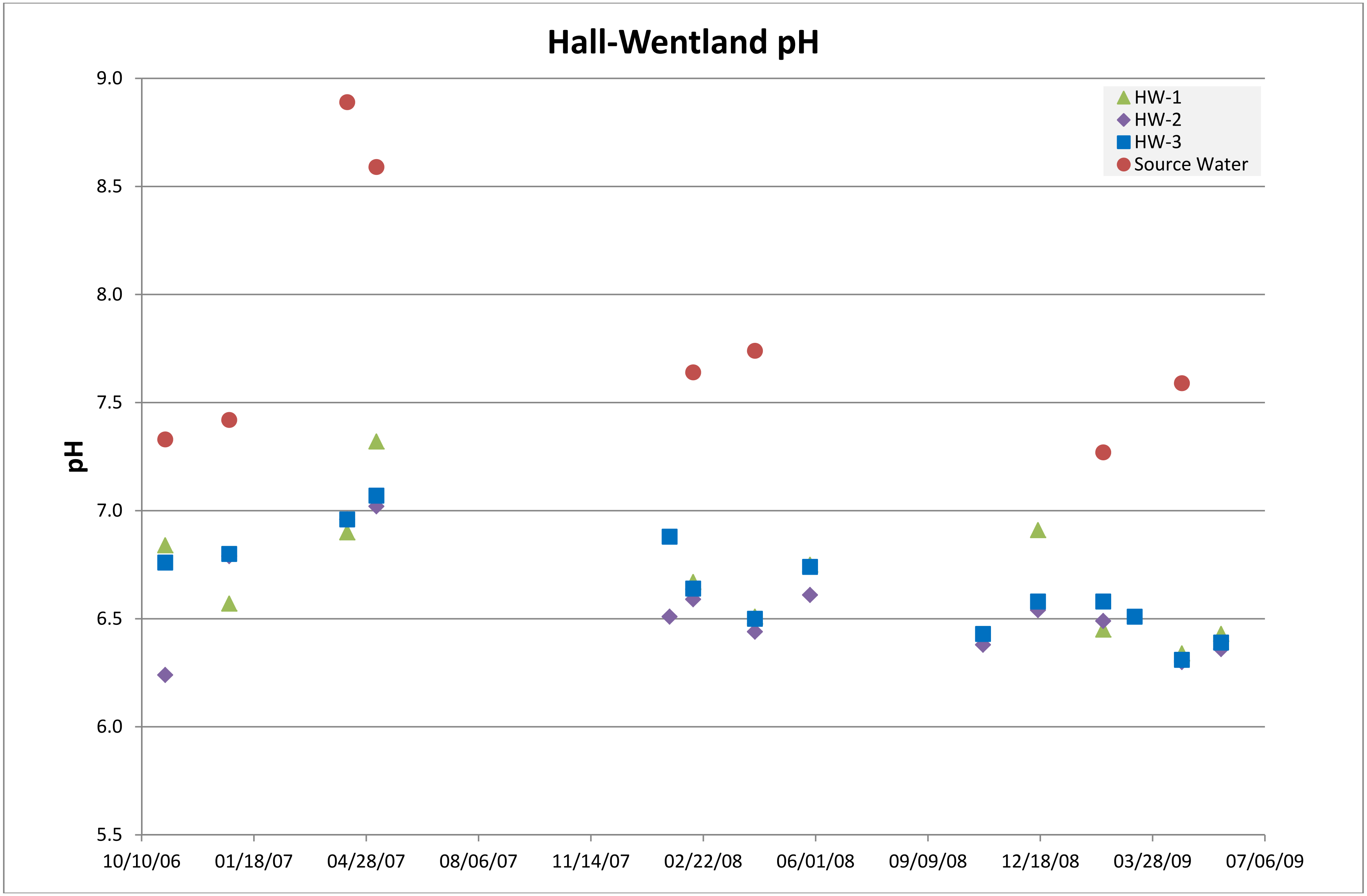

Figure B-1. Hall-Wentland pH. HW-1 = Hall-Wentland monitoring well 1. HW-2 = Hall-Wentland monitoring well 2. HW-3 = Hall-Wentland monitoring well 3.

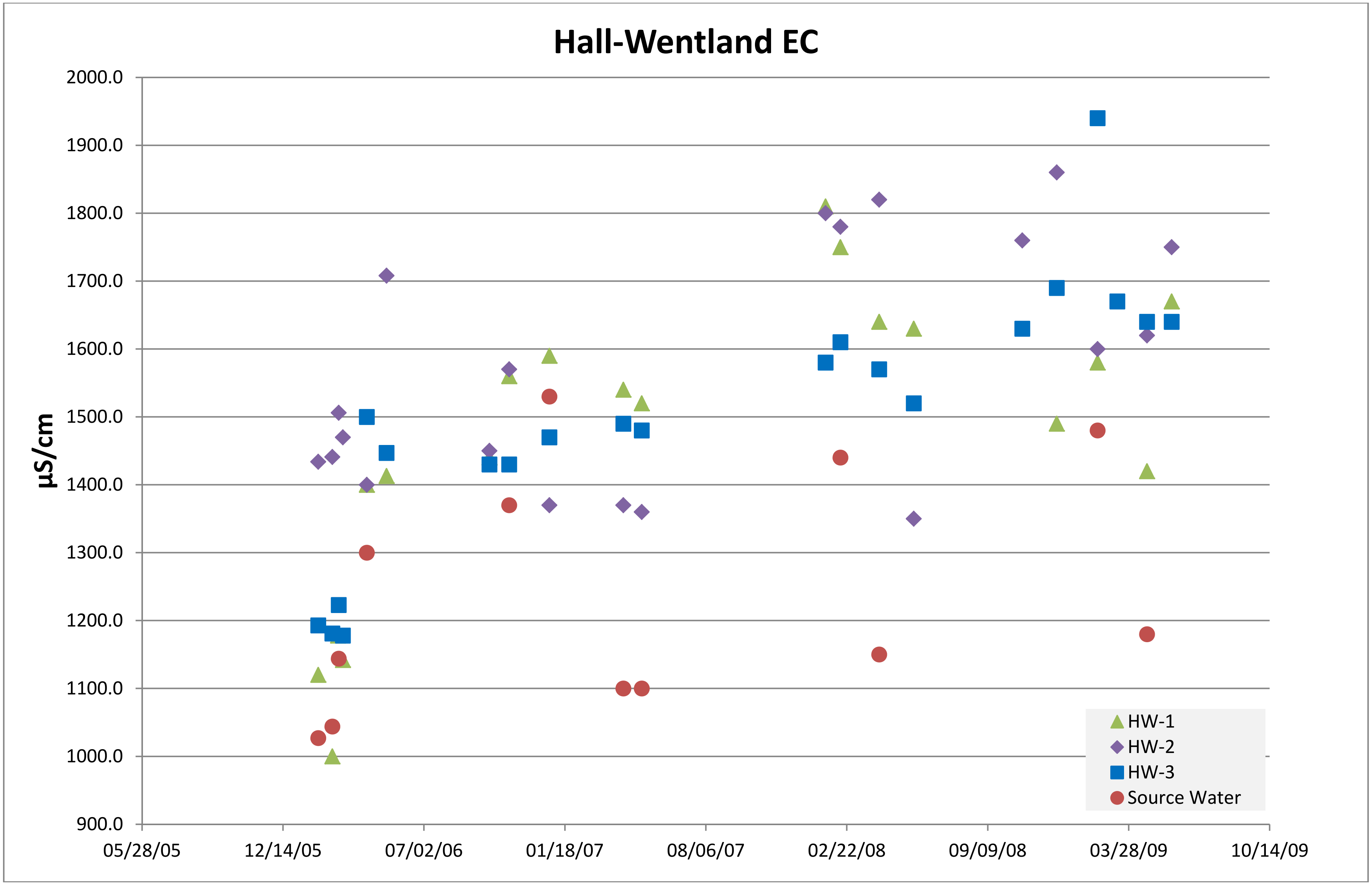

Figure B-2. Hall-Wentland electrical conductivity. HW-1 = Hall-Wentland monitoring well 1. HW-2 = Hall-Wentland monitoring well 2. HW-3 = Hall-Wentland monitoring well 3.

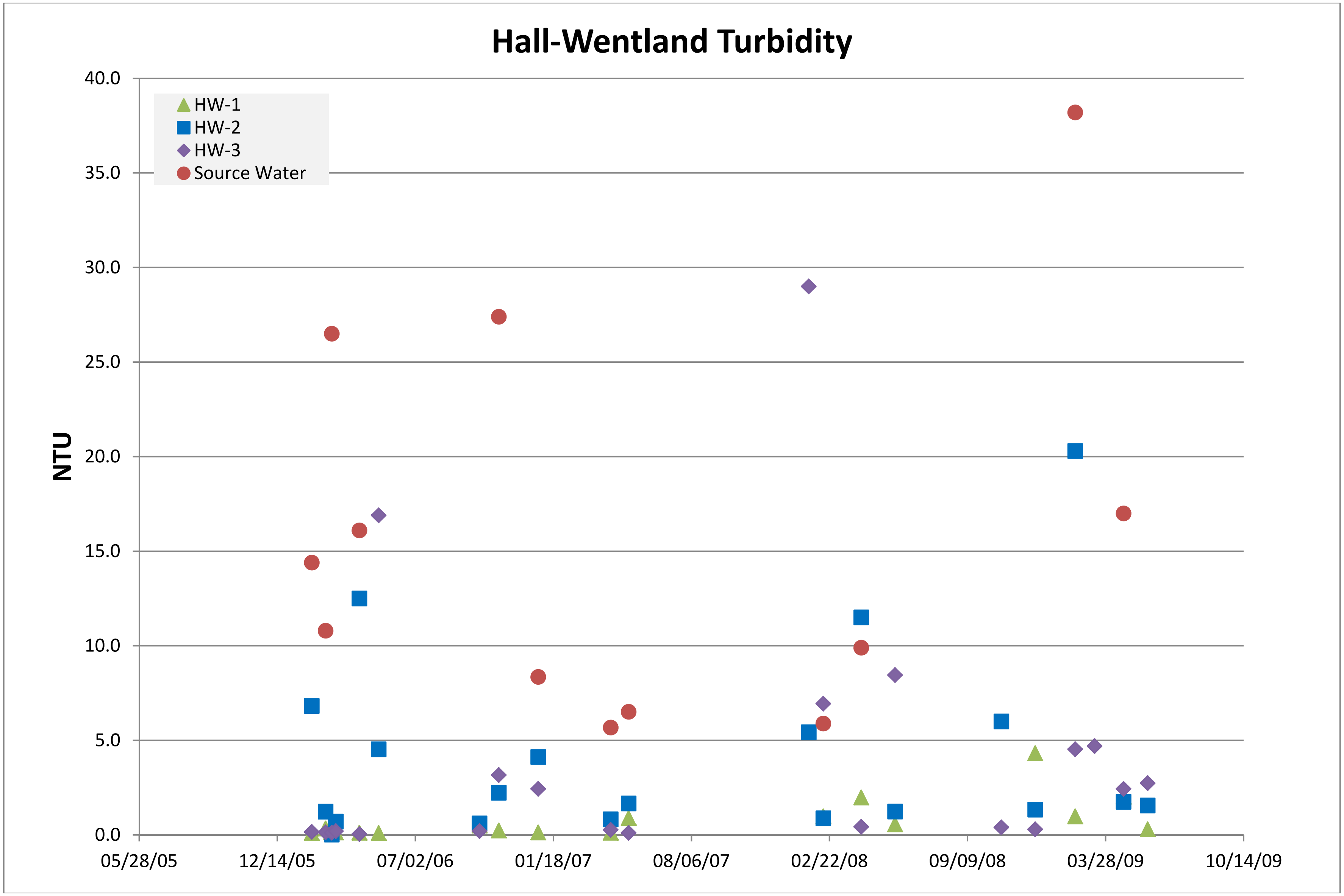

Figure B-3. Hall-Wentland turbidity. HW-1 = Hall-Wentland monitoring well 1. HW-2 = Hall-Wentland monitoring well 2. HW-3 = Hall-Wentland monitoring well 3.

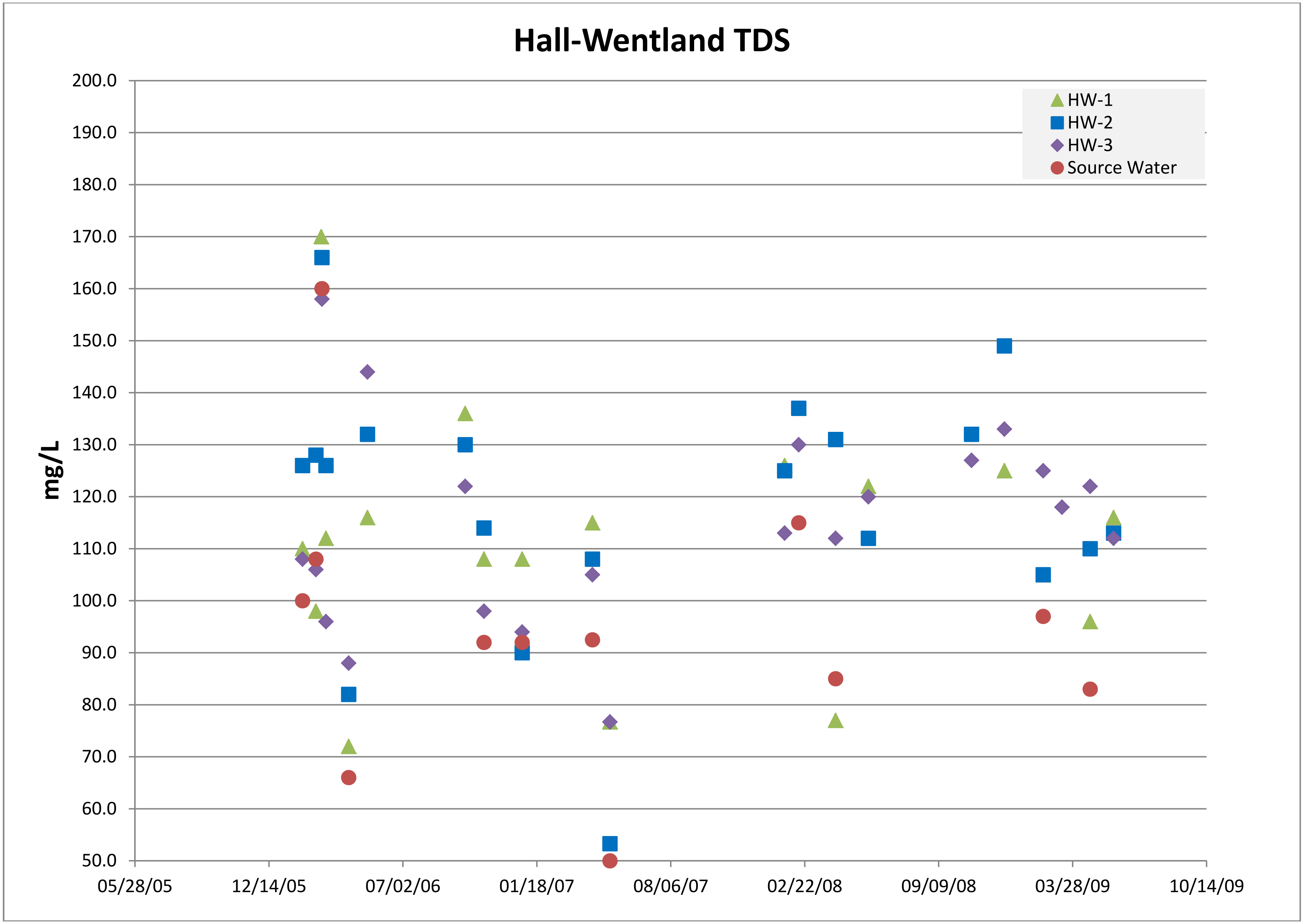

Figure B-4. Hall-Wentland total dissolved solids (TDS). HW-1 = Hall-Wentland monitoring well 1. HW-2 = Hall-Wentland monitoring well 2. HW-3 = Hall-Wentland monitoring well 3.

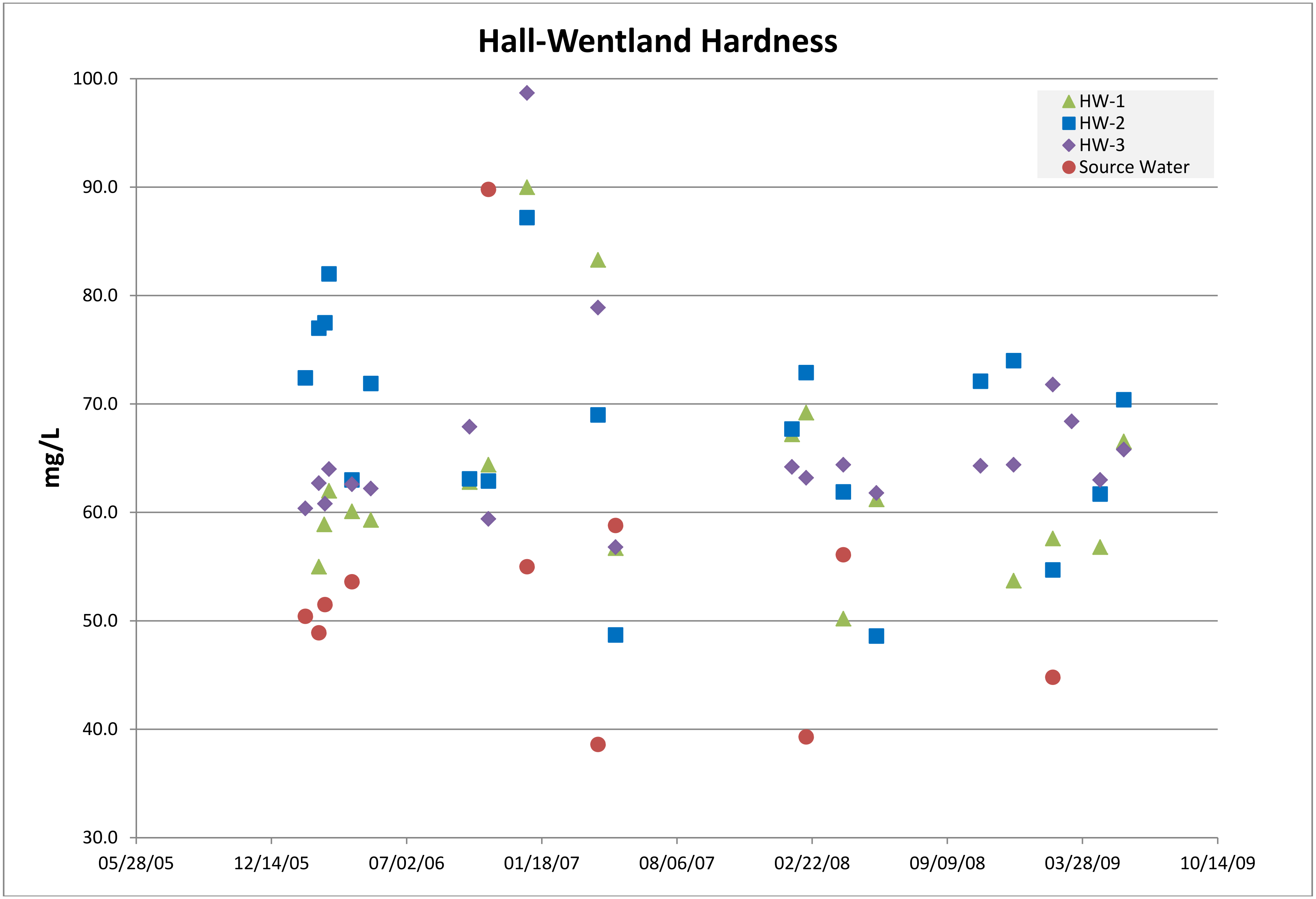

Figure B-5. Hall-Wentland Hardness. HW-1 = Hall-Wentland monitoring well 1. HW-2 = Hall-Wentland monitoring well 2. HW-3 = Hall-Wentland monitoring well 3.

