# Water Quality Criteria Evaluation of Horse Creek, Bear Creek and Dry Creek - North Platte River Basin, 2019-2020

Wyoming Department of Environmental Quality-Water Quality Division

**July 2021**

Cover Page: Horse Creek at 'Below EGHD' – June 2019 (top), Bear Creek at 'Below Little Bear Creek' – June 2020 (bottom left), Dry Creek at 'Mouth' – May 2020 (bottom right)

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| | | | | | | | |

**WYOMING DEPARTMENT OF ENVIRONMENTAL QUALITY**
**WATER QUALITY DIVISION**
**CHAPTER 1 CRITERIA ATTAINMENT/NON-ATTAINMENT**

**QUICK SUMMARY – HORSE CREEK SEGMENT 1**

| | |
|---|---|
| Waterbody ID | Horse Creek<br>HUCs 101800120106, 101800120107, 101800120108, 101800120201, 101800120203, 101800120206, 101800120208, 101800120601 |
| Basin Name | North Platte River Basin |
| Waterbody Classification | Class 2AB – Upstream of Stinking Water Creek<br>Class 2ABww – Downstream of Stinking Water Creek |
| Location | Laramie and Goshen Counties, Wyoming |
| Extent of Assessment | Approximately 160 stream miles from a point above the Interstate-25 crossing at latitude 41.450459, longitude -104.941061 downstream to the Wyoming/Nebraska state line |
| Years assessed | 2019-2020 |
| Assigned Designated Uses | Cold-water game fisheries (2AB only), warm-water fisheries (2ABww only), non-game fisheries, aquatic life other than fish, fish consumption, drinking water, recreation, wildlife, agriculture, industry and scenic value |
| Spatial Extent and Description of Chapter 1 Criteria Attainment/Non-Attainment | **Segment 1** - From a point above the Interstate-25 crossing at latitude 41.450459, longitude -104.941061 downstream to the Hawk Springs Reservoir supply canal diversion at latitude 41.682092, longitude -104.205316 (100.5 miles)<br><br>**Attainment** of numeric criteria protective of human health for:<br>• arsenic, iron and nitrate+nitrite-N (Section 18)<br><br>**Attainment** of numeric criteria protective of aquatic life for:<br>• aluminum, ammonia-N, arsenic, chloride and iron (Section 21) |
| Cause(s) of Pollutants | None applicable |
| Source(s) of Pollutants | None applicable |

**WYOMING DEPARTMENT OF ENVIRONMENTAL QUALITY**
**WATER QUALITY DIVISION**
**CHAPTER 1 CRITERIA ATTAINMENT/NON-ATTAINMENT**

**QUICK SUMMARY – HORSE CREEK SEGMENT 2**

| | |
|---|---|
| Waterbody ID | Horse Creek<br>HUCs 101800120601, 101800120604, 101800120611 |
| Basin Name | North Platte River Basin |
| Waterbody Classification | Class 2ABww |
| Location | Goshen County, Wyoming |
| Extent of Assessment | Approximately 160 stream miles from a point above the Interstate-25 crossing at latitude 41.450459, longitude -104.941061 downstream to the Wyoming/Nebraska state line |
| Years assessed | 2019-2020 |
| Assigned Designated Uses | Warm-water game fisheries, non-game fisheries, aquatic life other than fish, fish consumption, drinking water, recreation, wildlife, agriculture, industry and scenic value |
| Spatial Extent and Description of Chapter 1 Criteria Attainment/Non-Attainment | **Segment 2** - From the Hawk Springs Reservoir supply canal diversion at latitude 41.682092, longitude -104.205316 downstream to the Wyoming/Nebraska state line (59.7 miles)<br><br>**Attainment** of numeric criteria protective of human health for:<br>• iron and nitrate+nitrite-N (Section 18)<br><br>**Attainment** of numeric criteria protective of aquatic life for:<br>• aluminum, ammonia-N, arsenic, chloride and iron (Section 21)<br><br>**Non-Attainment** of numeric criteria protective of human health for:<br>• arsenic (Section 18) |
| Cause(s) of Impairment | Arsenic |
| Source(s) of Pollutants | Irrigated crop production, legacy pesticide application and natural geology/soils |

**WYOMING DEPARTMENT OF ENVIRONMENTAL QUALITY**
**WATER QUALITY DIVISION**
**CHAPTER 1 CRITERIA ATTAINMENT/NON-ATTAINMENT**

**QUICK SUMMARY – BEAR CREEK**

| | |
|---|---|
| Waterbody ID | Bear Creek<br>HUCs 101800120305, 101800120306 |
| Basin Name | North Platte River Basin |
| Waterbody Classification | Class 2AB |
| Location | Goshen County, Wyoming |
| Extent of Assessment | Approximately 52 stream miles from the confluence with Little Bear Creek downstream to the confluence with Horse Creek |
| Years assessed | 2019-2020 |
| Assigned Designated Uses | Cold-water game fisheries, non-game fisheries, aquatic life other than fish, fish consumption, drinking water, recreation, wildlife, agriculture, industry and scenic value |
| Spatial Extent and Description of Chapter 1 Criteria Attainment/Non-Attainment | From the confluence with Little Bear Creek downstream to the confluence with Horse Creek (52 miles)<br><br>**Attainment** of numeric criteria protective of human health for:<br>• arsenic, iron and nitrate+nitrite-N (Section 18)<br><br>**Attainment** of numeric criteria protective of aquatic life for:<br>• aluminum, ammonia-N, arsenic, chloride and iron (Section 21) |
| Cause(s) of Pollutants | None applicable |
| Source(s) of Pollutants | None applicable |

**WYOMING DEPARTMENT OF ENVIRONMENTAL QUALITY**
**WATER QUALITY DIVISION**
**CHAPTER 1 CRITERIA ATTAINMENT/NON-ATTAINMENT**

**QUICK SUMMARY – DRY CREEK**

| | |
|---|---|
| Waterbody ID | Dry Creek<br>HUCs 101800120608, 101800120609 |
| Basin Name | North Platte River Basin |
| Waterbody Classification | Class 2C |
| Location | Goshen County, Wyoming |
| Extent of Assessment | Approximately 18 stream miles from its headwaters at Hawk Springs Reservoir north dam at latitude 41.721387, longitude -104.177365 downstream to the confluence with Horse Creek |
| Years assessed | 2019-2020 |
| Assigned Designated Uses | Non-game fisheries, aquatic life other than fish, fish consumption, recreation, wildlife, agriculture, industry and scenic value |
| Spatial Extent and Description of Chapter 1 Criteria Attainment/Non-Attainment | From its headwaters at Hawk Springs Reservoir north dam at latitude 41.721387, longitude -104.177365 downstream to the confluence with Horse Creek (18 miles)<br><br>**Attainment** of numeric criteria protective of aquatic life for:<br>• aluminum, ammonia-N, arsenic, chloride and iron (Section 21)<br><br>**Non-Attainment** of numeric criteria protective of human health for:<br>• arsenic (Section 18) |
| Cause(s) of Impairment | Arsenic |
| Source(s) of Pollutants | Irrigated crop production, legacy pesticide application and natural geology/soils |

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## 1. EXECUTIVE SUMMARY

Horse Creek and its perennial tributaries Bear Creek and Dry Creek are spring-fed plains streams within the semi-arid lower North Platte River basin of southeast Wyoming. Horse Creek upstream of Stinking Water Creek and all of Bear Creek, are categorized as Class 2AB waters by the Wyoming Department of Environmental Quality-Water Quality Division (WDEQ/WQD). Class 2AB waters are protected for cold-water fisheries, non-game fisheries, aquatic life other than fish, drinking water, fish consumption, recreation, wildlife, industry, agriculture and scenic designated uses. Horse Creek downstream of Stinking Water Creek is a Class 2ABww that is protected for all the same uses with the exception that warm-water fisheries, rather than cold-water fisheries, is protected. Dry Creek is a Class 2C that is protected for all the same uses as a Class 2ABww with the exception of warm-water fisheries and drinking water. There are no permitted public or private drinking water intakes on any surface waters within the Horse Creek watershed. Public accessibility to Horse Creek and its perennial tributaries is limited and consequently any human consumption of fish from these waters is confined to private landowners and those individuals with whom private access is granted. However, Horse Creek is the primary water source for three off-channel publicly-accessible reservoirs in the lower watershed that support warm-water game fisheries: Hawk Springs, Bump-Sullivan and Goshen Hole Reservoirs. Irrigated agriculture and livestock grazing are the dominant human activities in the Horse Creek watershed. Only four WDEQ/WQD permitted point source facilities exist in the watershed, all of which are typically non-discharging. Mineral development is limited to a small area of oil and gas infrastructure in the upper portion of the watershed.

In 2016, the WDEQ/WQD conducted a survey of 50 randomly selected sites in the North Platte River basin to evaluate overall water quality condition of perennial streams in the basin – five of which were located within the Horse Creek watershed. Arsenic was detected at all five sites, though only in Horse Creek downstream of Hawk Springs Reservoir were concentrations above the state numeric human health arsenic criterion of 10 µg/L protective of fish consumption and drinking water. Considering these results and that Horse Creek is the source of water for Hawk Springs, Bump-Sullivan and Goshen Hole Reservoirs, WDEQ/WQD monitored the reservoirs in 2018 to evaluate arsenic concentrations with respect to the fish consumption criterion. Arsenic equaled or exceeded the 10 µg/L criterion at Bump-Sullivan and Goshen Hole Reservoirs. Historical sampling by the U.S. Environmental Protection Agency (USEPA) in 2010 documented arsenic concentrations >10 µg/L at Goshen Hole and Hawk Springs Reservoirs.

Based on these findings, the elevated arsenic in Horse Creek represents a pathway to an increased risk for human exposure to elevated arsenic through dietary intake of arsenic-contaminated fish harvested from these three reservoirs. Human exposure to elevated arsenic may also occur through consumption of arsenic-contaminated game fish taken directly from Horse Creek. To better understand these pathways required an understanding of the magnitude, variability and extent of arsenic in Horse Creek; along with possible sources and transport mechanisms. With the support of landowners and the South Goshen Conservation District, the WDEQ/WQD conducted a two-year study in 2019 and 2020 to evaluate the water quality conditions of Horse, Bear and Dry Creeks. The primary objectives of this study were to evaluate arsenic concentrations in surface waters of the watershed, determine linear extents for

attainment of the state's 10 µg/L arsenic criterion protective of fish consumption and drinking water, identify broad-scale sources, and infer possible mechanisms for arsenic mobilization.

It was concluded from the 2019-2020 study that arsenic in a 59.7-mile segment of Horse Creek from the Hawk Springs Reservoir supply canal diversion downstream to the Wyoming/Nebraska stateline exceeded the 10 µg/L arsenic criterion protective of fish consumption and drinking water. Furthermore, the entirety of Dry Creek (18 miles) from its headwaters at Hawk Springs Reservoir north dam downstream to its confluence with Horse Creek also exceeded the 10 µg/L arsenic criterion. For both segments, this translated to non-attainment of a numeric criterion protective of human health for Section 18, Chapter 1 of the Wyoming Water Quality Rules. The sources of the exceedances were identified as a combination of human activities associated with irrigated agriculture and natural geology/soils. Though present throughout, natural groundwater contributions (and to a limited degree soils) could only explain a portion of the criterion exceedances in these two segments. The conclusion of a human source was based on multiple lines of evidence that indicated notable departures in the surface water chemistry of these two segments from both local reference conditions and groundwater. Moreover, the surface water of these two segments displayed several chemical signatures of arsenic release mechanisms that were not associated with groundwater. All other applicable numeric surface water quality criteria protective of aquatic life and human health were attained in these two segments.

With regard to the two non-attained segments, water-bearing sedimentary geology is the dominant natural source of arsenic to the spring-fed streams in the watershed. Natural contributions of arsenic from soils would be limited to infrequent episodes of natural bank erosion and upland runoff minimal as the majority of arsenic naturally found in soils of the watershed would be bound to iron and aluminum complexes and remain insoluble. It is the leaching and transport of arsenic from irrigated soils that naturally contain arsenic, that represents the most probable human source. Arsenic in irrigation water along with frequent saturation-drying cycles of irrigated soils and shallow water tables may also influence the accumulation and release of arsenic in soils which in turn can be leached to surface waters. Leached soil arsenic may also include any residual contamination bound to soils from legacy arsenical pesticide application. Secondary pathways include evaporative enrichment through diversions and/or storage in reservoirs in addition to transport within fluvial sediment. Possible human influenced sediment transport mechanisms include resuspension of sediment in ditches and canals, runoff from fields and reservoir releases.

The study also concluded that a 100.5-mile segment of Horse Creek from approximately the Interstate-25 crossing downstream to the Hawk Springs Reservoir supply canal diversion and a 52-mile segment of Bear Creek from its confluence with Little Bear Creek downstream to the confluence with Horse Creek attained all applicable numeric surface water quality criteria protective of aquatic life and human health.

## 2. INTRODUCTION AND PURPOSE

The Federal Clean Water Act (CWA) § 305(b) requires States to describe the water quality condition of all their waters including all designated use determinations. In addition, CWA § 303(d) directs each State to

develop a list of all waters which do not fully support designated uses and require development of a Total Maximum Daily Load (TMDL). The Monitoring Program of the Wyoming Department of Environmental Quality-Water Quality Division (WDEQ/WQD) assesses surface water quality and determines if applicable numeric and narrative surface water quality criteria are being met. Findings from these assessments are then incorporated into the State's biennial Integrated 305(b) and 303(d) Report that is submitted to the U.S. Environmental Protection Agency (USEPA).

Located in the southeast corner of Wyoming, Horse Creek is a spring-fed plains stream with headwaters that originate in the southern Laramie Range and flows eastward to its confluence with the North Platte River in Nebraska. The major perennial tributaries to Horse Creek include Bear Creek and Dry Creek. Horse Creek is the primary water source for three publicly-accessible impoundments in the lower portion of the watershed: Hawk Springs, Bump-Sullivan and Goshen Hole Reservoirs. Horse Creek supports a cold/cool water fishery, including Brook and Brown trout upstream of U.S. Highway 85 with a transition to a warm-water fishery near the Town of LaGrange. Most of the Horse Creek watershed is privately owned and offers habitat for wildlife and aquatic life though is also used for the production of livestock and crops such as alfalfa, hay and grains. Irrigated agriculture is common in the watershed approximately downstream of U.S. Highway 85 and supported by diversions from Horse Creek and the nearby North Platte River.

During the summer of 2016, the WDEQ/WQD conducted a survey of 50 randomly selected sites in the North Platte River basin to identify perennial streams and rivers of high quality and those where designated use-support may be limited (i.e. 2016 Platte River Basin Probabilistic Survey – WDEQ/WQD 2016). Five of the 50 random monitoring sites were located in the Horse Creek watershed (four sites on Horse Creek and one site on its tributary Bear Creek). Arsenic was detected at all five sites. Specifically, single-sample arsenic concentrations in Horse Creek and Bear Creek upstream of Hawk Springs Reservoir were 3-4 µg/L whereas concentrations in Horse Creek below the reservoir were 11-12 µg/L – exceeding the state numeric human health criterion of 10 µg/L protective of fish consumption and drinking water.

Considering the 2016 results and that Horse Creek is the source of water for Hawk Springs, Goshen Hole and Bump-Sullivan Reservoirs, WDEQ monitored the reservoirs in 2018 to evaluate arsenic concentrations with respect to the 10 µg/L total arsenic criterion protective of fish consumption. Findings from this monitoring indicated arsenic concentrations were elevated in all three reservoirs with some concentrations approaching or exceeding the fish consumption criterion. Ranges of total arsenic concentrations from three separate sampling events at each reservoir were 22-25 µg/L for Bump-Sullivan Reservoir, 10-11 µg/L in Goshen Hole Reservoir, and 7-8 µg/L for Hawk Springs Reservoir. Historical sampling conducted by the USEPA in 2010 have shown total arsenic concentrations of 10-10.2 µg/L in Goshen Hole Reservoir and 8.5-10.1 µg/L in Hawk Springs Reservoir.

While no permitted drinking water intakes are present on Horse Creek and it is predominantly a non-game fishery, all three reservoirs support a warm-water game fishery to some degree. As such, elevated arsenic in Horse Creek may represent an important pathway for human exposure to elevated arsenic through dietary intake of arsenic-contaminated fish harvested from these three reservoirs. Though likely limited,

human exposure to elevated arsenic may also occur through consumption of arsenic-contaminated game fish taken directly from Horse Creek. To better understand these pathways requires an understanding of the magnitude, variability and extent of arsenic in Horse Creek; along with possible sources and transport mechanisms. With the support of landowners and the South Goshen Conservation District, a two-year targeted assessment of Horse Creek was implemented in 2019 and 2020. The objectives of this assessment were to 1) conduct a detailed evaluation of arsenic concentrations in surface waters of the Horse Creek watershed, 2) identify the geographic and temporal extents for attainment of the State's 10 µg/L arsenic criterion protective of fish consumption and drinking water, 3) identify broad-scale sources, and 4) identify possible mechanisms for arsenic mobilization. This report describes the monitoring, data analysis and findings from the 2019-2020 WDEQ/WQD Horse Creek arsenic study.

