Five-Year Data Review of Groundwater Monitoring Requirements Associated with Coal Bed Natural Gas Produced Water Impoundments

North District Groundwater Section
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1.0 INTRODUCTION

Production of Coal Bed Natural Gas (CBNG) in the Powder River Basin of Wyoming began in the mid-1980s. CBNG production involves pumping water out of a producing coal seam in order to decrease pressures and thus facilitate desorption of the gas. A byproduct of CBNG production is produced water. Several options are available for management of the water including, but not limited to: underground injection wells, surface and sub-surface irrigation, direct surface discharge, and discharge into unlined infiltration impoundments. According to statistics compiled by the Wyoming Department of Environmental Quality, Water Quality Division (WDEQ/WQD) staff, discharges to infiltration impoundments accounted for approximately 64% of the CBNG produced water in 2008 (Figure 1). The focus of this study is the potential for leachate to impact shallow groundwater beneath unlined infiltration impoundments.

The WDEQ/WQD, Wyoming Pollutant Discharge Elimination System (WYPDES) Program regulates effluent water quality that is discharged to the infiltration ponds. As part of the permitting process, WYPDES also requires the operator to obtain approval from the WDEQ/WQD Groundwater Section before discharging produced water to an impoundment. The basis for the groundwater monitoring program is that the application of water to an oxidized vadose zone containing soluble salts may result in the mobilization and leaching of naturally occurring salts into shallow groundwater aquifers.

The WDEQ instituted groundwater investigation and monitoring requirements in August, 2004. The objective of this project is to review all of the compliance monitoring data submitted through calendar year 2009 and to determine if the requirements of the current

compliance monitoring plan are appropriate to provide protection to shallow groundwater aquifers in the Powder River Basin.

2.0 BACKGROUND

2.1 Project Setting

The structural Powder River Basin of Wyoming is a Late Cretaceous to early Tertiary age asymmetrical syncline that extends from East-central Wyoming into southern Montana (Figure 2). It is bounded on the south by the Laramie Range and the Hartville uplift, on the southwest by the Casper arch, on the west by the Bighorn Mountains, and on the east by the Black Hills uplift. The axis of the basin is located near its western margin and trends from southeast to northwest (Flores, 2004). The project location does not include the portion that extends into Montana.

2.1.1 Geology

The geologic formations of interest in this study are the Quaternary-age unconsolidated deposits, Eocene-age Wasatch Formation and the Paleocene-age Fort Union Formation. The Wasatch Formation is exposed at the surface in the majority of the Powder River Basin, with the exception of the basin margins where the Fort Union Formation is exposed. The shallow valleys throughout the basin are typically filled with recent unconsolidated alluvial, colluvial, and eolian material.

The depositional environment in which the Wasatch and Fort Union formations were deposited was a dynamic northwest flowing fluvial system that included braided, anastamosed, and meandering streams in the basin center that were fed by alluvial fans at the basin margins (Flores, 2004). The Wasatch and Fort Union Formations in the study area are primarily

comprised of sediments including fine grained claystone and siltstone, fine to coarse grained sandstone, and coal. As a result of the dynamic nature of the depositional system, the strata of the Wasatch and Fort Union Formations are extremely discontinuous and heterogeneous.

2.1.2 Hydrogeology

Groundwater in the Wasatch Formation generally occurs in coal seams, in discontinuous sandstone lenses, and in shallow alluvial sediments. Local groundwater flow direction, gradient, and hydraulic properties are highly variable throughout the Wasatch and Fort Union Formations. Regional hydraulic conductivity is extremely slow due to the discontinuity of the sandstone beds (Flores, 2004). Groundwater quality is also highly variable in the shallow aquifers. In general, groundwater in sandstone and siltstone is calcium-sulfate or calcium-bicarbonate-type, while groundwater in coal is sodium-bicarbonate-type (Bartos and Ogle, 2002).

2.1.3 Soils

The soils of the Powder River Basin contain naturally occurring soluble salts which derive from the minerals that make up the soils and the exposed rocks in the area (Richards, 1969). During the process of chemical weathering, these salts are released and become soluble. The salts are then redistributed throughout the soil via surface water and groundwater. Because the Powder River Basin receives little precipitation, the salts may not be transported deep into the soil because much of the precipitated water evaporates and leaves the salts behind (Richards, 1969). The utilization of unlined infiltration pits for disposal of CBNG produced water may facilitate the flushing of the salts within the subsurface.

2.2 Current Compliance Monitoring Program Requirements

CBNG operators in the Powder River Basin of Wyoming have been monitoring groundwater and collecting data since new policy took effect in August 2004. Because CBNG development and the associated impacts from water management were relatively new at the time, current policy was based on very little empirical data.

Current approval from the WDEQ/WQD Groundwater Section consists of either a groundwater monitoring exemption or a groundwater compliance monitoring plan that requires a Water Quality Rules and Regulations, Chapter 3 Permit to Construct (permit). The permitting requirements are based on the quality of the underlying aquifer(s). In accordance with Water Quality Rules and Regulations, Chapter 8, groundwater is classified in order to apply standards to protect water quality as follows: Class I (domestic use), Class II (agricultural use), Class III (livestock use), and Class IV (industrial use).

If no groundwater is encountered to the required depth of investigation during the initial drilling program, the operator can request a groundwater monitoring exemption from the WQD. Likewise, the operator can obtain an exemption if Class IV groundwater is encountered. If Class III groundwater is encountered during the initial subsurface investigation, the operator must obtain a permit and an approved compliance monitoring plan prior to discharging to the impoundment. A typical groundwater compliance monitoring plan consists of quarterly sampling of groundwater in one well at each impoundment (See Compliance Monitoring and Siting Requirements for Unlined Impoundments Receiving Coalbed Methane Produced Water; http://deq.state.wy.us/wqd/groundwater/index.asp). Under current policy, the WQD does not allow discharges to occur to produced water impoundments located over Class I and Class II aquifers.

2.3 Groundwater Investigation and Monitoring to Date

Between August 2004, and December 2009, approximately 2013 impoundments with nearly 2300 associated monitoring wells or borings were evaluated for potential groundwater impacts (Figure 3). Of the 2013 impoundments, compliance monitoring plans and permits were issued for 273 impoundments, and groundwater monitoring exemptions were issued for 1484 impoundments. Approximately 146 impoundments (with 170 associated monitoring wells) which overlie Class III groundwater are actively receiving or have received CBNG produced water and are included in this study (Figure 4). The remaining proposed sites did not receive a permit or exemption for a variety of possible reasons. Compliance data are reviewed by the WDEQ/WQD for compliance and summary statistics are calculated on a quarterly basis.

3.0 RESEARCH OBJECTIVES

The primary objective of this project is to conduct a thorough review of five years of groundwater compliance monitoring data to determine if the requirements of the current compliance monitoring plan are appropriate for protection of shallow groundwater aquifers in the Powder River Basin. A comprehensive, critical review of the analytical and hydrogeologic data is essential to evaluate current impacts to groundwater and to anticipate risks to groundwater from the continuing operation of unlined CBNG impoundments.

4.0 METHODS

The criteria examined in this five-year groundwater data review include the following:

- geologic setting of impoundments and associated monitoring wells
- hydrogeologic setting of shallow aquifers

- groundwater geochemical trend
- spatial distribution of impoundments and wells
- volume of water and duration of discharge to each impoundment

Following is a discussion of the methods used to quantify, characterize and analyze each parameter listed above.

4.1 Surface and Bedrock Geology

Surface and bedrock geology rasters at a scale of 1:100,000 were imported into a Geographic Information System (GIS) workmap for geospatial analysis. Monitoring well locations were layered on top of the geology maps. The GIS layers were used to delineate bedrock monitoring well completions and the geologic setting of each impoundment.

4.2 Hydrogeology

Three hydrogeologic settings were identified during this study. Classification was based on the thickness of low permeability material overlying the water-bearing zone, and the level to which the groundwater rises in the well casing in relation to the top of the water-bearing zone. Low permeability material are any material described as “claystone” or “shale” in the geologists’ lithology logs. For purposes of this project, the following definitions are used:

Type A (confined) aquifers are defined as having more than five feet of low permeability material overlying the water-bearing zone, and the static water level rises at least five feet above

the top of the water-bearing zone (Figure 5). The five foot cut-off is somewhat arbitrary and accounts for some inaccuracies in the boring logs and natural fluctuations of static water levels.

Type B (unconfined) aquifers are defined as having no low permeability material overlying the water bearing zone, and the static water level is either at or below the level of the top of the water-bearing zone (Figure 5).

Type C (unconfined with overlying low permeability material) aquifers are defined as having more than five feet of low permeability material overlying the water-bearing zone, and the static water level is either at or below the level of the top of the water-bearing zone (Figure 5). From a risk perspective, Type C aquifers are considered to be more 'protected' from infiltration (by the overlying material) than *unconfined* aquifers, but do not exhibit the same degree of geochemical stability as the confined aquifers, and were split into a separate category for these reasons.

Lithology and well completion logs were compiled for all 170 compliance monitoring wells (Appendix A). For each borehole, the thickness of overlying low permeability material was tabulated and recorded in an Excel spreadsheet (Appendix B). The static water level (both depth to water and static water elevation) were also recorded in Appendix B, and the difference between the depth to water and depth to the top of the water-bearing zone were calculated. Because static water level is not a constant, best professional judgment was used to ensure that the calculation was based on static water levels that were as close as possible to background conditions and just prior to the date of initial discharge.

Every effort was made to keep interpretations to a minimum and to ensure that the analyses remain as objective as possible. As a result, twelve wells did not clearly fit into one of the three hydrogeologic setting categories (for a variety of reasons, the most common of which

was a lack of an accurate boring log) and were therefore not included in any hydrogeologic setting analyses.

4.3 Geochemistry

Time-concentration plots, which illustrate trends for static water level, total dissolved solids (TDS), sulfate, and selenium were created for all 170 compliance monitoring wells (Appendix C). Four geochemical trend categories were identified, and each well was assigned to a category based on the observable trend in the time-concentration plot. For purposes of this study, the categories for geochemical trend include *stable* (Figure 6), *upward trend* (Figure 7), *flushed* (Figure 8), and *improved* (Figure 9).

Stable geochemistry is defined as having a standard deviation of less than 200 mg/L for TDS and sulfate (Figures 10 and 11). Monitoring well data that exhibit an upward trend have a standard deviation greater than 200 mg/L for TDS and sulfate, and a positive slope for TDS and sulfate concentrations on the time-concentration plots, although the angle of the slope varies. Monitoring well data that exhibit a flushing trend show an increase in TDS and sulfate concentrations followed by a decrease in concentrations and typically a return to near background water quality. The degree of flushing is variable. Some trends show a sudden spike followed by a sudden drop in TDS and sulfate concentrations while other flushing trends are very subtle. The trend patterns for the data that exhibit improved water quality typically show a steady decrease in TDS and sulfate concentrations throughout the life of the well, although the angle of the slope varies. The stable category was quantified, while the remaining three are qualitative only.

4.4 Spatial Distribution

All compliance monitoring wells were plotted in a GIS layer overlying bedrock geology, topographic maps, and aerial photos. Wells were symbolized by geochemical trend and were plotted to examine relationships between geographic and geologic setting of the monitoring wells and impoundments with changes in groundwater quality.

4.5 Discharge Duration

CBNG operators are required by permit to report the date that each reservoir initially receives discharge to the WDEQ/WQD Groundwater Section. Although it is not implied that an impoundment receives continuous discharge, for the purpose of this study, discharge duration was simplified to the number of months elapsed since the initial discharge date.

4.6 Analysis

After details for the above parameters were compiled, plotted, and analyzed, a comprehensive analysis was conducted which accounted for relationships among geochemical trend and geology, hydrogeologic setting (including thickness of low permeability material, depth to water-bearing zone, and pressure head), location, and time in operation.

5.0 RESULTS AND DISCUSSION

The majority of the effort put into this project was dedicated to data compilation, hydrogeologic and geochemical characterization, GIS mapping, and analysis based on aquifer and geochemical classifications.

Final products of this project include:

- a compilation of all compliance monitoring well completions and borehole logs (Appendix A),
- a database containing well completion, lithology, discharge duration, geochemical trend, and other pertinent information for each compliance monitoring well (Appendix B),
- time-concentration plots of TDS, sulfate, selenium and static water level for the life of each compliance monitoring well (Appendix C), and
- a GIS workmap detailing well location, geochemical trend, and spatial and geologic setting.

