9. Holistic Analysis

Multivariate statistical techniques can be used to identify relationships between various water quality parameters and the potential sources and processes contributing to the water quality. A common combination of multivariate statistical techniques includes use of hierarchical classification with Principal Component Analysis (PCA). Hierarchical classification is used to group monitoring sites based on similarity in water quality. PCA identifies relationships between water quality parameters and uses these relationships to isolate factors or components that describe processes or sources that control water quality. The combination of the two techniques allows for understanding of spatial variations in water quality, processes, and pollution sources, providing a more holistic assessment of the data.

9.1.1. Hierarchical Classification

The hierarchal classification algorithm was based on the 20-year median concentrations of the measured water quality parameters (e.g. major ions, nutrients, and trace elements) of each site. Data on aquifer thickness and water surface elevation were excluded to reduce the influence of site location in the algorithm, since it is assumed that groundwater chemistry is inherently spatially correlated. This could help identify other potential patterns in groundwater chemistry not necessarily dependent on spatial distribution.

The classification algorithm separated the 51 monitoring locations into four groups as shown in Figure 104. The spatial distribution of the monitoring locations within each group is shown in Figure 105 and a summary of characteristics and water quality for each group is listed in Table 19.

A review of the results provides a quick check that the hierarchal classification worked as expected. Note that each set of nested wells at Hales Ale and 3rd and Havana are grouped together, indicating they are more like each other than other sites. In addition, other sets of adjacent sites are also grouped together, such as Sullivan Road and the springs at Sullivan Park, the two Orchard Avenue Irrigation District wells, and Waikiki Springs and the Spokane Fish Hatchery well.

However, sites that are not close to each other have also been grouped together because their water quality is similar without being in proximity, such as the monitoring wells at the Northeast Community Center and Frederick and Bowdish, the Sullivan Park monitoring well and the North Spokane Irrigation District well, and the monitoring well at the Fire Station on Houston and Regal with the City of Spokane Ray Street well.

The resultant classification scheme demonstrates the influence of source water, aquifer thickness (amount of groundwater), sewering, and confining layers on water quality.