## 3. DESCRIPTION OF ASSESSMENT AREA

Spring-fed Horse Creek originates in the southern Laramie Range flowing northeast to its confluence with the North Platte River in Nebraska. The spring-fed Bear, Dry and Little Horse Creeks are the primary perennial tributaries to Horse Creek. Horse Creek drains a 1,700 $mi^2$ watershed and is primarily situated within the Moderate Relief Rangeland, Flat to Rolling Cropland, and Platte River Valley and Terraces level IV ecoregions within the greater Western High Plains level III ecoregion (Chapman et al. 2003) (Figure 1). Collectively, these ecoregions represent a semi-arid landscape of short to mixed-grass prairie interspersed with irregular hills, terraces, pine-covered escarpments, cropland and stream riparian corridors of cottonwood, boxelder, sedges and rushes. The off-channel Bump-Sullivan, Goshen Hole and Hawk Springs Reservoirs are fed primarily by diversions from Horse Creek. Bedrock geology of the Horse Creek watershed is sedimentary and dominated by Arikaree, Lance, and Ogallala formations including the Brule and Chadron members of the White River formation (Figure 2) (Bartos and Hallberg 2011, Libra et al. 1981, Love and Christiansen 1985). Land ownership within the Horse Creek watershed is predominantly private interspersed with United States Bureau of Land Management (USBLM) and Wyoming State Land. Primary land uses in the Horse Creek watershed are irrigated agriculture, livestock grazing, wildlife habitat, municipal and recreation. Mineral development is limited with some oil and gas extraction located in the upper portion of the watershed (Figure 3).

## 4. STREAM CLASSIFICATION AND DESIGNATED USES

Horse Creek is designated a Class 2AB water from its headwaters downstream to the confluence with Stinking Water Creek (approximately the Laramie/Goshen County line) (WDEQ/WQD 2018). Downstream from Stinking Water Creek, Horse Creek is designated a Class 2ABww. The perennial tributary Bear Creek is also designated a Class 2AB water throughout its entire lengths The other perennial tributary Dry Creek is designated Class 2C throughout its entire length. Class 2AB waters are protected for the following designated uses: cold-water game fisheries, non-game fisheries, drinking water, fish consumption, aquatic life other than fish, recreation, wildlife, industry, agriculture and scenic values. Designated uses protected on Class 2ABww waters are the same for Class 2AB with the exception of cold-water game fisheries replaced with warm-water game fisheries. Class 2C waters are protected for non-

**Figure 1 – Horse Creek watershed with Level IV ecoregions.**

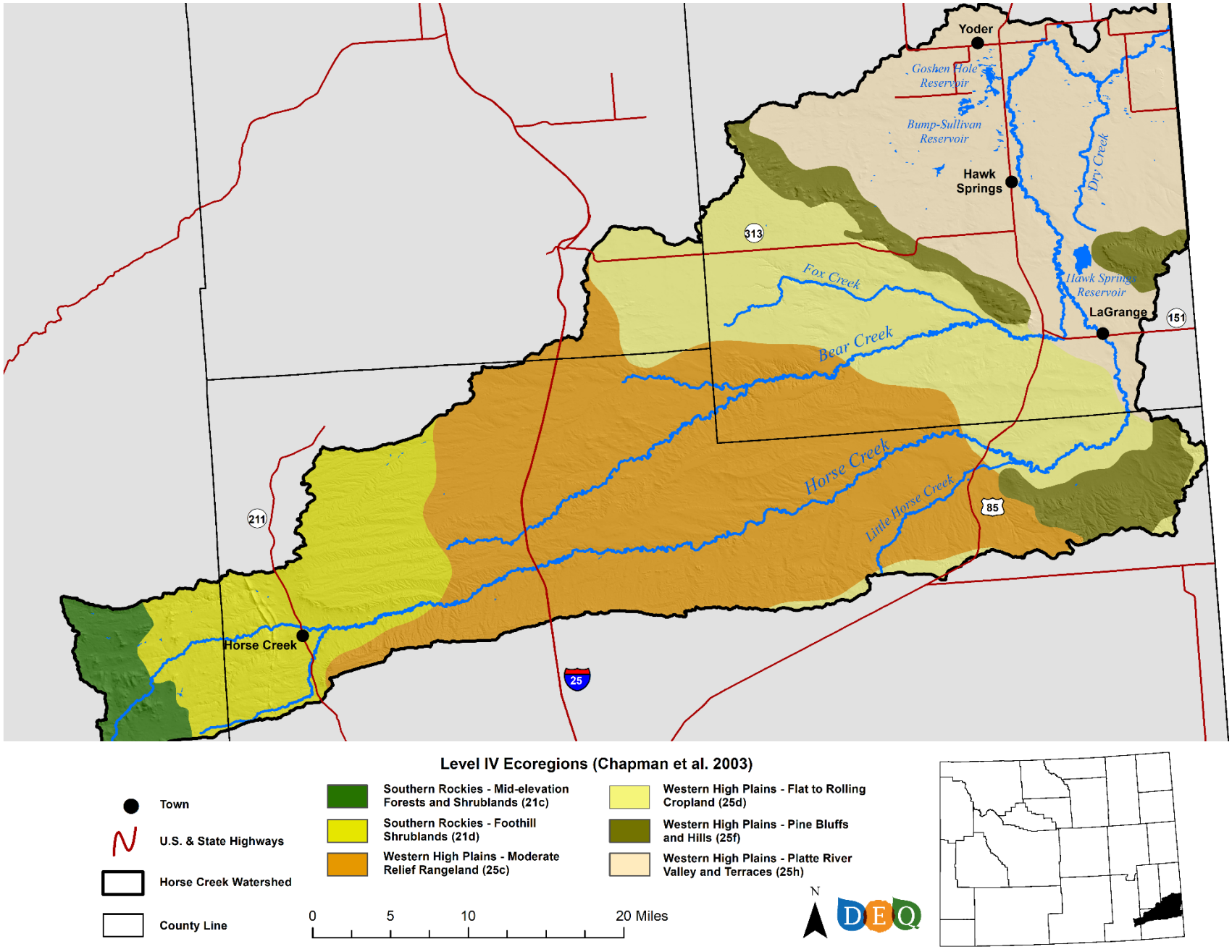


**Figure 2 - Dominant bedrock geology of the Horse Creek watershed and locations of representative wells sampled by the United States Geological Survey (Boughton 2014).**

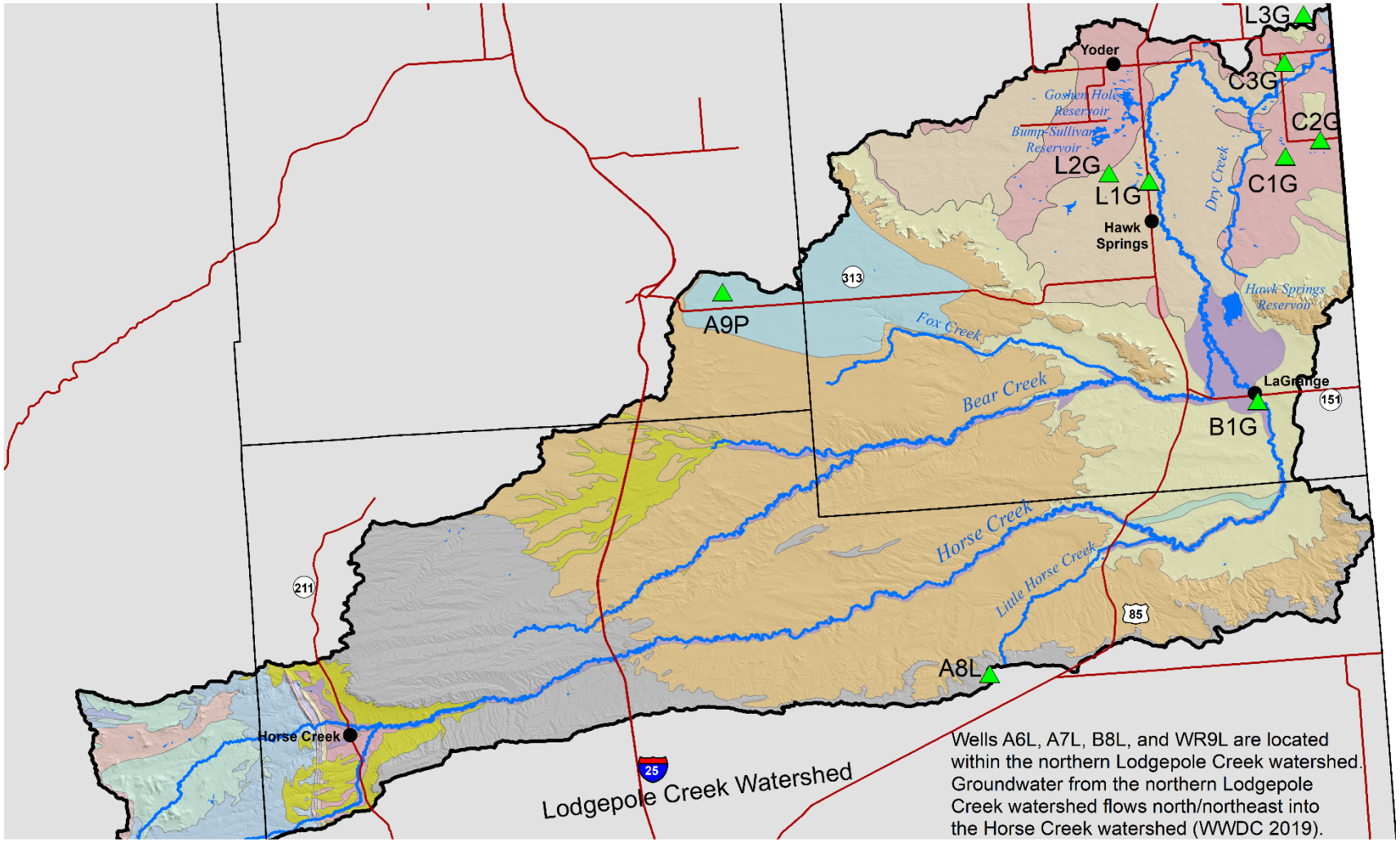
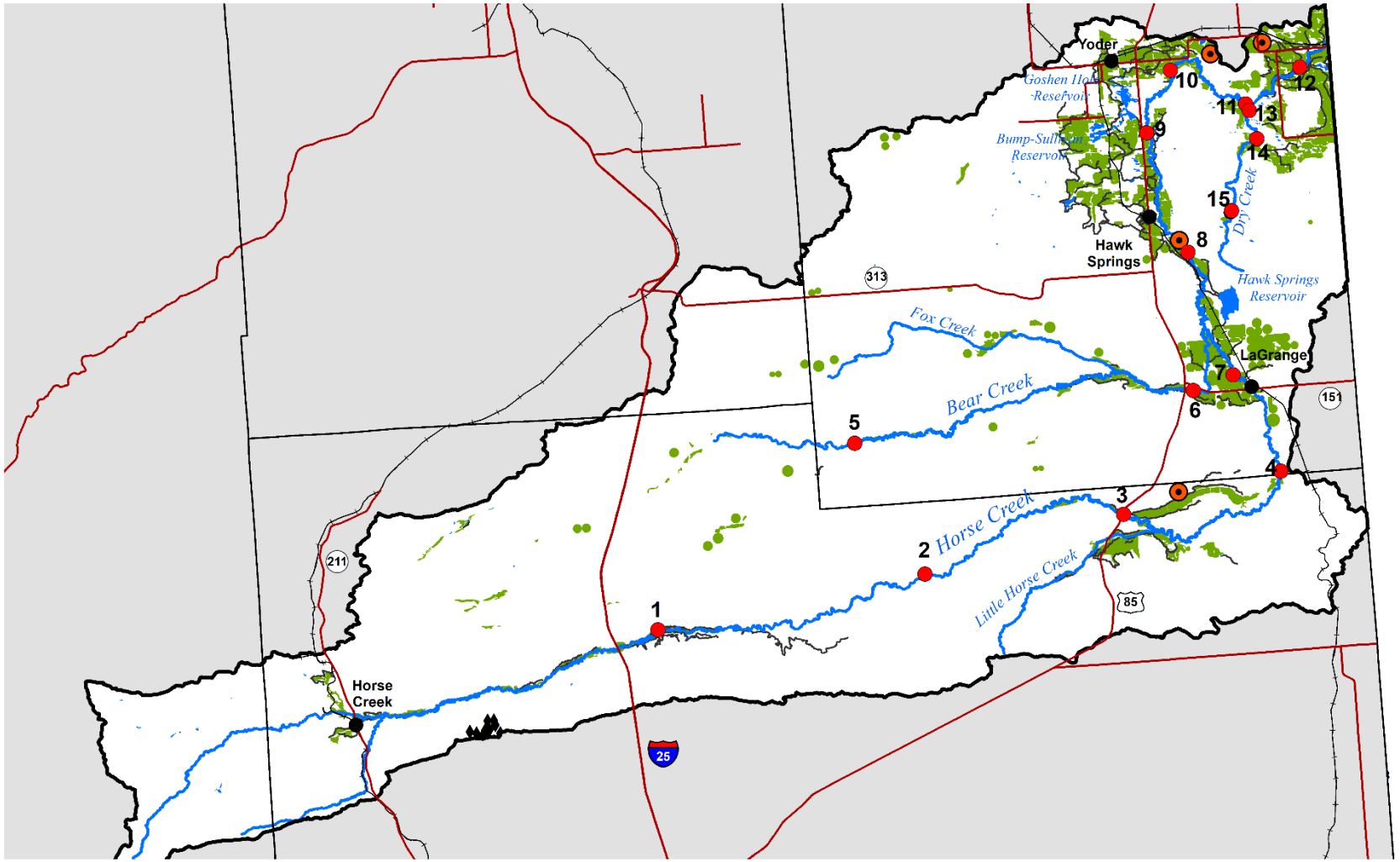


**Figure 3 - Horse Creek watershed with WDEQ /WQD monitoring site locations. Refer to Table 2 for monitoring site descriptions.**



game fisheries, fish consumption, aquatic life other than fish, recreation, wildlife, industry, agriculture and scenic values. Though Horse and Bear Creeks are protected for support of drinking water uses, there are no permitted public or private drinking water intakes on these waters. Public accessibility to Horse Creek and its perennial tributaries is limited and consequently any human consumption of fish from these waters is confined to private landowners and those individuals with whom private access is granted.

## 5. SURFACE WATER AND GROUNDWATER HYDROLOGY

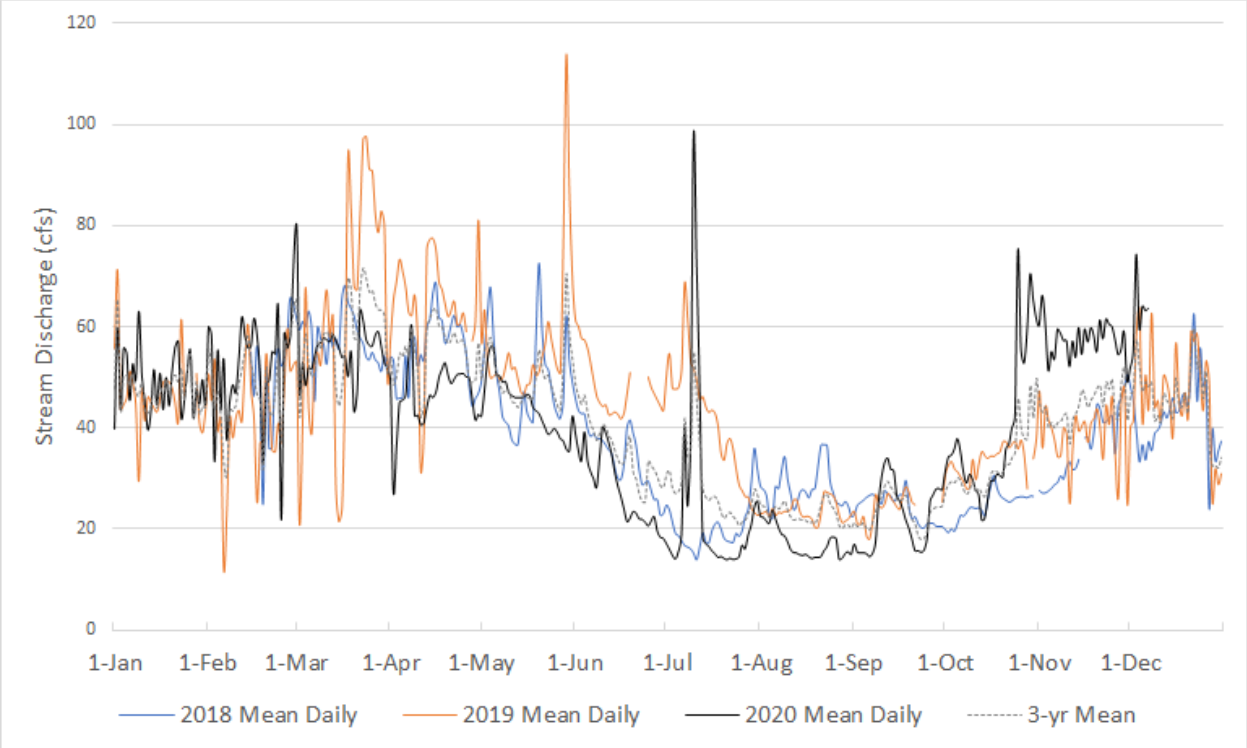
Horse Creek is a naturally spring-fed perennial system with characteristic peaks in stream flow during March, April and May that coincide with runoff from snow-melt, heavy rains and thunderstorms (WWDC 2019). The only active continuous stream gage on Horse Creek is at the Laramie/Goshen County line and operated by the Wyoming State Engineers Office (WSEO) which verifies the described perennial hydrologic regime (Figure 4). Diversions of water for crop and livestock production are minimal on Horse Creek upstream of U.S. Highway 85, however, downstream of this highway they are common (Figure 3). Surface water diversions are most active during the irrigation season of May 1 to September 30. Consequently, flows in Horse Creek during this time are greatly influenced by withdrawals and returns. One of the largest diversions of water from Horse Creek is to Hawk Springs Reservoir via the Hawk Springs Reservoir Supply Ditch located a short distance downstream from the confluence with Bear Creek. Hawk Springs Reservoir is also managed by the Wyoming Game and Fish Department (WGFD) as a warm-water game fishery and public recreational area. Storage water from Hawk Springs Reservoir is released into either the Hawk Springs Ditch or the Lincoln Land Company Ditch for distribution throughout the irrigated district (WWDC 2006). Downstream of Hawk Springs Reservoir, additional diversion structures take water from Horse Creek for storage in Goshen Hole (Springer) and Bump-Sullivan Reservoirs (Figures 3 and 5) where the water is later used for irrigation or livestock. Both reservoirs offer public recreation, are managed by the WGFD as warm-water fisheries, and are situated within a wetland complex known as the WGFD's Springer Wildlife Habitat Management Area (WHMA). Outflows from Goshen Hole and Bump-Sullivan Reservoirs enter ditches for distribution throughout the system.