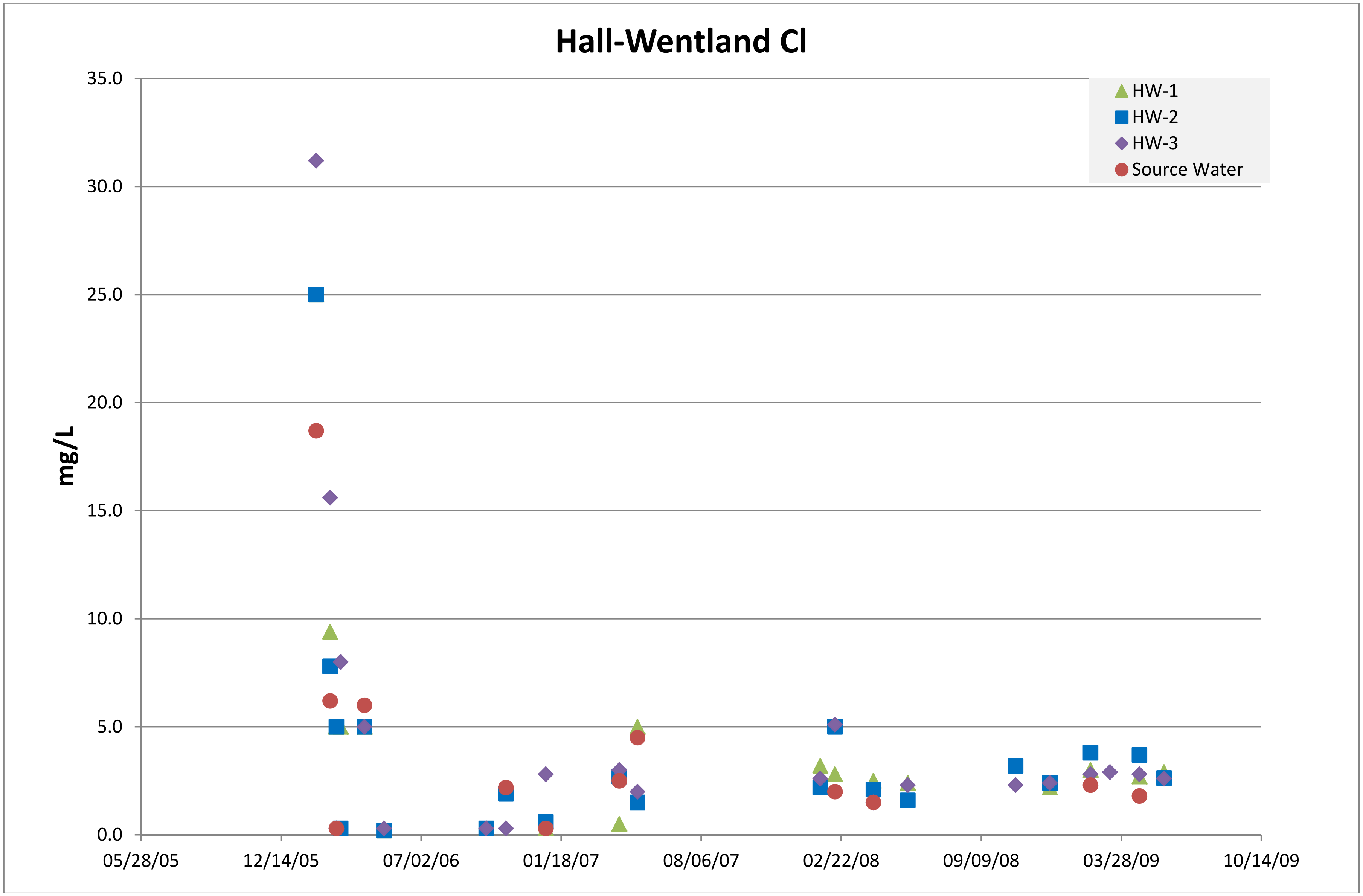

Figure B-6. Hall-Wentland chloride. HW-1 = Hall-Wentland monitoring well 1. HW-2 = Hall-Wentland monitoring well 2. HW-3 = Hall-Wentland monitoring well 3.

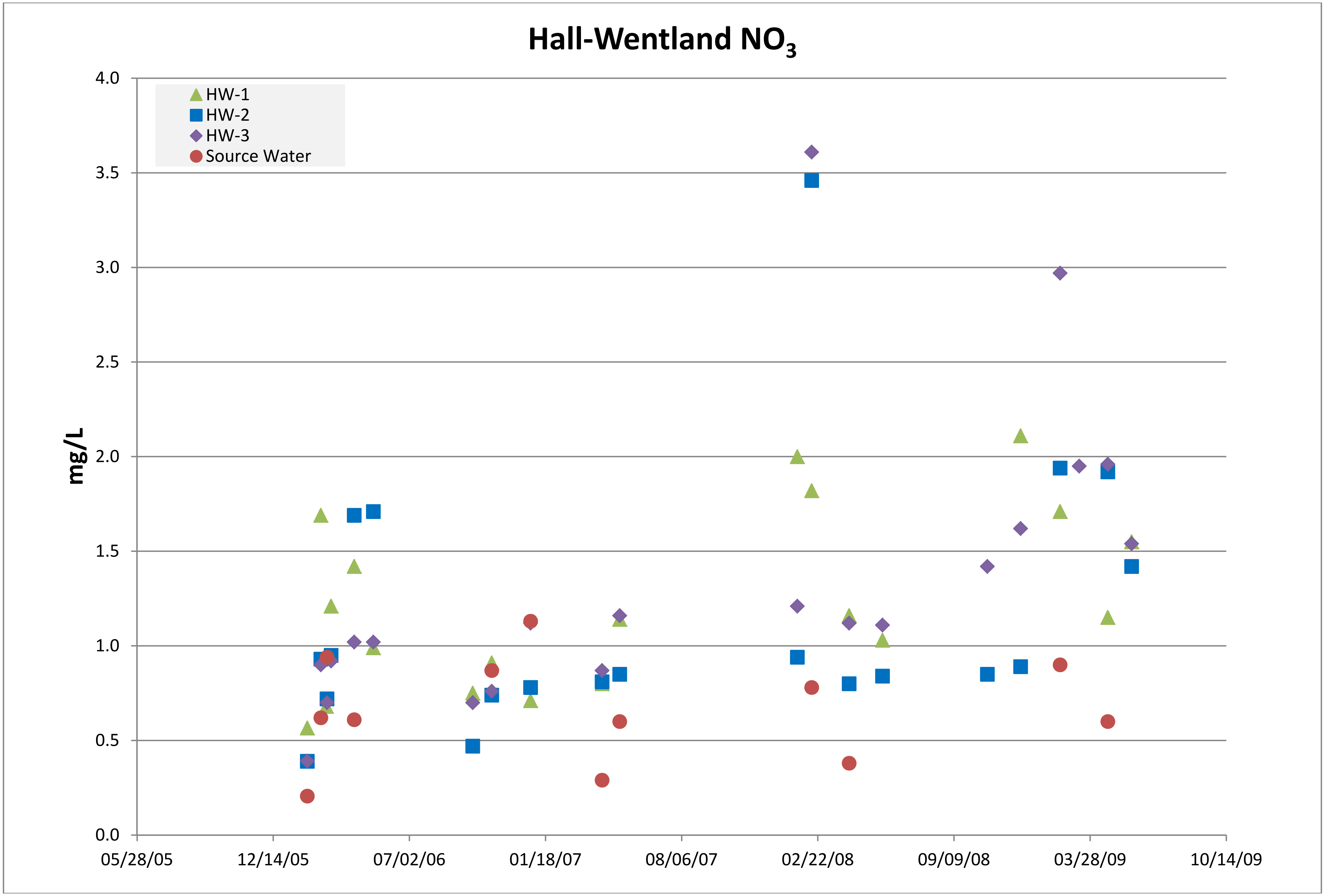

Figure B-7. Hall-Wentland nitrate-N. HW-1 = Hall-Wentland monitoring well 1. HW-2 = Hall-Wentland monitoring well 2. HW-3 = Hall-Wentland monitoring well 3.

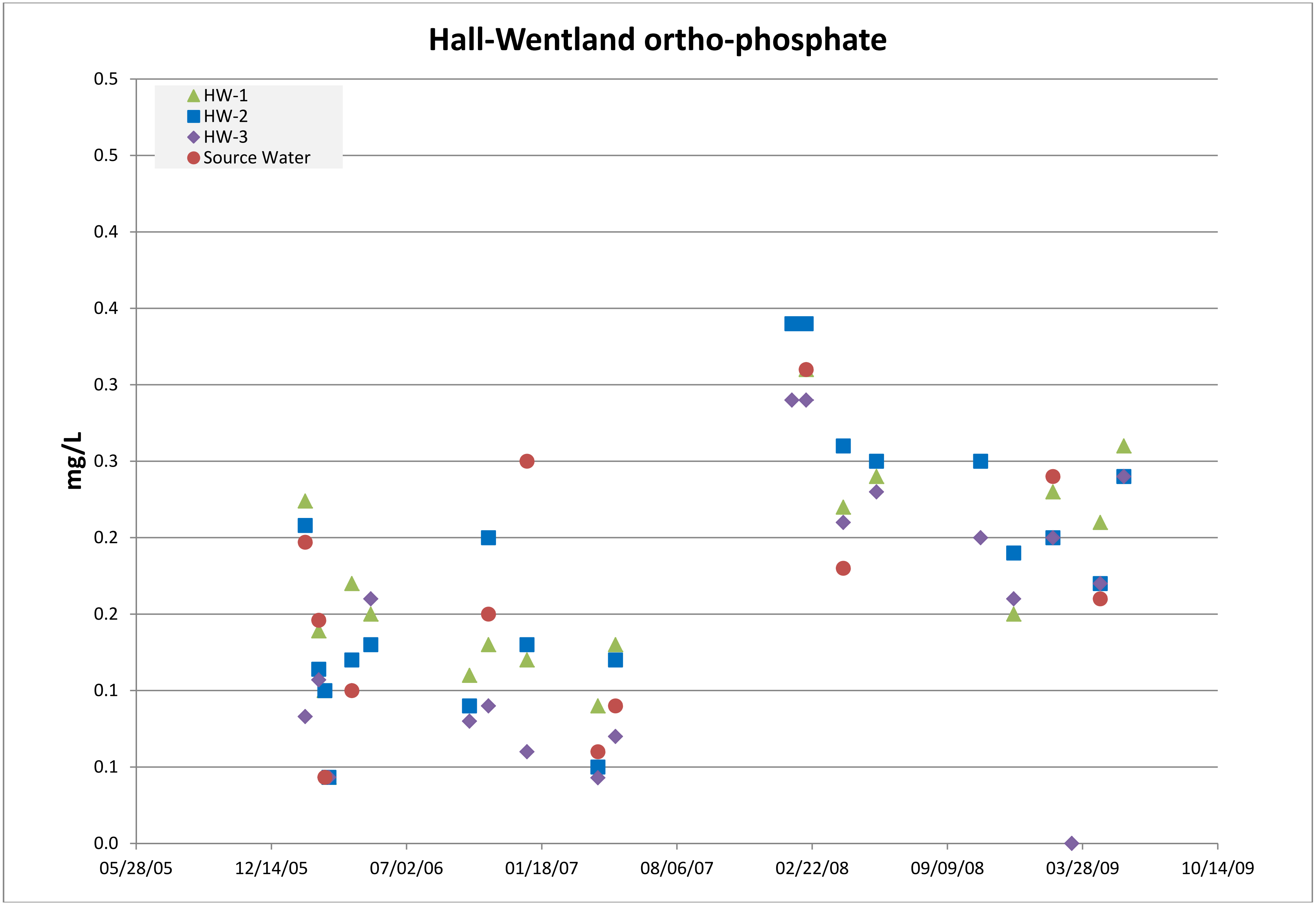

Figure B-8. Hall-Wentland ortho-phosphate. HW-1 = Hall-Wentland monitoring well 1. HW-2 = Hall-Wentland monitoring well 2. HW-3 = Hall-Wentland monitoring well 3.

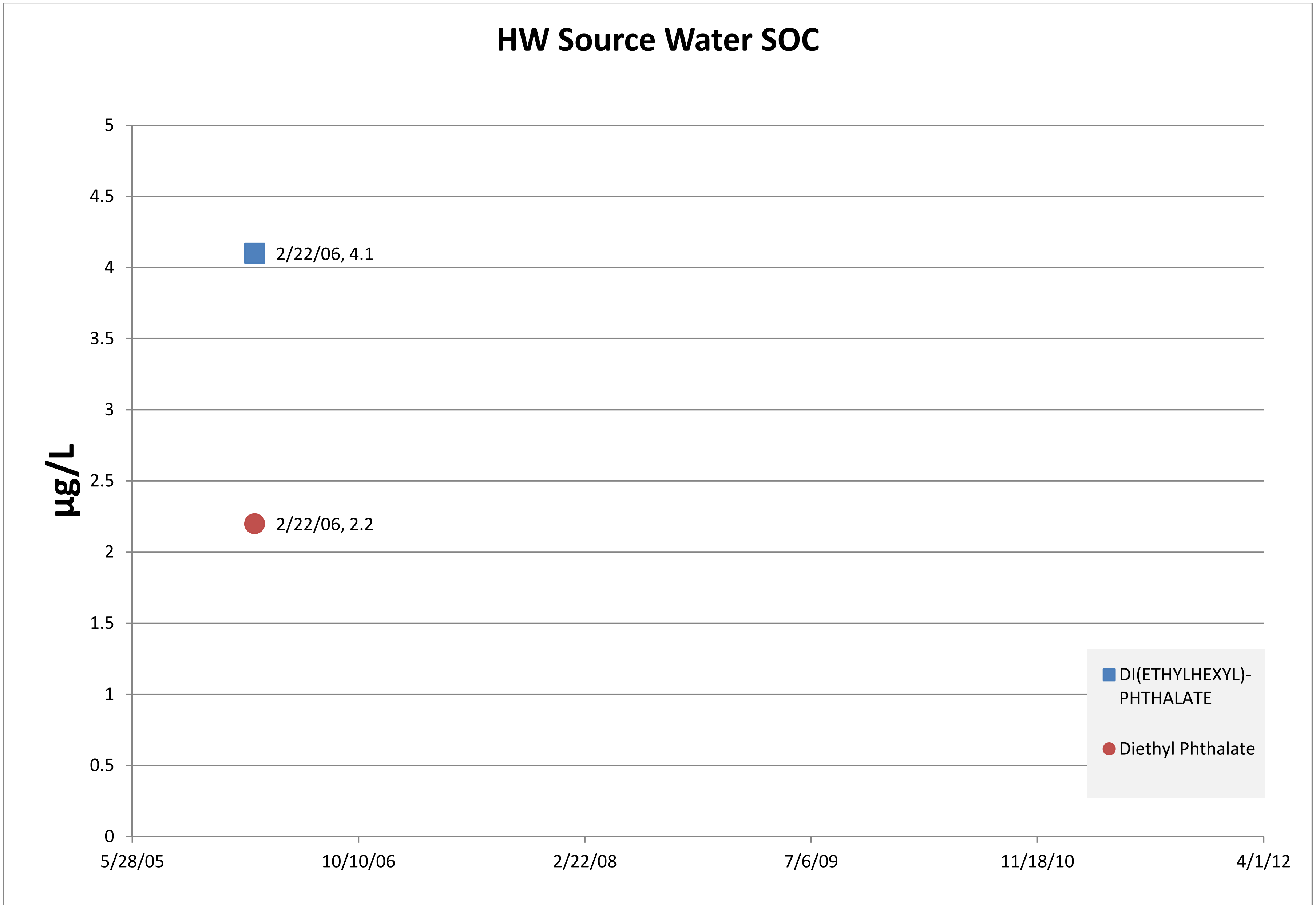

Figure B-9. Hall-Wentland source water SOC's.

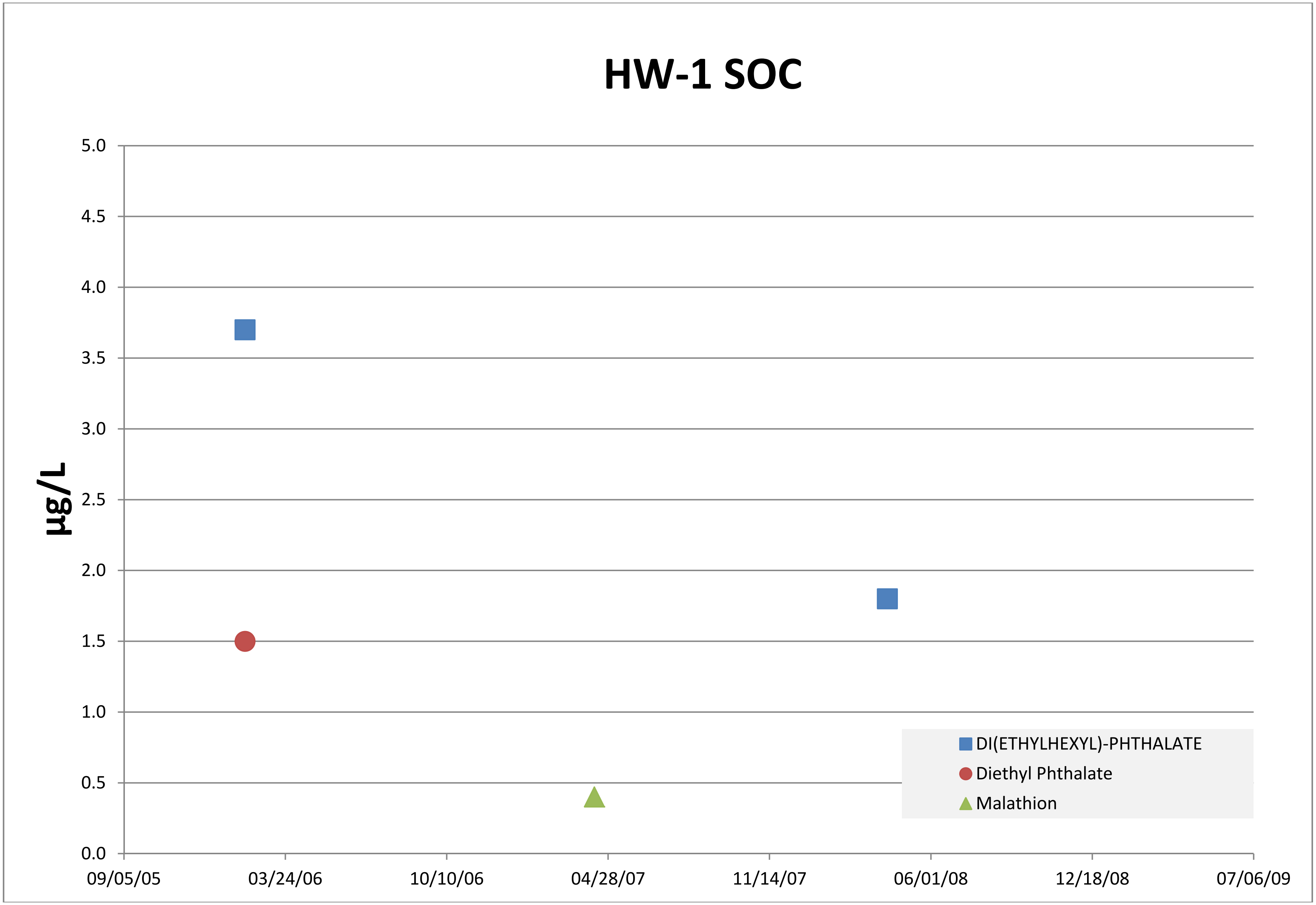

Figure B-10. Hall-Wentland monitoring well HW-1 water SOC’s.