Group 2 contains only the river and transitional monitoring sites. Therefore, all sites in Group 2 have some degree of influence from the Spokane River. As a group, these monitoring locations have the lowest concentrations of major ions and nitrates. This makes sense given the Spokane River has generally low concentrations of these constituents and that Group 2 does not include any sites that are currently influenced by septic systems. However, the influence of the Spokane River causes the groundwater to have higher temperatures and lower pH and dissolved oxygen.
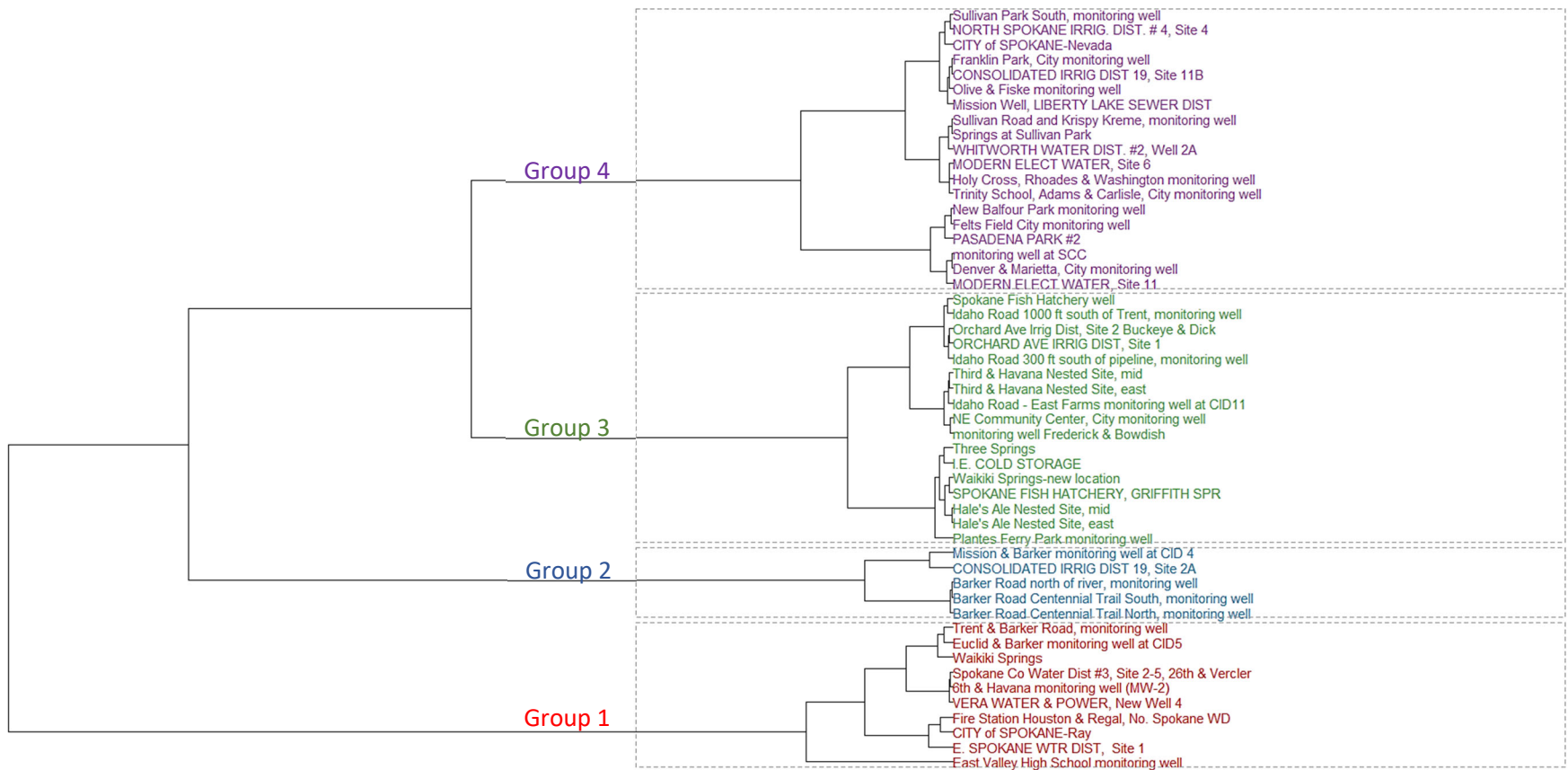
Figure 104. Cluster dendrogram grouping the Spokane Valley Rathdrum Prairie (SVRP) Aquifer monitoring locations by water quality characteristics.

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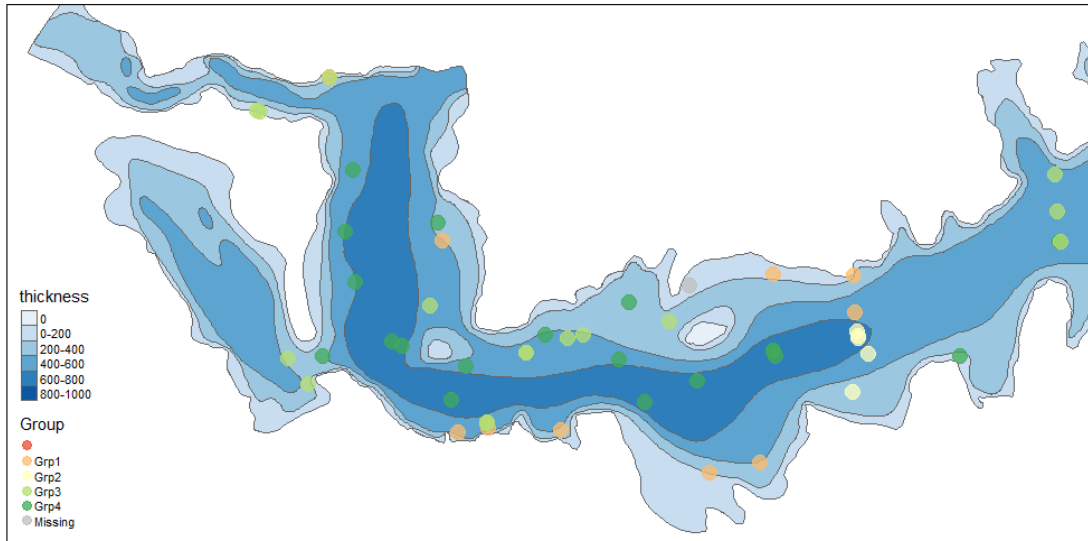Spokane County Water Resources, Dec. 2023