The trans-basin Fort Laramie Canal diverts water from the North Platte River and conveys that water directly into Horse Creek a short distance downstream from Goshen Hole Reservoir. Past this entry point, the remaining water in the Fort Laramie Canal is conveyed farther east and discharged into Dry Creek as well as laterals off the main canal to supply irrigation demands. Accordingly, during the irrigation season, much of the flow in Horse Creek from the Fort Laramie Canal downstream to the Wyoming/Nebraska Stateline is North Platte River water.

Seepage areas along the canal system of Horse Creek east of U.S. Highway 85 and particularly downstream of Hawk Springs Reservoir are common. This shallow subsurface seepage combined with irrigation return flows and runoff augments the flows in sections of Horse Creek which naturally were dry by mid-summer (GWWG 2018). However, in some segments of Horse Creek where such augmentation is minimal or absent, natural stream gains from groundwater contributions can be overwhelmed by surface water diversions rendering some segments nearly dry (WWDC 2019). Nevertheless, since the beginning of the 20$^{th}$ century, the influence of irrigated agriculture, reservoir construction and other developments has likely increased the acreages of wetlands in the watershed downstream of Hawk Springs Reservoir

(GWWG 2018). Though the infiltration of irrigation water that augments flows in Horse Creek is largely incidental to irrigation, it is a deliberate process in a portion of the watershed near the Town of La Grange (WWDC 2019). Diversions of water from Horse Creek are used to recharge the La Grange aquifer between the town and Hawk Springs Reservoir. The La Grange aquifer is an alluvial stratum hydraulically connected through fractures in the underlying Brule member of the White River formation. This may locally augment flows in segments of Horse Creek between the town and Hawk Springs Reservoir.

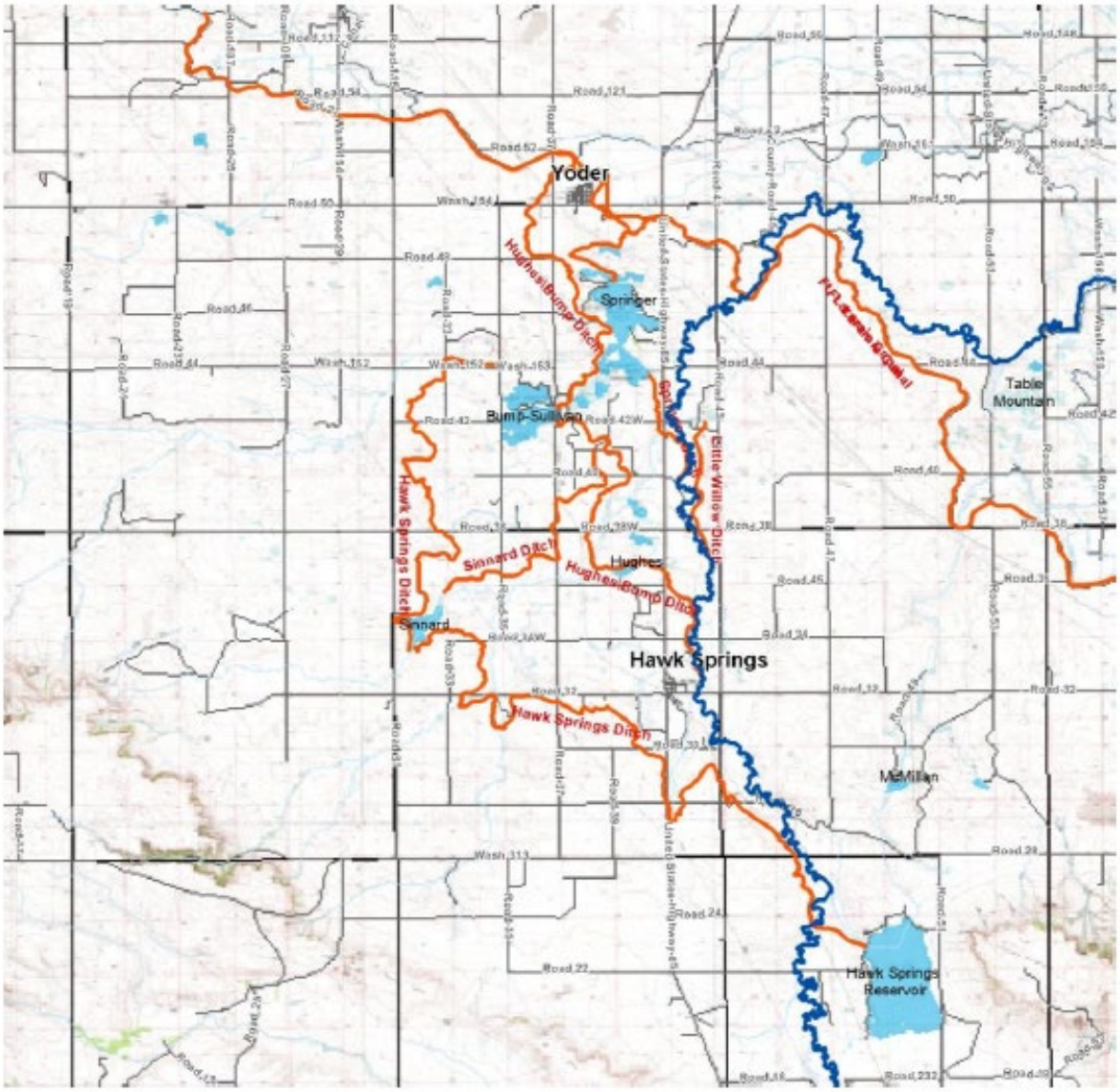
**Figure 4 – Mean daily discharge of Horse Creek at WSEO stream gauge 0102HRCK (http://seoflow.wyo.gov/).**




Flows in Dry Creek downstream of the Fort Laramie Canal entry point are perennial. During the irrigation season, much of the flow in this segment of Dry Creek is used for irrigation or is redistributed through a canal network that provides water to a managed wetland complex within the WGFD's publicly-accessible Table Mountain WHMA (Figure 6). Outflows from the wetland complex re-enter either Dry Creek or Horse Creek. Upstream of the Fort Laramie Canal, flows in Dry Creek are intermittent and flow only during the spring and early summer. The origins of the flows in Dry Creek upstream of the Fort Laramie Canal are either groundwater discharge or seepage below the north dam for Hawk Springs Reservoir. Flows in the remaining two perennial tributaries of Bear Creek and Little Horse Creek have spring-fed groundwater origins (WWDC 2019) though are influenced by irrigation diversions and returns primarily near the U.S. Highway 85 corridor downstream to their confluences with Horse Creek (Figure 3).

According to the Wyoming State Engineer's Office water rights database, the majority of adjudicated water rights for diversion of surface water on Horse, Bear, Little Horse and Dry Creeks have priorities that date back to the early 20$^{th}$ century (https://sites.google.com/a/wyo.gov/seo/).

**Figure 5 – Primary canals in the Horse Creek irrigation system between Hawk Springs Reservoir and the Fort Laramie Canal (GWWG 2018).**




Groundwater in the Horse Creek watershed generally flows east to northeast (WWDC 2019). Groundwater in the Arikaree and White River (Brule Member) formations from the northern Lodgepole Creek watershed to the south also flows north into the southern Horse Creek watershed. The relatively low permeability White River (Chadron Member) and Lance formations in the northern part of the Horse Creek watershed create a hydrogeologic barrier that forces northerly groundwater flow from the Arikaree and White River (Brule Member) to discharge to the surface (WWDC 2019). Thus, groundwater contributions to Horse Creek in the northern portion of the watershed are predominantly from the White River (Chadron Member) and Lance formations.

**Figure 6 – Dry Creek downstream of the Fort Laramie Canal.**

Groundwater contribution to Horse and Bear Creeks can vary in response to natural recharge and discharge as well as the impacts of high-volume groundwater pumping and surface water diversions. According to WSEO records, there are approximately 2,200 active groundwater permits in the Horse Creek watershed for domestic, stock, municipal and irrigation uses (WWDC 2019). Around 206 of these permits are for high-volume wells with >95% associated with irrigation use. The majority of these irrigation well permits are located in the La Grange aquifer area between the Town of La Grange and Hawk Springs Reservoir (WWDC 2019). Through an examination of available records, WWDC (2019) indicated that overall there has not been a significant upward or downward trend in groundwater levels (for aquifers of

the sedimentary formations) of the watershed since the 1970's. This implies negligible change in groundwater contributions to stream flows over that time from potential impacts associated with groundwater pumping or surface water diversions. The only exception is in the La Grange aquifer area where groundwater levels fluctuate 10-15 ft seasonally (WWDC 2019). These localized fluctuations in groundwater levels may influence groundwater contributions to stream flow for segments of Horse Creek within this area.

## 6. NATURAL SOURCES OF ARSENIC

Arsenic is a common element normally found in trace amounts in soils and geological formations. Naturally elevated concentrations of arsenic can be found in various oxide and hydrous metal oxide minerals in soils and their sedimentary rock origins (Magalhaes 2002, Goldberg 2002, Smedley and Kinniburgh 2002). In particular, arsenic concentrations in hydrous metal oxides of iron or aluminum are greater relative to silicate, sulphate or carbonate-based minerals. This is due to arsenic's strong adsorption properties to these complexes, particularly iron oxide. Some of the highest natural concentrations of arsenic tend to be associated with sulfide minerals, the most common form being pyrite (arsenopyrite - FeAsS) (Smedley and Kinniburgh 2002). Though pyrite is commonly found in igneous ore bodies, it can also occur in sedimentary layers that formed under reducing conditions such as shales and coal lenses.

Relative to soils throughout the conterminous United States, both iron and aluminum are abundant in the alkaline soils of the Horse Creek watershed with concentrations of 1.75-2.34 ($30^{th}$ - $60^{th}$ percentile) and 5.11-6.54 ($50^{th}$ – $80^{th}$ percentile) percent weight, respectively (Smith et al. 2014). Consequently, arsenic concentrations in soils of the Horse Creek watershed are also elevated and typically in the range of 2.7-5.0 mg/kg or approximately the $20^{th}$ to $50^{th}$ percentiles of soil concentrations nationally (Smith et al. 2014). These concentrations are within the baseline range of 5-10 mg/kg for arsenic soils globally (Smedley and Kinniburgh 2002) and the 5-$95^{th}$ percentile range of 1.3-13 mg/kg nationally (Smith et al. 2014). The dominant source of natural arsenic in soils is geological and therefore dependent on the concentrations of the parent material.

Arsenic concentrations in sedimentary geology are typically in the range of 5-10 mg/kg though sandstones tend to have lower concentrations at around 4 mg/kg (Smedley and Kinniburgh 2002). Non-marine shales interbedded within sandstones can have arsenic concentrations between 3-12 mg/kg. The Arikaree, Ogallala and White River formations that underly much of the Horse Creek watershed (Figure 2) consists of sandstone interspersed with siltstones and claystones (Bartos and Hallberg 2011, Libra et al. 1981). The Lance formation in the northern portion of the watershed is predominantly sandstone with occasional interbedded shale lenses (Libra et al. 1981). As with soils, the concentrations of arsenic in unconsolidated weathered sediments are similar to the geological formations from which they were derived (Smedley and Kinniburgh 2002).

The concentration of arsenic in groundwaters of sedimentary formations is largely controlled by mineral-water interactions under specific pH and redox conditions that allow for the desorption from or dissolution of the metal oxides, resulting in soluble forms of arsenic and other parameters. Total arsenic

**Table 1 – Chemistry of groundwaters in the Arikaree, White River (WR) and Lance formations within and near the Horse Creek watershed described in Boughton (2012). Wells are identified by station code in Figure 2.**

| Formation | Arikaree | | | | WR-Brule | |
|---|---|---|---|---|---|---|
| Station | A6L | A7L | A8L | A9P | B1G | B8L |
| USGS ID | 411522104243401 | 411930104210101 | 412534104285001 | 414516104442601 | 413756104095601 | 411953104070301 |
| Latitude | 41.25606 | 41.32508 | 41.42622 | 41.75444 | 41.63211 | 41.33144 |
| Longitude | -104.4094 | -104.3503 | -104.4804 | -104.7406 | -104.1655 | -104.1174 |
| Elevation (ft) | 5610 | 5588 | 5753 | 5453 | 4586 | 5324 |
| Depth (ft) | 260 | 250 | 380 | 165 | 100 | 220 |
| Water Level (ft) | 91.9 | 165.0 | 146.0 | 61.0 | 50.0 | 126.9 |
| Aluminum, Diss. (µg/L) | <100 | <100 | <100 | <2.2 | <100 | <100 |
| Aluminum, Tot. (µg/L) | <100 | <100 | <100 | <3.8 | <100 | <100 |
| Arsenic, Diss. (µg/L) | <4 | <4 | <4 | 9 | <4 | <4 |
| Arsenic, Tot. (µg/L) | 6.5 | <4 | <4 | 9.6 | 5.2 | 7 |
| Bicarbonate (mg/L) | 148 | 141 | 166 | 166 | 284 | 131 |
| Calcium, Diss. (mg/L) | 40 | 42 | 45 | 86.2 | 62 | 47 |
| Carbonate (mg/L) | 0 | 0 | 0 | 0 | 0 | 0 |
| Chloride (mg/L) | 3 | 12 | 5.1 | 48.9 | 8.6 | 11 |
| Hardness, Tot. (mg/L as CaCO3) | 131 | 145 | 150 | 346 | 211 | 169 |
| Iron, Diss. (µg/L) | <100 | <100 | <100 | <3.2 | <100 | <100 |
| Iron, Tot. (µg/L) | <100 | <100 | <100 | <3.2 | <100 | <100 |
| Magnesium, Diss. (mg/L) | 7.7 | 9.9 | 9 | 31.5 | 13 | 12 |
| Nitrate-N (µg/L) | 1500 | 3600 | 4900 | 10800 | 1900 | 5300 |
| Oxygen, Diss. (mg/L) | 5.2 | 8.1 | 8.8 | 7.5 | 3.2 | 8.7 |
| pH | 7.5 | 7.7 | 7.4 | 7.6 | 7.5 | 7.5 |
| Potassium, Diss. (mg/L) | 4.5 | 5.3 | 5.2 | 5.58 | 6.2 | 5.8 |
| Sodium, Diss. (mg/L) | 10 | 12 | 11 | 30.8 | 25 | 20 |
| Specific Conductivity (µS/cm) | 315 | 333 | 335 | 735 | 529 | 425 |
| Sulfate (mg/L) | 7.6 | 26 | 8.4 | 146 | 29 | 25 |

| Formation | WR | WR-Chadron | | | Lance | | |
|---|---|---|---|---|---|---|---|
| Station | WR9L | C1G | C2G | C3G | L1G | L2G | L3G |
| USGS ID | 411340104203801 | 414948104065101 | 415028104042701 | 415425104062501 | 414907104155401 | 414940104183001 | 415641104045401 |
| Latitude | 41.22775 | 41.83014 | 41.84125 | 41.90692 | 41.81861 | 41.82789 | 41.94483 |
| Longitude | -104.3438 | -104.1141 | -104.0743 | -104.1069 | -104.265 | -104.3084 | -104.0816 |
| Elevation (ft) | 5500 | 4202 | 4184 | 4206 | 4320 | 4363 | 4142 |
| Depth (ft) | 320 | 138 | 85 | 180 | 100 | 100 | 88 |
| Water Level (ft) | 85.8 | 17.6 | 5.0 | 84.9 | 30.0 | 26.7 | 65.0 |
| Aluminum, Diss. (µg/L) | <100 | <100 | <100 | <100 | <100 | <100 | <100 |
| Aluminum, Tot. (µg/L) | <100 | <100 | <100 | <100 | 640 | <100 | <100 |
| Arsenic, Diss. (µg/L) | <4 | <4 | 8.9 | <4 | <4 | <4 | <4 |
| Arsenic, Tot. (µg/L) | <4 | <4 | 12.9 | <4 | <4 | <4 | <4 |
| Bicarbonate (mg/L) | 109 | 371 | 430 | 426 | 833 | 479 | 756 |
| Calcium, Diss. (mg/L) | 39 | 2.2 | 18 | 63 | 2.2 | 37 | 17 |
| Carbonate (mg/L) | 0 | 6 | 2 | 1 | 20 | 1 | 6 |
| Chloride (mg/L) | 2.4 | 5.7 | 24 | 55 | 3.8 | 18 | 37 |
| Hardness, Tot. (mg/L as CaCO3) | 127 | 7.63 | 60.3 | 285 | 8.02 | 156 | 73.1 |
| Iron, Diss. (µg/L) | <100 | <100 | <100 | <100 | <100 | <100 | <100 |
| Iron, Tot. (µg/L) | <100 | <100 | <100 | <100 | 1200 | <100 | <100 |
| Magnesium, Diss. (mg/L) | 7.1 | 0.507 | 3.5 | 30 | 0.596 | 15 | 7 |
| Nitrate-N (µg/L) | 1900 | <5 | 5400 | 6000 | <5 | 4300 | 1400 |
| Oxygen, Diss. (mg/L) | 6.8 | 0.1 | 0.6 | 3.7 | 0.1 | 3.5 | 6.3 |
| pH | 7.6 | 8.6 | 7.8 | 7.7 | 8.7 | 7.6 | 8.1 |
| Potassium, Diss. (mg/L) | 3.7 | 4.6 | 14 | 43 | 4.2 | 9.2 | 12 |
| Sodium, Diss. (mg/L) | 8.5 | 190 | 260 | 560 | 320 | 180 | 590 |
| Specific Conductivity (µS/cm) | 284 | 804 | 1330 | 2770 | 1230 | 984 | 2440 |
| Sulfate (mg/L) | 7.3 | 4.1 | 240 | 930 | 3.8 | 92 | 610 |

concentrations in calcium bicarbonate to sodium bicarbonate dominated groundwater of the Arikaree, White River and Lance formations (Bartos and Hallberg 2011, Libra et al. 1981) within the Horse Creek watershed range from 4-12.9 µg/L (mean: 5.6 µg/L) (Table 1). Concentrations of total and dissolved fractions of iron and aluminum in these groundwaters are generally non-detect (<100 µg/L). Rarely are arsenic concentrations in groundwaters appreciably >10 µg/L and where present are not necessarily related to arsenic concentrations in the geology but rather the geochemical conditions and past and present hydrogeology, many of which have been altered by human activities (Smedley and Kinniburgh 2002). These areas which include Bangladesh, China, Mexico, Vietnam and the southwestern United States are characterized by arsenic concentrations in groundwater chronically >50 µg/L.