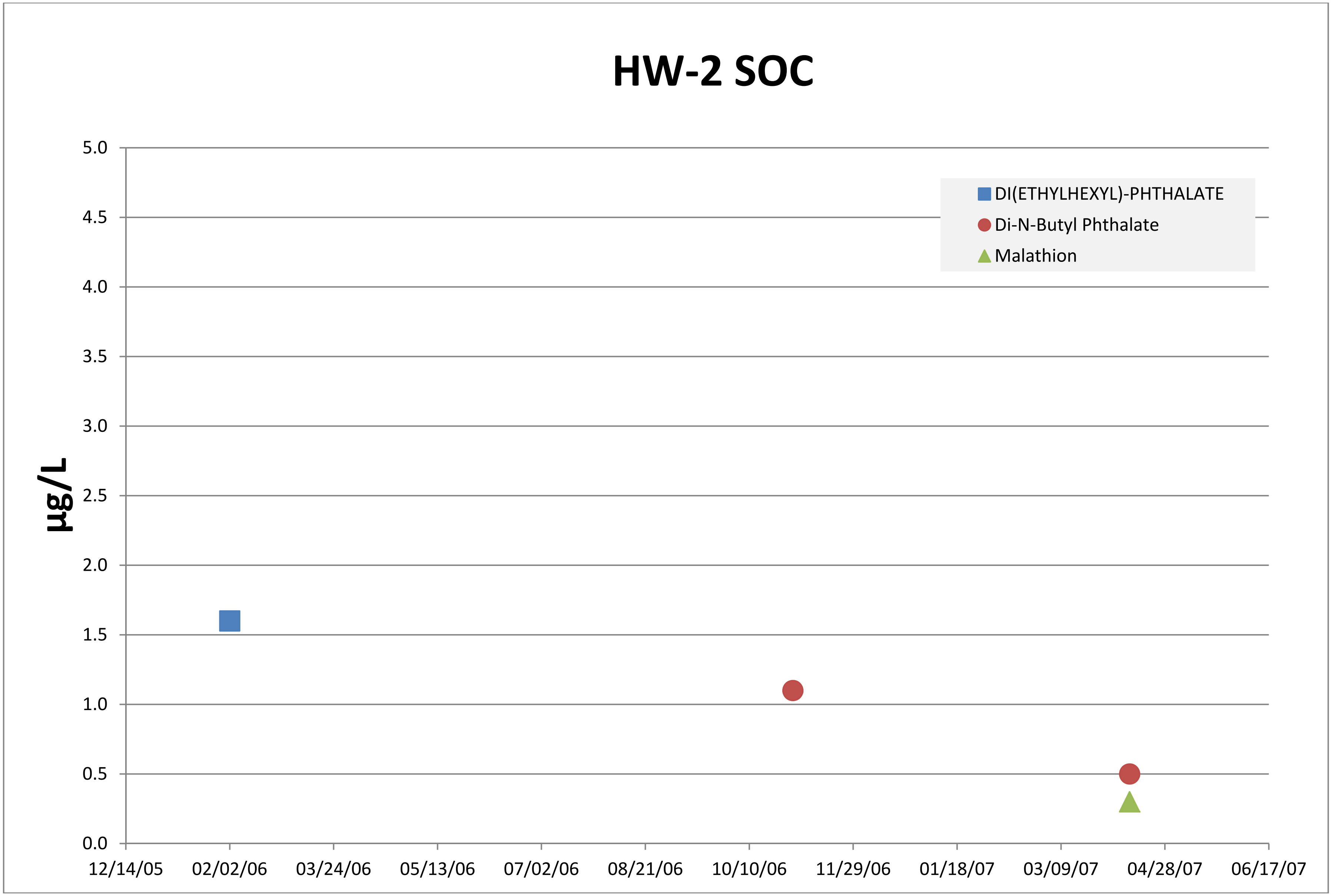

Figure B-11. Hall-Wentland monitoring well HW-2 water SOC’s.

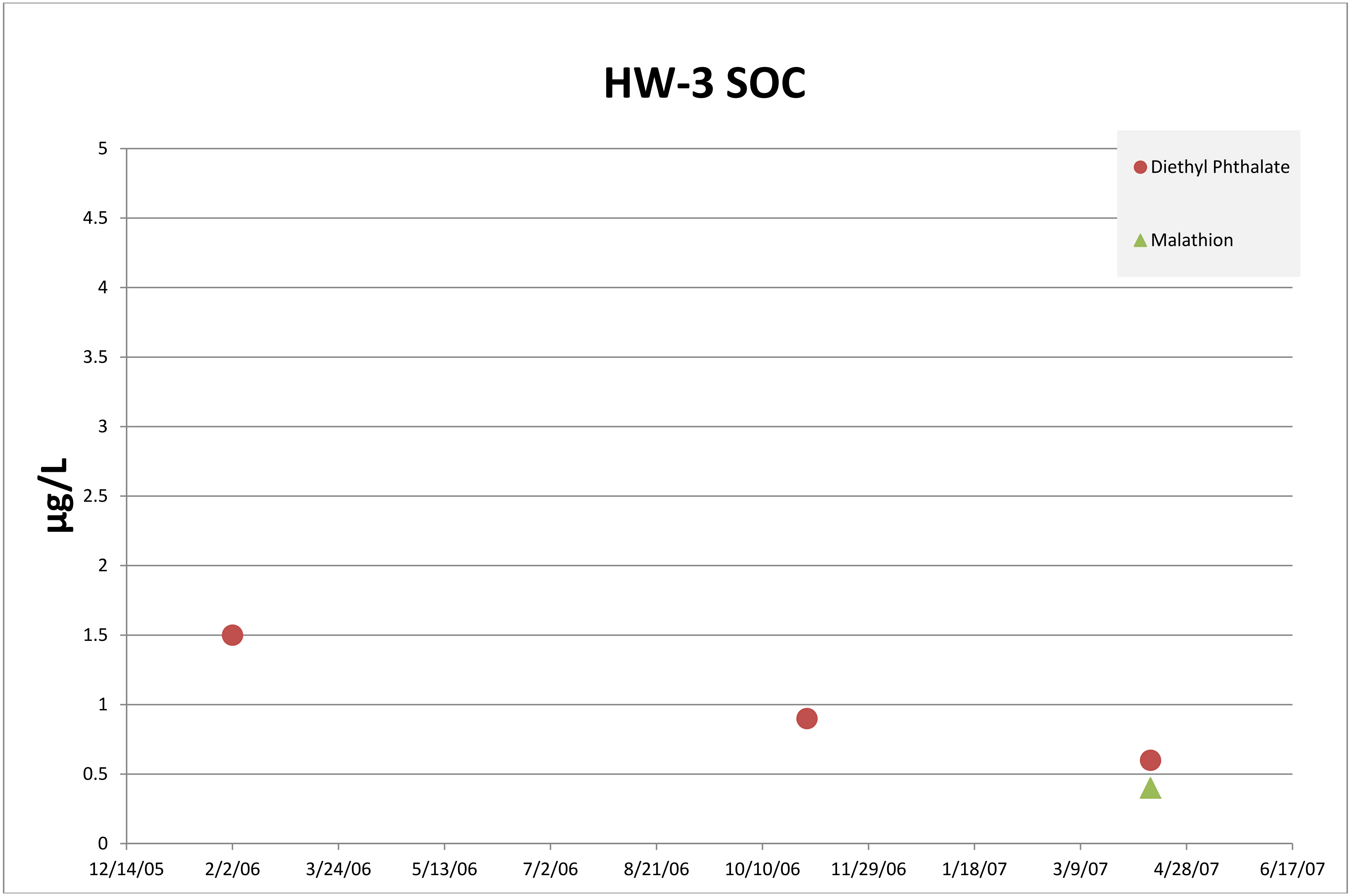

Figure B-12. Hall-Wentland monitoring well HW-3 water SOC’s.

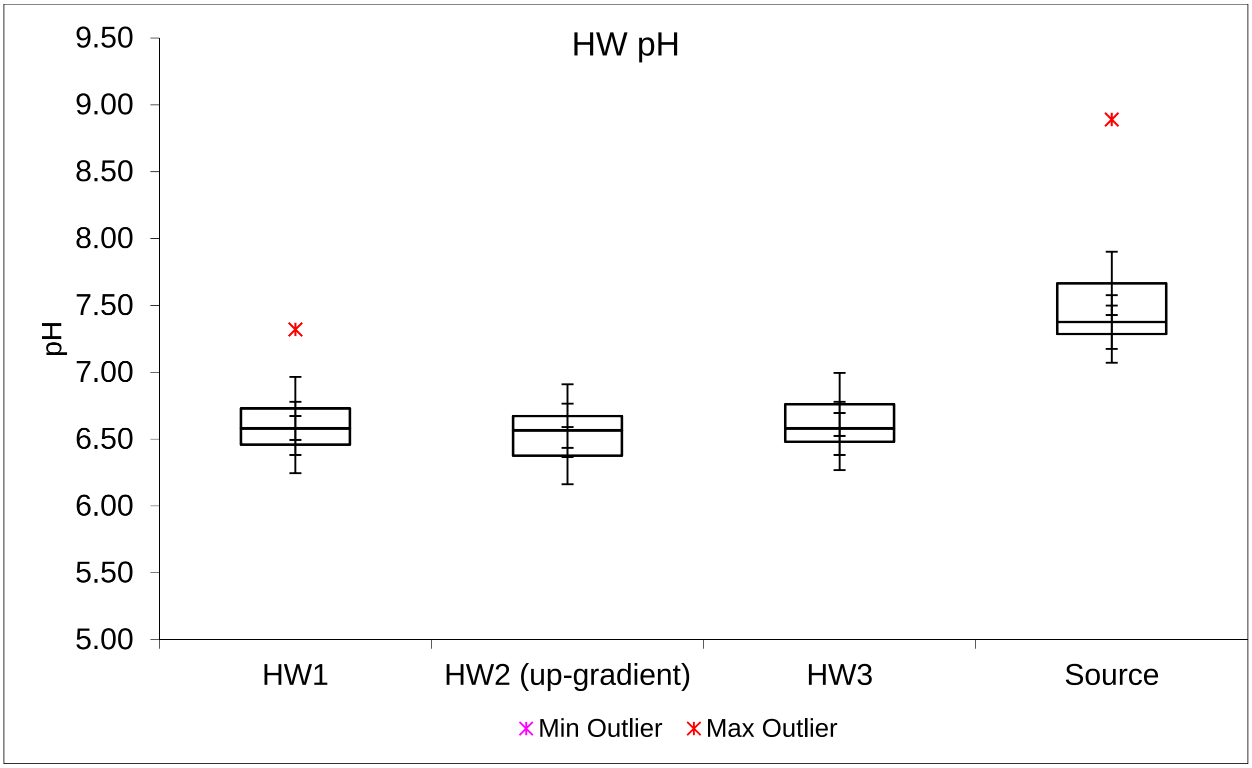

Figure B-13. Hall-Wentland pH box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

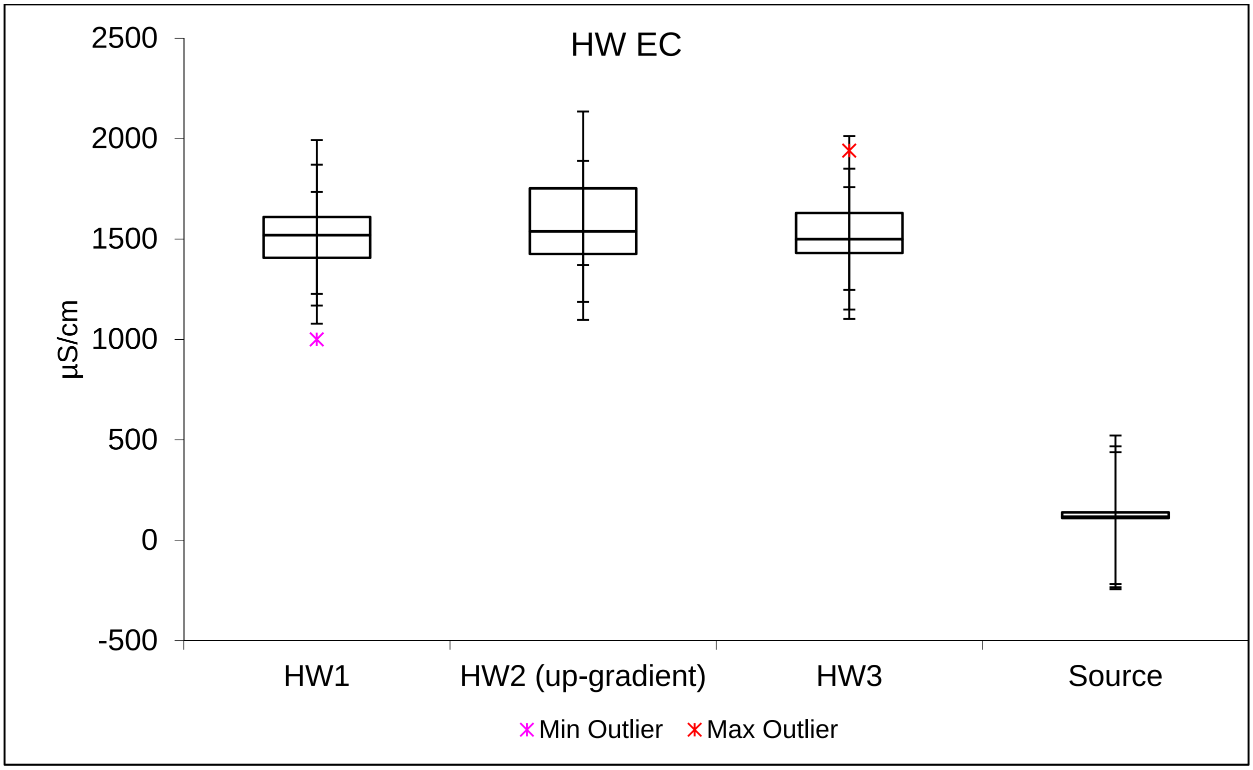

Figure B-14. Hall-Wentland EC box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

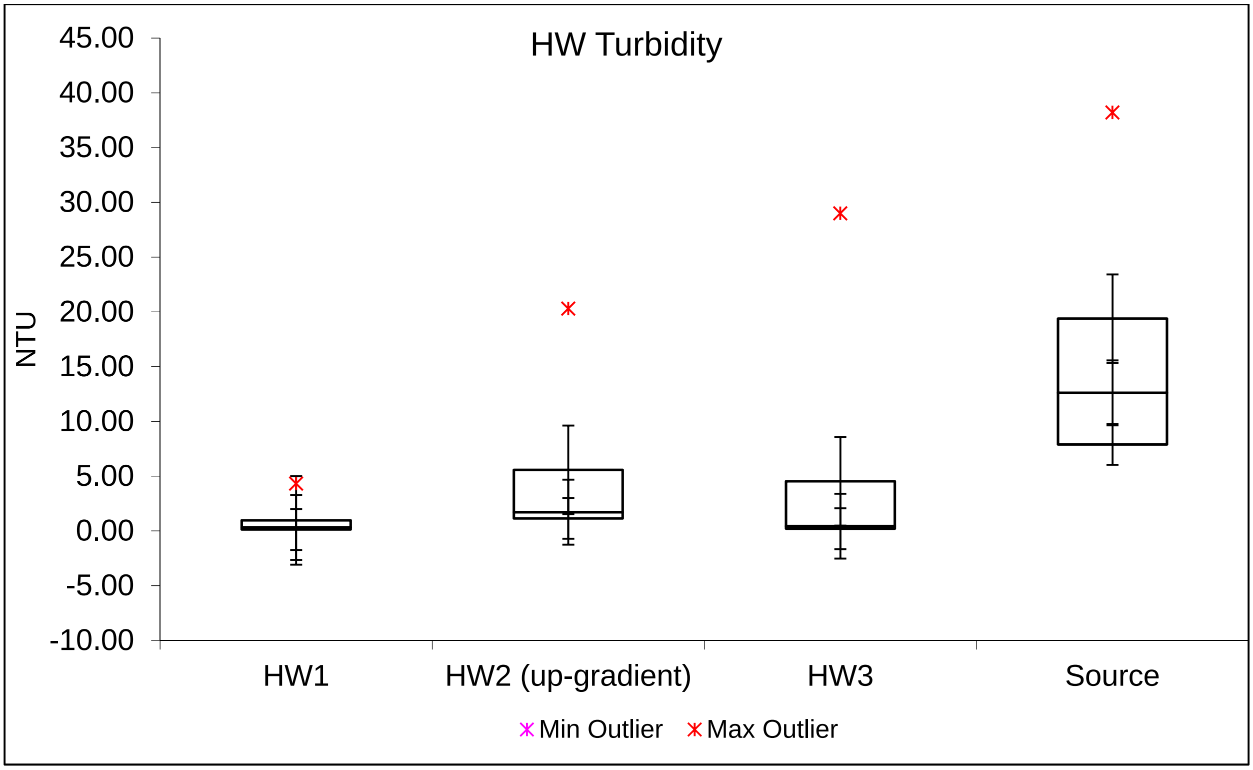

Figure B-15. Hall-Wentland turbidity box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