Figure 105. Spatial distribution of the Spokane Valley Rathdrum Prairie (SVRP) Aquifer monitoring locations by the group in which they were classified in the cluster dendrogram (Figure 104).

Groups 1, 3, and 4 contain all regional monitoring locations, which lack any influence from the Spokane River. These three groups generally have higher concentrations of major ions, nitrates, and arsenic. However, the concentrations of these constituents are the greatest in Group 1, followed by Group 3 and then Group 4 due to the influence of aquifer thickness, sewer installation, and presence of confining layers.

Group 1 contains regional monitoring locations at or near the margin of the aquifer where the aquifer is thinnest (Figure 105). This group also includes three non-sewered monitoring locations: two along Barker Road and one in North Spokane. This indicates groundwater at sewered sites where less groundwater is available to provide for dilution has similar chemistry as sites in non-sewered areas.

Group 3 contains monitoring locations closer to the main body of the aquifer than those in Group 1. This group also contains the four locations on Idaho Road outside of the sewer service areas. The Idaho Road sites are the furthest upgradient and within the main body of the aquifer, which allows them to be considered "background" for the other monitoring sites. For this reason, it makes sense that these sites are grouped with sites that do not have the highest concentrations of constituents even though they are located outside of the sewer service area.

Group 4 contains monitoring locations within or near the main body (or thickest part) of the aquifer. The only non-sewered location included in Group 4 is the North Spokane Irrigation District Site 4 well, which is completed beneath a confining layer. This indicates the confining layer is protective of groundwater quality such that the groundwater in the confined aquifer underlaying a non-sewered area has similar chemical composition as sewered sites where large amounts of groundwater can provide for dilution of chemical constituents.

	Group 1	Group 2	Group 3	Group 4

Table 19. Summary of the characteristics of each grouping of the Spokane Valley Rathdrum Prairie (SVRP) Aquifer monitoring locations resulting from the hierarchical classification analysis based physical and water quality attributes. Aquifer thickness, depth to water, well depth, and all water quality parameter values are the median measurements calculated by group.

	Group 1	Group 2	Group 3	Group 4
Number of sites	10	5	17	19
% of sites	19.61	9.80	33.33	37.26
Characteristics				
Source water	Regional	River/ Transitional	Regional	Regional
Aquifer thickness (ft)	255.08	576.34	433.94	490.18
Depth to water* (ft)				
Well depth* (ft)	125.0	97.0	118.2	148.2
# Purveyor wells	4	1	4	8
# Monitoring wells	5	4	10	10
# Springs	1	0	3	1
# Non-sewered sites	3	0	4	1
based on monitoring wells only				
Water Quality				
Temperature (C)	11.55	12.46	11.33	12.10
pH	7.64	6.97	7.79	7.91
Dissolved Oxygen (mg/L)	9.01	7.55	8.89	7.96
Conductivity (uS/cm)	387.05	58.00	302.00	240.00
Calcium (mg/L)	48.55	6.13	34.85	27.90
Chloride (mg/L)	10.98	1.47	5.24	3.31
Magnesium (mg/L)	18.02	1.86	14.50	11.45
Potassium (mg/L)	2.81	0.90	2.14	1.85
Sodium (mg/L)	7.96	2.07	4.45	3.11
Sulfate (mg/L)	16.10	4.24	14.20	10.70
Nitrate (mg/L)	2.97	0.22	1.63	1.12
Total Phosphorus (mg/L)	0.01	0.01	0.005	0.005
SRP (mg/L)	0.0085	0.008	0.004	0.003
Arsenic (mg/L)	0.0036	0.0	0.0028	0.0028
Zinc (mg/L)	0	0.0104	0	0

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9.1.2. Principal Component Analysis

The PCA identified five Principal Components that explain ~85 percent of the data's variability. Each component represents different aquifer characteristics, hydrogeochemical processes, and/or pollution sources influencing groundwater quality as summarized in Table 20.