Following is a discussion of the results of this groundwater data review.

5.1 Surface and Bedrock Geology

Of the 170 monitoring wells that were studied, 34 are completed in unconsolidated or alluvial sediments, 133 are completed in bedrock, and logs are not available for 3. Of the 133 bedrock wells, 94 are screened across sandstone, 24 across coal, 7 across siltstone, and 8 are screened across two or more lithologies. Of the bedrock wells, 44 are completed in the Fort Union Formation and 89 are completed in the Wasatch Formation, as determined by well location relative to surficial geology (Section 4.1, Figure 4).

5.2 Hydrogeology

The distribution of hydrogeologic settings for all compliance monitoring wells is as follows: 67 Type A (confined), 70 Type B (unconfined) and 21 Type C (unconfined with overlying low permeability material) (Figure 12, Table 1). As mentioned before, twelve wells did not clearly fit into any category for a variety of reasons including, but not limited to, the absence of an adequate lithology log or well completion, or lithology logs that were not detailed enough to make a determination.

As expected, all alluvial wells fell into the Type B (unconfined) category. Several relationships in regards to mean thickness of low permeability material, mean depth to the top of a shallow aquifer, and mean depth to static water level are tabulated in Table 2. For example, the static water level is, on average, 36.4 feet *above* the top of the water bearing zone in Type A (confined) systems, and 25.5 feet *below* the top of the water bearing zone in Type B (unconfined) systems. These relationships are expected, and support our approach to defining and classifying hydrogeologic settings.

5.3 Geochemistry

Of the 170 wells that were studied (in all hydrogeologic settings), 72% (122 wells) exhibited stable groundwater chemistry, 12% (20 wells) show TDS and sulfate concentrations on an upward trend, 6% (10 wells) have flushed, and 6% (10 wells) exhibit an improvement in water quality (Figure 13, Table 1). Groundwater geochemical trend did not fit clearly into any category for 8 wells.

It is extremely important to note that the qualitative classifications are only based on *trends*, and do not in any way imply magnitude or cause of changes to groundwater quality, as these need to be examined on an individual basis.

5.4 Spatial Distribution

CBNG produced water impoundments and associated monitoring wells are scattered throughout the entire Powder River Basin, but tend to be clustered into CBNG development areas or federal plans of development (PODs) (Figure 4). Many factors including access and landowner agreement dictate the siting of CBNG produced water impoundments.

5.5 Discharge Duration and Volume

Quantifying discharge duration and volume proved to be very difficult, due to inconsistencies in discharge reporting. The Wyoming Oil and Gas Conservation Commission requires operators to report rates and volumes of produced water from each production well. Total volumes of water produced per well, therefore, are fairly accurate. However, how that water is managed (i.e., which outfalls it may be sent to at a given time) is quite variable.

While WYPDES requires reporting of daily maximum and monthly average flows at each outfall, these discharges may not accurately represent the discharge history of an individual outfall. Water from multiple wells is commonly routed and re-routed among multiple outfalls in a CBNG production area. It is common practice for companies to distribute the total volume of water pumped from a group of production wells evenly among all outfalls that are plumbed into those wells when reporting discharge volumes.

In addition, companies have different field methods for measuring flow. Some companies have continuously recording flow meters at each outfall whereas other companies measure flow once a month with a bucket and stopwatch. Measurements made with either method may be reported as daily maximum or as monthly average.

Because some companies measure discharge at the outfall while others measure discharge at the production well, and some companies continually collect data while others collect a flow reading once a month, discharge duration and volume records are highly inconsistent and can be very inaccurate. Because WYPDES combines flow data from many outfalls to estimate mass loading of electrical conductivity and sodium, they are not necessarily interested in accurate flow measurements from each outfall.

For the reasons above, discharge volumes for each impoundment were not included as part of any comprehensive analysis in this study.

5.6 Data Analyses

After all of the borehole logs and well completions were accumulated, relevant data were compiled into a database and each well was classified by geologic setting, hydrogeologic setting, and geochemical trend. The relationships between geology, hydrogeology, and changes in groundwater quality were then investigated.

Following is a discussion of each analysis. Note that each analysis investigates the importance of local geology and hydrogeology when predicting changes in groundwater chemistry.

5.6.1 Geochemical Trend and Hydrogeologic Setting

With four geochemical trend categories and three hydrogeologic settings, 12 combinations are possible. Two primary methods were used for illustrating the relationships between hydrogeology and geochemistry: 1) the distribution of hydrogeologic settings within each geochemical trend group (Figure 14), and 2) the distribution of geochemical trends within each hydrogeologic setting (Figure 15).

5.6.1.1 Geochemical Trend

Stable

Of the 122 wells that exhibit a stable geochemical trend, 50% (61 wells) are found in Type A (confined) systems, 33% (40 wells) in Type B (unconfined) systems, and 11% (14 wells) in Type C (unconfined with overlying low permeability material) systems (Figure 14, Table 1).

Upward Trend

Of the 20 wells that exhibit an upward geochemical trend, 70% (14 wells) are found in Type B (unconfined) systems, 20% (4 wells) in Type C (unconfined with overlying low permeability material systems, and 5% (1 well) in Type A (confined) systems (Figure 14, Table 1).

Flushed

Of the 10 wells that exhibit a flushed trend, 67% (5 wells) are found in Type B (unconfined) systems, 22% (2 wells) in Type C (unconfined with overlying low permeability material) systems, and 11% (1 well) in Type A (confined) systems (Figure 14, Table 1).

Improved Water Quality

Of the 10 wells that exhibit an improvement in water quality, 80% (8 wells) are found in Type B (unconfined) systems, 20% (2 wells) are found in Type A (confined) systems, and 0% (0 wells) are found in Type C (unconfined with overlying low permeability material) systems (Figure 14, Table 1).

It is not assumed that all wells that show an improvement in water quality have been influenced by infiltration of CBNG produced water. Other possible explanations for the trend are poor initial well development, a response to the end of a very long drought, or other changes in natural conditions.

5.6.1.2 Hydrogeologic Setting

Type A (confined)

Of the 67 wells that are completed in a Type A (confined) system, 91% (61 wells) exhibit stable geochemistry, 1.5% (1 wells) exhibit geochemistry on an upward trend, 1.5% (1 well) exhibit flushed geochemistry, and 3% (2 wells) exhibit improved water quality (Figure 15).

The four wells that are completed in Type A (confined) systems and exhibit unstable geochemistry warrant analysis on an individual basis because of their inconsistency with the strong trends that are evident throughout this study. A variety of possible explanations exist for the discrepancies including, but not limited to: poor well construction, poor initial well development, local structure and/or faulting, or inadequately logged borings resulting in a mis-interpretation of hydrogeologic setting.

Type B (unconfined)

Of the 70 wells that are completed in an Type B (unconfined) system, 57% (40 wells) exhibit stable geochemistry, 20% (14 wells) exhibit geochemistry on an upward trend, 11% (8 wells) exhibit improved water quality, and 7% (5 wells) exhibit flushed geochemistry (Figure 15, Table 1).

Type C (unconfined with overlying low permeability material)

Of the 21 wells that are completed in a Type C (unconfined with overlying low permeability material) system, 67% (14 wells) exhibit stable geochemistry, 19% (4 wells) exhibit geochemistry on an upward trend, 10% (2 wells) exhibit flushed geochemistry, and 0% (0 wells) exhibit improved water quality (Figure 15).

Individual investigations should also be performed for the six wells completed in Type C systems that exhibit unstable geochemical trends. Further investigation may help delineate which characteristics contribute to the distinctiveness of this category.

In general, the results of these analyses are as expected with the Type B (unconfined) aquifers exhibiting more unstable geochemistry and the majority of Type A (confined) systems showing stable geochemistry. Note that these analyses do not include discharge duration or volume, depth to groundwater, or several other relevant factors. Therefore, the relationships observed do not imply that the cause of all changes in water quality is directly attributable to infiltration of CBNG produced water.

5.6.2 Correlations between increased TDS, Sulfate and Selenium

In general, a strong correlation exists between increases in TDS and sulfate for all hydrogeologic settings (Table 3). This is expected because gypsum (calcium sulfate) is a common evaporate deposit found throughout the Powder River Basin. The dissolution of gypsum is largely accountable for increases in TDS and sulfate.

The correlation between TDS/sulfate and selenium is not as straight-forward, but patterns emerge when sites are grouped and analyzed by their hydrogeologic setting and geochemical trend (stable vs. non-stable). A very strong correlation exists between an increase in selenium and TDS/sulfate for Type B (unconfined) sites (Table 3). However, the correlation between increased TDS/sulfate and selenium does not exist for Type A (confined) settings (Table 3).

The lack of correlation, coupled with the stable nature of mid-basin, deep, Type A (confined) settings implies that infiltration of CBNG is not the cause of increased selenium in confined aquifers. Instead, the rise in selenium may be due to sampling technique, lab error, or changes in oxidation/reduction potential as a result of well installation.

As implied by the lack of correlation between increased TDS/sulfate and selenium in Type A (confined) wells, without further field investigation and analysis, one cannot assume that the cause of every change in groundwater quality is directly related to infiltration of CBNG produced water.

5.6.3 Geochemical Trend and Spatial Distribution

Wells that exhibit stable geochemistry are scattered throughout the Powder River Basin and are found in both the Fort Union Formation and Wasatch Formation and in all hydrogeologic settings (Figure 17).

Many of the wells that exhibit geochemistry on an upward trend or flushed are located in the northern section of the basin and are completed in Fort Union bedrock (Figures 18 and 19). However, several sites are located in the central portion of the basin. Each site that indicates impacts from infiltration of CBNG produced water warrants investigation on an individual basis. Some shallow aquifers fluctuate due to natural conditions. Also, faulty well construction cannot be discounted as a primary conduit for groundwater contamination at some sites.

Approximately 88% of the wells that indicate an improvement in groundwater quality are located in the northern portion of the Powder River Basin (Figure 20). Again, an explanation for changes in groundwater quality would require an individual study of each site.

5.6.4 Sites Exceeding Groundwater Quality Standards

Of 170 wells, 4% (7 wells) have ever exceeded class of use standards for TDS or sulfate and selenium, 3% (5 wells) have exceeded class of use standards for selenium only, and 3% (5 wells) have exceeded standards for TDS and sulfate only (Figure 16). Two of the selenium-only sites are located in the central portion of the basin and are completed in a Type A (confined) water-bearing zone in the Wasatch Formation. Since there are no other indicators, it is very unlikely that the cause of the increased selenium at such sites is attributable to infiltration from the overlying CBNG infiltration impoundment. On the other hand, the sites in the northern portion of the basin that have exceeded standards for TDS, sulfate and selenium are likely resultant from infiltration of CBNG produced water dissolving the in-situ salt deposits.

As of the end of the fourth quarter of 2009, 3% (5 wells) of the 170 compliance monitoring wells were out of compliance for exceeding class of use standards for sulfate and

TDS; 1.8% (3 wells) were out of compliance for exceeding class of use standards for selenium only.

6.0 CONCLUSIONS

The following conclusions are based on the analyses of the data submitted to date:

1. Groundwater in Type B (unconfined) systems is more vulnerable to changes in water quality, whether resulting from infiltration of CBNG produced water or variations in natural recharge. The results are varied with the groundwater quality in the majority of the monitoring wells remaining stable, while others show changes in groundwater chemistry, some positive and some negative.

2. Groundwater quality in mid-basin Type A (confined) wells has typically remained stable, and no Type A (confined) wells have shown an exceedance of State groundwater standards for the parameters analyzed in this study with the exception of selenium (2 wells).

3. To date, a small percentage of monitoring wells below permitted impoundments have shown changes in groundwater quality that exceed State groundwater standards. However, although this is a 5-year study, many of the impoundments have received discharge for less than 5 years. A maximum discharge duration of 6 years and a mean of 37 months may not be enough data to draw conclusions about potential changes to groundwater quality, especially in deeper geologic settings. The typical “lifespan” of a CBNG produced water impoundment is 5 to 8 years.

4. The requirements implemented by the WQD in August, 2004 have provided sufficient subsurface information to establish groundwater compliance monitoring plans for each permitted impoundment in order to protect the state's shallow groundwater resources. Based on the data analyses, a more rigorous monitoring program is not necessary at this time. However, operators may be required to install additional monitoring wells to investigate the extent of groundwater contamination that may result from the operation of the impoundment.