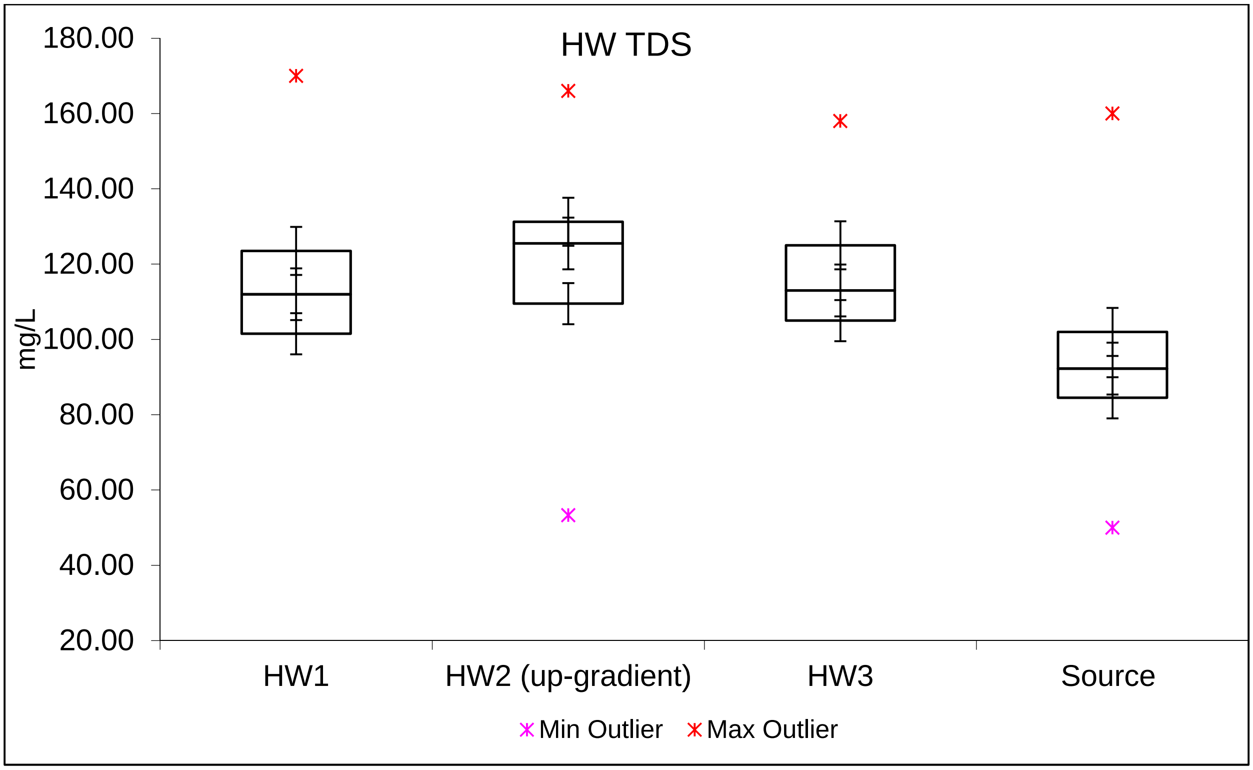

Figure B-16. Hall-Wentland TDS box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

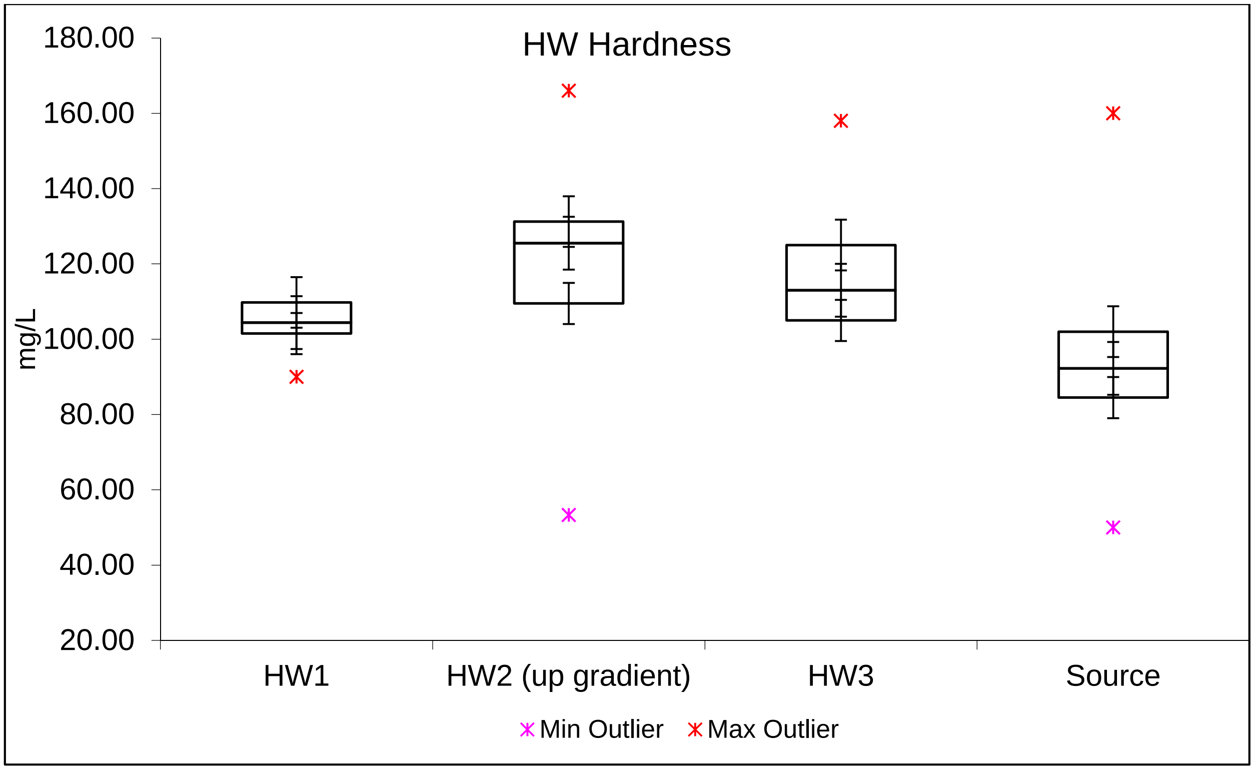

Figure B-17. Hall-Wentland hardness box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

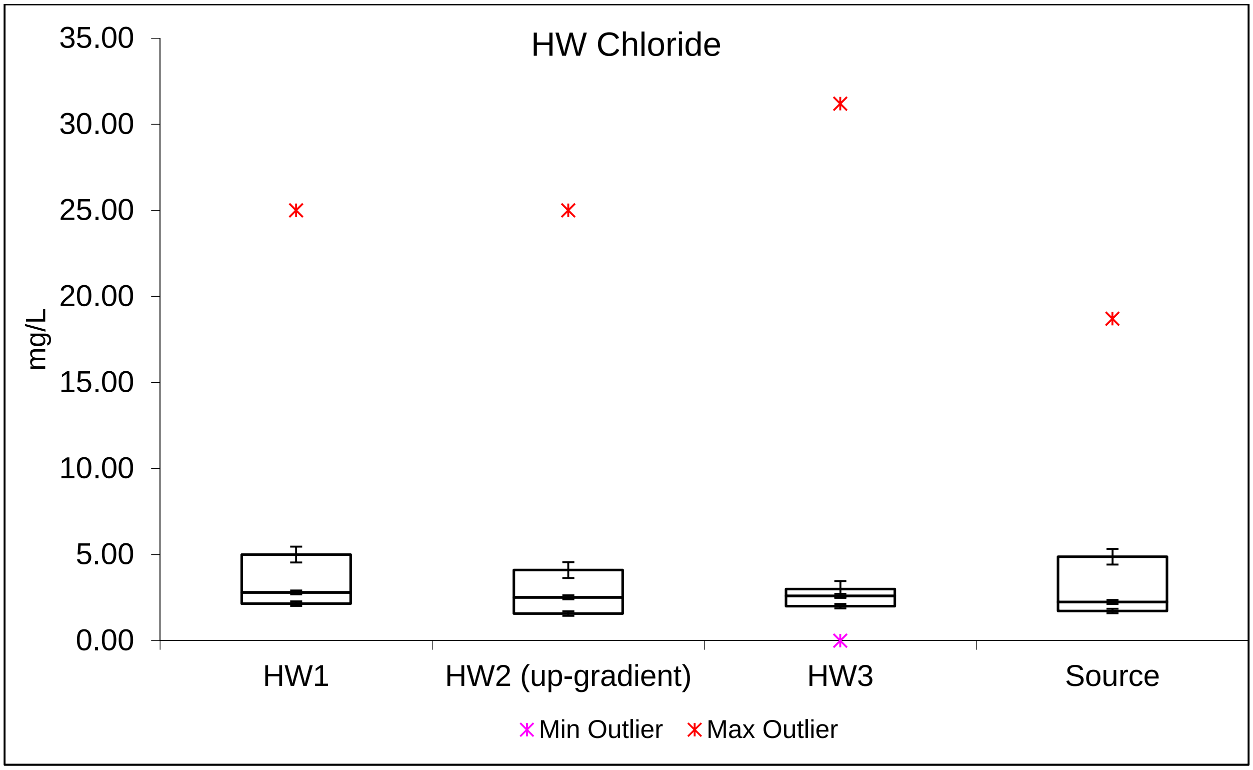

Figure B-18. Hall-Wentland chloride box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

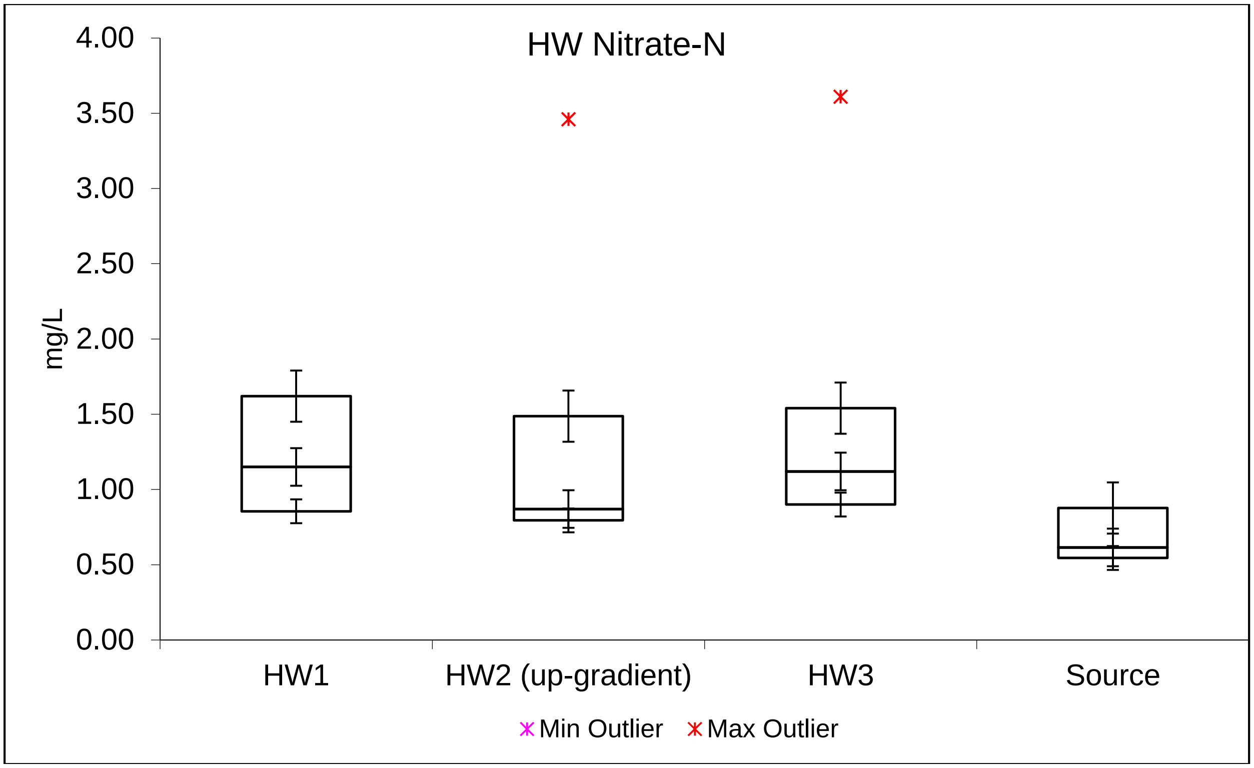

Figure B-19. Hall-Wentland nitrate-N box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

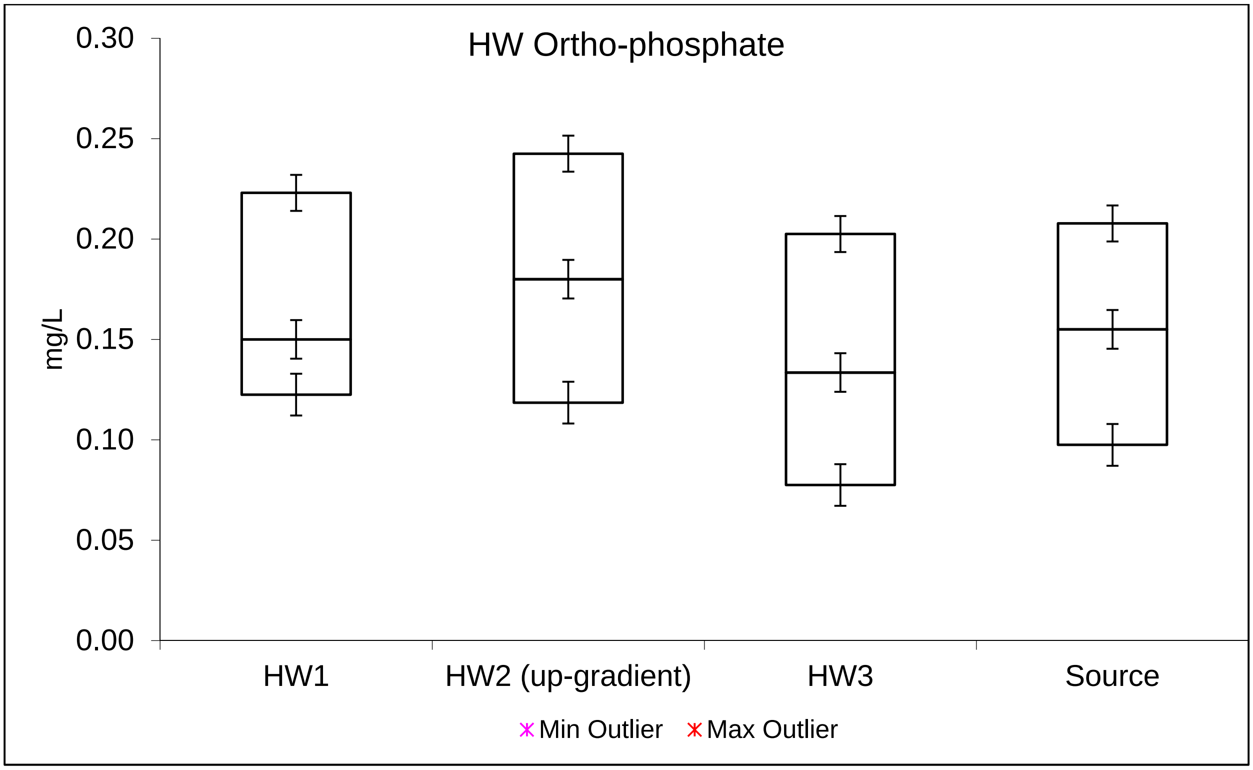

Figure B-20. Hall-Wentland ortho-phosphate box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

Appendix C

Locher Road Data Plots

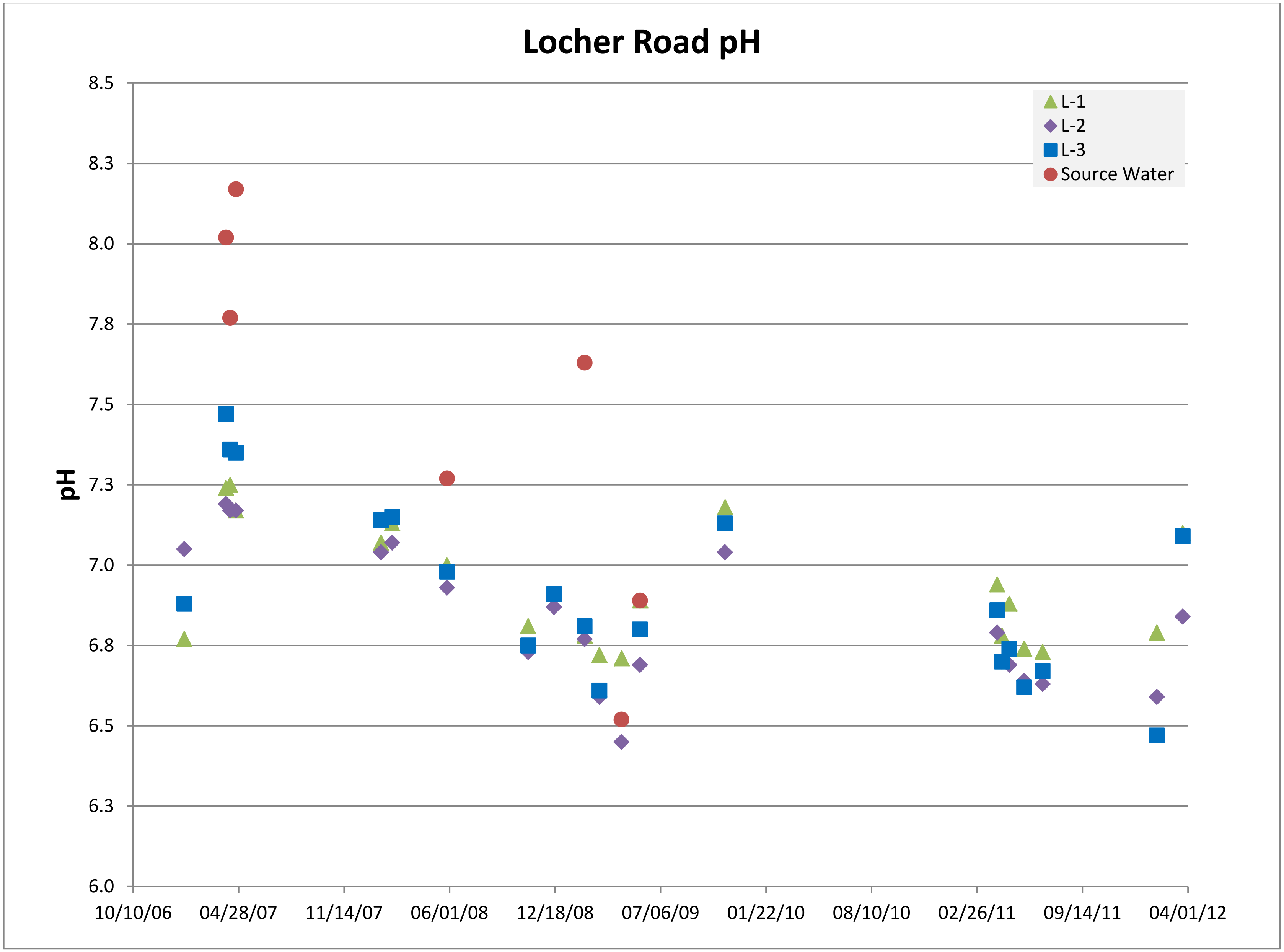

Figure C-1. Locher Road pH. L-1 = Locher Road monitoring well L-1. L-2 = Locher Road monitoring well L-2. L-3 = Locher Road monitoring well L-3.