Principal Component	% of variance	Cumulative % of variance	Loadings	Groundwater Influences
Table 20. Principal Components (PC) in order of the percent (%) of the groundwater data variance explained, including the loadings of the major contributing parameters and the interpretation of groundwater influences driving each PC.				
PC1 Conductance factor	36.00	---	Conductivity (0.84), K (0.98), Na (0.90), Sulfate (0.85), Ca (0.73), Mg (0.73)	Groundwater conductivity and ion concentrations modified by accumulation/dilution
PC2 Geochemical/ Sewer Factor	28.41	64.41	DO (0.79), NO3 (0.66), Ca (0.60), pH (0.56), As (0.56); Mn (-0.79), Fe (-0.78), Total P (-0.75)	Redox and sorption processes, and their influence on water quality; specifically, elements sensitive to these processes such as nitrate (NO3), arsenic (As), manganese (Mn), iron (Fe), and total phosphorus. Septic system discharge is a secondary influence for the nitrate loading.
PC3 Zinc Factor	8.92	73.33	Zn (0.68), pH (-0.68)	Sources of zinc (Zn); Spokane River influence; sorption processes influencing zinc transport/fate
PC4 Temperature Factor	6.09	79.42	Temp (0.77)	Influences leading to warmer groundwater, e.g. Spokane River, urban areas, longer residence time
PC5 Copper Factor	5.45	84.87	Cu (0.80)	Sources of copper (Cu), e.g. purveyor wells, wells with steel casing, and the Spokane River

The first principal component (PC1) consists of positive loadings for conductivity and most of the major ions. Groundwater naturally dissolves minerals from the subsurface materials, some of which disassociate in water as ions (charged particles). The major ions (calcium, chloride, magnesium, potassium, sodium, and sulfate) come from minerals and salts abundant within soil and rocks. The concentration of ions in the groundwater directly affects its conductivity: the greater the ion concentration, the greater the conductivity. PC1 recognizes this relationship, since all the loadings are positive. For this reason, PC1 is considered the conductance factor.

The second principal component (PC2) includes positive loadings of dissolved oxygen, nitrate, calcium, pH, and arsenic and negative loadings of manganese, iron, total phosphorus, and fluoride. PC2 can be primarily interpreted as the influence of redox reactions and adsorption processes on water quality in the aquifer. Redox reactions are driven by dissolved oxygen levels and adsorption is driven by pH levels. The positive loading of both dissolved oxygen and pH suggests oxic-alkaline conditions are the prevailing

geochemical controls. Given the other loadings, PC2 recognizes how these redox-sorption conditions control various other parameters. Secondarily, PC2 accounts for the influence of septic system discharge since nitrates have a large positive loading and these do not have a natural source in the aquifer.

The third principal component (PC3) is characterized by a positive loading for zinc and a negative loading for pH. Therefore, PC3 is driven by inputs of zinc into the aquifer. The mobility of zinc in groundwater is controlled by adsorption processes regulated by pH levels. As a cation, zinc is more mobile in acidic conditions and tends to adsorb to aquifer sediments at more alkaline pH levels. PC3 recognizes this inverse relationship between zinc and pH and is considered the zinc factor.

The fourth principal component (PC4) is dominated by groundwater temperature. The locations with positive PC4 scores generally have higher groundwater temperatures (median >12C) and are primarily located in the western half of the SVRP (Figure 108). Therefore, it is likely that PC4 is temperature driven with chromium. (e.g. basalt) (e.g. industry).

The fifth principal component (PC5) is dominated by copper. Though copper can be controlled by adsorption processes like other metals, the loadings do not indicate an influence from pH. In fact, copper tends to have complete absorption at pH levels typical in the aquifer, which reduces its presence in groundwater. This suggests PC5 is driven by a source(s) of copper that may not be affected by adsorption. Many of the locations with positive PC5 scores are purveyor wells. It is possible that the copper is being introduced via the piping/infrastructure of the purveyor wells.