7.0 ONGOING AND FUTURE WORK

This study is a baseline analysis of common trends and summary statistics for five years of groundwater monitoring of shallow aquifers underlying unlined CBNG produced water impoundments. Future work may include several more detailed analyses that focus on understanding the causes for trends that became evident during this study. Future work may include:

- **Carbon Isotope Sampling and Analysis:** Research on dissolved inorganic carbon for use as a CBNG produced water tracing tool is being conducted at the University of Wyoming. The WDEQ/WQD Groundwater Section staff has begun utilizing the tool to determine whether or not produced water has reached shallow groundwater and is the cause of observable changes in groundwater quality. Case by case studies of carbon isotope work in conjunction with fate and transport analysis may prove very useful for determining risk to groundwater from overlying impoundments.

- **Shallow Geophysical Techniques**: The Groundwater Section is working with the US Department of Energy to attempt to delineate shallow groundwater plumes emanating from unlined impoundments using non-invasive geophysical (resistivity) techniques.

- **Discharge Duration Analysis**: An attempt should be made to correlate the discharge duration with geochemical trends. Discharge duration, which is simplified as the number of months an impoundment has been in operation, whether it has received continual discharge or not, will be used in a very general sense to demonstrate the locations of the earliest development and the subsequent expansion of CBNG development throughout the basin.

- **Depth to Groundwater Analysis**: Correlation of depth to water and geochemical trend will be calculated for each hydrogeologic setting.

- **Extent of Contamination Investigations**: Individual sites that showed significant water quality changes will be investigated to determine the extent of groundwater contamination. Several such studies are currently underway.