## 7. ARSENIC RELEASE MECHANISMS AND TRANSPORT

Arsenic occurs primarily in two oxidation states, As-V (arsenate) and As-III (arsenite) (Smedley and Kinniburgh 2002). Both forms typically co-exist, although arsenate predominates under oxidizing conditions whereas arsenite occurs under anaerobic reducing conditions. In acidic to slightly alkaline (up to pH 8) environments, both arsenate and arsenite strongly adsorb to oxides of iron and aluminum that are insoluble in sedimentary formations and soils. Arsenic also adsorbs to insoluble sulfide minerals (pyrite) commonly found in shales or coal lenses of some geological formations (Smedley and Kinniburgh 2002). Releases of arsenic from these metal oxides and sulfide minerals is controlled by oxidation-reduction (redox) state, pH and of course the degree of interaction with water. The release of arsenic from metal oxides or pyrite to a soluble (and mobile) aqueous phase can be triggered by way of four general mechanisms each occurring under specific chemical conditions: pH enhanced oxidative desorption, competitive ion displacement, evaporative enrichment or reductive dissolution which are described below.

pH Enhanced Oxidative Desorption - Under oxidizing conditions with elevated pH (>8.5), solid phase arsenic becomes less strongly sorbed and is released from iron and aluminum oxide complexes through desorption (Dixit and Hering 2003, Smedley and Kinniburgh 2002). Upon release from these metal oxides, arsenic becomes soluble and readily transported. An increase in pH is commonly associated with increased salinity. Under these same conditions, pyrite may oxidize to iron oxides coincident with release of soluble sulfate and arsenic acids (Smedley and Kinniburgh 2002).

Competitive Ion Displacement – Oxidative desorption of arsenic from metal oxides to a soluble phase is promoted through competitive ion displacement with elevated concentrations of phosphate or bicarbonate, since both are chemical analogs to arsenic and strongly bound to iron oxides under elevated pH (Anawar et al. 2004, Camacho et al. 2011, DeVore et al. 2019, Dietrich et al. 2016, Smedley and Kinniburgh 2002, Strawn 2018). Arsenic solubility also is influenced by the presence of nitrate which causes the formation of iron oxides and adsorption of arsenic to those oxides (Hohn et al. 2006, Peters 2008, Senn and Hemond 2002). Other studies have found that in alkaline environments, calcium increases arsenic (as well as phosphate) adsorption whereas sodium increases desorption from mineral oxides (Jia and Demoupoulous 2005, Scanlon et al. 2009, Smedley and Kinniburgh 2002). Consequently, elevated concentrations of nitrate or calcium can correspond with low soluble arsenic concentrations due to binding with iron oxides.

Reductive Dissolution – A change from aerobic to anaerobic conditions will cause a reduction of arsenate to arsenite, which promotes arsenic desorption since arsenite is generally less strongly adsorbed to metal oxides than arsenate. This co-occurs with a reduction of sulfate and/or ferric iron Fe(III). As reducing conditions become more pronounced, dissolution of arsenic-oxide complexes occur resulting in the increased solubility of both arsenic and iron (Rawson et al. 2016, Smedley and Kinniburgh 2002, Voegelin et al. 2019) making them mobile. Under reducing conditions, increases in salinity can further promote arsenic desorption particularly around circum-neutral pH, though in oxygenated environments, salinity has no effect on arsenic desorption from mineral oxides (Vengosh 2014).

Evaporative Enrichment – Evaporative enrichment causes the accumulation of soluble arsenic and other co-occurring constituents, which are transported by water. This may be particularly important in semi-arid areas with shallow water-tables or where there are frequent cycles of saturation followed by drying (Busbee et al. 2009, Camacho et al. 2011, Smedley and Kinniburgh 2002). The frequent saturation-drying cycles increase arsenic, sodium, chloride and bicarbonate concentrations as well as pH thereby promoting additional release of soluble arsenic from metal oxides through oxidative desorption along with competitive ion displacement.

Though these mechanisms can release soluble arsenic into groundwater from sedimentary formations, they are rate-limited in aquifers through natural controls on diffusion of dissolved oxygen and changes in pH. The result is a slow but consistent release of arsenic to groundwater over geologic time scales and arsenic concentrations in groundwater remain relatively consistent over time absent wide-spread hydrogeologic alterations. Consequently, in spring-fed streams where groundwater is the dominant source of both flow and arsenic, stream arsenic concentrations should exhibit near chemostatic behavior. Under chemostatic conditions, concentrations of a constituent vary minimally across large variations in stream flow (Godsey 2009). Because Horse Creek and its perennial streams are naturally spring-fed, groundwater contributions represent the dominant conveyor of natural arsenic.

As mentioned earlier, arsenic is common in the soils of the Horse Creek watershed and under natural conditions much of the soil arsenic would be insoluble and immobile (except for those areas adjacent to surface waters) due to the strong adsorption to metal oxides and limited interaction with water in the semi-arid environment. However, given their abundance in iron and aluminum oxides with adsorbed arsenic, the soils of the Horse Creek watershed provide a readily available source of arsenic to surface waters given the appropriate chemical and hydrological conditions. In addition, the fate and transport of soil and weathered materials from sedimentary formations that are contained in fluvial sediment is a fifth mechanism for the release and transport of natural arsenic.

## 8. HUMAN SOURCES OF ARSENIC

Anthropogenic sources of arsenic include pesticides, mine tailings, smelting operations, fly ash sediments from coal combustion, wood preservatives, sewage sludge application, and antibiotic byproducts in poultry waste (Punshon et al. 2017). Of these, the most probable non-natural human source of arsenic in the Horse Creek watershed is historical application of arsenical pesticides. Both calcium and lead arsenate were used extensively as agricultural pesticides in the United States during the first half of the 20$^{th}$ century

though decreased after the 1950s and eventually banned from use in 1988 (Punshon et al. 2017). These pesticides were used on a range of crops though most commonly applied to fruit trees, berries, potatoes, vegetables and cotton. Residual arsenate has a long residence time and where applied, is almost entirely retained within soils (Peryea and Creger 1994). There is no information available on the quantities or locations of historical arsenical pesticide application in the Horse Creek watershed though it is presumed these pesticides were applied to irrigated soils in the watershed.

With regard to point sources of pollution, there are only four Wyoming Pollutant Discharge Elimination System (WYPDES) permitted point source discharges in the Horse Creek watershed (Figure 3) represented by three confined animal feeding operations (CAFO) (Permits WY0035769, WY0094935 and WY0095371) and one gravel quarry (Permit WY0053457). These facilities only discharge to surface waters under emergency conditions and none are considered sources of arsenic.

Though the addition of non-natural human sources of arsenic to the Horse Creek watershed are limited, of perhaps greater importance are human activities that could trigger the release and transport of arsenic from its natural immobile solid phase in the sedimentary formations and soils of the watershed. Of the two natural sources, the soils of the Horse Creek watershed (and by extension fluvial sediments or those sediments transported by streams) are perhaps the most vulnerable to human caused arsenic release and transport. As mentioned earlier, human alterations to groundwater contributions from the underlying sedimentary formations appear largely negligible with the possible local exception being the area near the Town of La Grange.

Potential human factors of importance include water distribution and artificial recharge associated with irrigated agriculture and reservoir storage. Examples of artificial recharge include infiltration of water below the root zone in irrigated soils, and infiltration below canals, ditches and reservoirs. The increase in recharge and redistribution of water in a semi-arid landscape that naturally receives minimal recharge may result in increased saturated areas, increased discharges (e.g. seeps) to drains and streams, and increased evaporative accumulation. Combined, such factors create conditions in the soils that trigger the release of natural arsenic into a soluble form that leaches from soils directly to streams or indirectly via alluvial aquifers and shallow saturated areas. Consequently, release of residual arsenic in the soils from historical pesticide application would occur.

The storage and release of soils and weathered sedimentary bedrock contained in fluvial sediments also functions as a human induced arsenic release and transport mechanism. The redox state of a reservoir and the amount of organic material found within may promote arsenic release from any impounded fluvial sediments (Clement and Faust 1981, Whitmore et al. 2008). Additionally, arsenic that remains adsorbed to metal oxides in fluvial sediments can be transported to downstream surface waters during a reservoir release. Sediment-bound arsenic discharged from canals and ditches or contained within runoff from erodible lands eventually will reach streams and be transported as part of the larger fluvial sediment load.

# 9. METHODS AND ANALYTICAL APPROACHES

## 9.1 Study Area

The study area begins just upstream of the Interstate-25 crossing of Horse Creek and extends downstream approximately 160 stream miles to the Wyoming/Nebraska stateline (Figure 1). The study area also includes a 52-mile segment of Bear Creek from the confluence with Little Bear Creek downstream to its confluence with Horse Creek, and an 18-mile segment of Dry Creek from Hawk Springs Reservoir dam downstream to its confluence with Horse Creek.

## 9.2 Site Selection and Assessment Zones

A network of 15 sites represent arsenic conditions among the primary perennial streams of the Horse Creek watershed (Table 2). Monitoring sites account for potential changes in water quality due to influences from major perennial tributaries, land uses (e.g., rangeland grazing, irrigated lands, municipalities), diversions and trans-basin inputs, and bedrock geology to effectively 'bracket' potential causes and sources of arsenic. This bracketing partitioned the study area into five assessment zones each with unique combinations of natural and anthropogenic characteristics: *Above 85*, *Above Hawk*, *Hawk-Fl*, *Below Fl* and *Dry* (references to assessment zones are italicized throughout the report). *Above 85* represents Horse Creek and Bear Creek upstream of U.S. Highway 85 where the flow regime is largely natural and dependent on groundwater contributions, irrigated agriculture along with diversions are limited, and rangeland activities are common. *Above Hawk* captures Horse and Bear Creeks from U.S. Highway 85 downstream to the diversion for the Hawk Springs Reservoir supply canal. *Above Hawk* represents groundwater contributions, rangeland activities, irrigated agriculture, diversions and localized influences near the town of La Grange. The third zone *Hawk-Fl* represents Horse Creek from the Hawk Springs Reservoir supply canal diversion downstream to the entry point of Fort Laramie Canal water into Horse Creek. The *Hawk-Fl* segment captures influences from irrigated agriculture, the greatest number of diversions in the watershed for irrigation and storage in Bump-Sullivan and Goshen Hole Reservoirs, seepage and return flows along the canal network, and groundwater contributions. The *Below Fl* zone represents the remainder of Horse Creek downstream to the Wyoming/Nebraska stateline and captures the influences of North Platte River water from the Fort Laramie Canal, seepage and return flows along the canal network, diversions, irrigated agriculture, rangeland activities and contributions from Dry Creek and groundwater. The final *Dry* zone represents Dry Creek from immediately below the Hawk Springs Reservoir north dam downstream to the confluence with Horse Creek. This zone captures seepage from Hawk Springs Reservoir, groundwater contributions, rangeland activities, irrigated agriculture, trans-basin inputs from the Fort Laramie Canal, diversions, and outflows from the Table Mountain WHMA.

**Table 2 – Descriptive information for WDEQ/WQD Horse Creek, Bear Creek and Dry Creek monitoring sites. Sites are also categorized by Assessment Zone and identified by the Map IDs shown in Figure 3.**

| Site Name | Site ID | Map ID | Assess-ment Zone | Latitude | Longitude | Catch-ment ($mi^2$) | Elevation (ft) | Legal (Sec/T/R) | Years Monitored | Parameters Collected |
|---|---|---|---|---|---|---|---|---|---|---|
| Horse Creek - Rd 232 | WHP0063 | 1 | Above 85 | 41.467222 | -104.862778 | 226 | 5907 | SWSW Sec. 2, T17N, R67W | 2019 2020 | a |
| Horse Creek - Bullwhacker | WHP0057 | 2 | | 41.504745 | -104.543047 | 321 | 5290 | NENW Sec. 28, T18N, R64W | 2019 2020 | a, b |
| Bear Creek - Blw Little Bear Ck | WHP20 | 5 | | 41.616056 | -104.609575 | 287 | 5145 | NESW Sec. 13, T19N, R65W | 2019 2020 | a |
| Horse Creek - Hwy 85 | WHP0064 | 3 | Above Hawk | 41.541667 | -104.319720 | 426 | 4934 | NESW Sec. 9, T18N, R62W | 2019 2020 | a |
| Horse Creek - County Line | WHP0065 | 4 | | 41.572778 | -104.144167 | 595 | 4670 | SENW Sec. 36, T19N, R61W | 2019 2020 | a |
| Horse Creek - Rd 14 | WHP0067 | 7 | | 41.651667 | -104.188056 | 637 | 4546 | SWSW Sec. 34, T20N, R61W | 2019 2020 | a, b |
| Bear Creek - 85 / 151 | WHP0066 | 6 | | 41.641667 | -104.241667 | 530 | 4605 | NWSW Sec. 6, T19N, R61W | 2019 2020 | a |
| Horse Creek - DurocB | WHP0068 | 8 | Hawk - FI | 41.752778 | -104.223611 | 1235 | 4380 | NWNW Sec. 32, T21N, R61W | 2019 2020 | a, b |
| Horse Creek - Rd 42 | WHP0069 | 9 | | 41.856110 | -104.262778 | 1330 | 4242 | NWNW Sec. 25, T22N, R62W | 2019 2020 | a, b |
| Horse Creek - Blw EGHD | WHP0070 | 10 | Below FI | 41.905689 | -104.228545 | 1340 | 4206 | NESE Sec. 6, T22N, R61W | 2019 2020 | a |
| Horse Creek - Rd 53 | WHP0072 | 11 | | 41.872535 | -104.150670 | 1495 | 4130 | SESE Sec. 14, T22N, R61W | 2019 2020 | a, b |
| Horse Creek - Rd 48 | WHP0073 | 12 | | 41.899730 | -104.086160 | 1587 | 4086 | NENW Sec. 9, T22N, R60W | 2019 2020 | a |
| Dry Creek - Rd 32 | WHP0075 | 15 | Dry | 41.784020 | -104.175200 | 38 | 4300 | SWSE Sec. 15, T21N, R61W | 2020 | a |
| Dry Creek - Rd 40 | WHP0076 | 14 | | 41.843615 | -104.139212 | 69 | 4172 | SWSE Sec. 25, T22N, R61W | 2020 | a |
| Dry Creek - Mouth | WHP0071 | 13 | | 41.869440 | -104.147780 | 77 | 4133 | NWNW Sec. 24, T22N, R61W | 2019 2020 | a, b |

[a] T. alkalinity, D. and T. aluminum, ammonia-N, D. and T. arsenic, calcium, chloride, T. hardness, D. and T. iron, magnesium, nitrate+nitrite-N, T. nitrogen, dissolved oxygen, pH, T. phosphorus, potassium, sodium, specific conductivity, sulfate, total dissolved solids, temperature, total suspended solids, stream discharge

[b] D. and T. arsenic (V) and arsenic (III)

## 9.3 Study Design

The Horse Creek assessment uses a gradient study design to detect spatial changes in water quality within a large watershed. This study design also determines broad-scale sources and relative scales of pollutant

impact. Repeated sampling over two years also allows for evaluation of variability in pollutants at individual sites. Among the five zones for the Horse Creek assessment, the *Above 85* zone represents least-impacted reference conditions regarding arsenic concentrations due to limited anthropogenic activities in this zone that may contribute arsenic.

### 9.4 Data Collection

Data collection and analytical methods used in this project were conducted in accordance with approved standard operating procedures established by the WDEQ/WQD (2021a). All data for the Horse Creek assessment were collected synoptically approximately monthly from May to October in 2019 and 2020. Eleven synoptic sample events resulted in 148 samples collected over the two-year period. A list of parameters collected at each site along with descriptions and references to associated sample and analytical methods can be found in the WDEQ/WQD Evaluation of Arsenic in Horse Creek and Tributaries, Goshen and Laramie Counties, Wyoming Sampling and Analysis Plan for 2019-2020 (WDEQ/WQD 2020a). Any data that did not meet quality assurance/quality control standards (WDEQ/WQD 2021b) were noted in this report. Otherwise, data were determined to be complete and accurate.