9.1.3. Drivers of Water Quality

The PCA combined with the hierarchical classification provides insight regarding the influences on water quality. Plots of the monitoring sites based on their scores for the first three principal components is a way to assess similarities or differences among individual sites and among their assigned groups from the hierarchal classification. A three-dimensional and several two-dimensional plots are provided for visualization. The first three principal components are used because they account for most of the variation in the site data (Table 20).
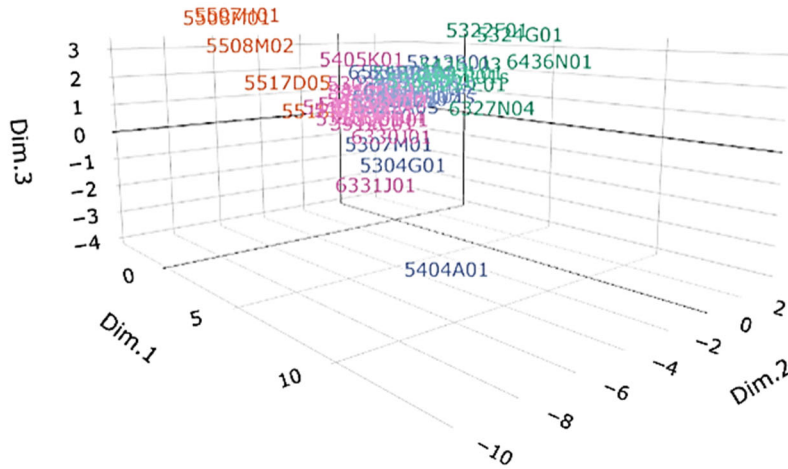
Figure 106. Three-dimensional plot of the 51 monitoring locations along the first three principal components colored by their groups assigned in the hierarchical classification (Figure 104). Dimension (Dim.) is equivalent to Principal Component (PC) (e.g., Dim.1 is PC1).
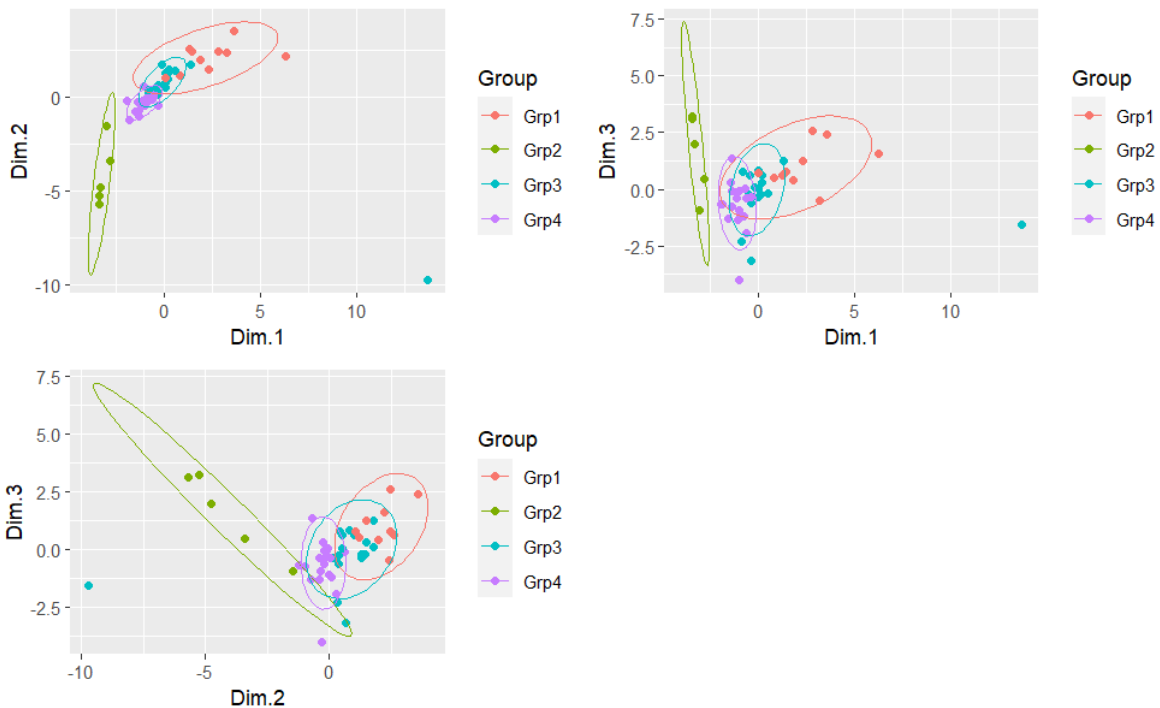