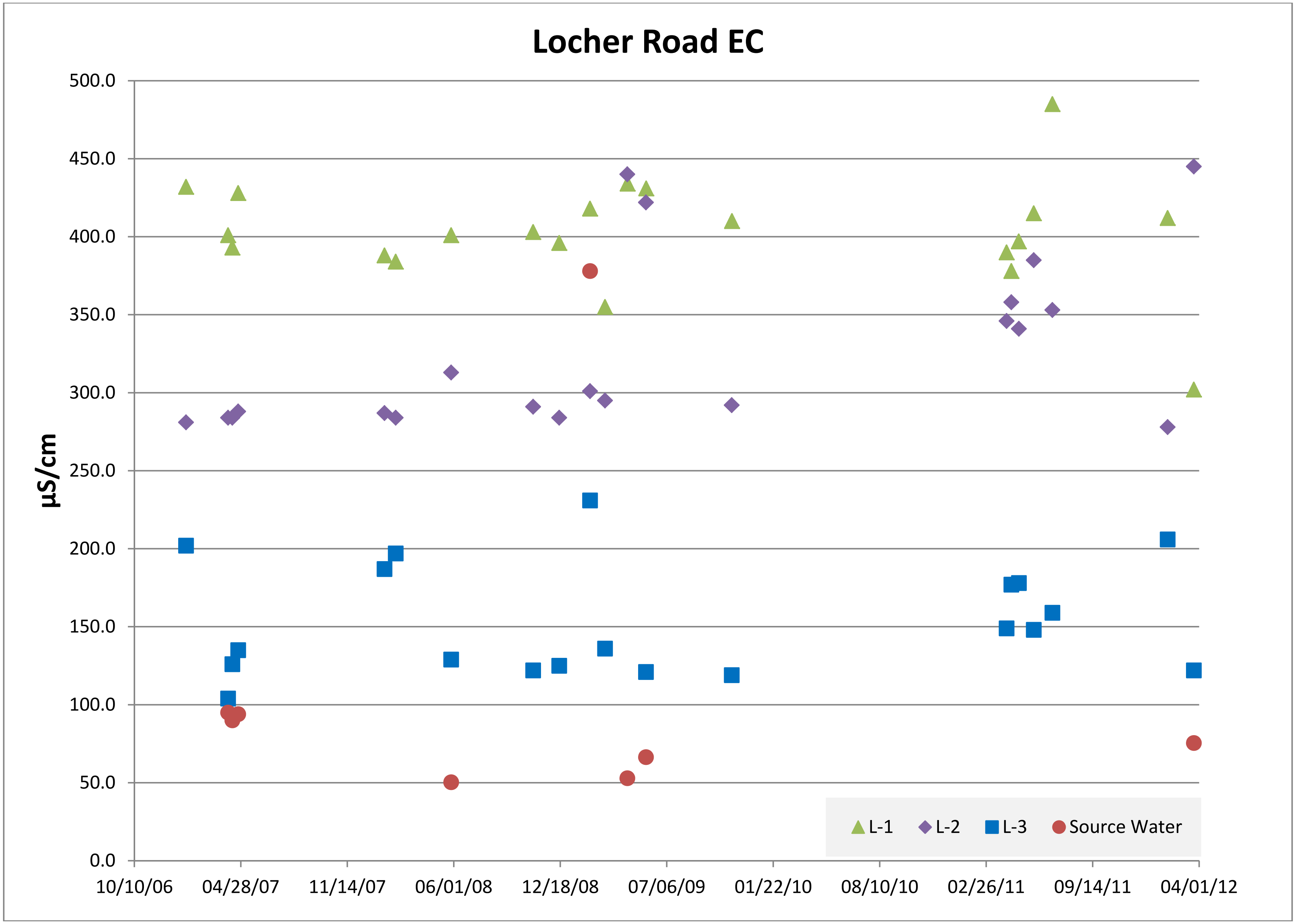

Figure C-2. Locher Road electrical conductivity (EC). L-1 = Locher Road monitoring well L-1. L-2 = Locher Road monitoring well L-2. L-3 = Locher Road monitoring well L-3.

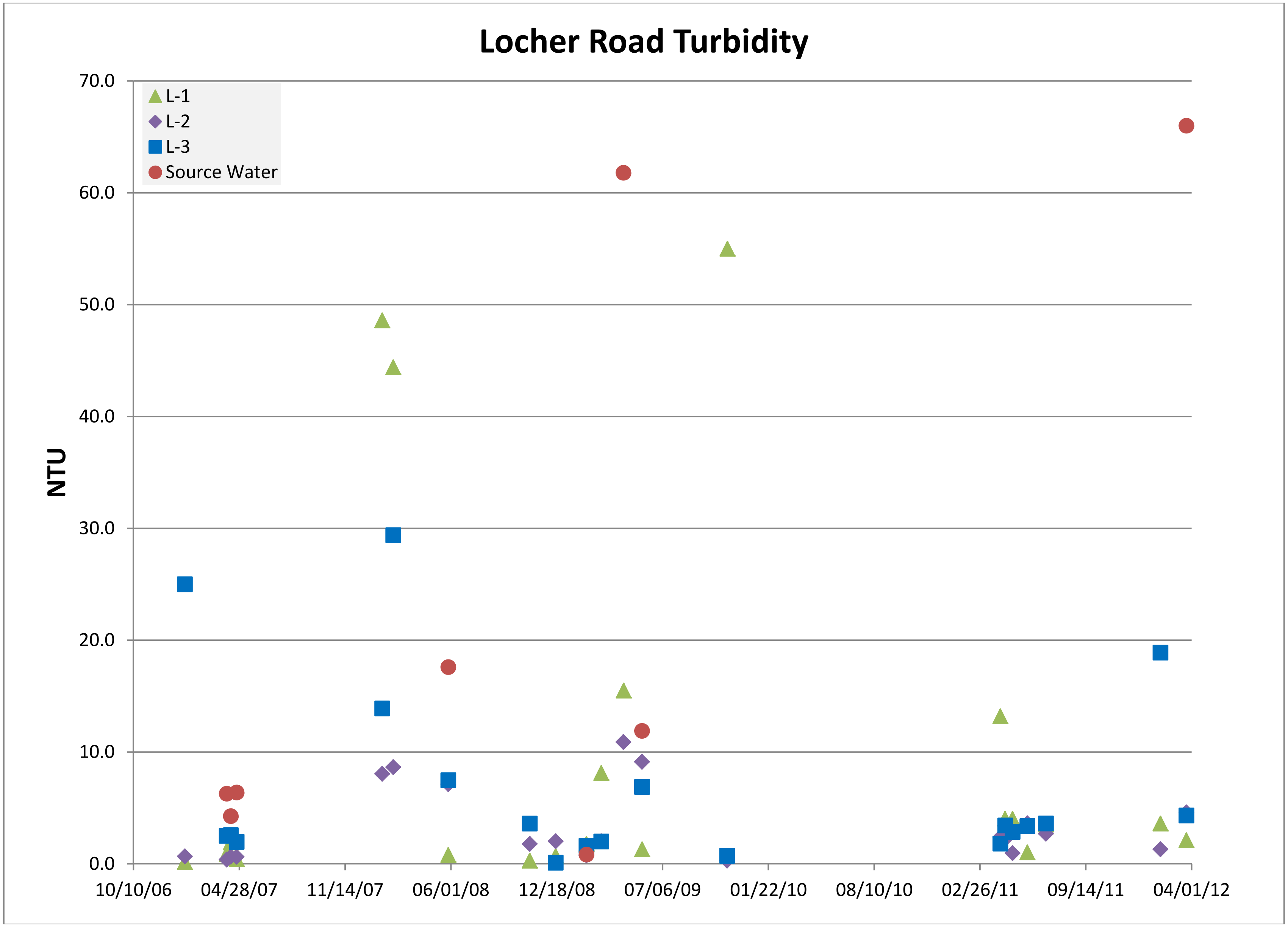

Figure C-3. Locher Road turbidity. L-1 = Locher Road monitoring well L-1. L-2 = Locher Road monitoring well L-2. L-3 = Locher Road monitoring well L-3.

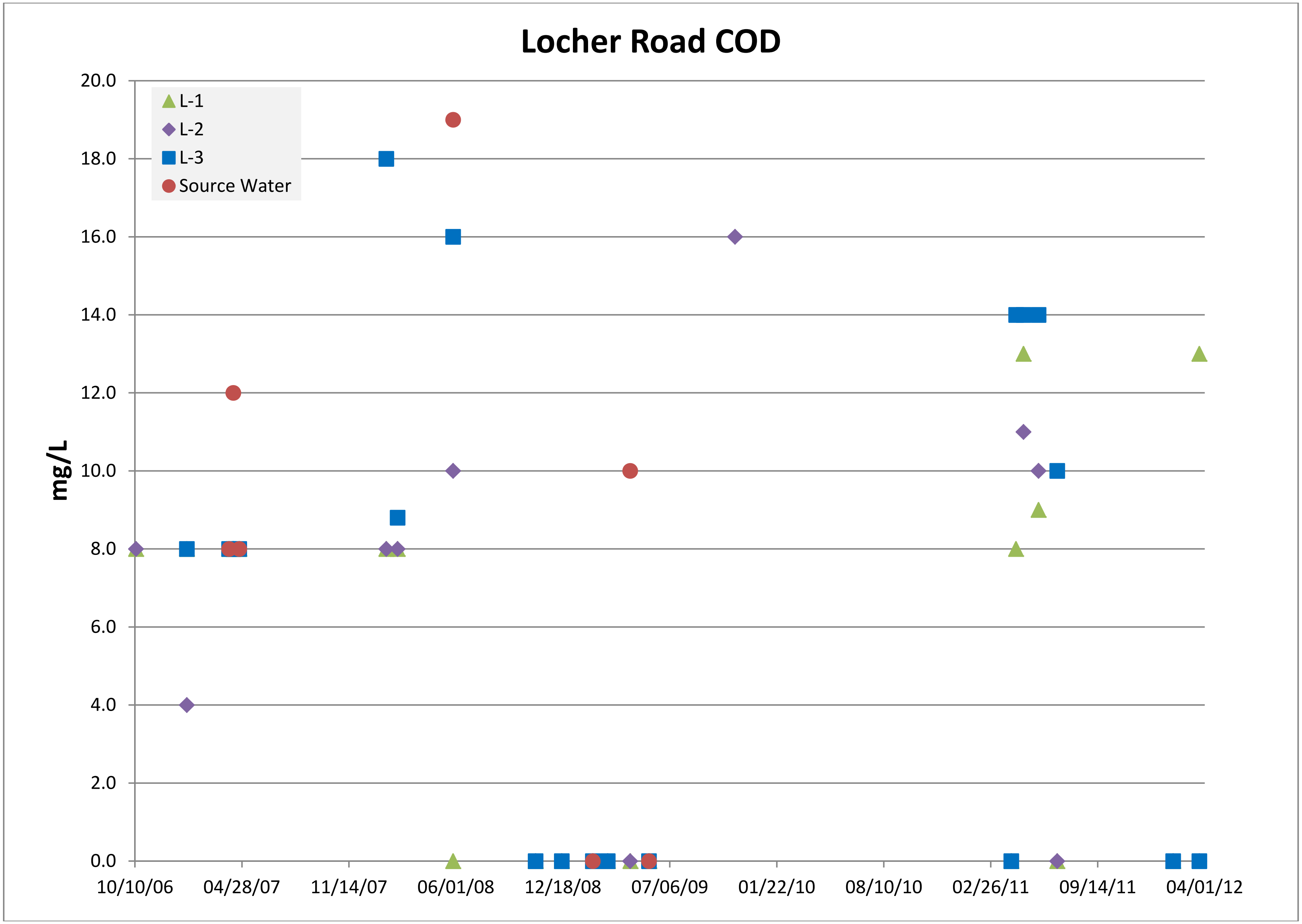

Figure C-4. Locher Road chemical oxygen demand (COD). L-1 = Locher Road monitoring well L-1. L-2 = Locher Road monitoring well L-2. L-3 = Locher Road monitoring well L-3.

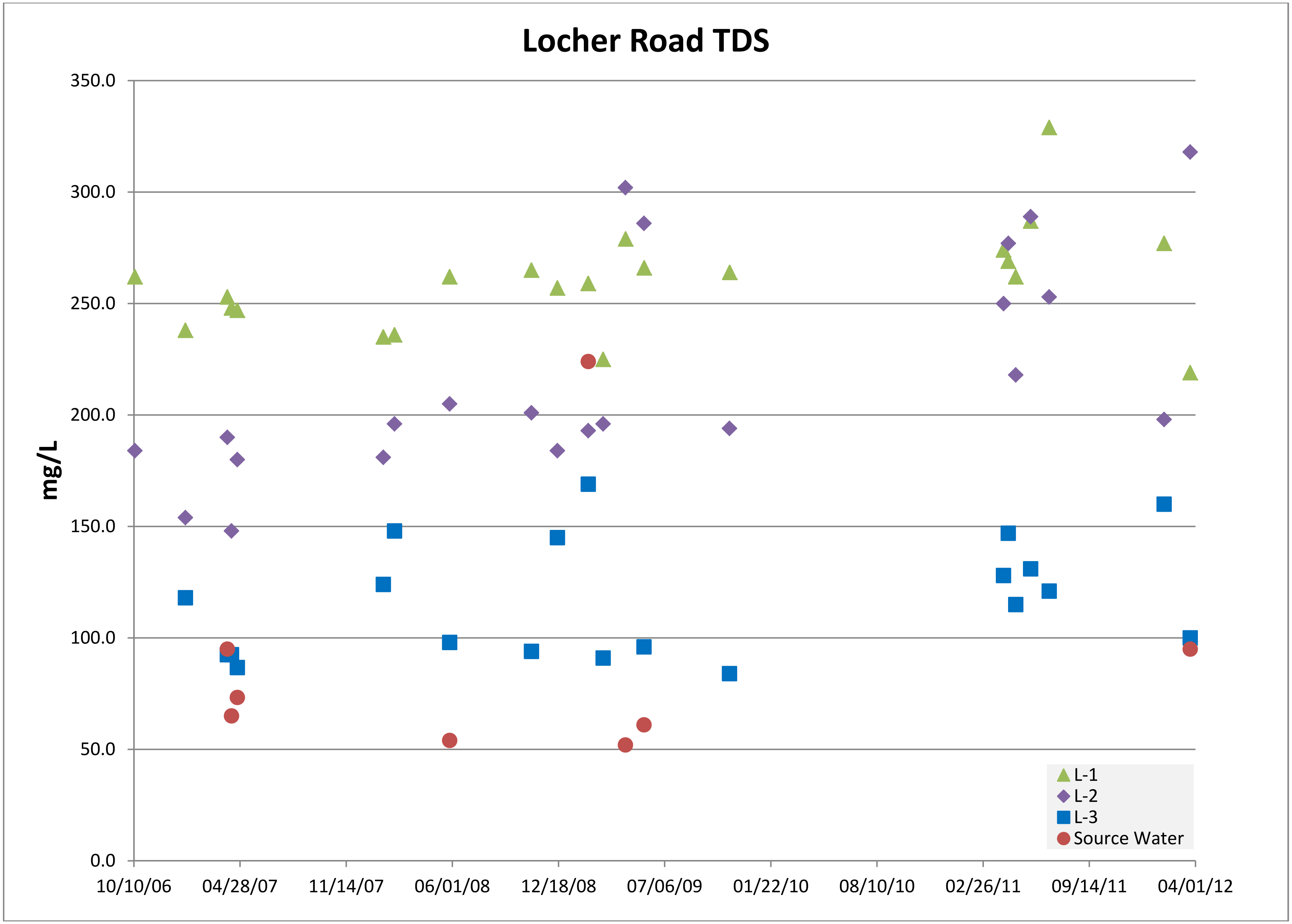

Figure C-5. Locher Road total dissolved solids (TDS). L-1 = Locher Road monitoring well L-1. L-2 = Locher Road monitoring well L-2. L-3 = Locher Road monitoring well L-3.

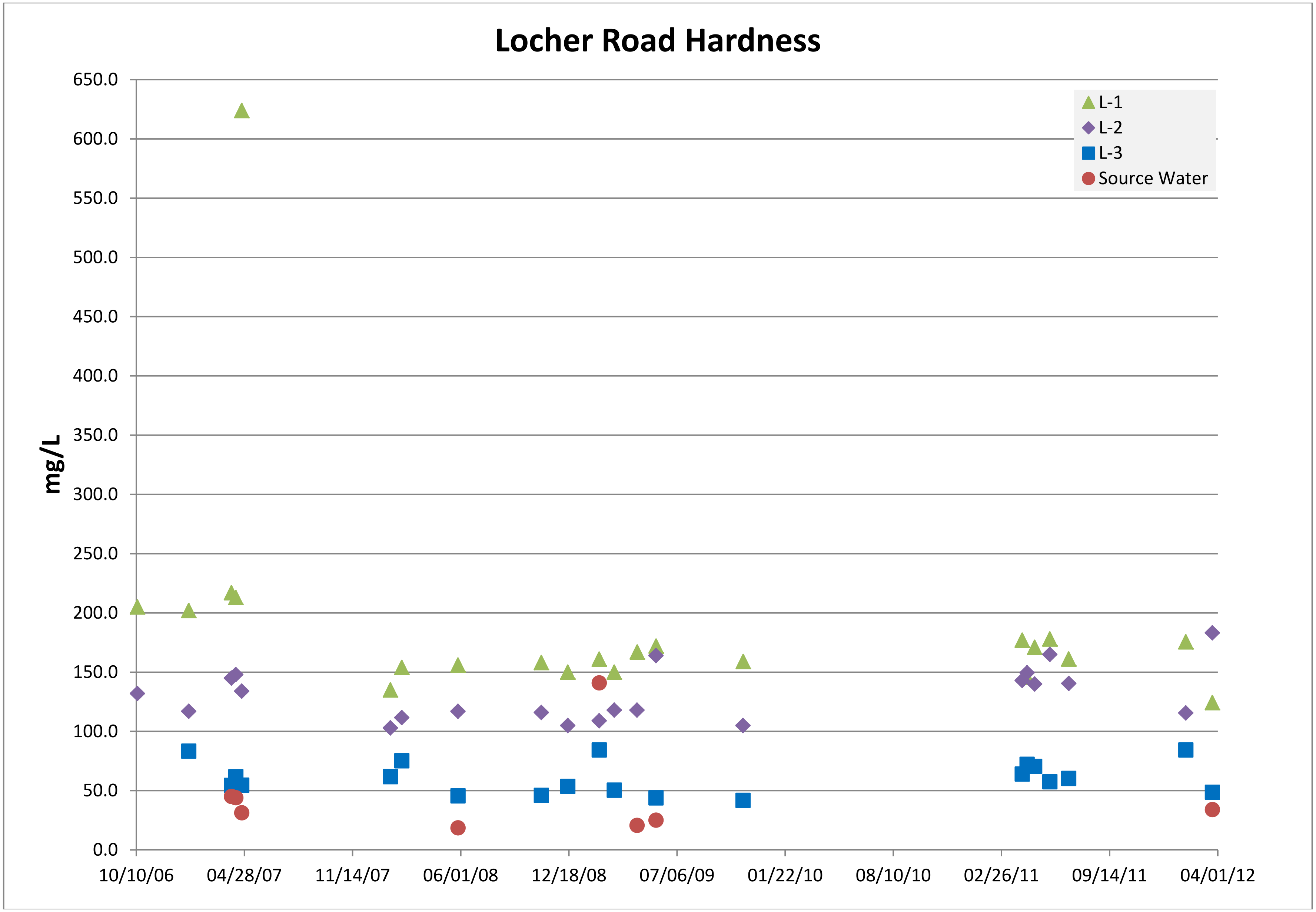

Figure C-6. Locher Road hardness. L-1 = Locher Road monitoring well L-1. L-2 = Locher Road monitoring well L-2. L-3 = Locher Road monitoring well L-3.