### 9.5 Data Analysis

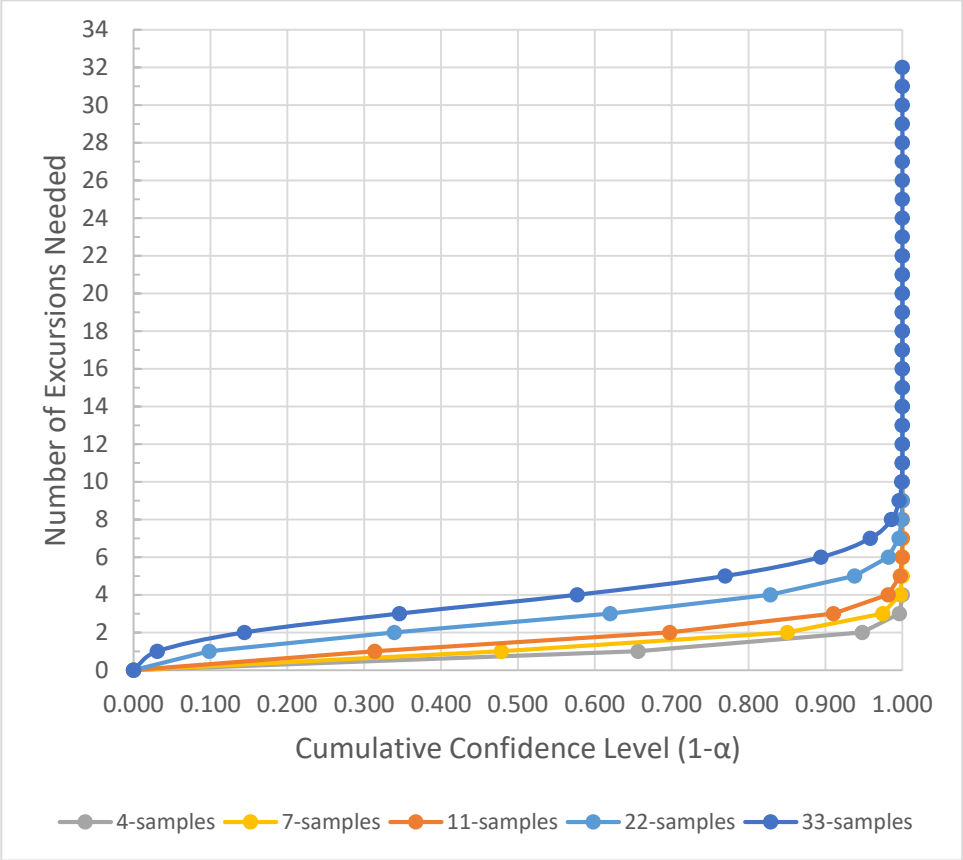
The WDEQ/WQD determines compliance with applicable numeric and narrative surface water quality criteria (WDEQ/WQD 2018) through an evaluation of 'credible data' using a multiple lines of evidence approach (WDEQ/WQD 2020b). The foundation of this approach involves a comparison of data to State surface water numeric criteria for arsenic (as well as other pollutants) to determine water quality standards attainment. Where arsenic exceeded the applicable numeric criteria, further analysis was necessary to determine whether the arsenic originated from groundwater contributions, soil leaching or fluvial sediment.

As described in Section 7, there are five mechanisms by which arsenic in soils (and weathered bedrock sediments) could be released and transported through interactions with water, each characterized by specific chemical and physical conditions. The physicochemical signatures of these mechanisms inform evaluations of both surface and groundwater chemistries of the Horse Creek watershed using three analytical methods (Spearman correlations, principal components analysis and Piper diagrams). The evidence derived from these methods are used to infer the sources and release mechanisms from which arsenic in surface water originates as well as potential human factors that contribute to arsenic release if soil or fluvial sediment are implicated. Explanations on comparisons to surface water numeric criteria and how the three analytical methods can be used to infer arsenic sources and causes as described below.

*State Numeric Criteria* - Water chemistry results were compared to relevant State acute and/or chronic numeric criteria protective of aquatic life and human health uses on Class 2 waters found in Chapter 1 of the Wyoming Water Quality Rules (WDEQ/WQD 2018). Samples with concentrations higher than the criterion are referred to as excursions. Using the BINOM.DIST function in Excel®, a binomial distribution curve was developed to determine the minimum number of excursions needed for multiple samples sizes to conclude with 90% confidence that the percentage of excursions is greater than 10% (Figure 7). For purposes of this report an occurrence of excursions greater than 10% of the time would be considered an exceedance of a numeric criterion. This 10% threshold is based on USEPA guidance that indicates that a

criterion should not be exceeded more than once every three years on average. According to USEPA (2002), 1-in-3-year average frequency can mean that the number of excursions must be less than 10% of the time to maintain the desired level of protection for the use.

**Figure 7 – Cumulative binomial distribution curves for multiple sample sizes to determine the minimum number of excursions needed for exceedance of a criterion more than 10% of the time with 90% confidence (α = 0.05).**




*Spearman Correlations* – The strength and direction of associations between total arsenic and 18 water chemistry parameters was evaluated with Spearman rank order correlations for each of the five assessment zones. The 18 water chemistry parameters were pH, chloride, sulfate, calcium, magnesium, potassium, sodium, dissolved and total aluminum, dissolved arsenic, dissolved and total iron, bicarbonate, nitrate+nitrite-N, TSS, stream discharge, total nitrogen and total phosphorus. A positive correlation indicates the response variable (e.g. arsenic) increases as the explanatory variable increases whereas a negative correlation indicates an inverse relationship. Significant ($p < 0.05$) correlations with r values ≥ 0.7 were considered strong associations. Strong correlations do not indicate causality though can provide insight into possible arsenic sources and release mechanisms particularly when evaluated against groundwater. To conduct comparisons against groundwater, correlations were performed on groundwater data collected from wells in the watershed (Table 1). To evaluate the influence of flow augmentation on the associations of arsenic with other water quality parameters, separate correlations were performed for samples collected when flow augmentation was occurring and for samples where

stream flows were not influenced by augmentation. These additional correlations were conducted only for samples collected from sites within the *Below FI* and *Dry* zones where stream flows can be augmented by releases from the Fort Laramie Canal. Samples were identified as flow augmented when flows were recorded in the Fort Laramie Canal (based on WSEO gauge 0114FCWY http://seoflow.wyo.gov/) and when flow was observed in the canal within the study area on the days of collection. Spearman rank correlations were performed in STATISTICA®.

*Principal Component Analysis* – Principal component analysis (PCA) is a multivariate statistical method that combines multiple correlated explanatory variables into principal components (axes) to make interpretation of large datasets more practical and visually understandable. The strength of each variable along each principal component is provided by its loading value, which is a correlation coefficient between the original variable and the principal component. Variables that exhibited loading values >±0.3 were considered strong variables. Partial regression correlation coefficients ($r^2$) calculated between variable loadings and principal components are another means to evaluate the strength of each variable in structuring the distribution of samples along a principal component. Each principal component accounts for a proportion of the variance in the observed data and was used to determine the strength of observed patterns. PCA was performed on the Horse Creek study dataset with samples classified by assessment zone along with groundwater data from Table 1. Samples identified by assessment zone and groundwater wells were then plotted along the PCA axes. Variables with the highest loadings on each PCA axis are plotted as vectors. Each variable vector shows how strongly it influences a PCA axis and structures groups of samples. The further away the end of the variable vector is from the graph origin the greater the importance of that variable. Variable vectors with smaller angles relative to an axis implies a positive correlation with that axis. Also, the direction of a vector relative to other vectors indicates the degree of covariance (how two or more variables change together). The direction of the vector also reflects a concentration gradient with higher values closer toward the arrow and lower values opposite the direction of the arrow. Groupings of samples that plot in proximity to variable vectors are strongly structured by those variables. Groupings of samples along the principal components and variable vectors identify spatial patterns in arsenic concentrations as well as the most important combinations of variables that influence those patterns. Samples with similar concentrations of parameters cluster together whereas those with marked differences plot farther from one another. Information obtained from PCA was used to evaluate similarities between surface and groundwater as well as infer possible arsenic sources and release mechanisms. PCA was performed in PC-ORD®.

*Piper Diagram* – A Piper diagram was used to visually describe the major ionic composition of surface water among the five assessment zones along with comparisons to the groundwater chemistry of the watershed. Major ions included bicarbonate, calcium, carbonate, chloride, magnesium, sodium, and sulfate. The major ions were plotted on two trilinear diagrams as percentages of milliequivalents so that the total anions and cations sum to 100%. Samples that plot in any of the three outside quadrants of the trilinear diagrams are dominated by a particular anion or cation. Samples that plot in the middle of the trilinear diagrams do not have a dominant anion and/or cation. Datapoints from the two trilinear diagrams are then plotted on a diamond grid to show the combined cation/anion composition of each sample. Samples that plot in the upper one-half of the top quadrant represent calcium sulfate waters. The left

quadrant is for calcium or magnesium bicarbonate waters, the right quadrant for sodium chloride and the bottom one-half quadrant for sodium bicarbonate waters. Samples that plot in the lower one-half of the top quadrant or the upper one-half of the bottom quadrant do not have a definitive geochemical composition and are considered mixed. The diamond grid is useful to evaluate patterns in the geochemical properties of multiple samples. Samples with similar major ion chemistries tend to cluster together whereas those with different chemistries plot farther from one another. Piper diagram results are useful for developing inferences on the relative influence of groundwater on surface water chemistry. Piper diagrams were developed in Excel®.

## 9. RESULTS – COMPARISONS TO NUMERIC CRITERIA

### 9.1 Aluminum

With the exception of three samples, concentrations of dissolved aluminum in the remaining 145 samples throughout the study area were below the numeric criterion of 750 µg/L protective of aquatic life (WDEQ/WQD 2018) (Appendix 1). Excursions of the dissolved aluminum criterion occurred once at Horse Creek sites 'Blw EGHD' (1,239 µg/L) and 'Rd 53' (908 µg/L) though did not equate to an exceedance based on Figure 7 and the total sample sizes of 11 for each site. The excursion of 846 µg/L at Dry Creek-Rd 32 was not considered an exceedance as this was the only sample collected from this site.

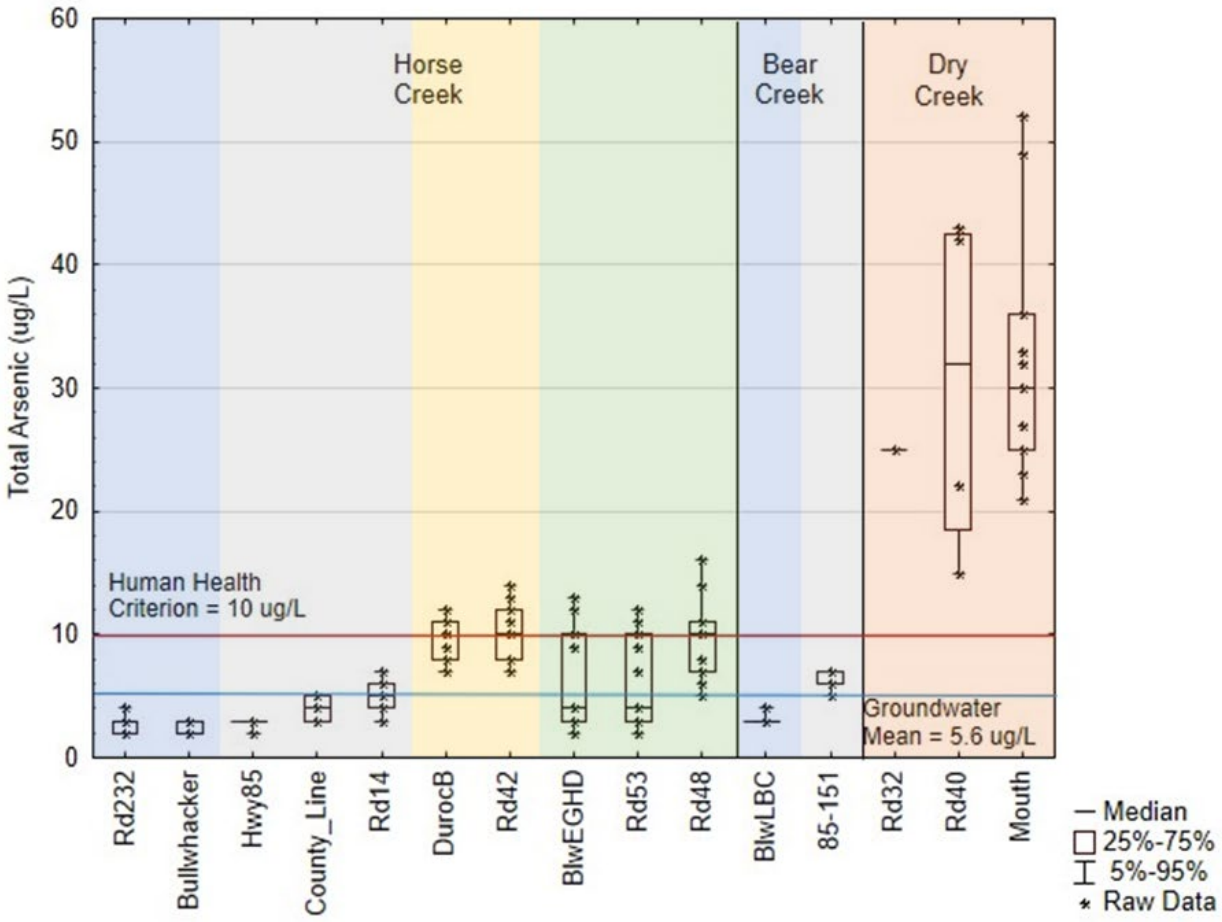
### 9.2 Ammonia-N

Table a(ii) of Appendix C in Chapter 1 of the Wyoming Water Quality Rules (WDEQ/WQD 2018) was used to determine excursions of the ammonia-N criterion. Assuming that early life stages of fish had the potential to be present at every site on each sampling event for the Horse Creek study, there were no excursions of the ammonia-N criterion. In fact, approximately 93% of ammonia-N concentrations among sites were below detection (<0.05 mg/L).

### 9.3 Arsenic

Average concentrations of total arsenic increased with distance downstream in Horse, Bear and Dry Creeks (Figure 8). The *Above 85* zone (sites 'Rd 232', 'Bullwhacker' and 'Blw Little Bear Ck') exhibited minimal variation in total arsenic with concentrations ranging from 2-4 µg/L (mean: 2.8 µg/L) (Figure 8, Appendix 1). Total arsenic in *Above Hawk* (sites 'Hwy 85', 'County Line', 'Rd 14' and '85-151') were similar to *Above 85* with concentrations of 2-7 µg/L (mean: 4.4 µg/L) (Appendix 1). Concentrations of total arsenic within *Hawk-Fl* (sites 'DurocB' and 'Rd 42') were more variable relative to upstream zones and at least partially associated with diversions into and releases out of Hawk Springs Reservoir. When outflows from Hawk Springs Reservoir were supplying the irrigation canal network within *Hawk-Fl*, total arsenic concentrations were 9-14 µg/L (mean: 11 µg/L) and slightly greater compared to when reservoir outflows were not occurring (7-11 µg/L, mean: 10 µg/L) (Appendix 1). All samples in *Hawk-Fl* were above the average groundwater concentration of 5.6 µg/L.

**Figure 8 – Total arsenic concentrations at monitoring sites on Horse, Bear and Dry Creeks in 2019-2020. Sites on the x-axis are ordered from upstream (left side) to downstream (right side). Mean groundwater concentrations from Table 1 noted by the blue line. The total arsenic human health criterion for arsenic is noted by the red line. Assessment zones are color coded: *Above 85* (purple), *Above Hawk* (gray), *Hawk-Fl* (yellow), *Below-Fl* (green) and *Dry* (red)**




Arsenic concentrations within the *Below Fl* assessment zone (sites 'Blw EGHD', 'Rd 53' and 'Rd 48') were the most variable relative to other assessment zones due to the dilution effect of trans-basin water entering from the Fort Laramie Canal. When the Fort Laramie Canal was active, total arsenic concentrations within *Below-Fl* ranged from 2 to 9 µg/L (mean: 4 µg/L) (Appendix 1). When the Fort Laramie Canal was inactive, total arsenic concentrations within *Below Fl* increased appreciably to a range of 9-16 µg/L (mean: 11 µg/L). Most samples in *Below Fl* were above the average groundwater concentration of 5.6 µg/L.

Total arsenic concentrations within the *Dry* zone (sites 'Rd 32', 'Rd 40' and 'Mouth) were the highest recorded in the study area and ranged from 15 to 49 µg/L (Appendix 1). Dilution effects from the Fort Laramie Canal inputs were also observed at Dry Creek sites below the canal ('Rd 40' and 'Mouth) with total arsenic concentrations of 15-42 µg/L (mean: 27 µg/L) during flow augmentation and 30-52 µg/L (mean: 40 µg/L) when the canal was inactive (Appendix 1). All samples in *Dry* were above the average groundwater concentration of 5.6 µg/L.

With respect to the 10 µg/L arsenic criterion protective of human health, concentrations of total arsenic from all samples collected within the *Above 85* and *Above Hawk* zones were below the criterion (Appendix 1). However, there were multiple excursions of the 10 µg/L human health arsenic criterion among all sites within the *Hawk-Fl*, *Below Fl* and *Dry* assessment zones over the two-year study period (Appendix 1). Excursions ranged from 11-14 µg/L within *Hawk-Fl* and 11-13 µg/L within *Below-Fl*. All samples collected within *Dry* were above the 10 µg/L criterion and ranged from 15-49 µg/L. The total number of excursions within each of the *Hawk-Fl*, *Below Fl* and *Dry* (with the exception of site 'Rd 32') zones and for most sites within each of these assessment zones, met the sample-size dependent minimum number of excursions (Figure 7) for a criterion exceedance. This indicates that with 90% confidence, total arsenic concentrations within these three assessment zones exceeded the 10 µg/L total arsenic criterion more than 10% of time.