Figure 107. Two-dimensional plots of the 51 monitoring locations along the first three principal components colored by their groups assigned in the hierarchical classification (Figure 104), including a 95 percent confidence level. Dimension (Dim.) is equivalent to Principal Component (PC) (e.g., Dim.1 is PC1).

All the regional groups (Groups 1, 3 and 4) have some overlap in the PCA plots, indicating that these groups are generally influenced by the same processes but to a slightly different degree. Sites in Group 2 (river-influenced groundwater) are separated from the other groups in the PCA plots (Figures 106 and 107). This confirms the Spokane River has a distinguishable effect on groundwater quality along the losing reach at Barker Road.

River-influenced groundwater (Group 2) is generally defined by negative scores for PC1 and PC2 with positive scores PC3 (Figure 107). The negative scores for PC1 (conductance factor) are indicative of the low conductivity and ion concentrations measured at these sites. The spread along PC1 among sites within Group 2 accounts for the river-influenced groundwater (5507H01, 5508M01, and 5508M02) having lower conductivity and major ion concentrations than the transitional sites (5507D01 and 5518R01).

PC2 and PC3 generate more spread among the sites within Group 2 than PC1, indicating these factors are responsible for more of the variation within the group (Figure 107). The gradient along both PC2 and PC3 is due to the shift from acidic conditions in river-influenced groundwater (5507H01, 5508M01, and 5508M02) to the alkaline conditions at the transitional sites (5507D01 and 5518R01) and regional sites, along with the associated responses in the affected parameters. For example, under PC2 arsenic is not found in the river-influenced groundwater due to adsorption under acidic conditions. Under PC3, zinc is detectable in the river-influenced groundwater but not in the transitional sites due to adsorption under alkaline conditions. The gradient along PC2 is also impacted by septic influence. The river-influenced groundwater has lower levels of nitrates due to earlier sewer installation than the transitional sites.

The regional groups have a greater spread across PC1 (conductance factor), indicating this is responsible for most of the variance within and between the three groups (Figure 107). The conductance factor has the strongest influence on Group 1 (all sites have positive PC1 scores), some influence on Group 3 (mix of positive and negative PC1 scores) and the least influence on Group 4 (all sites have negative PC1 scores). This gradient is primarily based on conductivity and ion concentrations, which are regulated by the amount and flow of groundwater.

Sites in Group 1 and Group 3 with positive scores along PC1 are located more on the edge of the aquifer where major ions that increase conductance tend to accumulate (Figure 108). At the margins of the aquifer, the aquifer sediments are thinner and groundwater moves slower. This allows ions to accumulate in these locations, resulting in higher conductivity. In the main body of the aquifer, where the aquifer is thicker and groundwater moves faster, ion concentrations are diluted by the larger volume of groundwater.

PC2 accounts for less variation within the regional groups than it did for the river-influenced group (Figure 107). This is because sites within the regional groups do not vary in geochemical conditions; all regional sites have oxic, alkaline groundwater. Therefore, the septic discharge aspect of PC2 plays a larger role in regional groundwater quality. Most sites in Groups 1 and 3 have positive scores in PC2 (Figure 108). These two groups include the majority of the non-sewered sites and sites that have higher nitrate levels, including those impacted by upgradient inputs (Table 19). Most sites in Group 4 have negative PC2 scores and generally have lower nitrate levels. The only non-sewered site included in this group is the confined aquifer sampled at the North Spokane Irrigation District well (Table 19).