FIGURES

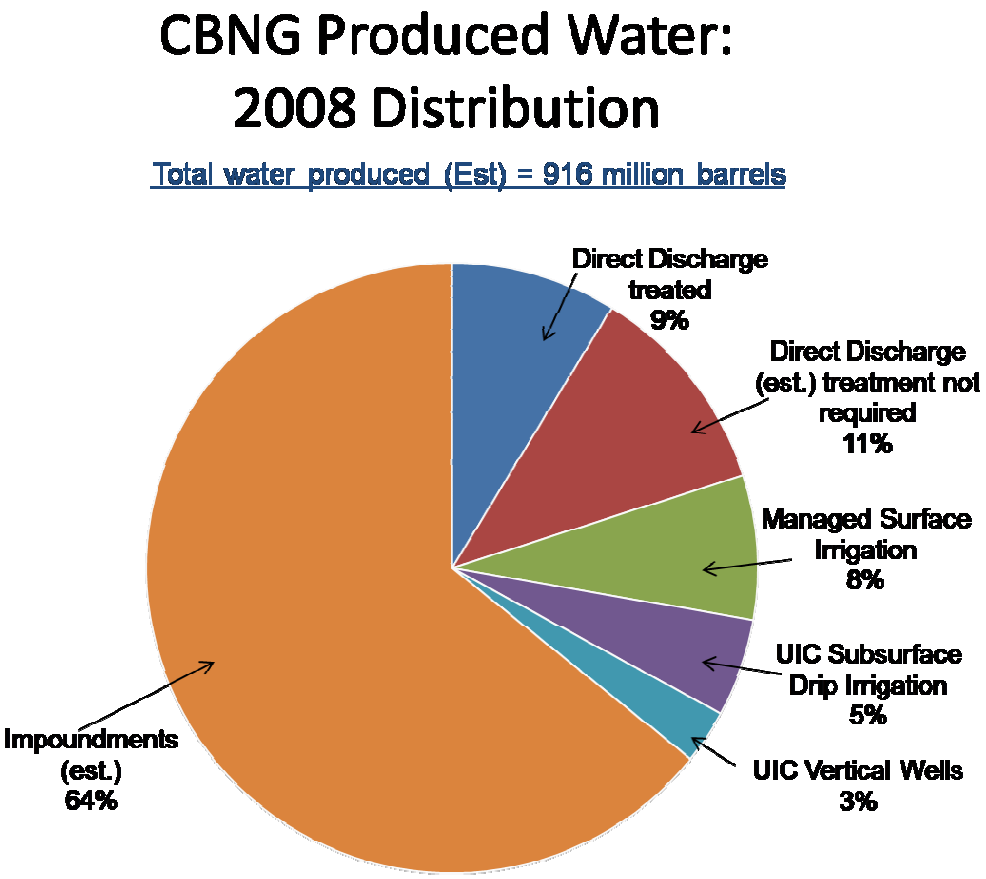

Figure 1: Distribution of CBNG produced water for calendar year 2008

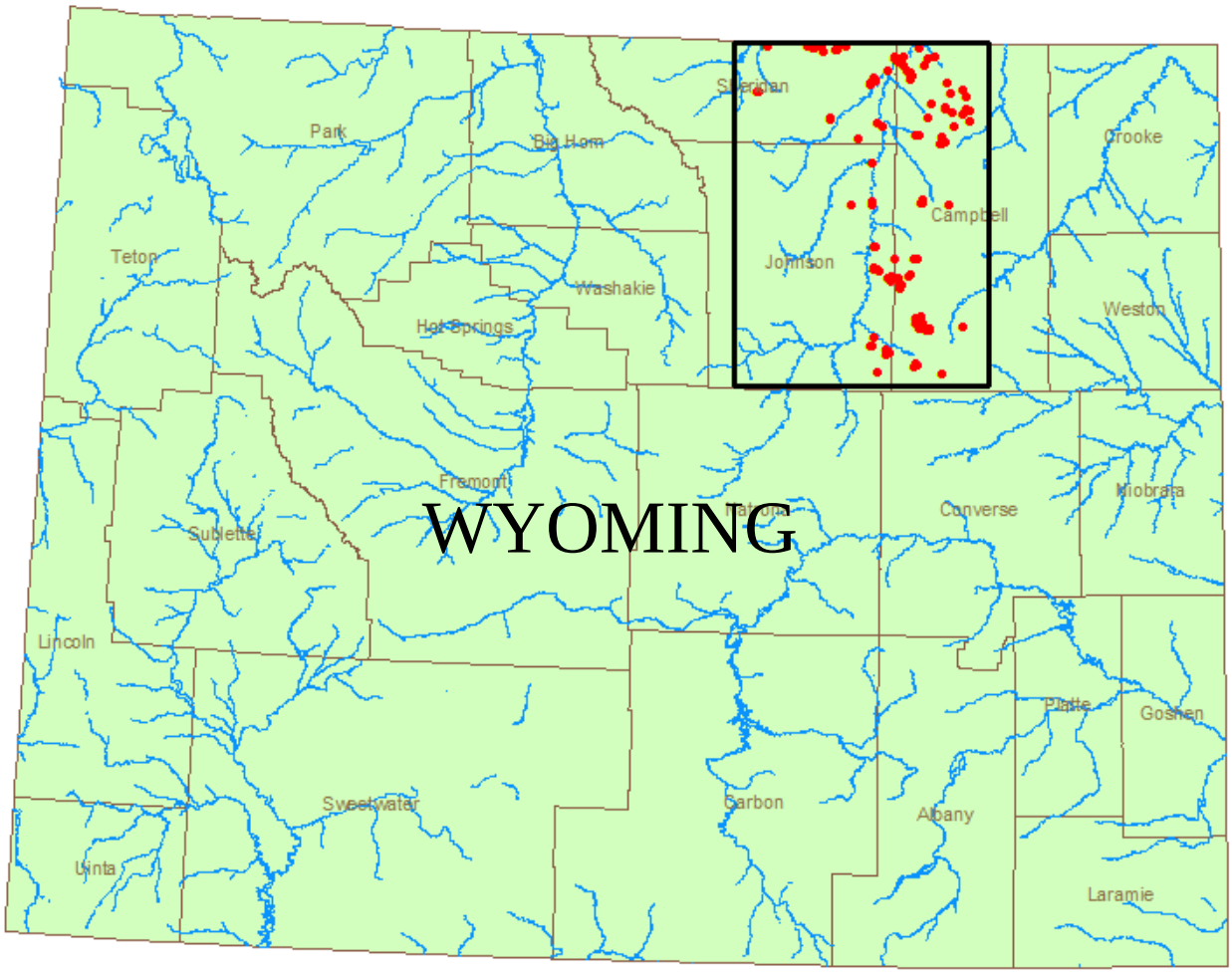

Figure 2: Project location; compliance monitoring well locations

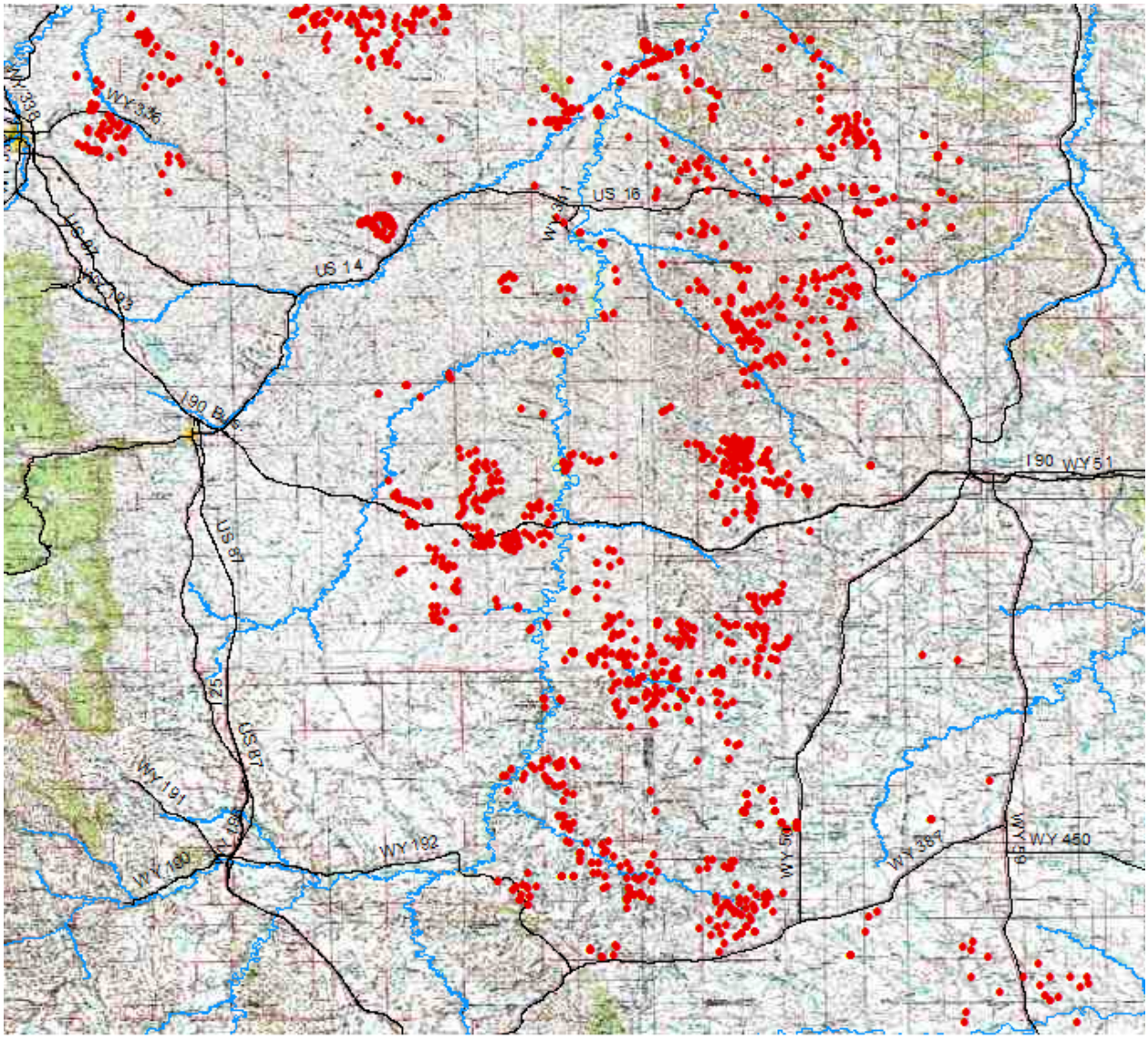

Figure 3: All sites investigated; includes exempt and permitted sites

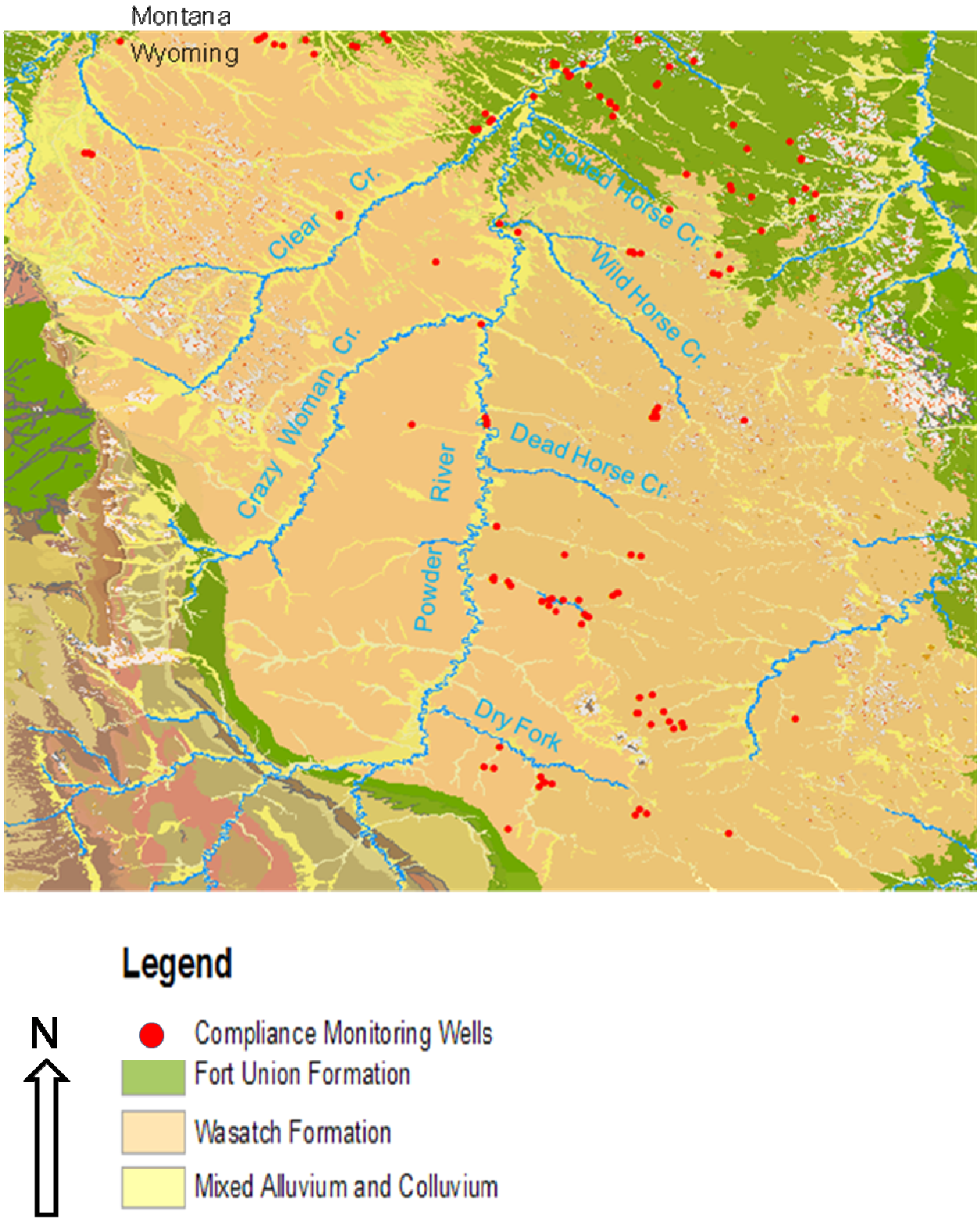

Figure 4: Compliance monitoring wells and bedrock geology

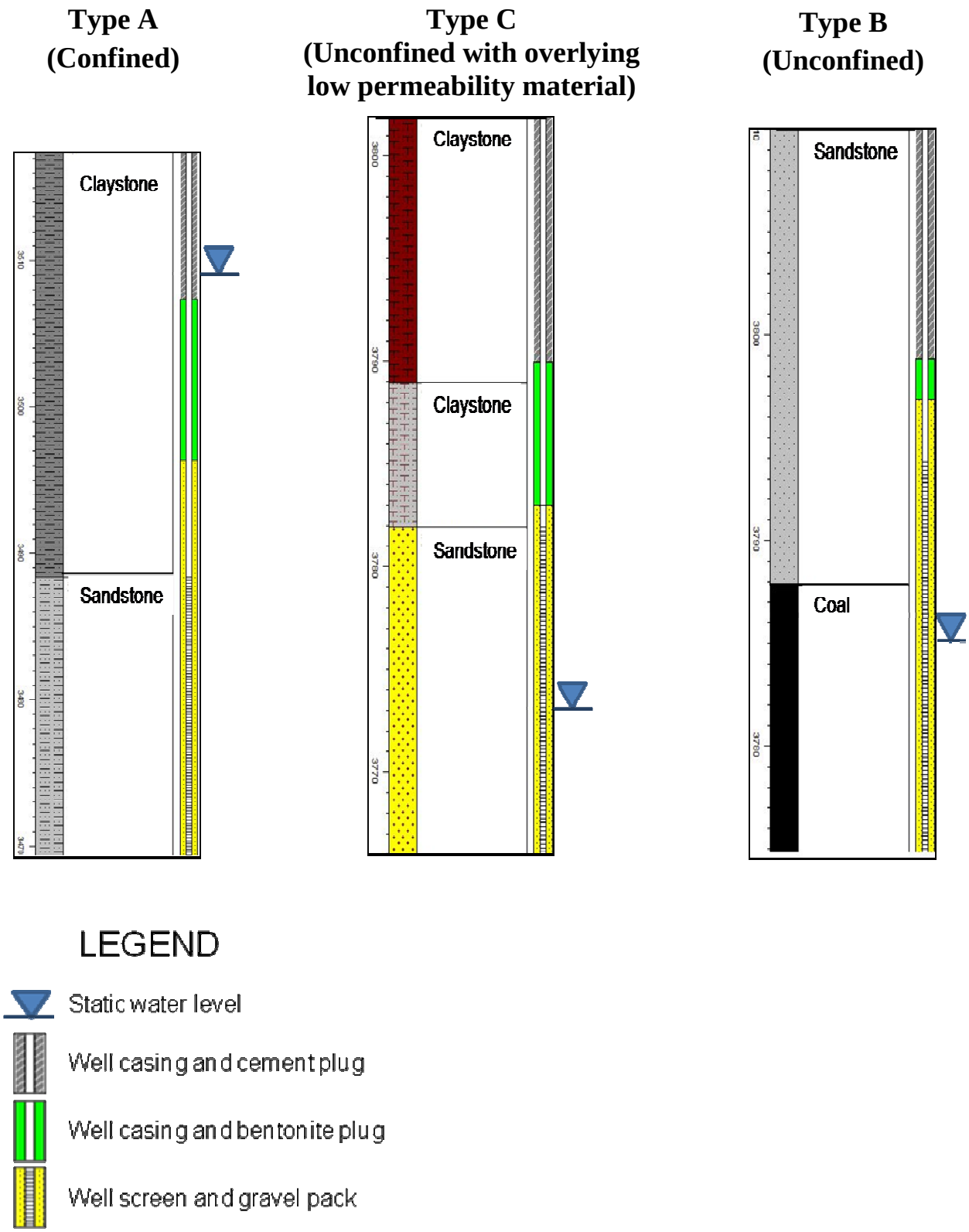

Figure 5: Example of a well completed in each hydrogeologic setting

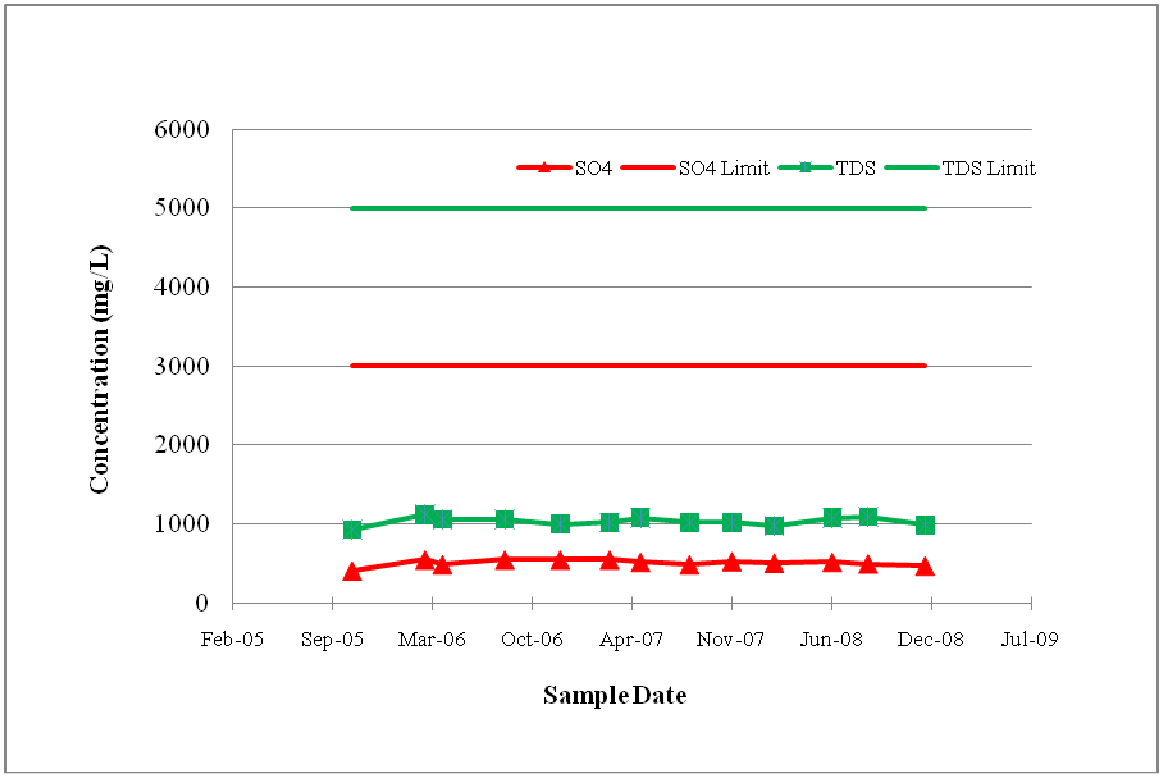

Figure 6: Example of 'stable' TDS and sulfate concentrations

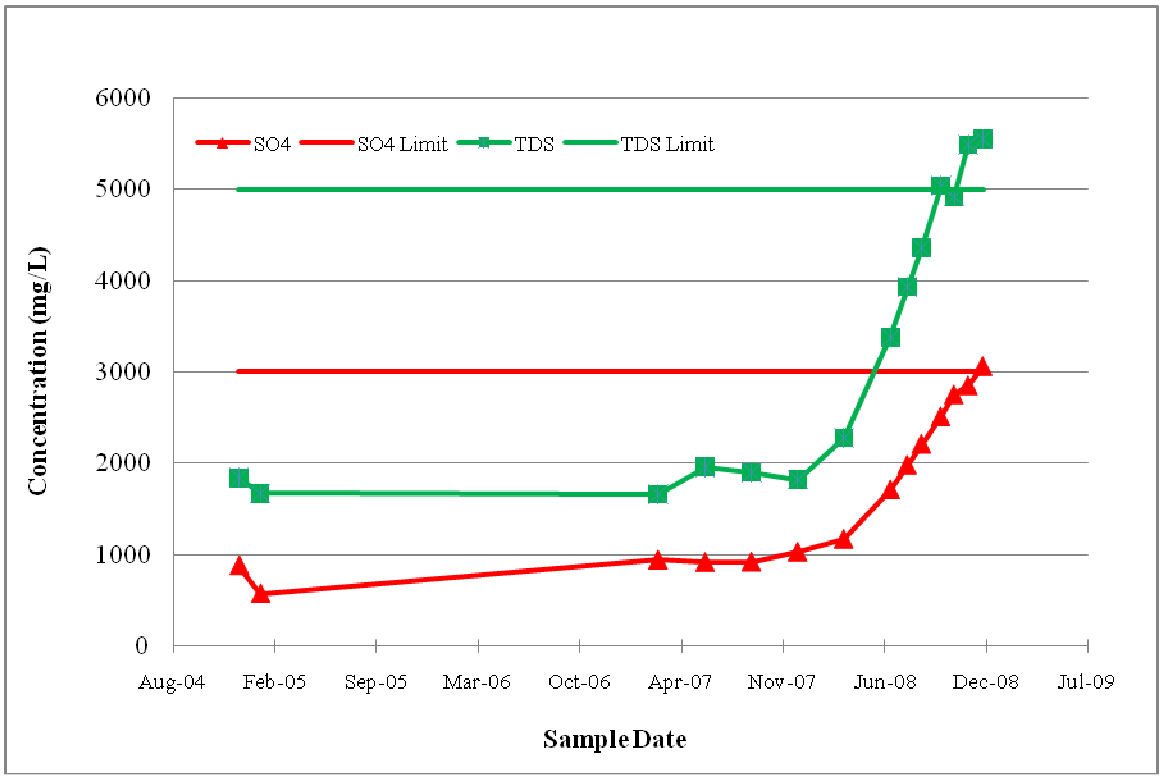

Figure 7: Example of TDS and sulfate concentrations on an 'upward trend'