Concentrations of dissolved arsenic for all samples collected within the study area were below the numeric arsenic chronic criterion of 150 µg/L protective of aquatic life (WDEQ/WQD 2018). The majority of total arsenic within all five assessment zones was comprised of the dissolved fraction with increases in the particulate form generally coincident with increased suspended sediment (as measured by TSS).

Arsenic speciation analysis for select samples indicated that arsenate (As-V) was the dominant form of arsenic in surface waters of the study area (Appendix 1).

### 9.4 Chloride

Concentrations of chloride generally increased with distance downstream in Horse, Bear and Dry Creeks and ranged from 5 to 56 mg/L (Appendix 1). Average chloride concentrations by zone were 7 mg/L (*Above 85*), 6 mg/L (*Above Hawk*), 16 mg/L (*Hawk-Fl*), 19 mg/L (*Below Fl*) and 38 mg/L (*Dry*). For all samples collected within the study area, chloride concentrations were below the numeric chloride chronic criterion of 230 mg/L protective of aquatic life (WDEQ/WQD 2018).

### 9.5 Iron

Similar to previous parameters, concentrations of dissolved and total iron generally increased with distance downstream in Horse, Bear and Dry Creeks and ranged from <30 to 1,069 µg/L (Appendix 1). Average dissolved/total iron concentrations by zone were 43/173 µg/L (*Above 85*), 54/917 µg/L (*Above Hawk*), 64/1,277 µg/L (*Hawk-Fl*), 111/928 µg/L (*Below Fl*) and 213/1375 µg/L (*Dry*). There was only one excursion of the 1,000 µg/L criterion protective of aquatic life (WDEQ/WQD 2018) at Horse Creek 'Below EGHD'. Excursions of the 300 µg/L criterion protective of human health occurred on Horse Creek at 'Below EGHD' and 'Rd 53'.

### 9.6 Nitrate+Nitrite-N

Nitrate+nitrite-N concentrations were variable at most sites throughout the two-year study and ranged from <50 to 1,110 µg/L (Appendix 1). These concentrations were all below the numeric nitriate+nitrite-N criterion of 10,000 µg/L protective of human health (WDEQ/WQD 2018). The highest average concentration of nitrate+nitrite-N occurred on Horse Creek at 'County Line' (839 µg/L) and the lowest at 'Rd 232' (70 µg/L). Average nitrate+nitrite-N concentrations by zone were 342 µg/L (*Above 85*), 518 µg/L (*Above Hawk*), 433 µg/L (*Hawk-Fl*), 195 µg/L (*Below Fl*) and 123 µg/L (*Dry*). Dilution effects associated with

augmented flows from the Fort Laramie Canal likely contributed to the lower average concentrations within *Below Fl* relative to other zones in the study area.

### 9.7 Dissolved Oxygen

Among sites located within the Class 2AB segment of Horse Creek ('Rd 232', 'Bullwhacker' and 'Hwy 85') and Bear Creek, single-sample dissolved oxygen concentrations in both years were generally above the 4 mg/L and 8 mg/L one-day minimum criteria protective of a Class 2AB cold-water fishery for adult and early life stages, respectively (WDEQ/WQD 2018) (Appendix 1). Though some site-level excursions of either criterion were present, only at 'Rd 232' on Horse Creek (five excursions ranging from 2.2 to 7.1 mg/L) was an exceedance of the 8 mg/L criterion identified. However, the criterion exceedance at 'Rd 232' was likely associated with outflows of less oxygenated water from beaver ponds immediately upstream of the sample location that were often stagnant over the study period and not due to anthropogenic activities. For the remainder of the Class 2ABww Horse Creek and Class 2C Dry Creek, single-sample dissolved oxygen concentrations in both years were above the 3 mg/L and 5 mg/L one-day minimum criteria protective of warm-water and non-game fisheries for adult and early life stages, respectively (WDEQ/WQD 2018).

### 9.8 pH

With three exceptions, instantaneous pH at all sites in both years were within the criterion range of 6.5-9.0 protective of aquatic life and human health (WDEQ/WQD 2018) (Appendix 1). Though two excursions of the criterion occurred at 'Bullwhacker' (9.32 and 9.34) and one excursion at 'Rd 42' (9.18), both on Horse Creek, neither constituted an exceedance of the criterion. In all three cases, the pH excursions were likely the result of high photosynthetic activity at mid-day (when samples were collected) from abundant macrophytes in the channel. Average pH by zone was 8.31 (*Above 85*), 8.49 (*Above Hawk*), 8.53 (*Hawk-Fl*), 8.28 (*Below Fl*) and 8.30 (*Dry*).

### 9.9 Temperature

Among sites located within the Class 2AB segment of Horse Creek ('Rd 232', 'Bullwhacker' and 'Hwy 85') and Bear Creek, excursions of the maximum 20°C criterion protective of a cold-water game fishery (WDEQ/WQD 2018) occurred at most sites (Appendix 1). Excursions ranged from 0.1 to 7.7°C above the criterion with the largest and greatest number of excursions at 'Hwy 85' on Horse Creek and on Bear Creek at '85/151'. These excursions resulted in exceedances of the 20°C criterion at both 'Hwy 85' and '85/151'. The exceedance at 'Hwy 85' was likely associated with withdrawal of surface water a short distance upstream whereas irrigation return flows are presumably responsible for the exceedance at '85/151'. Throughout the remainder of the Class 2ABww Horse Creek and Class 2C Dry Creek, instantaneous water temperatures were all below the maximum 30°C criterion protective of warm-water and non-game fisheries (WDEQ/WQD 2018).

### 9.10 Total Nitrogen and Total Phosphorus

Total nitrogen varied considerably within the study area over the two-year period and ranged from 200 to 1,500 µg/L (Appendix 1). The highest average concentration of total nitrogen occurred on Horse Creek at 'County Line' (1,076 µg/L) with the lowest at 'Rd 232' (313 µg/L). Average total nitrogen concentrations by zone were 553 µg/L (*Above 85*), 794 µg/L (*Above Hawk*), 1,003 µg/L (*Hawk-Fl*), 619 µg/L (*Below Fl*) and 1,019 µg/L (*Dry*). Approximately 64% of the total nitrogen within *Above 85* and *Above Hawk* was

represented by nitrate+nitrate-N and to a lesser extent ammonia-N. The approximate proportion of these nitrogenous compounds that makeup total nitrogen for the other three zones is 48% for *Hawk-Fl*, 39% for *Below Fl* and 18% in *Dry*. This indicates that much of the total nitrogen in these three zones was organic and existed either in dissolved form or attached to organic materials. The dissolved form can originate from organic decomposition, soil leachate, nitrogenous animal waste or atmospheric deposition.

A similar pattern was observed for total phosphorus with concentrations that ranged from 10 to 560 µg/L (Appendix 1). The highest average concentration of total phosphorus occurred on Dry Creek at 'Mouth' (212 µg/L) and the lowest at 'Bullwhacker' on Horse Creek (10 µg/L). Average total phosphorus concentrations by zone were 16 µg/L (*Above 85*), 39 µg/L (*Above Hawk*), 88 µg/L (*Hawk-Fl*), 47 µg/L (*Below Fl*) and 203 µg/L (*Dry*).

Dilution effects associated with augmented flows from the Fort Laramie Canal likely contributed to the lower average concentrations of both total nitrogen and total phosphorus within *Below Fl* relative to other zones in the study area. The WDEQ/WQD has no numeric water quality criteria for total phosphorus or total nitrogen protective of designated uses.

### 9.11 Other Major Ions, TDS and TSS

Mimicking chloride, concentrations of sodium increased with distance downstream (Appendix 1). Average concentrations of sodium among the five assessment zones were 20 mg/L (*Above 85*), 25 mg/L (*Above Hawk*), 90 mg/L (*Hawk-Fl*), 111 mg/L (*Below Fl*) and 288 mg/L (*Dry*). The spatial patterns among assessment zones for both potassium and sulfate concentrations were similar to sodium and chloride. Average concentrations of sulfate were 29 mg/L (*Above 85*), 18 mg/L (*Above Hawk*), 53 mg/L (*Hawk-Fl*), 155 mg/L (*Below Fl*) and 258 mg/L (*Dry*). Average potassium concentrations were 6 mg/L (*Above 85* and *Above Hawk*), 14 mg/L (*Hawk-Fl*), 11 mg/L (*Below Fl*) and 20 mg/L (*Dry*). Among the five assessment zones, there was minimal variation in average concentrations of both calcium (range: 46-62 mg/L) and magnesium (range: 13-19 mg/L). The largest proportion of the total dissolved solids (TDS) for each sample was generally represented by sodium, chloride and sulfate. Consequently, the spatial pattern for TDS concentrations among the five assessment zones was similar to these three ions.

Total suspended solids (TSS), a measure of both organic and inorganic suspended particles in the water column, ranged from 2 to 713 mg/L across sites for the two-year study period and tended to increase with distance downstream (Appendix 1). Average TSS concentrations among the five zones with 14 mg/L (*Above 85*), 51 mg/L (*Above Hawk*), 73 mg/L (*Hawk-Fl*), 52 mg/L (*Below Fl*) and 39 mg/L (*Dry*). TSS concentrations in *Below Fl* were influenced by dilution effects from Fort Laramie Canal inputs to Horse Creek. Higher concentration in *Hawk-Fl* may be associated with contributions from return flows and drains.

### 9.12 Numeric Criterion Exceedances of Concern

Based on the multiple lines of chemical evidence, exceedances of the total arsenic criterion protective of human health occurred in assessment zones *Hawk-Fl*, *Below Fl* and *Dry*. Though instantaneous water temperatures at Horse Creek 'Rd 232' and 'Hwy 85' and Bear Creek '85-151' exceeded the numeric criterion protective of cold-water fisheries, there is insufficient evidence to suggest the exceedances pose

an adverse influence to aquatic life of these waters. This is because temperature criteria protective of aquatic life would normally be evaluated through a collection of continuous representative temperature data combined with biological data collections of fish and benthic macroinvertebrate assemblages (WDEQ/WQD 2020b). These data were not collected as part of the Horse Creek study and thus the exceedances of the temperature criterion are noted but a conclusion on criterion attainment cannot be made. Likewise, attainment of numeric criteria for pH and dissolved oxygen cannot be determined for the same reasons as temperature. Therefore, the remainder of this report will focus on identification of potential sources and causes of elevated total arsenic among the five Horse Creek assessment zones.

## 10. RESULTS – SPEARMAN RANK CORRELATIONS

### 10.1 Above 85

Within *Above 85*, there were no strong significant correlations of total arsenic with other parameters other than its dissolved fraction (Table 3, Appendix 2). Correlations between the dissolved and total fraction concentrations are interpreted as distribution coefficients between arsenic dissolved in the water compared to arsenic bound to sediment. The high correlation of total to dissolved arsenic ($r = 0.82$) indicates most of the arsenic within this zone was in the dissolved fraction (98%) with greater mobility relative to the smaller fraction attached to particulates (e.g. sediment).

### 10.2 Above Hawk

Within *Above Hawk*, total arsenic displayed strong significant correlations with sodium, total aluminum, dissolved arsenic, total iron, bicarbonate and total phosphorus (Table 3, Appendix 2). The high correlation of total arsenic with sodium and bicarbonate indicates these parameters co-occur and may be mobilized under similar conditions. This correlation may reflect a tendency for arsenic to desorb from mineral oxides under alkaline conditions and accumulate through evaporative enrichment. The strong association with bicarbonate may also indicate a potential bicarbonate-enhanced alkaline arsenic desorption process. The strong positive correlation of total arsenic with total iron and total aluminum indicates arsenic co-occurs with these metals in surface waters within *Above Hawk*. Considering the strong correlations ($r > 0.9$) of total iron and total aluminum with TSS, it is likely some arsenic is also bound to iron and aluminum oxides contained within suspended sediments of the water. This is further supported considering that most of the total iron and total aluminum within this zone was in the particulate rather than dissolved fractions and total arsenic displayed a moderate significant correlation ($r = 0.67$) to TSS. This may also explain total arsenic's strong positive correlation with total phosphorus, which is also correlated to TSS ($r = 0.84$).

### 10.3 Hawk-Fl

Total arsenic within *Hawk-Fl* was strongly correlated with pH, chloride, sodium and dissolved arsenic (Table 3, Appendix 2). Similar to *Above 85* and *Above Hawk*, the majority of total arsenic within *Hawk-Fl* was in the dissolved form. Total arsenic within this zone may desorb from mineral oxides under alkaline oxidizing conditions given the strong positive correlation with pH and moderate positive correlation with sulfate ($r = 0.69$) suggesting oxidation of sulfide minerals. The strong correlations with chloride and sodium suggest that these parameters are mobilized with arsenic under similar environmental conditions.

Hydrological dilution and/or evaporative enrichment may also influence total arsenic considering the moderate negative correlation (r = -0.68) with stream discharge.

### 10.4 Below Fl

Regardless of whether flows within *Below Fl* were augmented with North Platte River water releases from the Fort Laramie Canal, dissolved arsenic comprised the majority of total arsenic in this segment of Horse Creek (r = 0.96) (Table 3, Appendix 2). There were however marked differences in correlations of total arsenic with other parameters dependent on when flow augmentation was occurring. During augmentation, strong positive correlations existed between total arsenic and chloride, potassium, sodium, bicarbonate and total nitrogen. This evidence indicates these parameters co-occur and are co-mobilized under similar environmental conditions. Approximately 63% of the total nitrogen in Horse Creek during augmentation was organic (rather than inorganic nitrate+nitrite-N or ammonia-N). The strong correlation with bicarbonate suggests bicarbonate-enhanced arsenic desorption from mineral oxides under alkaline oxidizing conditions and/or evaporative enrichment. The moderate negative correlation with stream discharge (r=-0.55) suggests some influence from dilution and/or evaporative enrichment associated with hydrology when augmentation is occurring. When Horse Creek flows were not augmented, only nitrate+nitrite-N exhibited a strong inverse correlation with total arsenic. This suggests the mobilization of arsenic may be mediated when nitrate+nitrite-N concentrations are elevated, possibly through limits on arsenic desorption from mineral oxides. Mean nitrate+nitrate-N concentrations were higher when augmentation was absent (mean: 273 µg/L) versus when present (mean: 130 µg/L).

### 10.5 Dry

Dissolved arsenic comprises the majority of total arsenic for zone *Dry* (Table 3, Appendix 2). Similar to *Below Fl*, flow augmentation from the Fort Laramie Canal influenced correlations of total arsenic with other parameters within *Dry*. When the Fort Laramie Canal was active, total arsenic exhibited strong positive correlations with chloride, potassium, sodium, dissolved aluminum, total iron, bicarbonate and total nitrogen. Total arsenic was also moderately correlated (r = 0.65) to dissolved iron. This suggests that chloride, potassium, sodium, dissolved aluminum, and total nitrogen co-occur with arsenic and are mobilized under similar environmental conditions. Greater than in *Below Fl*, approximately 86% of the total nitrogen in Dry Creek during augmentation was organic. Competitive desorption from iron oxides under alkaline oxidizing conditions and/or evaporative enrichment may be mechanisms that release arsenic within *Dry* considering the strong correlation with bicarbonate. When evaluated with other parameters, the strong correlation of total arsenic with total iron also suggests arsenic desorption from iron oxides though may also implicate reductive dissolution and/or oxidative desorption from pyrite. To explain, a strong correlation (r = 0.85) existed between total and dissolved iron among all samples where on average 21% of total iron in *Dry* was in the soluble dissolved form. Dissolved iron concentrations (average: 213 mg/L) in *Dry* were consistently elevated relative to the rest of the Horse Creek watershed (average: 67 mg/L). considering that dissolved iron in the streams of the alkaline Horse Creek watershed would likely precipitate as insoluble iron (oxy)hydroxides.

Dissolved iron typically exists as ferrous Fe(II) iron reflective of reduced environments. When exposed to oxygen, ferrous Fe(II) iron oxidizes to form ferric Fe(III) precipitates such as iron (oxy)hydroxides, however, Fe(III) may become soluble under strong alkaline conditions. Considering the pH of *Dry* (average: 8.30)

was similar to the other four assessment zones (average: 8.40), it is more likely that Fe(II) comprises the dissolved iron in *Dry*. This suggests a direct entry of dissolved Fe(II) from reduced source areas.