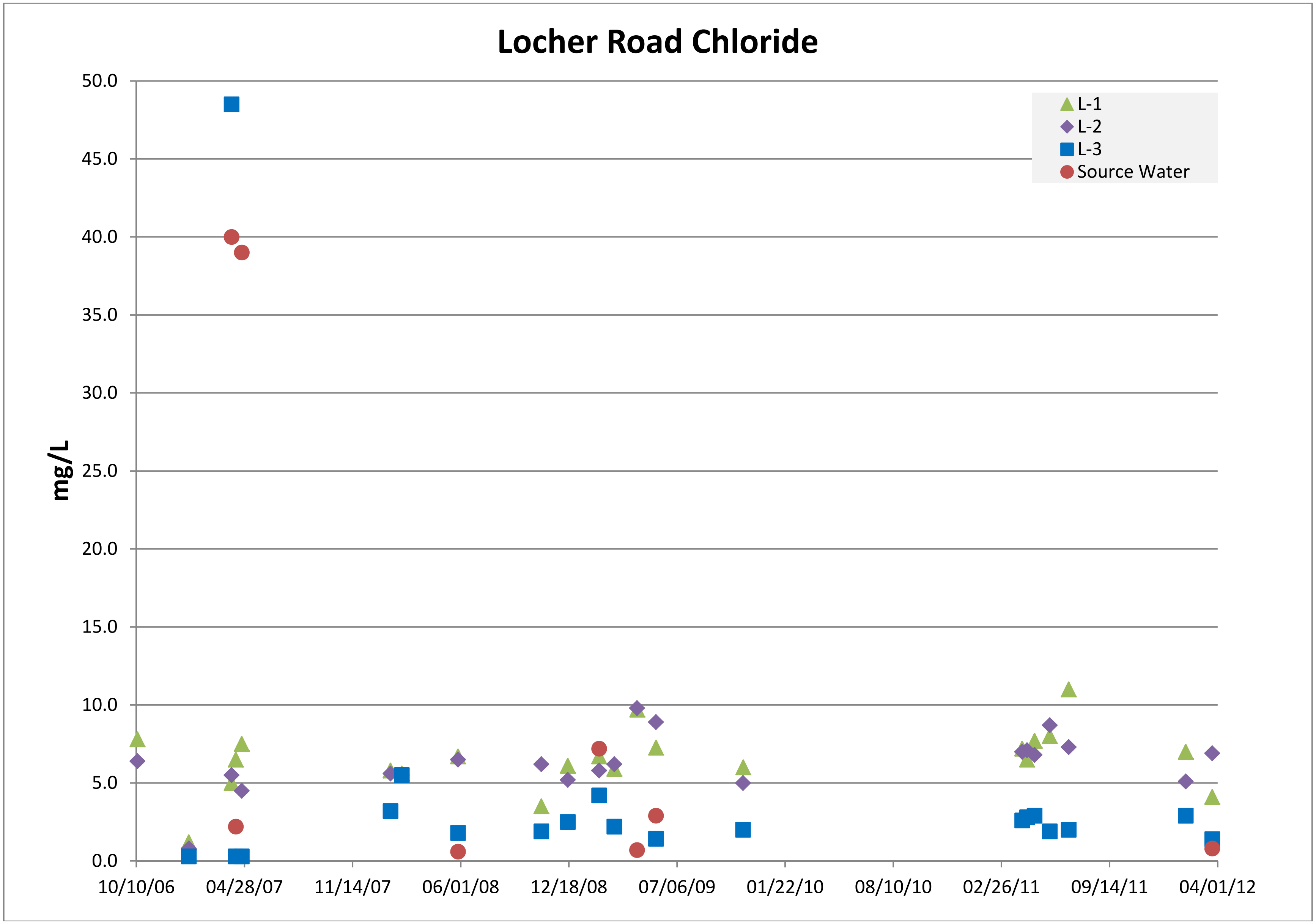

Figure C-7. Locher Road chloride. L-1 = Locher Road monitoring well L-1. L-2 = Locher Road monitoring well L-2. L-3 = Locher Road monitoring well L-3.

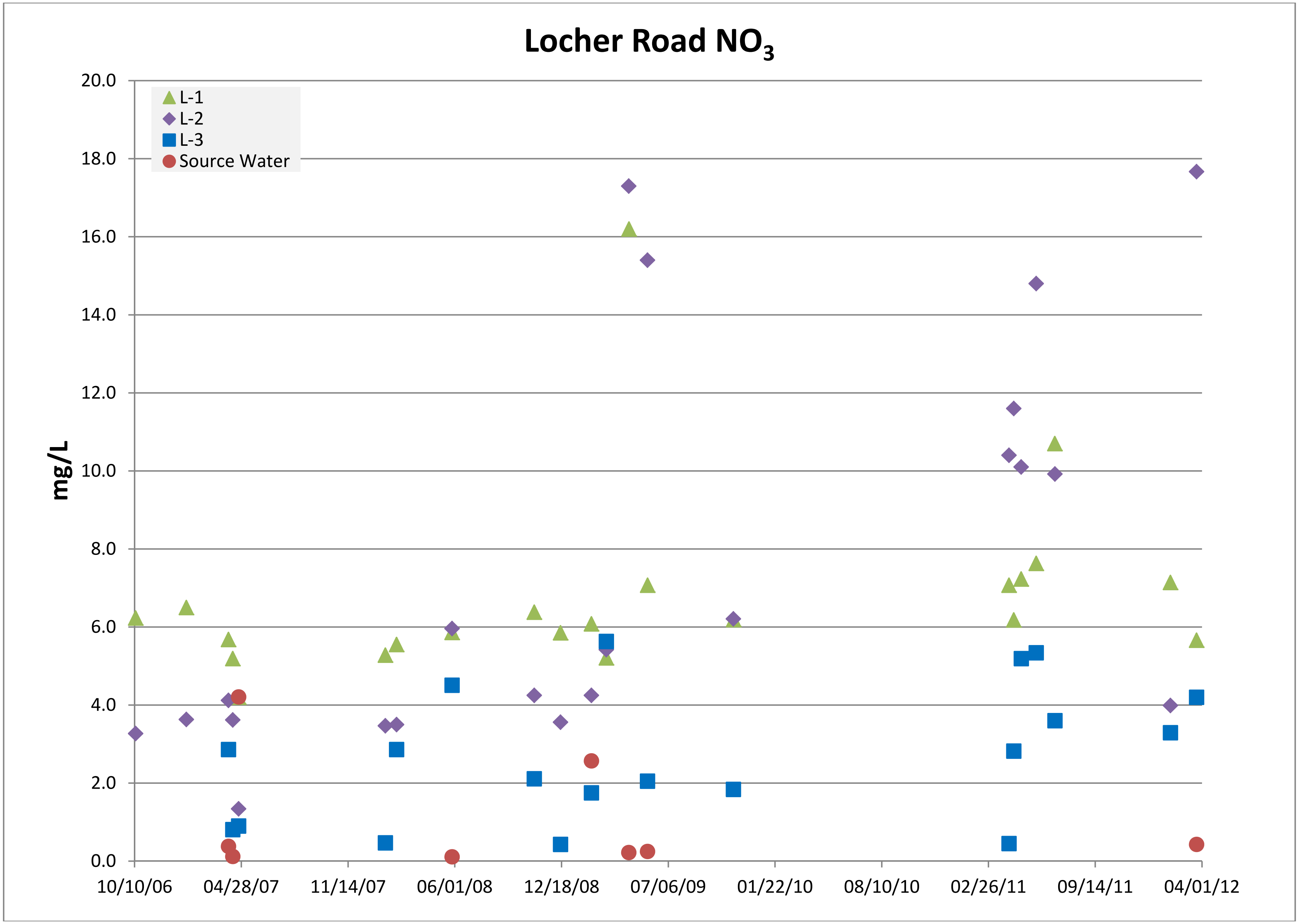

Figure C-8. Locher Road nitrate-N. L-1 = Locher Road monitoring well L-1. L-2 = Locher Road monitoring well L-2. L-3 = Locher Road monitoring well L-3.

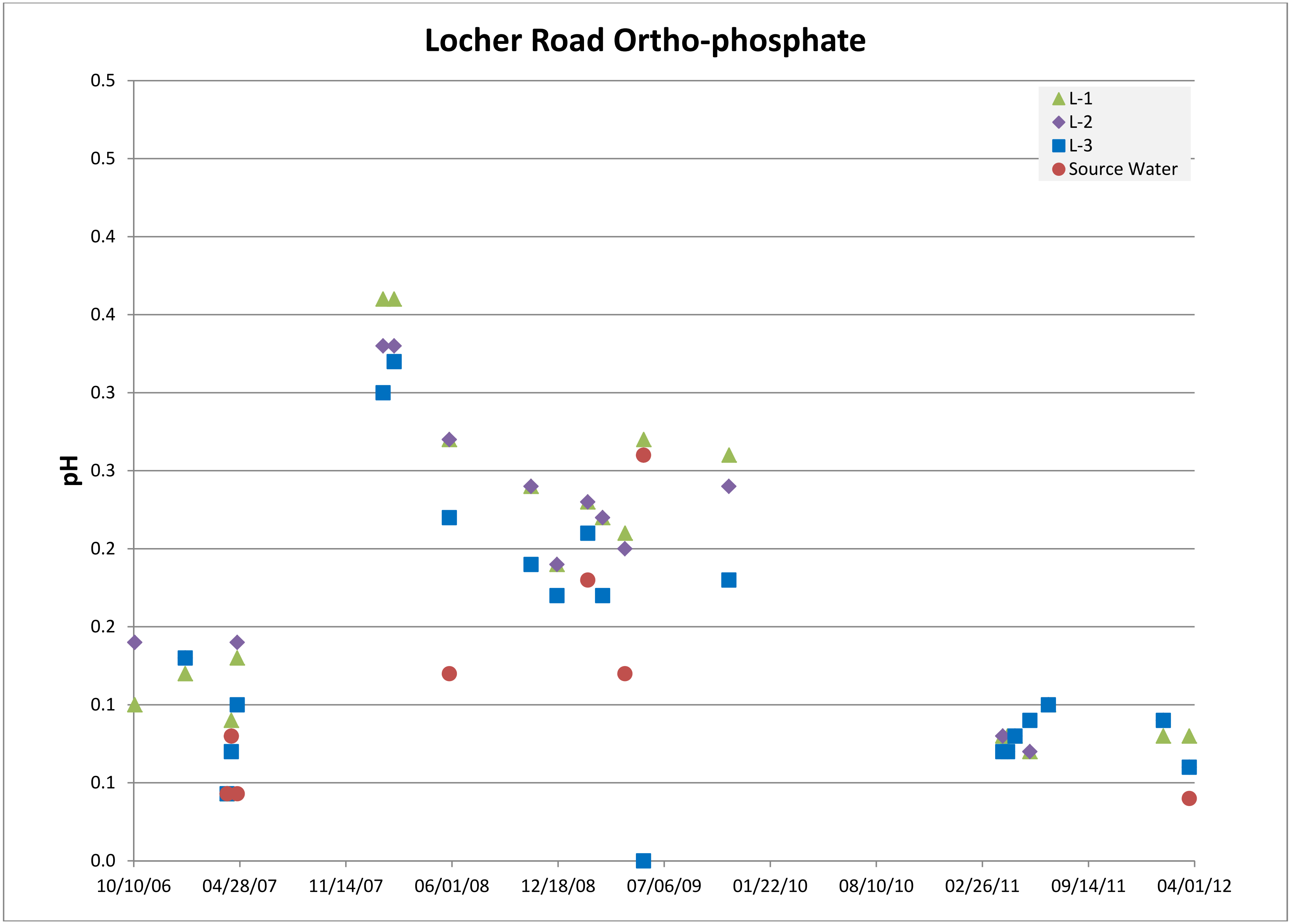

Figure C-9. Locher Road ortho-phosphate. L-1 = Locher Road monitoring well L-1. L-2 = Locher Road monitoring well L-2. L-3 = Locher Road monitoring well L-3.

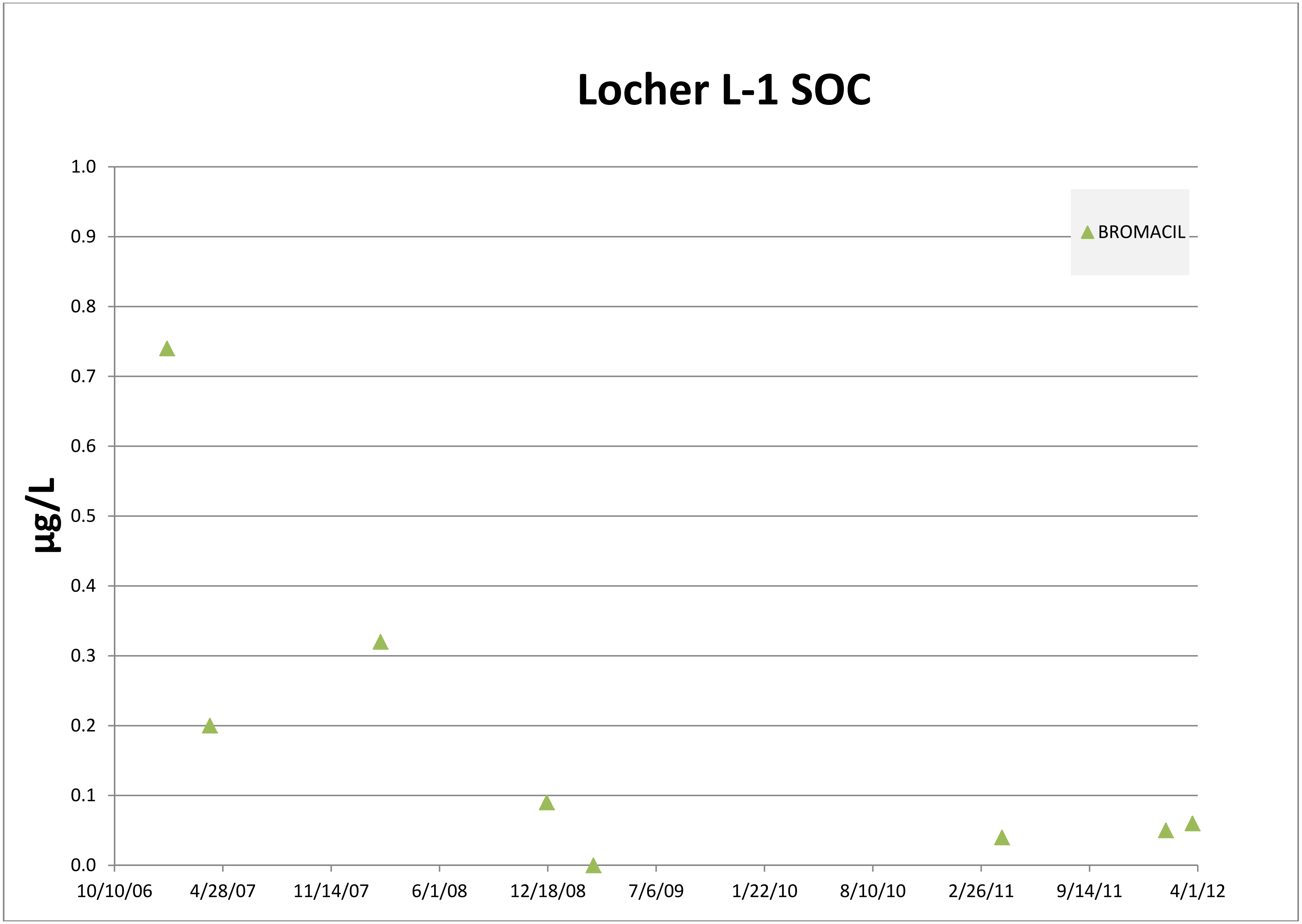

Figure C-10. Locher Road monitoring well L-1 SOC’s.