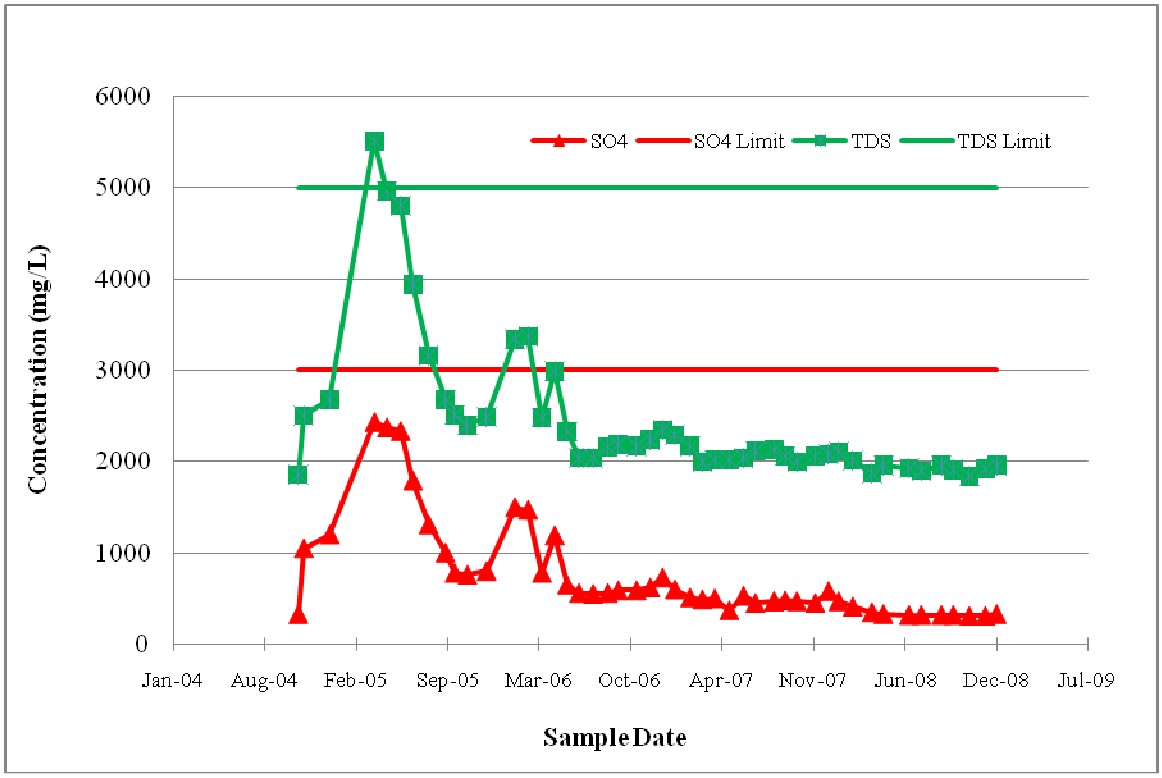

Figure 8: Example of 'flushed' TDS and sulfate concentrations

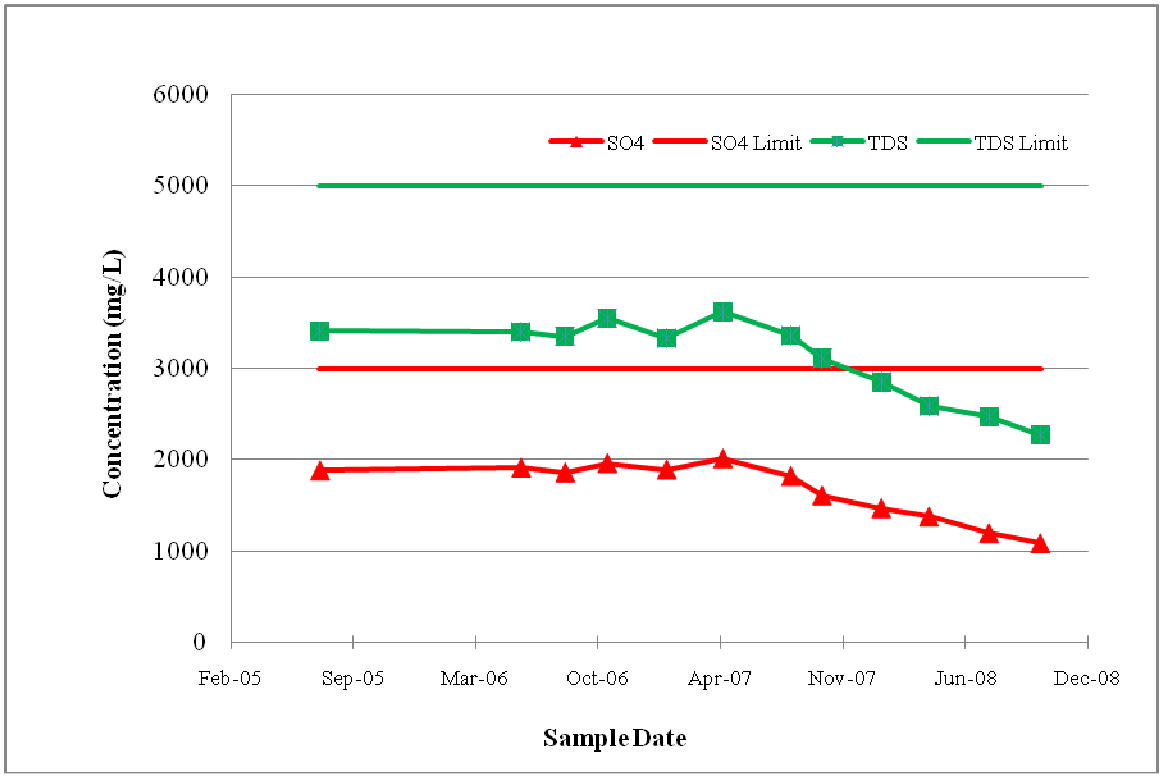

Figure 9: Example of 'improved' TDS and sulfate$_4$ concentrations

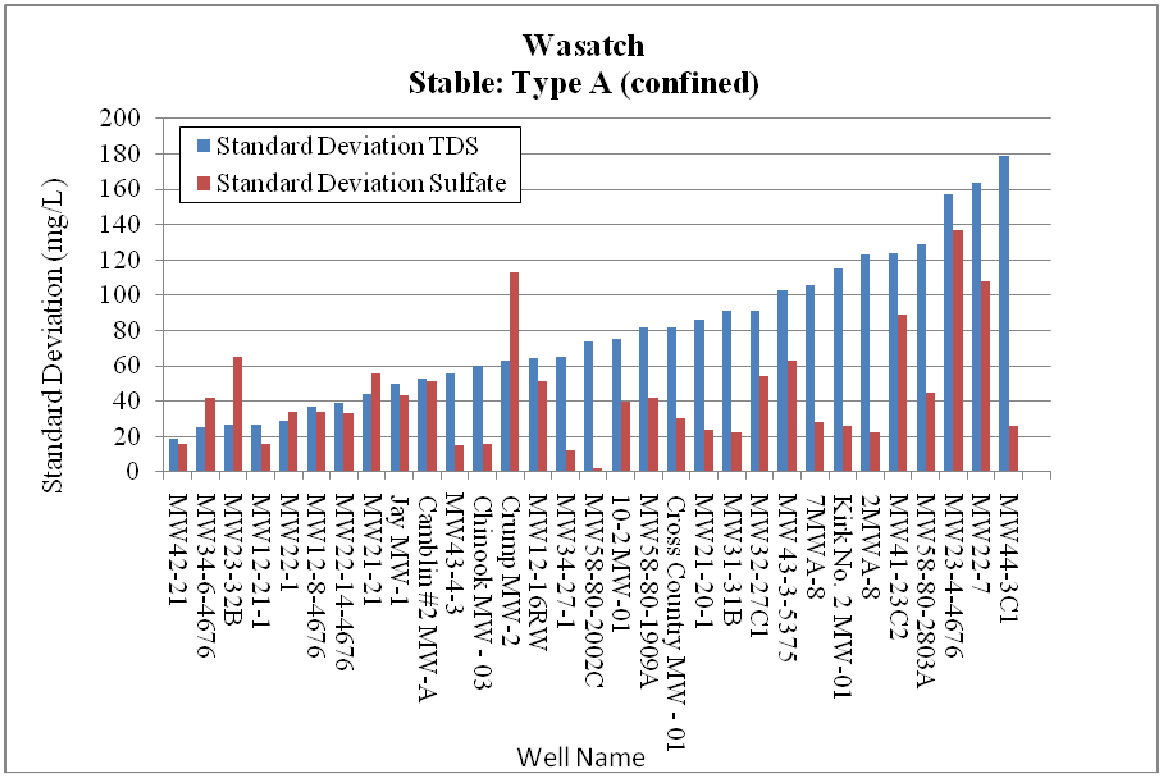

Figure 10: Standard deviation of TDS and sulfate for stable Type A (confined) wells completed in Wasatch Bedrock

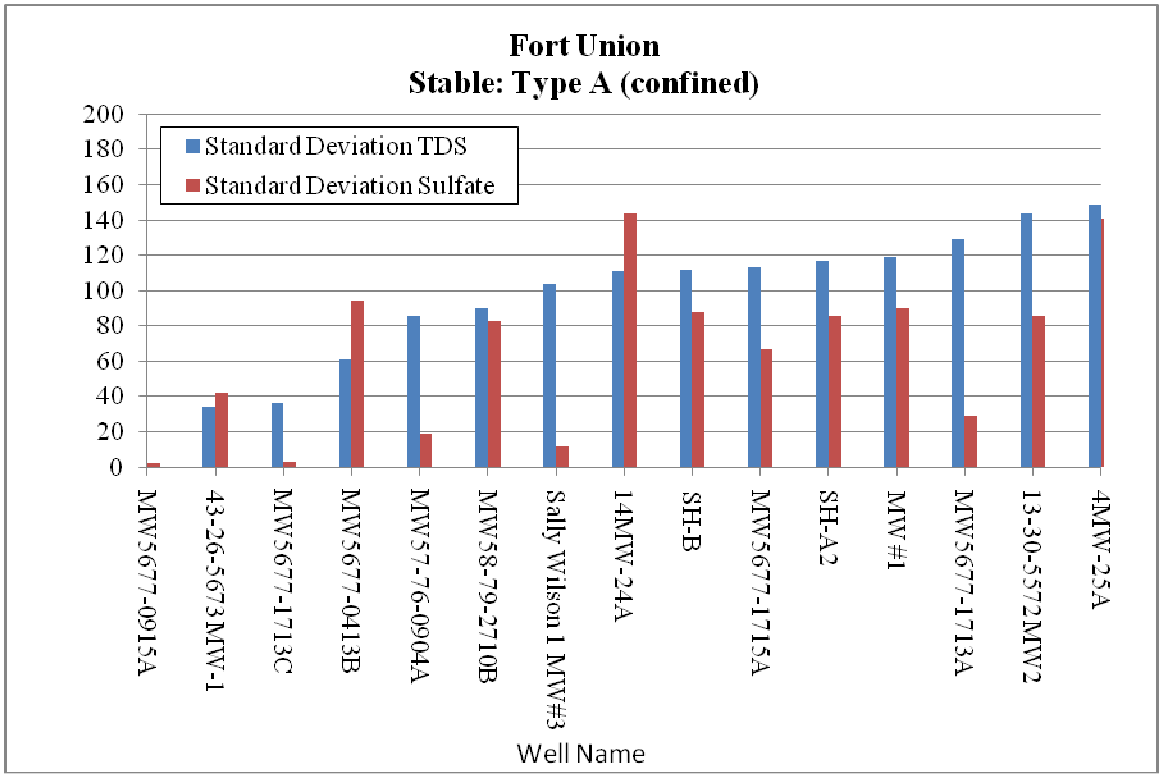

Figure 11: Standard deviation of TDS and sulfate for stable Type A (confined) wells completed in Fort Union Bedrock