**Table 3 – Spearman correlations (r) between total arsenic and 18 water quality parameters for all five assessment zones and groundwater wells identified in Table 1. For the *Below FI* and *Dry* zones, correlations are provided for samples collected when the Fort Laramie Canal was active (Aug) and inactive (No Aug). Values in red are significant at p<0.05. Strong correlation values (r >0.7) are shaded in gray. NC indicates no correlation due to absence of variability in the data.**

| | Above 85 | Above Hawk | Hawk-FI | Below FI | | Dry | | Wells |
|---|---|---|---|---|---|---|---|---|
| | | | | No Aug | Aug | No Aug | Aug | |
| pH | -0.124 | 0.093 | 0.737 | 0.255 | -0.503 | 0.234 | 0.583 | -0.304 |
| Chloride | 0.157 | 0.552 | 0.731 | 0.102 | 0.902 | 0.306 | 0.800 | 0.194 |
| Sulfate | -0.090 | -0.336 | 0.692 | 0.085 | 0.361 | 0.018 | 0.433 | 0.238 |
| Calcium | 0.271 | 0.644 | -0.191 | -0.410 | -0.134 | -0.234 | -0.879 | 0.358 |
| Magnesium | -0.145 | 0.335 | 0.668 | -0.362 | -0.007 | -0.767 | -0.276 | 0.200 |
| Potassium | 0.286 | 0.383 | 0.554 | -0.087 | 0.913 | -0.487 | 0.917 | 0.226 |
| Sodium | 0.256 | 0.887 | 0.768 | 0.153 | 0.820 | 0.180 | 0.900 | -0.122 |
| Aluminum, Diss. | NC | 0.393 | -0.006 | 0.560 | 0.358 | -0.036 | 0.780 | |
| Aluminum, Tot. | 0.421 | 0.729 | -0.402 | 0.264 | 0.064 | 0.667 | 0.400 | -0.220 |
| Arsenic, Diss. | 0.819 | 0.975 | 0.895 | 0.943 | 0.951 | 0.991 | 0.950 | 0.707 |
| Iron, Diss. | -0.257 | 0.149 | -0.413 | 0.152 | 0.441 | 0.144 | 0.650 | NC |
| Iron, Tot. | 0.373 | 0.730 | -0.410 | 0.264 | 0.035 | 0.667 | 0.700 | -0.220 |
| Bicarbonate | 0.201 | 0.790 | 0.645 | 0.316 | 0.918 | -0.174 | 0.967 | -0.218 |
| Nitrate+Nitrite-N | -0.265 | 0.157 | -0.419 | -0.724 | 0.507 | -0.145 | -0.020 | 0.486 |
| TSS | 0.317 | 0.666 | -0.415 | 0.091 | -0.078 | 0.541 | 0.118 | - |
| Stream Discharge | 0.064 | -0.014 | -0.677 | 0.119 | -0.549 | 0.811 | -0.008 | - |
| Nitrogen, Tot. | -0.113 | 0.353 | -0.051 | -0.247 | 0.873 | -0.144 | 0.717 | - |
| Phosphorus, Tot. | 0.300 | 0.804 | 0.056 | 0.424 | 0.055 | 0.378 | 0.525 | - |

Arsenic released through dissolution under reduced conditions would be the arsenite form and though not detected in samples from *Dry*, may have been present at concentrations below the laboratory reporting limit of 5 µg/L. The co-occurrence of arsenic and total iron may also be associated with pyrite oxidation. Though a significant correlation to sulfate (an oxidized ion) was not detected, it's important to note that the concentration of sulfate in *Dry* was on average about four times greater compared to other zones in the study area. This suggests a more prominent source of sulfate not found in other areas of the watershed which again may be associated with oxidation of pyrite (FeS) bound with arsenic. The absence of a negative correlations with pH may be due to the abundance of bicarbonate that will neutralize any acidity resulting from the oxidation of pyrite. Mobilization of arsenic attached to inorganic sediment is not implicated as an important transport mechanism due to the absence of a correlation between total iron and TSS. During times when flows were not augmented, a strong correlation existed between total arsenic and stream discharge (r = 0.81).

### 10.6 Wells

Other than most total arsenic being in the dissolved form, there were no significant correlations of total arsenic with other parameters from groundwater wells in the study area (Table 3, Appendix 2). Exploratory analysis also did not indicate any significant correlations when wells were differentiated by formation. This suggests that other parameters are not strongly associated or co-occur with the chemical reactions involving the release of arsenic from metal oxides in the sedimentary formations.

**Table 4 – Principal components analysis (PCA) results for the 161 samples collected within the five Horse Creek assessment zones and from groundwater wells in the study area. Results are provided for each PCA axis with high variable loadings (>±0.3) in bold and partial regression correlation coefficients ($r^2$) >0.6 in red.**

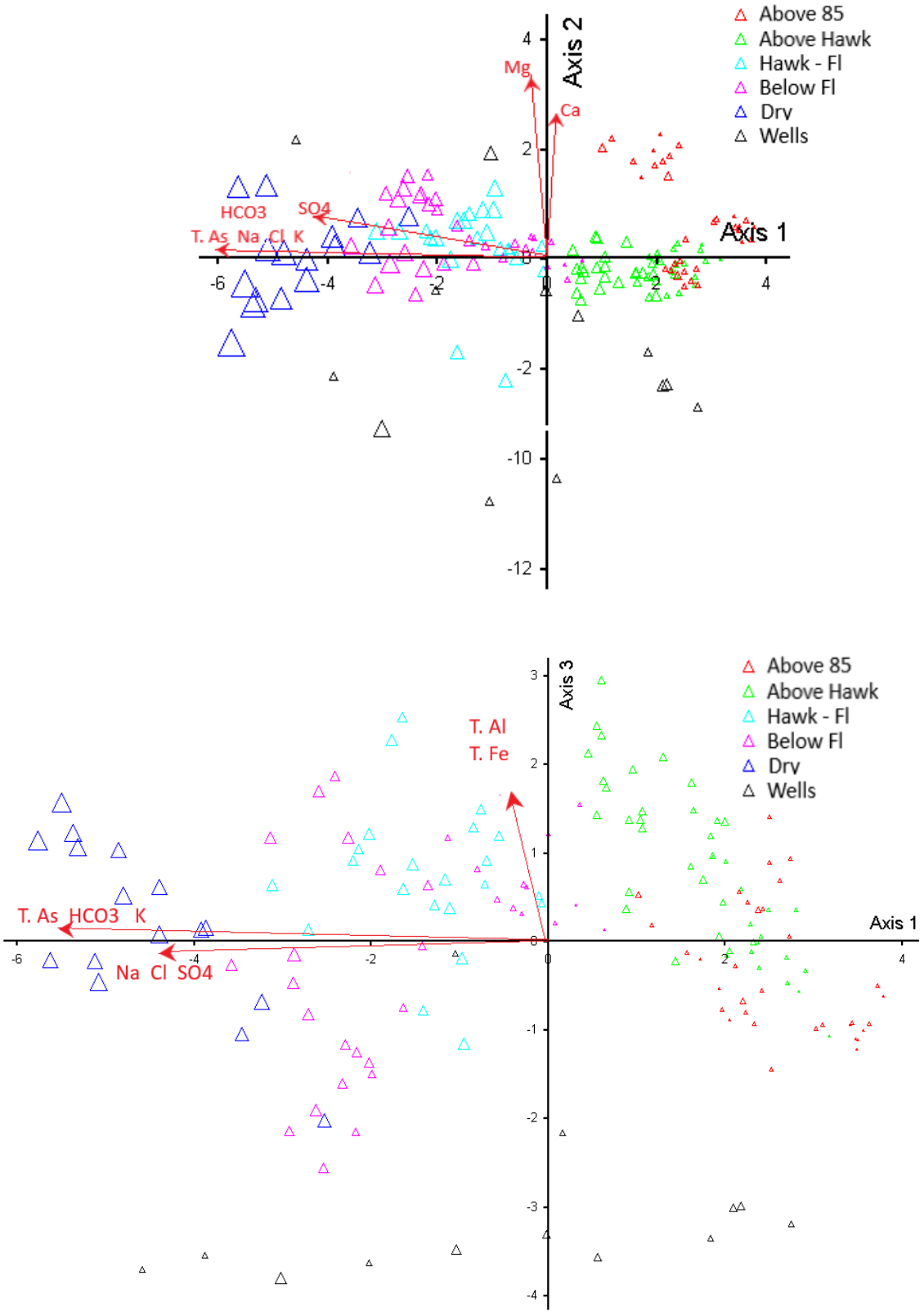
| | Axis 1 | | Axis 2 | | Axis 3 | |
|---|---|---|---|---|---|---|
| | Loading | $r^2$ | Loading | $r^2$ | Loading | $r^2$ |
| Chloride | **-0.375** | 0.869 | 0.159 | 0.056 | -0.066 | 0.008 |
| Sulfate | **-0.328** | 0.664 | 0.250 | 0.139 | -0.126 | 0.030 |
| Calcium | 0.069 | 0.029 | **0.600** | 0.800 | 0.078 | 0.012 |
| Magnesium | -0.097 | 0.058 | **0.618** | 0.851 | 0.069 | 0.009 |
| Potassium | **-0.357** | 0.786 | 0.120 | 0.032 | 0.018 | 0.001 |
| Sodium | **-0.385** | 0.917 | -0.044 | 0.004 | -0.045 | 0.004 |
| Total Aluminum | -0.167 | 0.172 | -0.117 | 0.030 | **0.580** | 0.648 |
| Total Arsenic | **-0.353** | 0.770 | -0.010 | 0.000 | 0.082 | 0.013 |
| Total Iron | -0.172 | 0.183 | -0.149 | 0.049 | **0.567** | 0.618 |
| Bicarbonate | **-0.315** | 0.613 | 0.016 | 0.001 | 0.026 | 0.001 |
| Nitrate | 0.076 | 0.036 | 0.064 | 0.009 | -0.223 | 0.096 |
| pH | 0.052 | 0.017 | -0.032 | 0.002 | 0.334 | 0.215 |
| | | | | | | |
| Eigenvalue | 6.18 | | 2.23 | | 1.93 | |
| Proportional (%) | 44.12 | | 15.90 | | 13.75 | |
| Cumulative (%) | 44.12 | | 60.02 | | 73.77 | |

## 11. RESULTS – PRINCIPAL COMPONENTS ANALYSIS

The PCA results of 12 variables from the 161 surface (Appendix 1) and groundwater (Table 1) samples are shown in Table 4. For metals, only the total concentrations were used in the PCA to represent the combined dissolved and particulate fractions. Three principal components or axes together explained 73.8% of variance in the dataset. Axis 1 explained almost one-half (44.1%) of the total variance in the data with high loadings (>0.3) and $r^2$ values (>0.6) for bicarbonate, chloride, potassium, sodium, sulfate, and total arsenic. Axis 1 is a gradient of arsenic desorption from mineral oxides under alkaline oxidizing conditions that may be enhanced by bicarbonate. The strong associations with chloride, sodium and potassium indicate these parameters co-occur and are mobilized together and may also reflect an evaporative enrichment gradient. The strong association of sulfate along Axis 1 also suggests leaching of sulfate through oxidation of pyrite.

Axis 2 accounted for 16% of the total variance with high loadings and $r^2$ values for calcium and magnesium. Axis 2 appears to represent a gradient of geologic, soil and other influences on the co-occurrence and proportion of these two major cations in the chemistries of surface and groundwater in the watershed. Among total variance in the data, 13.8% is explained by Axis 3 which has high loadings and $r^2$ values for total iron and total aluminum. Additional analysis showed strong correlation of this axis with TSS and therefore represents a proportional gradient in the concentrations of total iron and total aluminum

**Figure 9 – Plots for the first and second axes (top) and first and third axes (bottom) of the principal components analysis (PCA) for the 161 samples collected within the five Horse Creek assessment zones and from groundwater wells in the study area. Variables with high loadings identified in Table 4 are illustrated with red vector arrows. Sample points are classified by assessment zone where size is proportional to total arsenic concentration (larger size = higher concentration).**



associated with suspended sediment. Plotting the surface and groundwater samples along the three PCA axes with sample point size proportional to total arsenic concentration and overlays of variable vectors with high loadings, revealed patterns among the five assessment zones and groundwater wells (Figure 9). The water chemistry of *Above 85* and *Above Hawk* was distinctly different relative to other zones in the watershed exhibiting relatively low concentrations of total arsenic, bicarbonate, chloride, potassium, sodium and sulfate. Sediment-bound arsenic (through complexation with iron and aluminum oxides) appeared partially responsible for higher concentrations of arsenic in some samples within all five of the Horse Creek assessment zones. However, it can be inferred that arsenic leaching following alkaline oxidative desorption from mineral oxides enhanced by bicarbonate competition, oxidation of pyrite and/or combined with evaporative enrichment, may be the primary driver for the elevated total arsenic concentrations found within the *Hawk-Fl*, *Below Fl* and *Dry* zones.

Though groundwater contributions from the sedimentary aquifers in the watershed influenced total arsenic concentrations within *Hawk-Fl*, *Below Fl* and *Dry*, they do not appear to be a dominant factor considering the marginal and dispersed overlap of the well samples (with much lower concentrations of total arsenic) relative to the samples from these three zones. Well samples also displayed the lowest total iron and total aluminum concentrations and in some cases calcium and magnesium, implying these parameters in surface water were largely derived from sources other than groundwater (i.e. soils and/or weathered sediments).

## 12. RESULTS – PIPER DIAGRAM

Results of the Piper Diagram revealed distinguishable patterns in major ion chemistry of surface water among the five Horse Creek assessment zones and groundwater wells of the watershed (Figure 10). Surface waters within *Above 85* and *Above Hawk* classify as calcium bicarbonate dominant, similar to groundwater from wells A8L and B1G, which represent the dominant Arikaree and White River (Brule Member) formations within these assessment zones (Figure 2). In fact, the distribution of these samples in Figure 10 align with historical Piper diagram patterns for groundwater from the Arikaree and White River formations throughout southeast Wyoming (Figures 11-12). This similarity not only supports the hydrologic connectivity of groundwater and surface water within these zones but also indicates that the major ionic chemistry for much of Horse and Bear Creeks within *Above 85* and *Above Hawk* remains relatively unchanged from the contributing groundwater.

Downstream of these zones the general major ion chemistry of surface water transitions to a mixed calcium and sodium bicarbonate type, primarily within *Hawk-Fl*. This mixed calcium-sodium bicarbonate water becomes dominant in the *Below Fl* and *Dry* zones. This transition is due in part to groundwater contributions from the Lance and White River (Chadron Member) formations as evidenced by the proximity of wells L2G, L3G and C2G in the Piper diagram. This is supported by the fact that these two formations are expected to be the dominant groundwater contributors within *Below Fl* and *Dry* (Figure 2), and that the same general transition of major ionic composition was documented by Libra et al. (1981) (Figures 12-13). Some samples where excursions of the numeric total arsenic criterion of 10 µg/L (enclosed by the dashed polygon) were observed plot close to these wells suggesting groundwater contributions as a likely source for these particular excursions. However, the majority of samples from *Below Fl* and some

**Figure 10 – Piper diagram illustrating the major ion chemistry within the five assessment zones for Horse, Bear and Dry Creeks and groundwater wells within the study area. Well samples are identified by the Station code provided in Table 1. Samples where total arsenic concentrations were above the 10 µg/L numeric human health criterion are enclosed by the dashed polygon. Dominant anion, cation and anion-cation combination quadrants are labeled in red.**

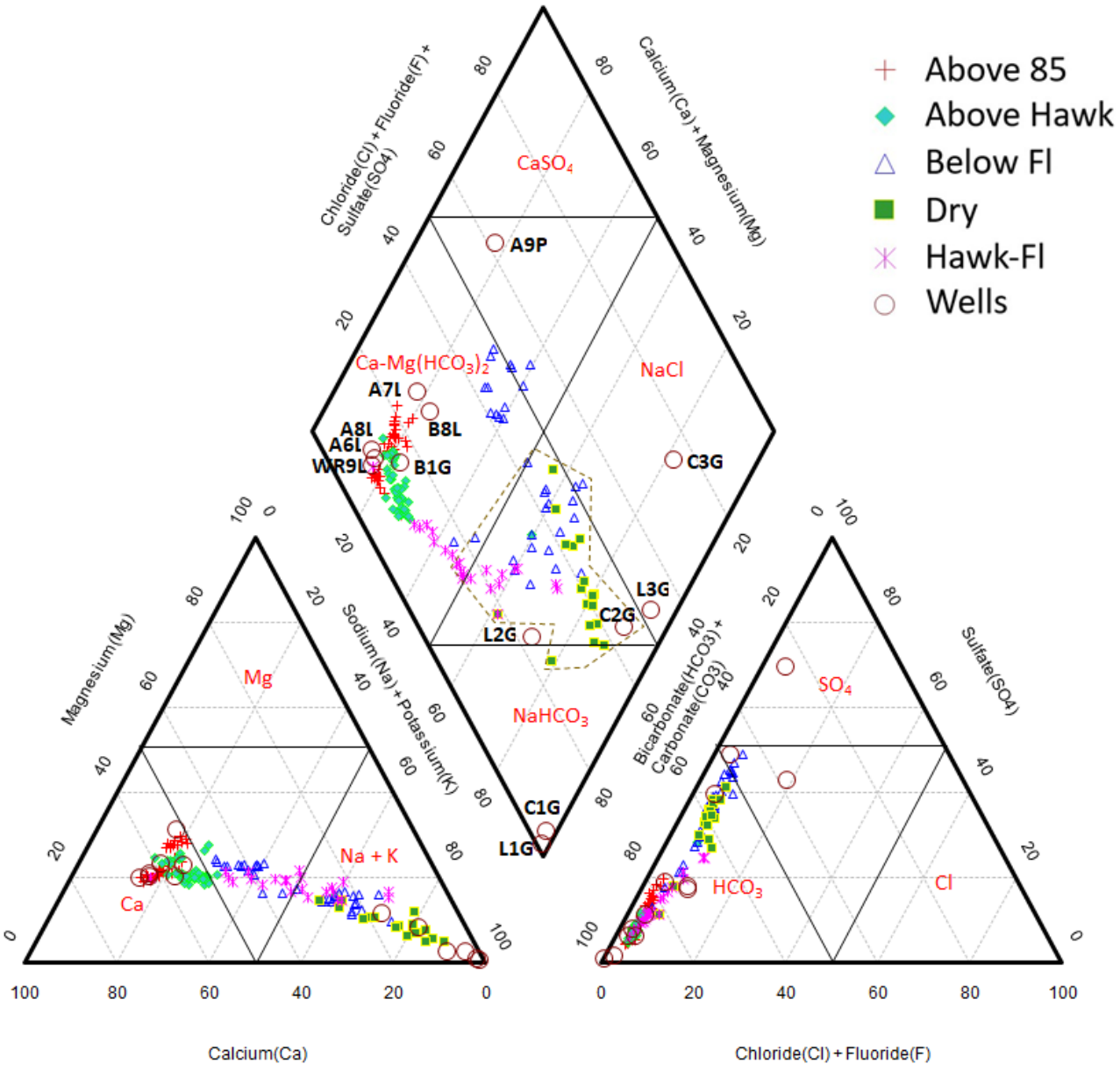


**Figure 11 - Piper diagram from Libra et al. (1981) illustrating major ion chemistry of groundwater within the Arikaree and Ogallala formations in the Denver-Julesburg basin of Wyoming (i.e. southeast Wyoming). The dashed polygon that contained surface water samples with total arsenic concentrations >10 µg/L illustrated in Figure 11 has been superimposed for comparisons to groundwater chemistry.**