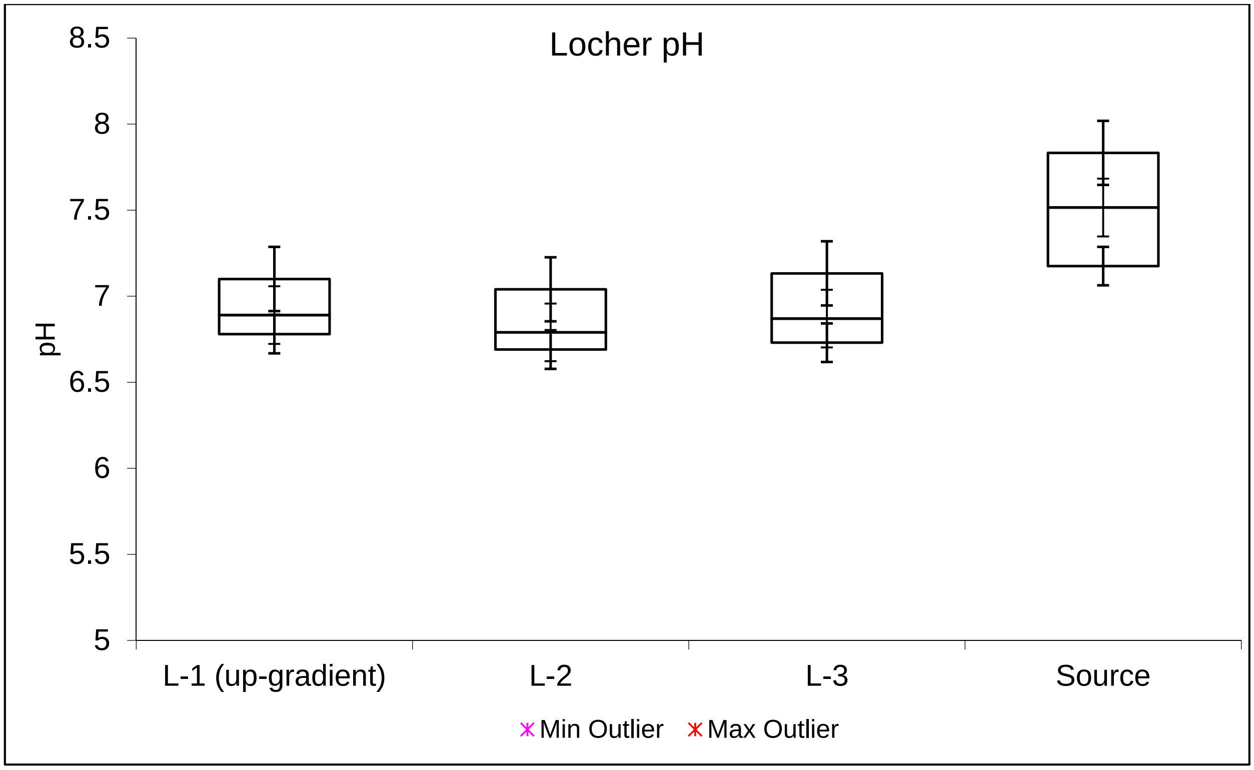

Figure C-11. Locher Road pH box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

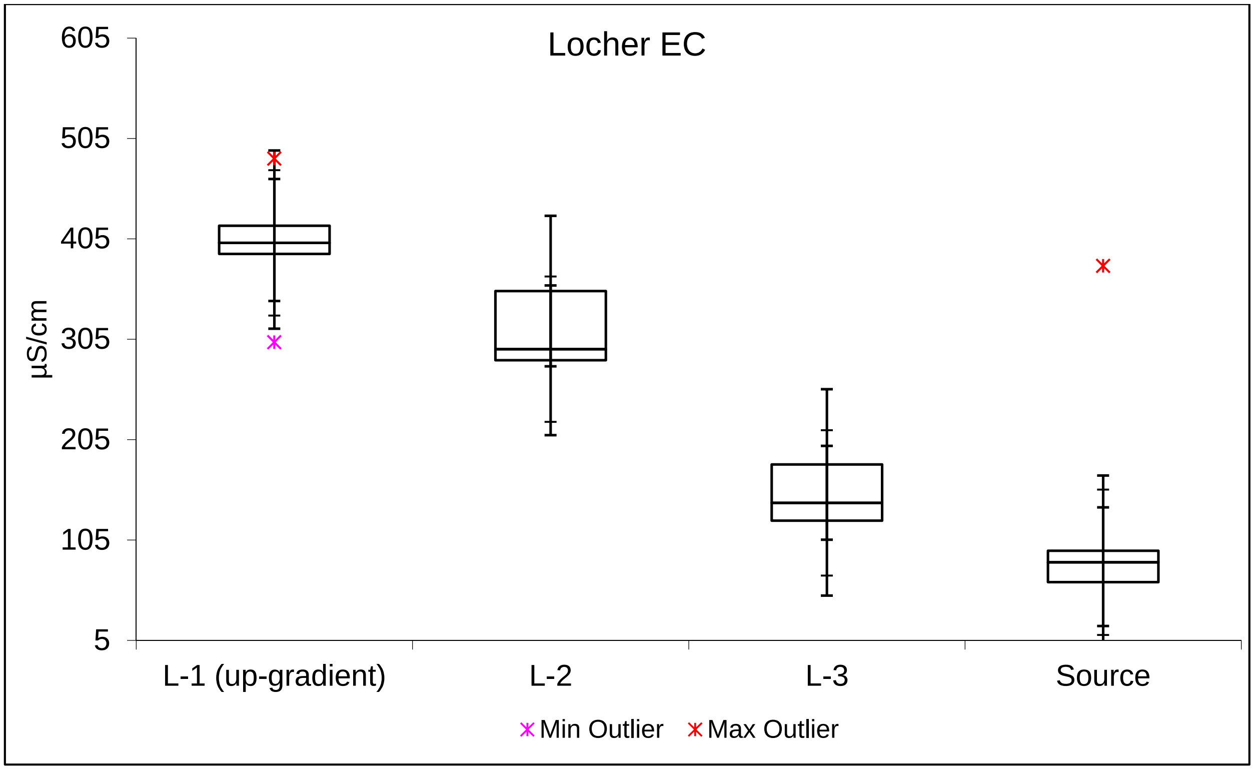

Figure C-12. Locher Road EC box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

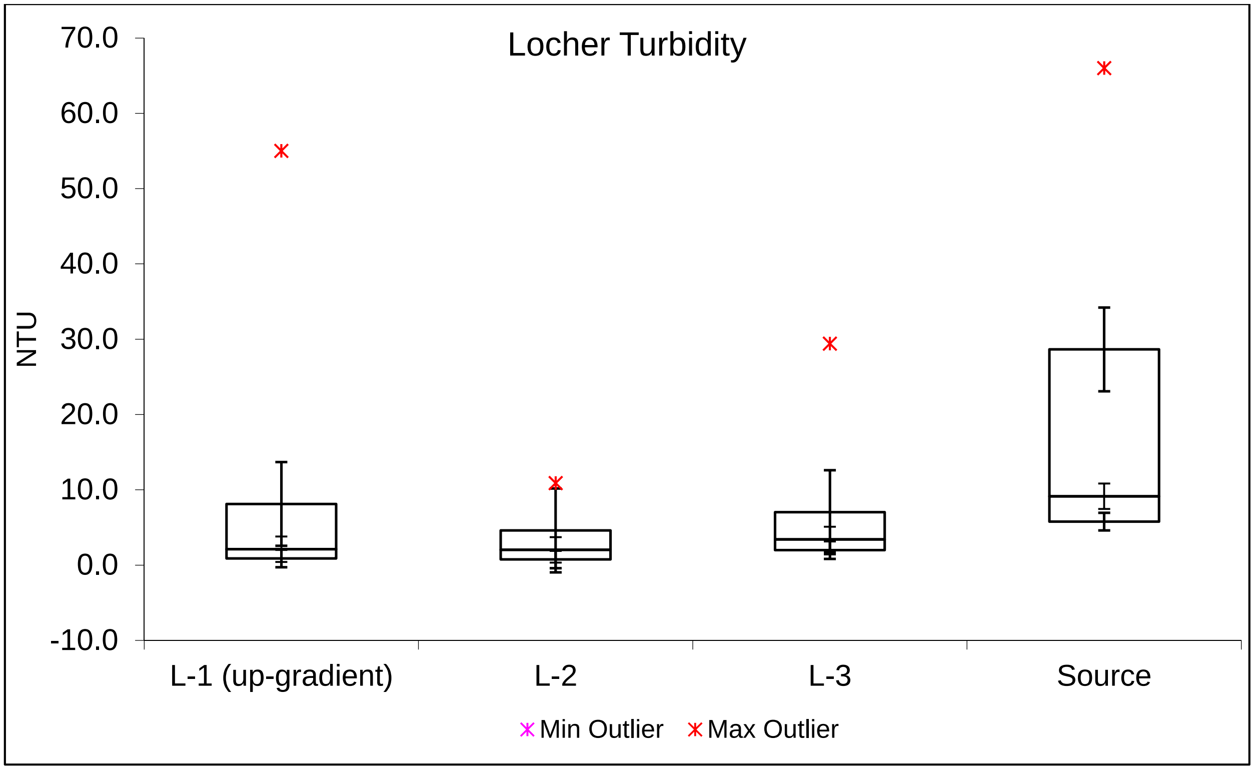

Figure C-13. Locher Road turbidity box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

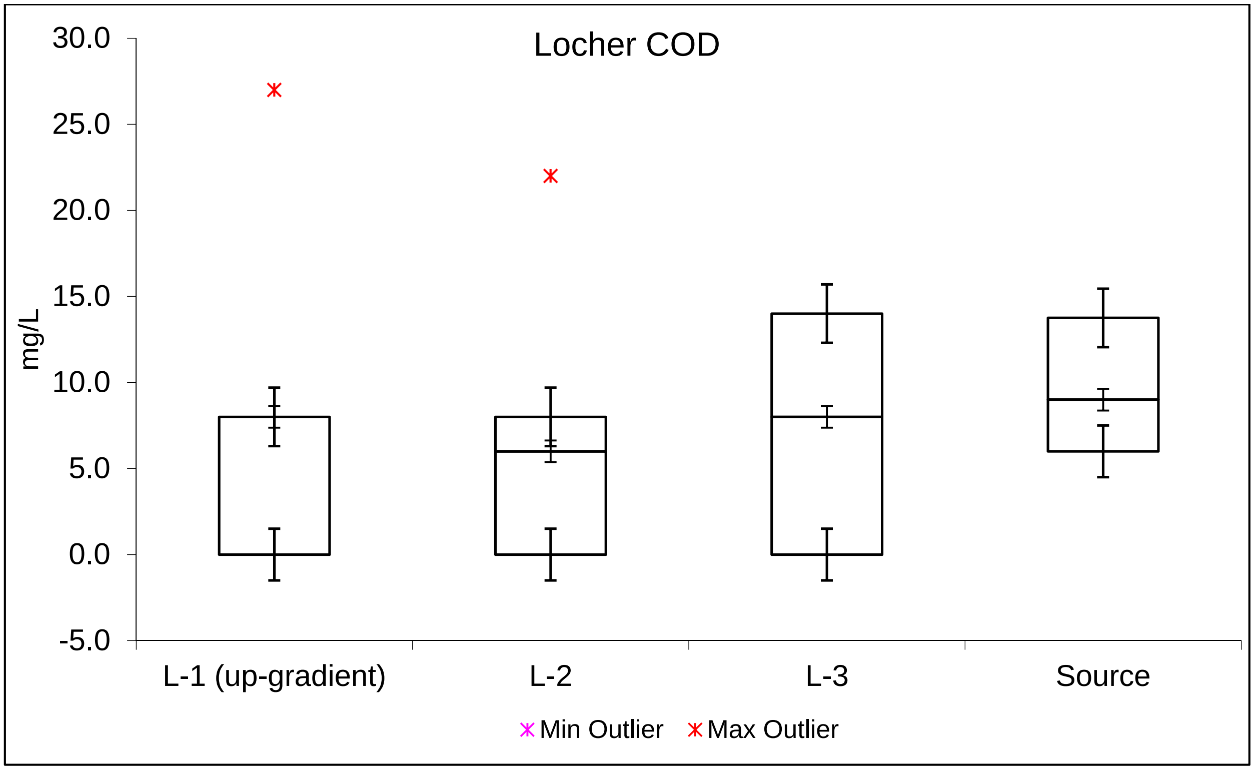

Figure C-14. Locher Road COD box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

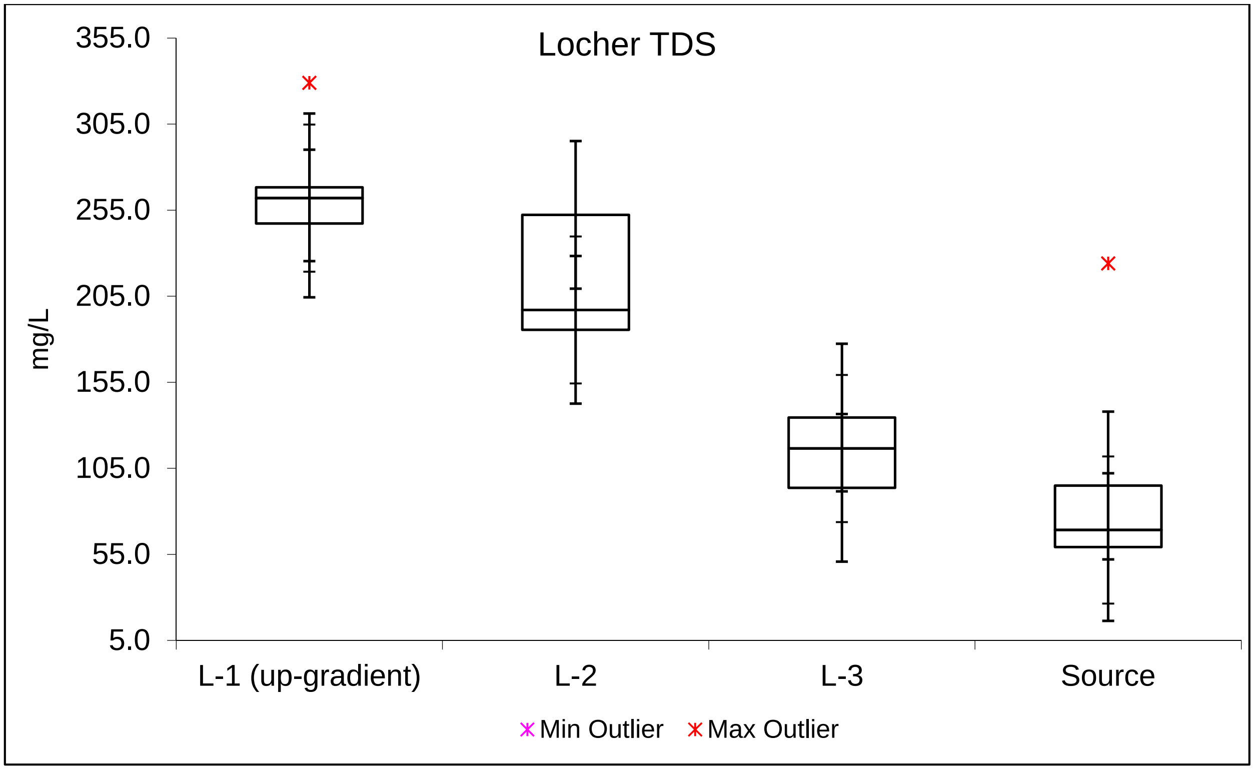

Figure C-15. Locher Road TDS box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

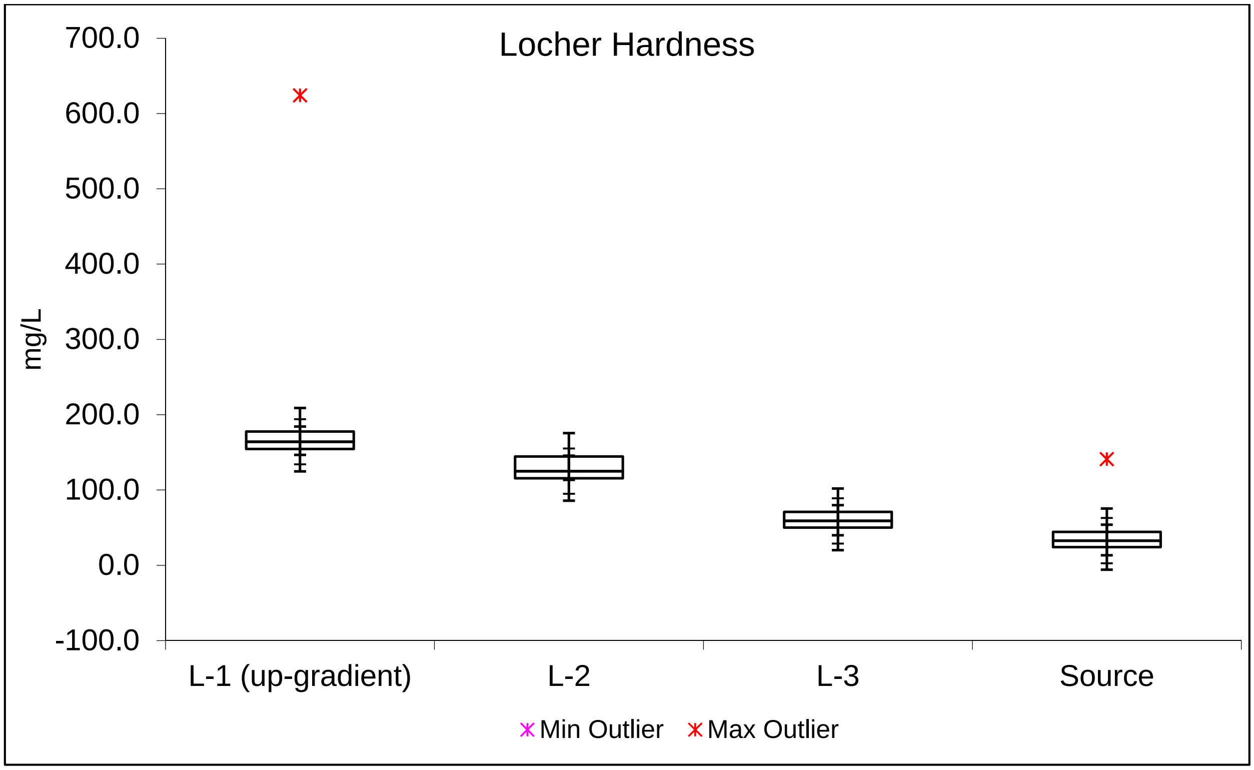

Figure C-16. Locher Road TDS box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

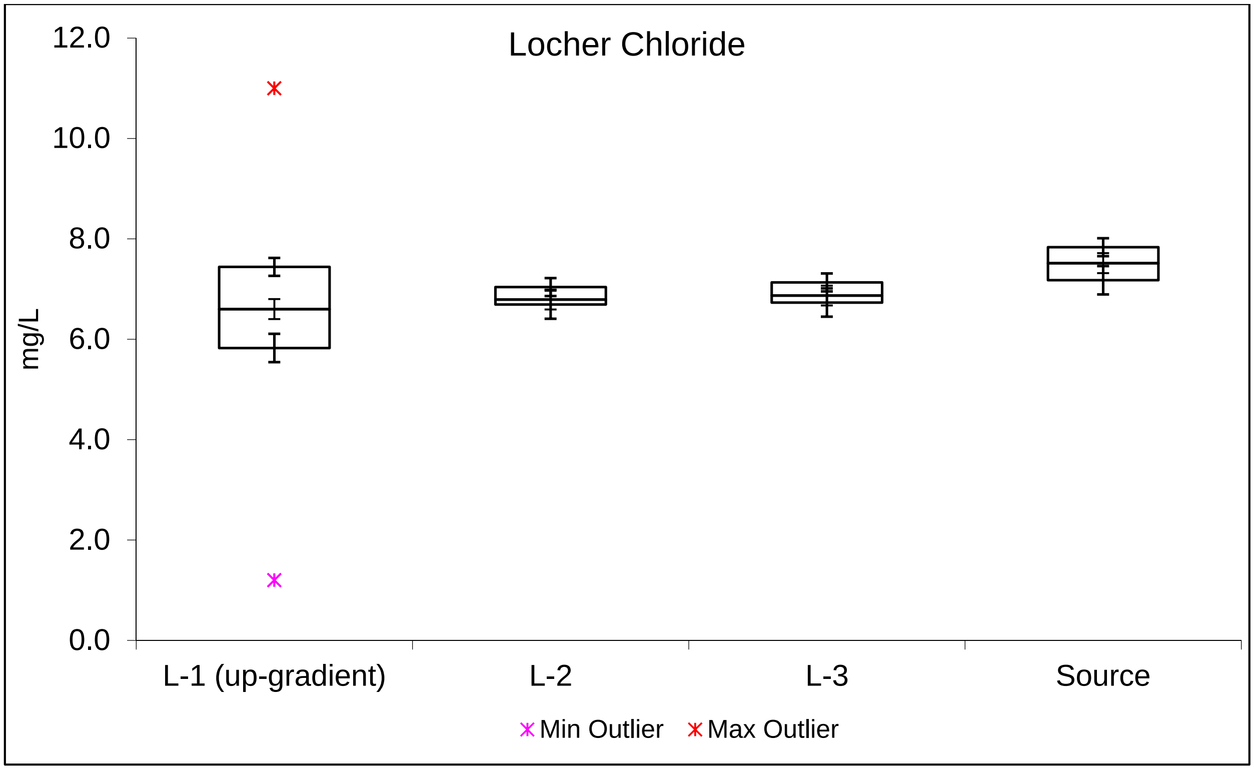

Figure C-17. Locher Road chloride box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