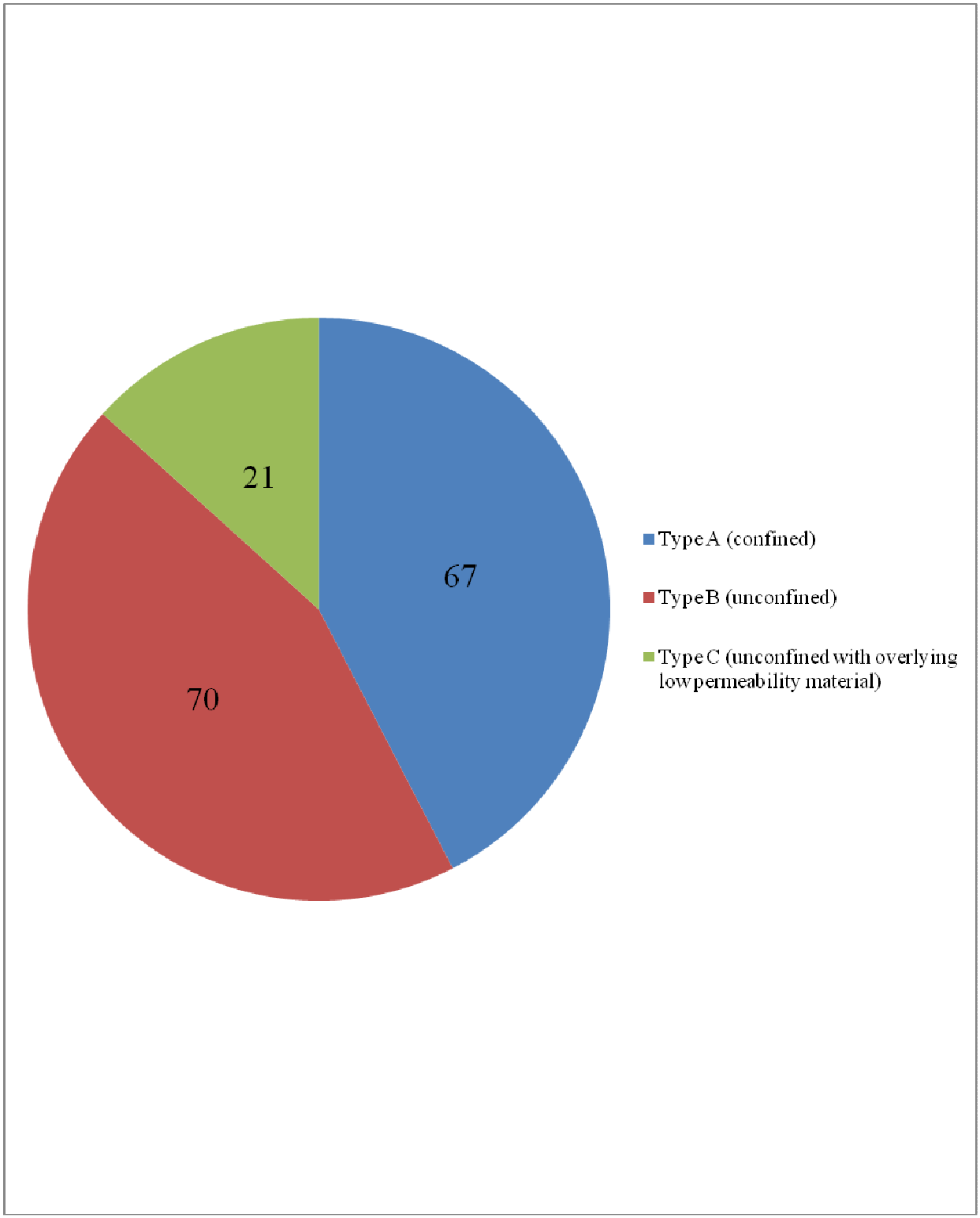

Figure 12: Number of wells completed in each hydrogeologic setting

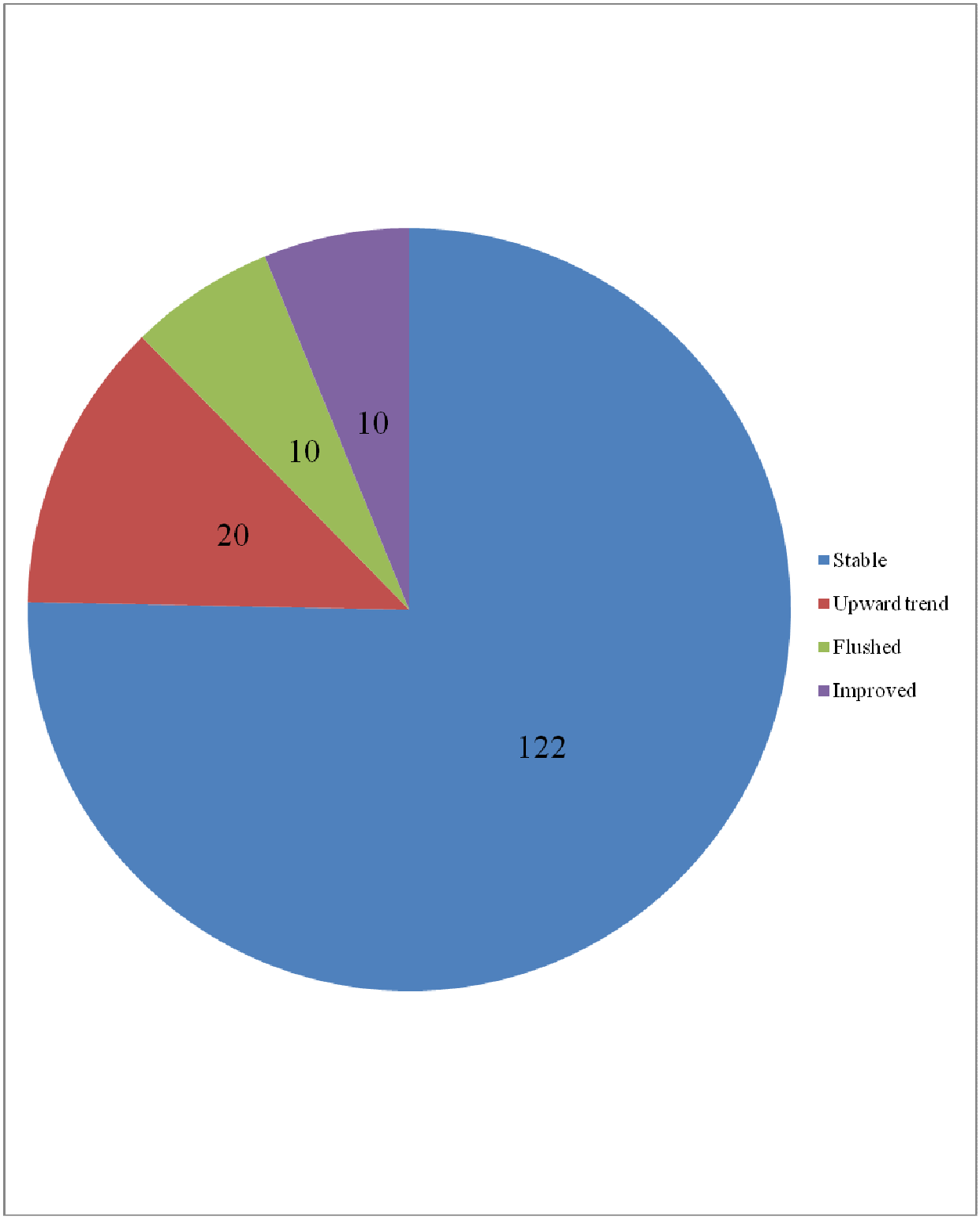

Figure 13: Number of wells that reflect each geochemical trend.

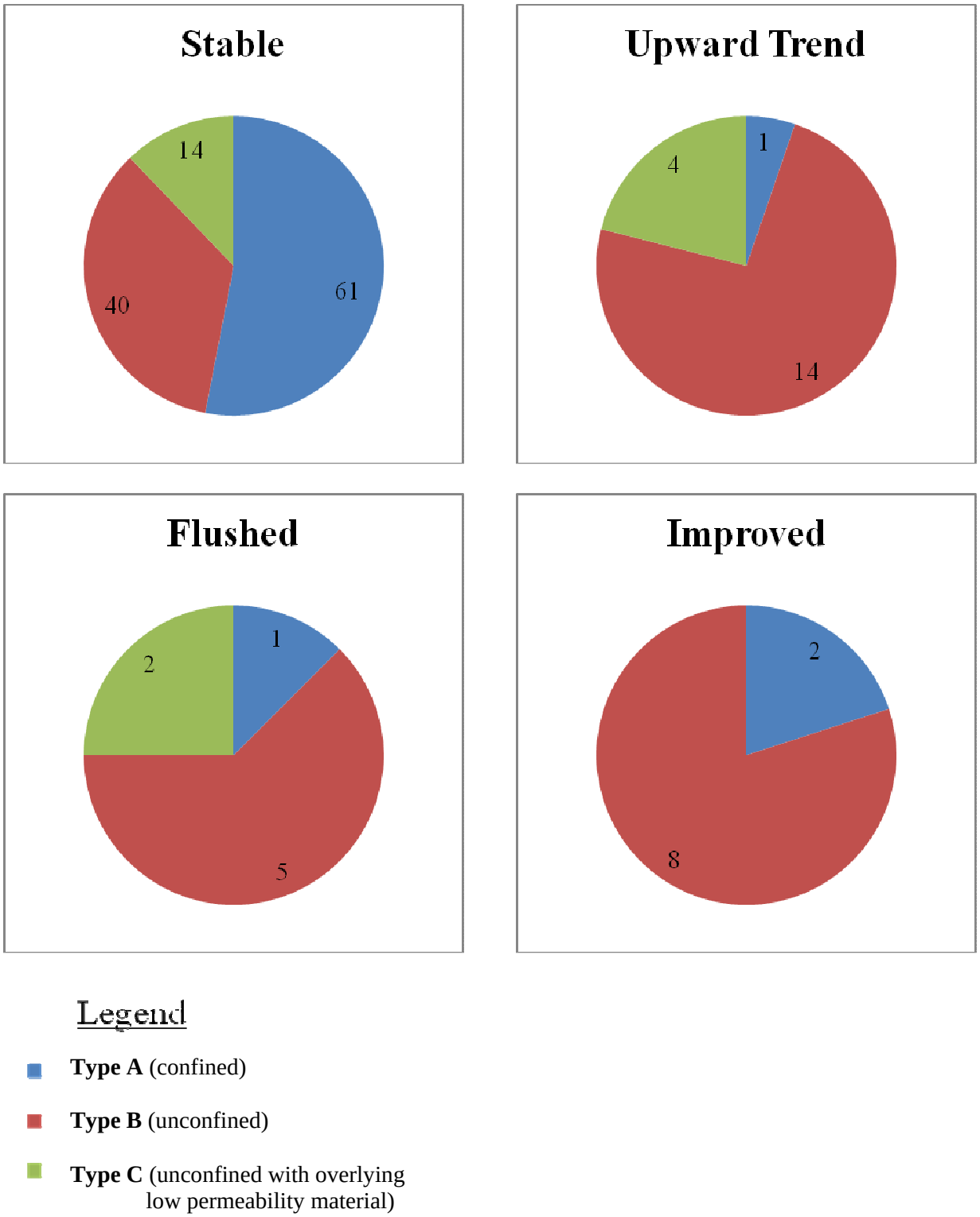

Figure 14: Number of wells in each hydrogeologic setting, categorized by geochemical trend