The regional groups have even less variation across PC3 (Figure 107). Zinc is generally not detectable in the aquifer because it is more mobile under acidic conditions. Most sites in Group 1 have positive PC3 scores, and most sites in Groups 3 and 4 have negative PC3 scores. Of the regional sites that have positive scores, only three have median concentrations of zinc at detectable levels. The other regional sites with positive PC3 scores generally have a pH below 8.0, which is the pH level above which zinc has complete adsorption. Therefore, a positive PC3 score appears to recognize groundwater locations that might be sensitive to contamination from zinc.

One site, the monitoring well at Plantes Ferry (5404A01), plots far outside of the 95 percent confidence limits of its group and is separate from any other site on the plot. This indicates the water quality of the confined aquifer sampled from the Plantes Ferry well is unique. It is the only location defined by a positive PC1 scores and negative PC2 and PC3 scores. The negative PC2 score is due to the confined aquifer's anoxic, acidic conditions and non-detectable levels of nitrates. The anoxic groundwater promotes denitrification in addition to the confining layer likely providing some protection from nitrogen transport from septic system discharge. In addition, the anoxic, acidic conditions also allow for the high levels of manganese, iron and phosphorus accounted for in PC2.
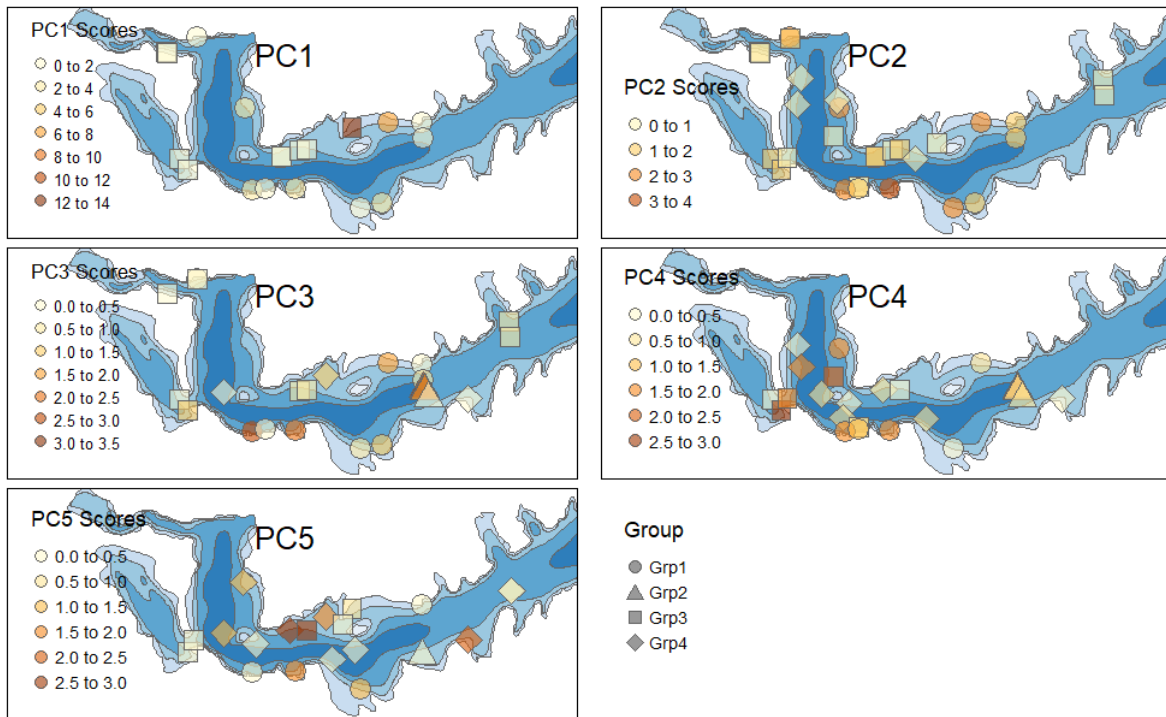

Figure 108. Spatial distribution of sites with positive scores for each of the principal components by group.

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