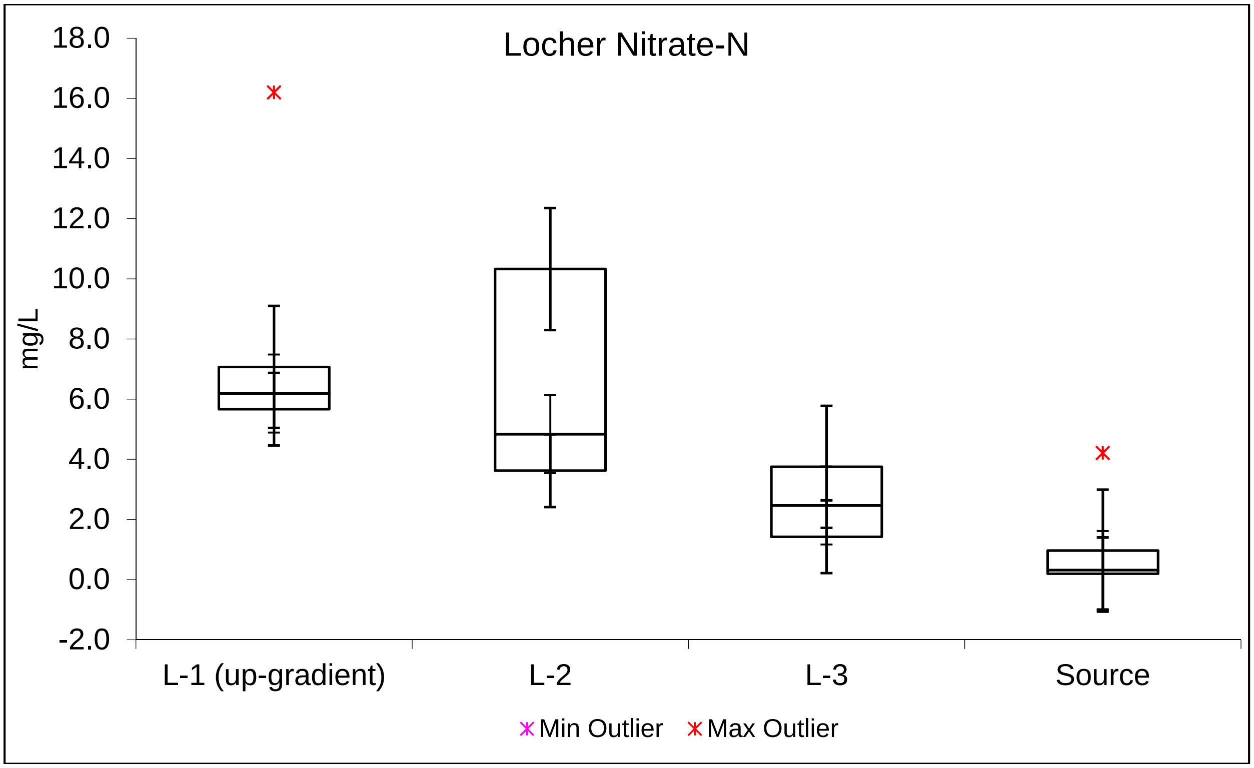

Figure C-18. Locher Road nitrate-N box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

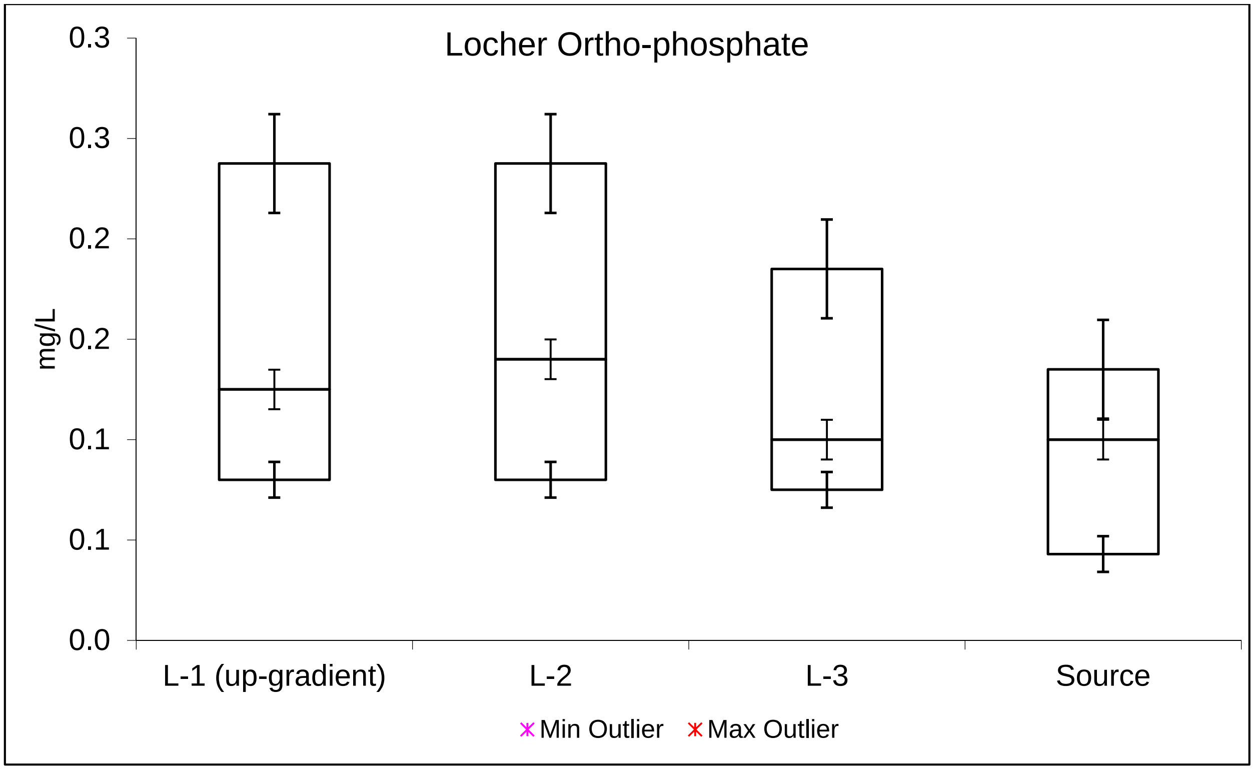

Figure C-19. Locher Road ortho-phosphate box-plot comparison displaying standard error bars for the median, upper and lower interquartile ranges.

Appendix D

Stiller Pond Data Comparison Histograms

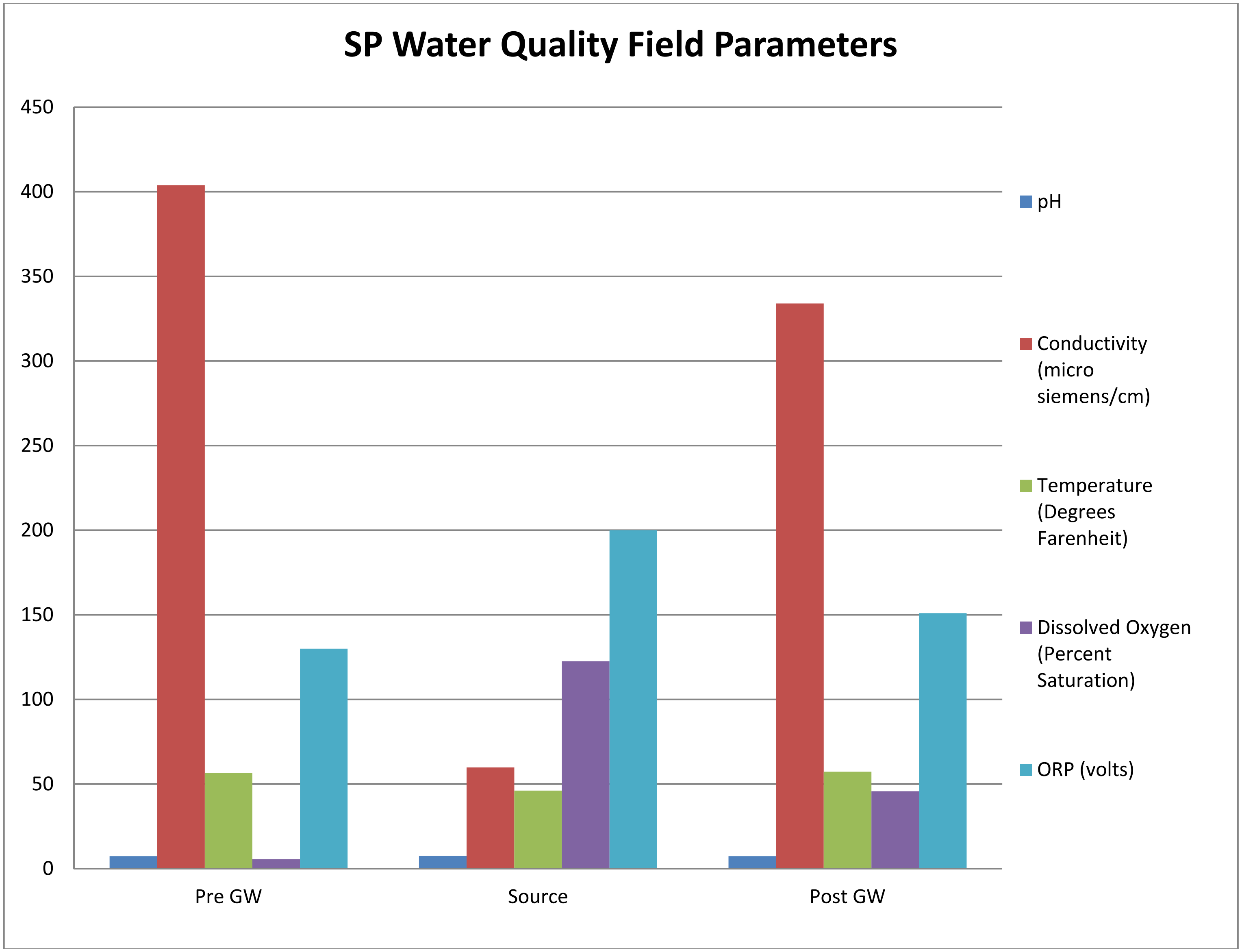

Figure D-1. Stiller Pond field parameters. Pre GW = pre-recharge groundwater sample; Source = recharge source water sample; Post GW = post-recharge groundwater sample. All groundwater samples were collected from monitoring well MWSP-1.

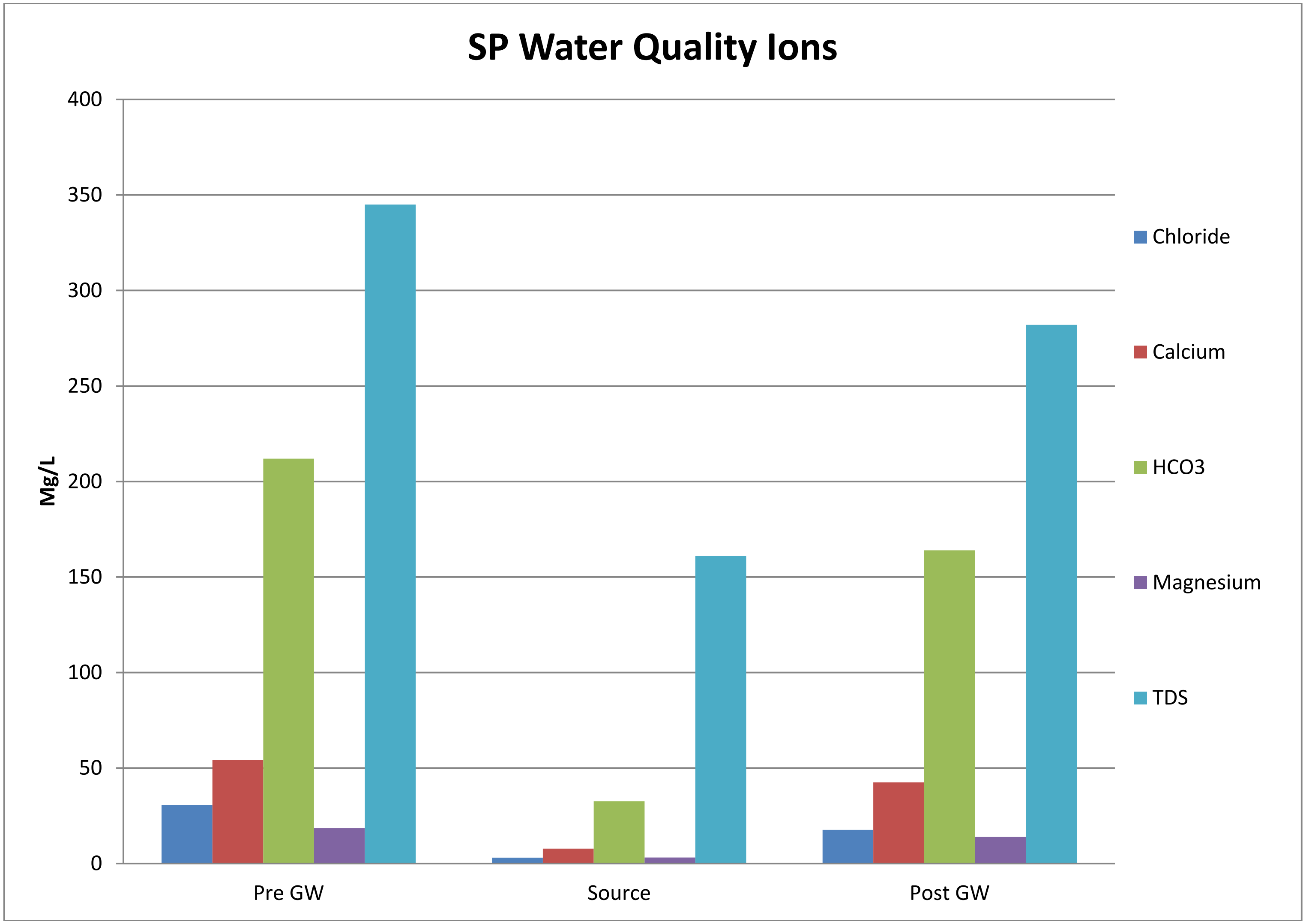

Figure D-2. Stiller Pond water quality ions. Pre GW = pre-recharge groundwater sample; Source = recharge source water sample; Post GW = post-recharge groundwater sample. All groundwater samples were collected from monitoring well MWSP-1. TDS = total dissolved solids.

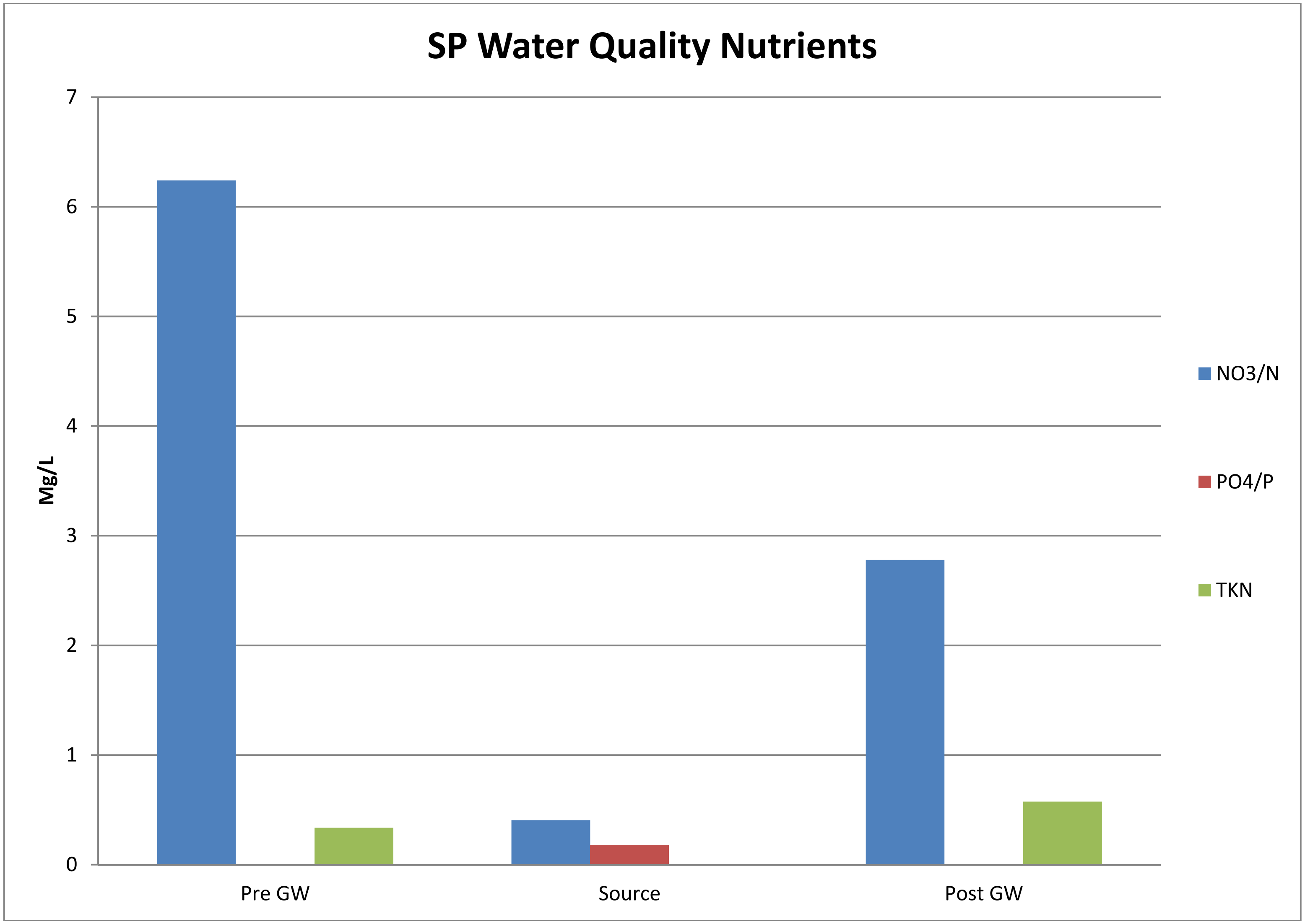

Figure D-3. Stiller Pond water nutrients. Pre GW = pre-recharge groundwater sample; Source = recharge source water sample; Post GW = post-recharge groundwater sample. All groundwater samples were collected from monitoring well MWSP-1. TKN = total Kjeldahl nitrogen.