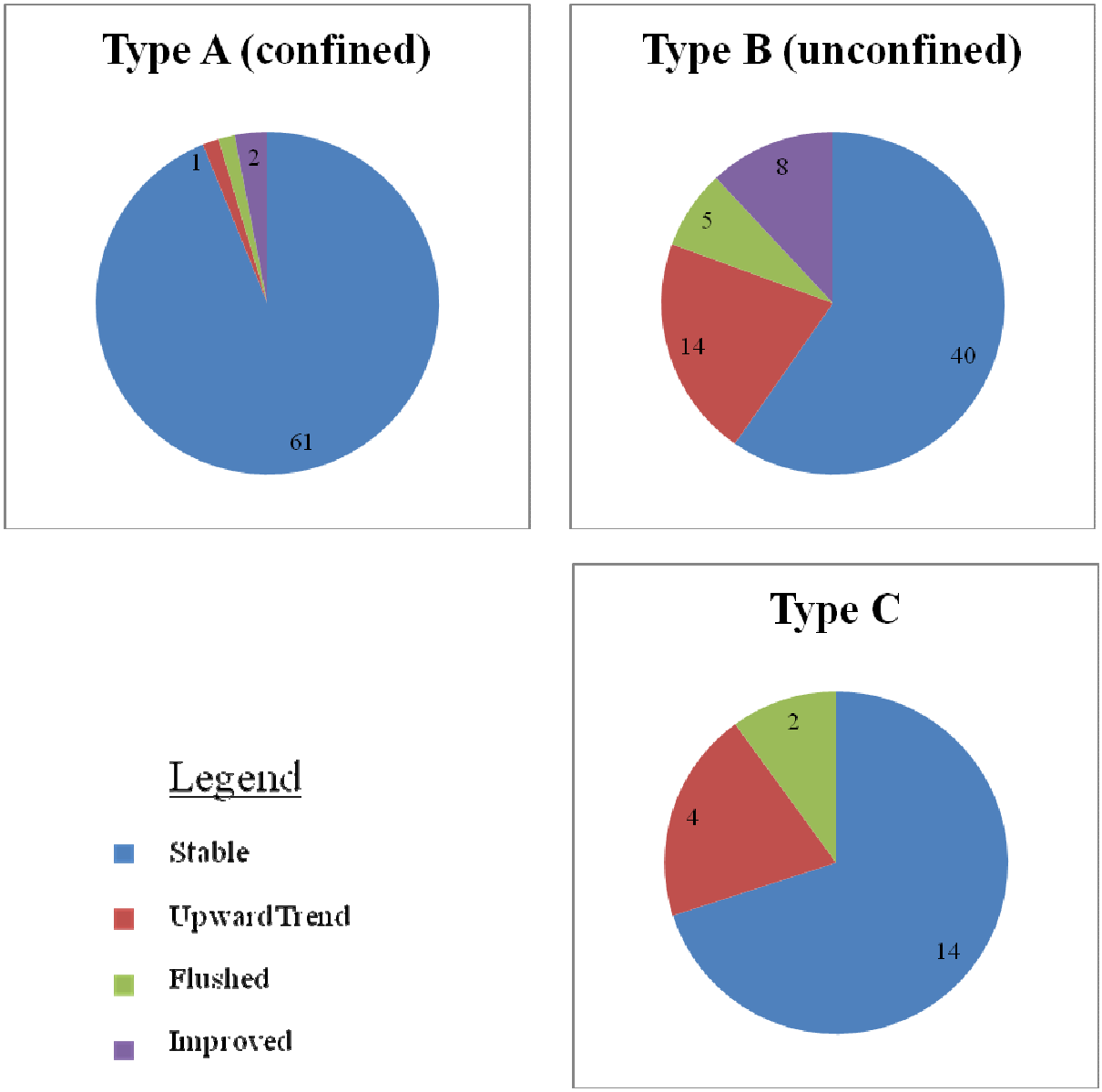

Figure 15: Number of wells in each geochemical trend group, categorized by hydrogeologic setting

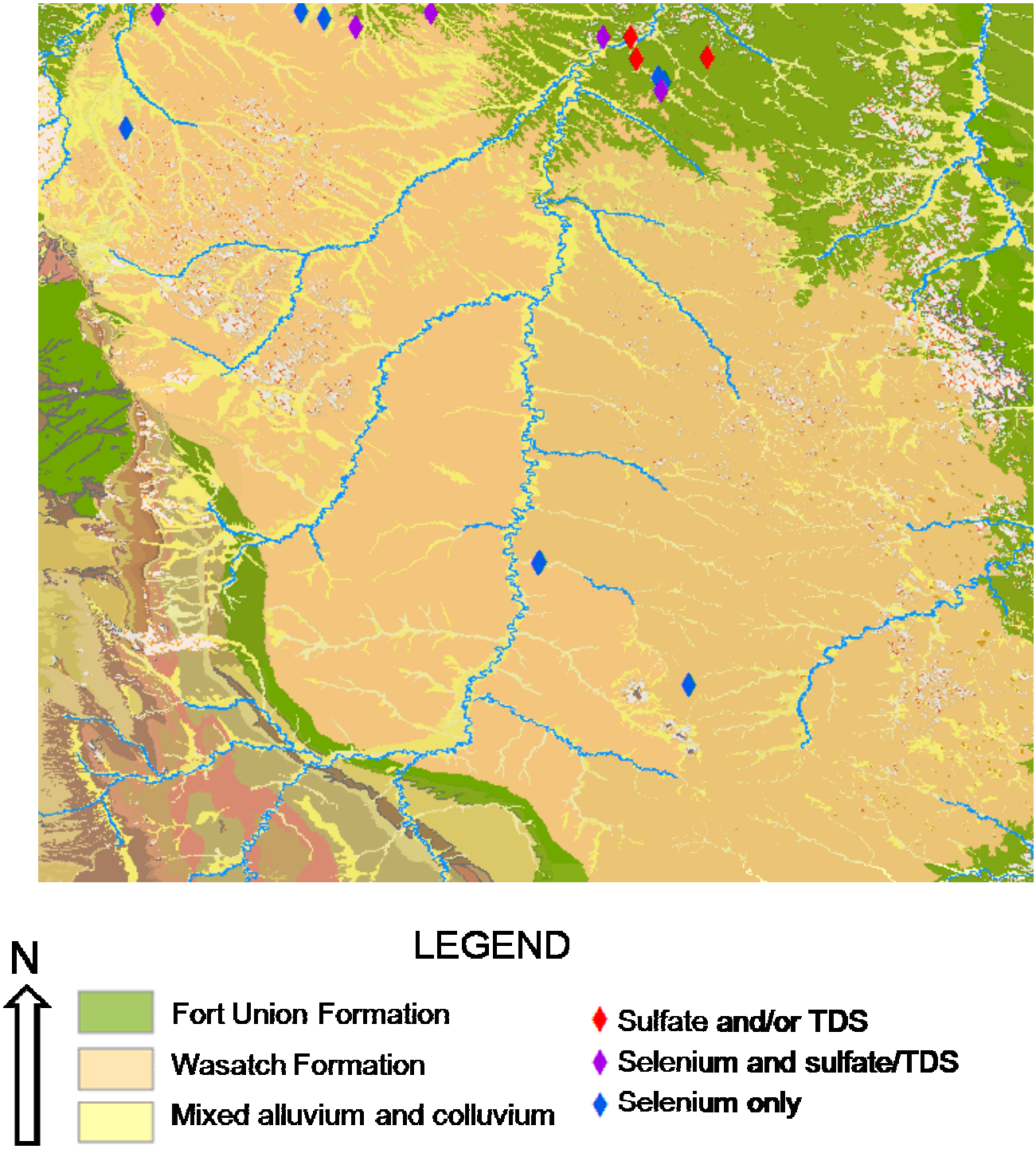

Figure 16: Geospatial distribution of wells in which geochemical parameters have ever exceeded class of use standards.

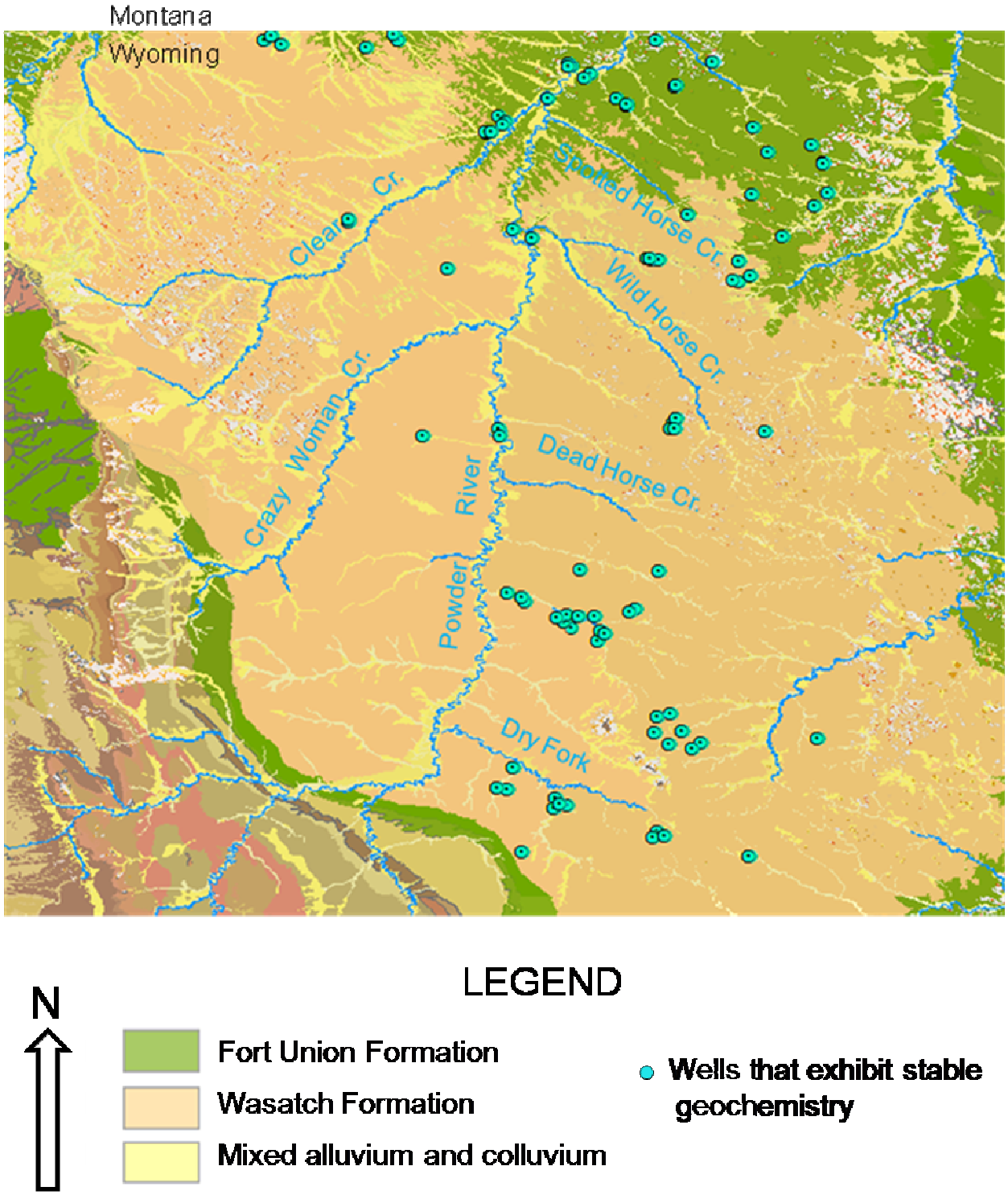

Figure 17: Geospatial distribution of monitoring wells completed in shallow aquifers (all types) exhibiting a stable geochemical trend.

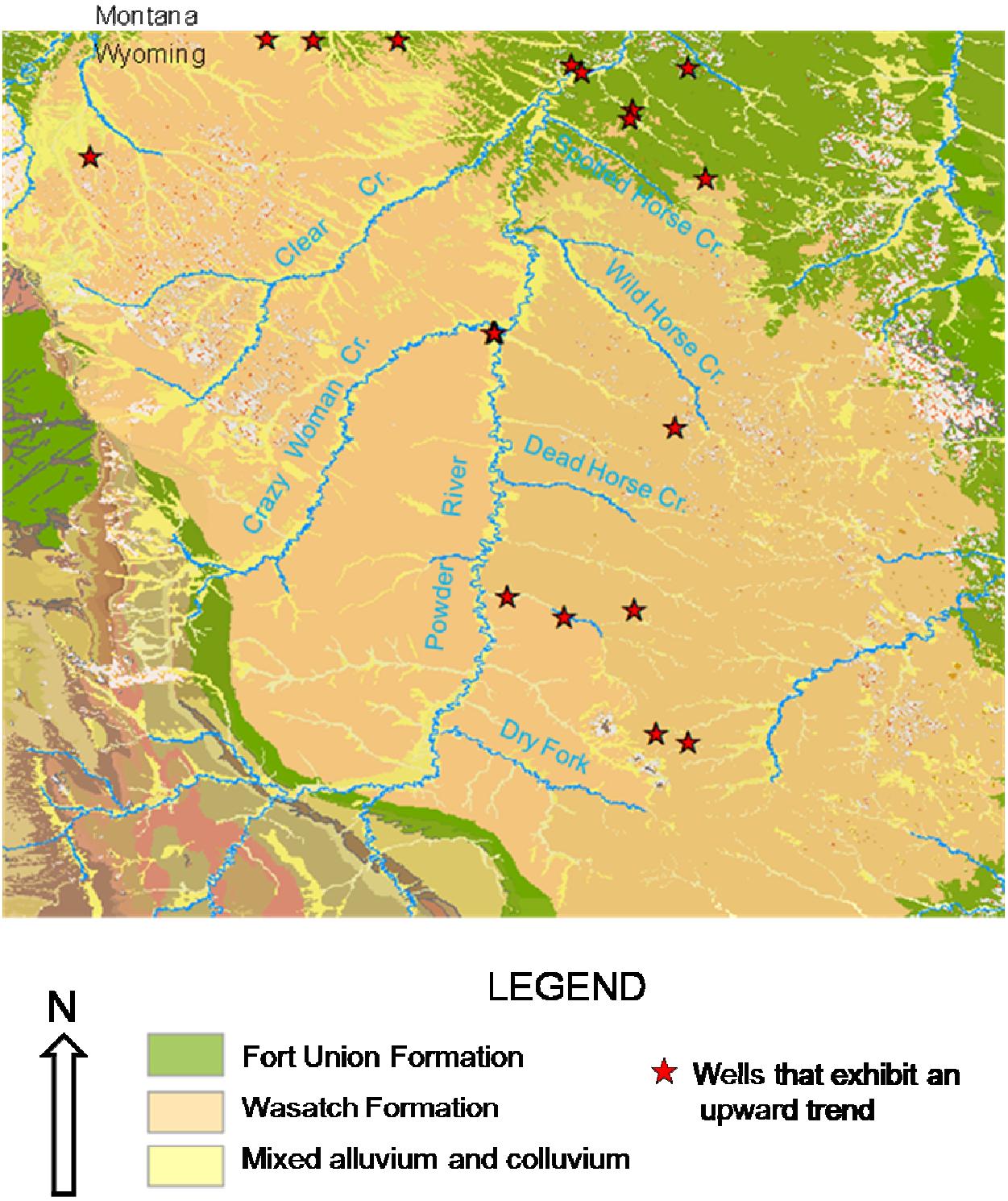

Figure 18: Geospatial distribution of monitoring wells completed in shallow aquifers (all types) exhibiting an upward geochemical trend.

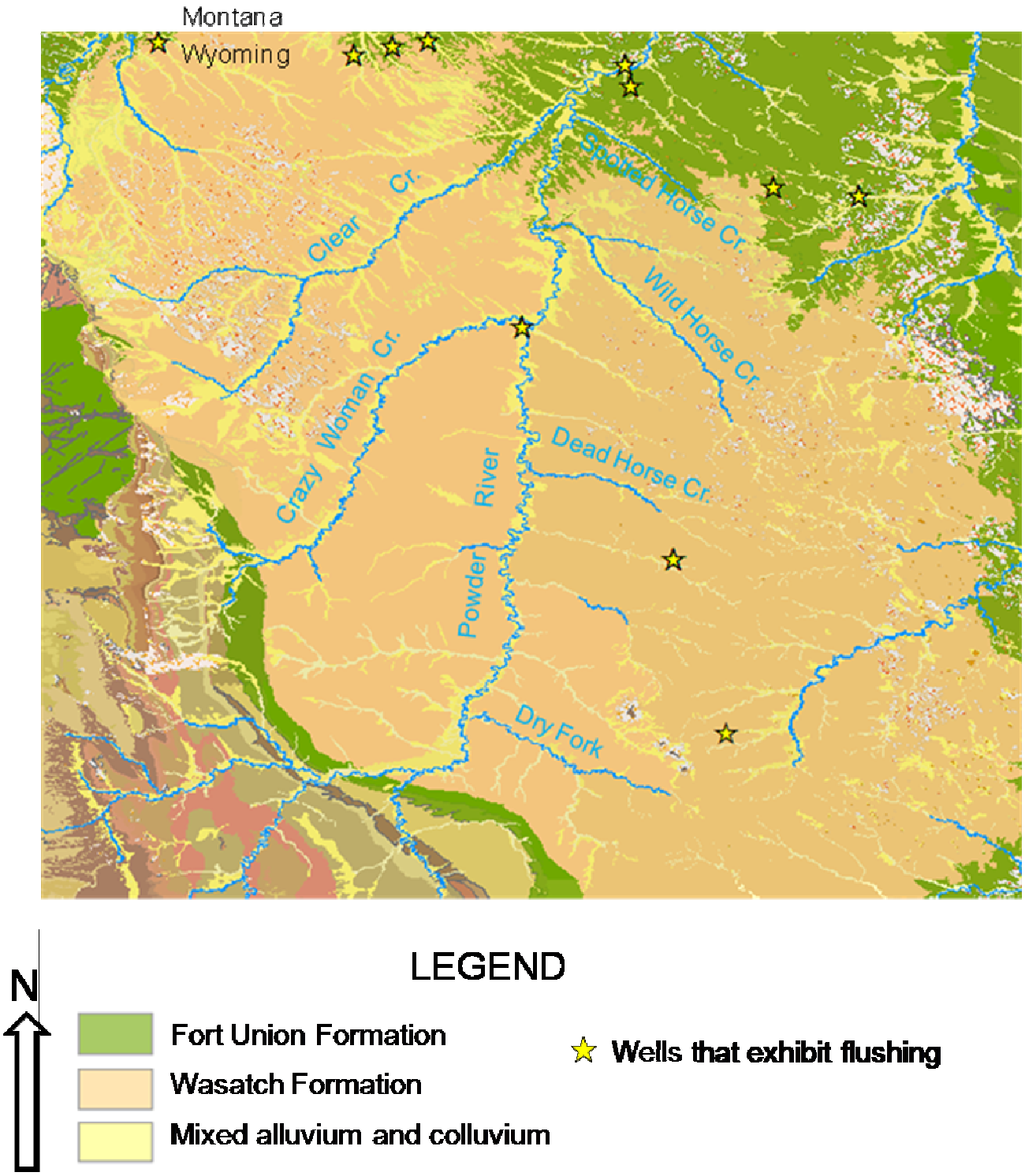

Figure 19: Geospatial distribution of monitoring wells completed in shallow aquifers (all types) exhibiting a flushed geochemical trend.

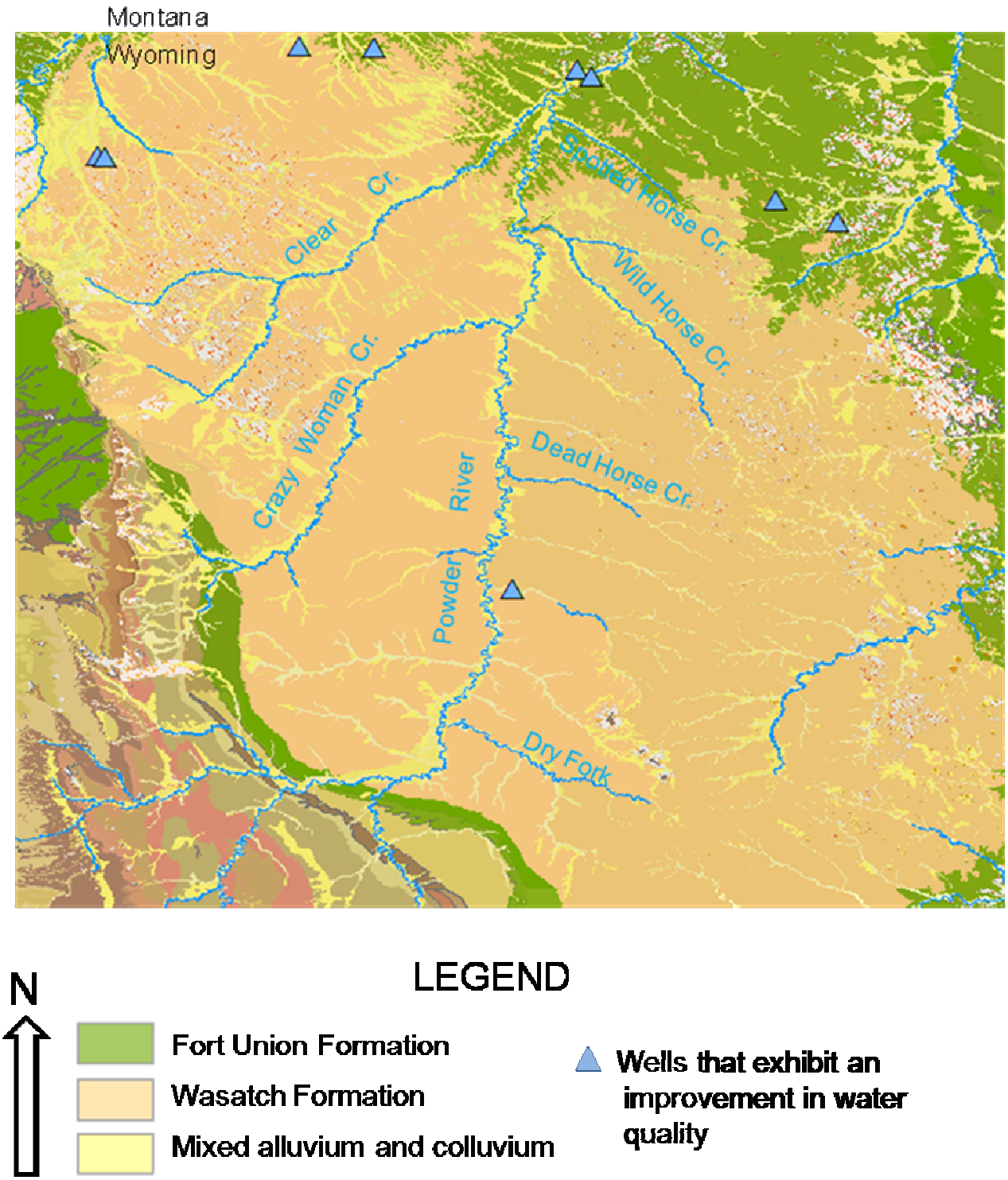

Figure 20: Geospatial distribution of monitoring wells completed in shallow aquifers (all types) exhibiting improved water quality.

TABLES

		Hydrogeologic Setting				
		Type A	Type B	Type C	?	TOTAL
Geochemical Trend	Stable	61	40	14	7	**122**
	Upward trend	1	14	4	1	**20**
	Flushed	1	5	2	2	**10**
	Improved	2	8	0	0	**10**
	?	2	2	1	1	**6**
	TOTAL	**67**	**70**	**21**	**11**	

Table 1: Summary statistics for hydrogeologic and geochemical groupings

	Type A	Type B		Type C
Aquifer Type (# of wells)	**Bedrock (67)**	**Alluvial/Colluvial (34)**	**Bedrock (36)**	**Bedrock (21)**
Depth to Aquifer	90.1 ft	2.6 ft	11.3 ft	68.6 ft
Depth to Water	53.7 ft	14.8 ft	45.1 ft	94.1 ft
Thickness of confining material	33.8 ft	0	0.4 ft	24.1 ft

Table 2: Average aquifer characteristics

			Hydrogeologic setting		
			Type A	Type B	Type C
Geochemical Trend	Stable	TDS and Sulfate	0.62	0.86	0.84
		TDS and Selenium	0.03	-0.01	0.05
		Sulfate and Selenium	0.20	0.00	-0.07
	Non-Stable	TDS and Sulfate	**0.98**	**0.95**	0.93
		TDS and Selenium	**0.03**	**0.66**	-0.21
		Sulfate and Selenium	**-0.14**	**0.52**	-0.20

Table 3: Summary of r^2 values for correlations between maximum increase (maximum concentration minus baseline concentration) for sulfate, TDS, and selenium.

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