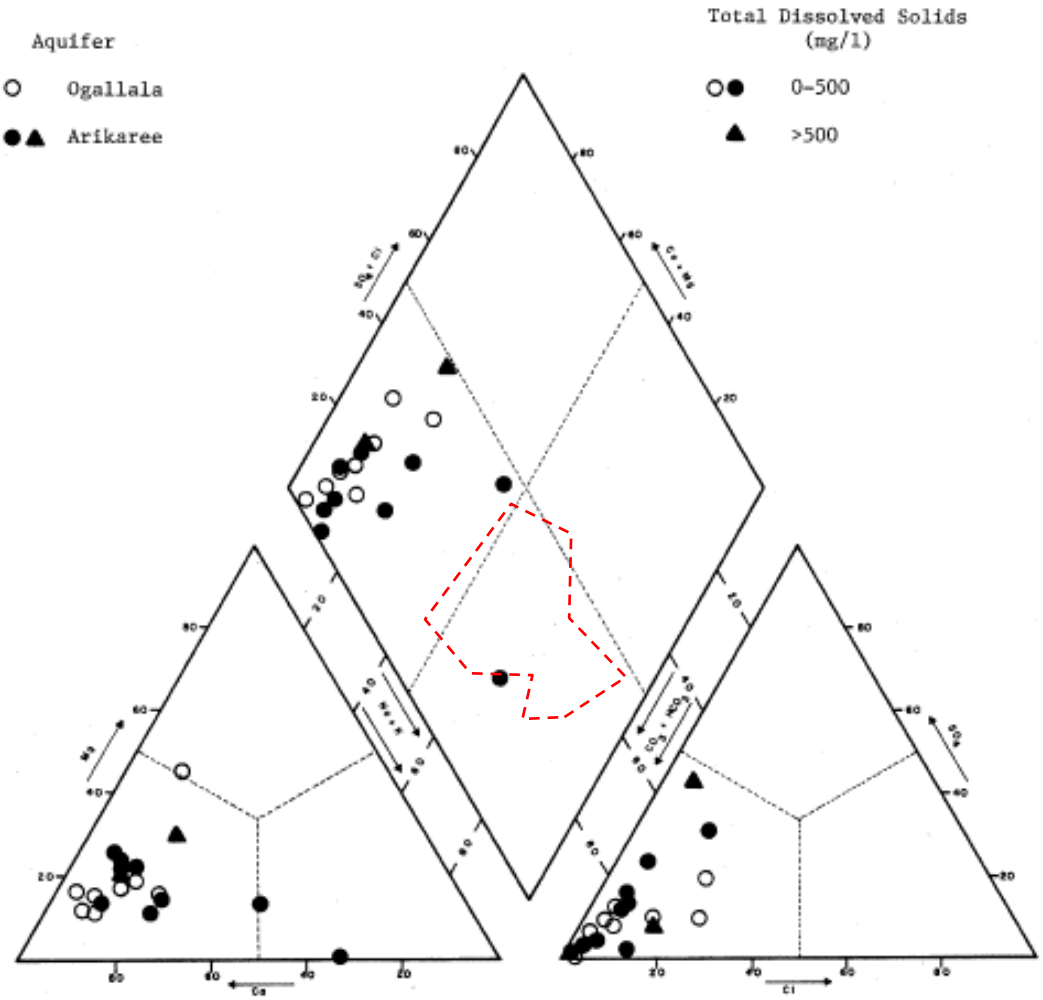



Figure V-5. Major ion composition of representative waters of the Arikaree and Ogallala aquifers, Tertiary aquifer system, Denver-Julesburg basin, Wyoming.

**Figure 12 - Piper diagram from Libra et al. (1981) illustrating major ion chemistry of groundwater within the White River formation in the Denver-Julesburg basin of Wyoming (i.e. southeast Wyoming). The dashed polygon that contained surface water samples with total arsenic concentrations >10 µg/L illustrated in Figure 11 has been superimposed for comparisons to groundwater chemistry.**

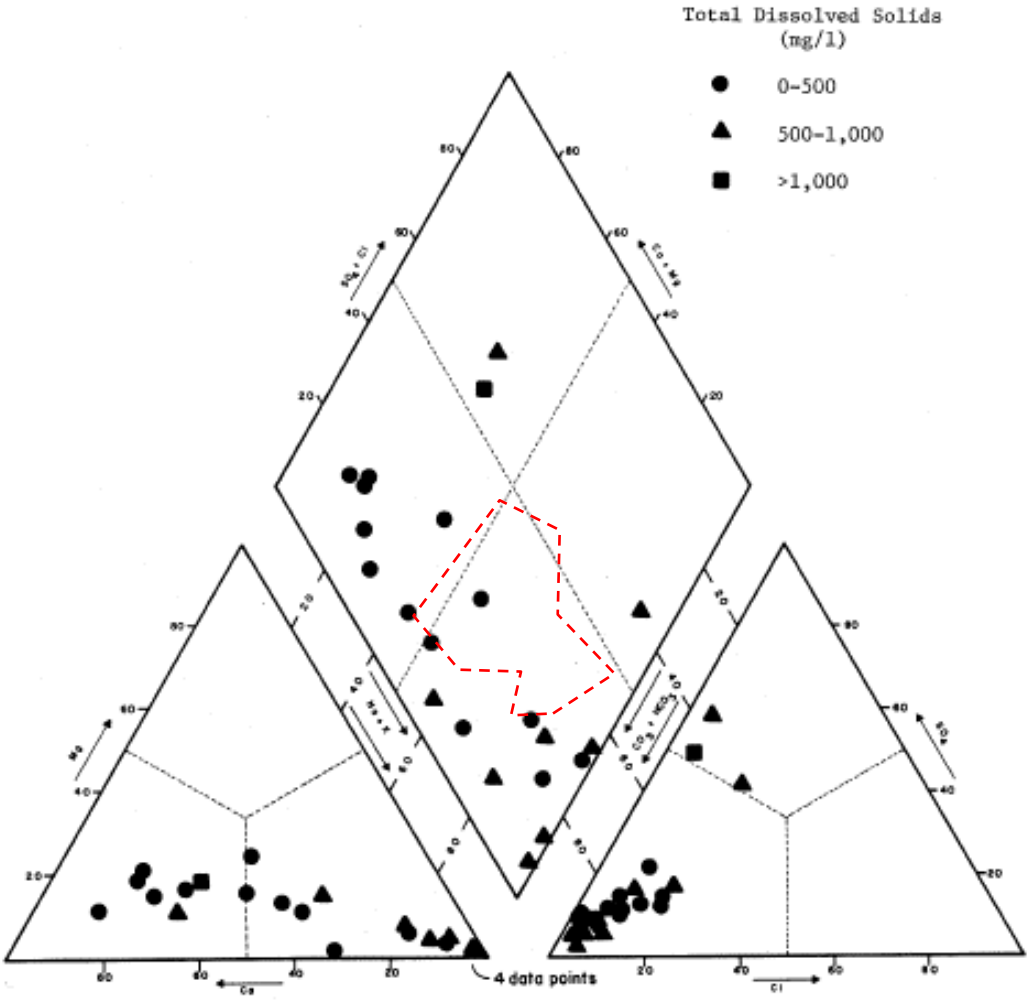



Figure V-4. Major ion composition of representative waters of the White River aquifer, Tertiary aquifer system, Denver-Julesburg basin, Wyoming.

**Figure 13 - Piper diagram from Libra et al. (1981) illustrating major ion chemistry of groundwater within the Lance/Fox Hills formation in the Denver-Julesburg basin of Wyoming (i.e. southeast Wyoming). The dashed polygon that contained surface water samples with total arsenic concentrations >10 µg/L illustrated in Figure 11 has been superimposed for comparisons to groundwater chemistry.**

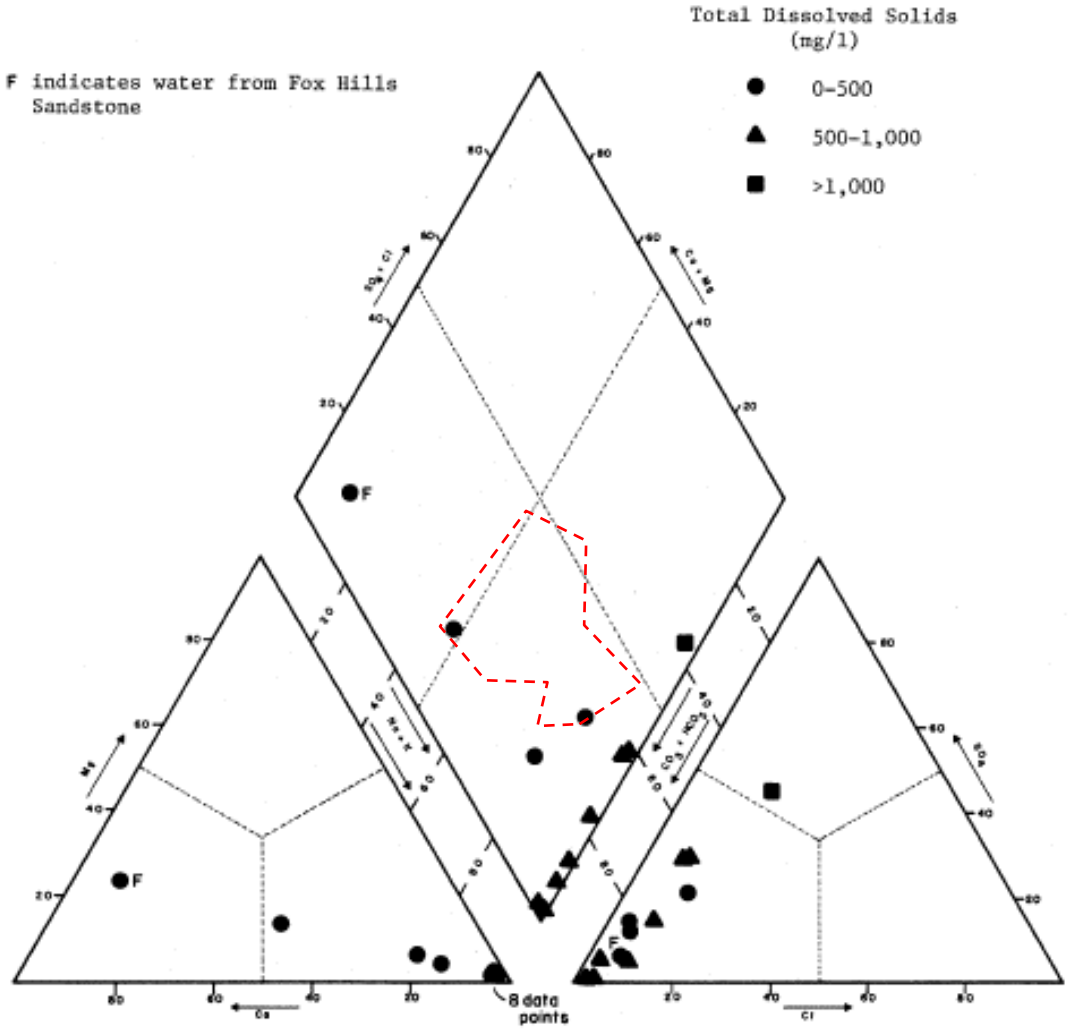



Figure V-3. Major ion composition of representative waters from the Lance/ Fox Hills aquifer, Denver-Julesburg basin, Wyoming.

from *Hawk-Fl* and *Dry* trend toward greater proportions of chloride, potassium, sodium and sulfate (located closer to the center of the diamond plot) with a divergence from the major ionic composition of the groundwater. This divergence is also evident when comparing the distribution of these samples in Figure 10 to the groundwater chemistry in Figures 12 and 13. Combined, these results suggest the divergence is attributed to influences other than natural groundwater contributions. It is these samples that represent the majority of the 10 µg/L arsenic criterion excursions described earlier. With contributions of North Platte River water from the Fort Laramie Canal, major ionic chemistry in *Below Fl* shifts back towards a calcium bicarbonate type (cluster of blue triangles to the left of center in the diamond plot) coincident with an absence of arsenic criterion excursions.

Groundwater in other locations of the watershed was dissimilar to that of surface water and variable. This variability in groundwater was represented by sodium bicarbonate dominated (wells C1G and L1G), sodium chloride dominant (C3G) and a mixed calcium bicarbonate-sulfate type (A9P). Wells C1G and C3G represent the White River (Chadron Member), L1G represents the Lance formation and A9P represents the Arikaree formation. Though dissimilar to the surface water, the groundwater chemistry from these wells generally aligns with expected conditions (Figures 11-13). Total arsenic concentrations from all four of these wells was generally well below 10 µg/L.

## 12. CAUSAL ANALYSIS AND SOURCE IDENTIFICATION

Based on the findings from Section 9, the total arsenic criterion protective of human health was exceeded within the assessment zones *Hawk-Fl*, *Below Fl* and *Dry*. Applicable numeric criteria for all other chemical parameters were either not exceeded or insufficient information was available to conclude a harm to a designated use (i.e., dissolved oxygen, pH, water temperature).

Information presented in Sections 6 and 7 indicates the majority of arsenic in the study area is naturally found in the sedimentary geology and soils of the watershed. The evidence summarized in Sections 9 – 12 were evaluated within a causal analysis framework (USEPA 2000) to determine probable sources and causes of arsenic within the five Horse Creek assessment zones. Conclusions of the causal analysis are summarized below with detailed information on the basis for these determinations provided in Table 5. Included with the summaries below are probable sources and causes.

***Above 85*** – Total arsenic concentrations did not exceed the criterion protective of fish consumption and drinking water. Horse and Bear Creeks within *Above 85* represent least-impacted arsenic reference conditions for the Horse Creek watershed. The evidence indicates that total arsenic concentrations within *Above 85* are predominantly tied to groundwater contributions. The source of arsenic in the groundwater is natural and associated with natural release of arsenic contained within the underlying sedimentary geology. This inference is supported by the strong similarities in the chemical composition (including total arsenic concentrations) of surface water relative to the underlying groundwater. Arsenic is also likely to be attached to soils and potentially transported to streams during runoff from uplands or through bank erosion. Arsenic in soils associated with legacy arsenical pesticide application is assumed limited within Above 85 considering irrigated agriculture within this assessment zone is also limited.

***Above Hawk*** – Total arsenic concentrations did not exceed the criterion protective of fish consumption and drinking water in *Above Hawk*. Total arsenic concentrations within *Above Hawk* were similar to that of the groundwater that is the dominant source of flow for these streams. As such, total arsenic concentrations in *Above Hawk* are predominantly tied to groundwater contributions. The source of arsenic in the groundwater is natural and associated with arsenic-bearing minerals in the underlying sedimentary geology. The evidence to support this inference is the same as that described for *Above 85*. Transport of soil bound arsenic to streams is also a factor in *Above Hawk.* Arsenic is also likely to be attached to soils and potentially transported to streams during runoff from uplands or through bank erosion. Most soil arsenic is considered natural, though there is an assumption that an unknown quantity of arsenic in irrigated soils may have originated from legacy arsenical pesticide application.

***Hawk-Fl, Below Fl*** **and** ***Dry*** – Total arsenic concentrations exceed the criterion protective of fish consumption and drinking water in *Hawk-Fl*, *Below Fl* and *Dry* with the highest concentrations occurring in *Dry*. Criterion exceedances only occurred in *Below Fl* when the Fort Laramie Canal was inactive. Otherwise, trans-basin inputs of North Platte River water into Horse Creek from the Fort Laramie Canal diluted total arsenic concentrations during the irrigation season to concentrations at or below the human health criterion. Trans-basin water from the Fort Laramie Canal also diluted total arsenic concentrations in the lower portions of Dry Creek though did not lower concentrations below the numeric criterion.

The elevated concentrations of total arsenic from approximately Hawk Springs Reservoir downstream to the Wyoming/Nebraska stateline and all of Dry Creek appear to largely be linked to a combination of groundwater contributions and leaching of arsenic from irrigated soils. The source of arsenic in the groundwater appears largely natural and associated with arsenic-bearing minerals in the underlying sedimentary geology. However, groundwater contributions only partially explain exceedances of the arsenic criterion. This inference is supported by multiple chemical signatures of arsenic release and mobilization associated with elevated arsenic concentrations in surface water that were not present in the underlying groundwater. Moreover, the chemical composition of most surface water samples with total arsenic concentrations greater than the human health criterion exhibited distinct differences from that of ground water suggesting non-groundwater influences. Considering this information and that human sources of arsenic derived from outside the watershed are limited, the most probable explanation is that the arsenic exceedances are also associated with the leaching of natural arsenic from soils. Under natural conditions, contributions of arsenic from soils and weathered sediments would be minimal. It is therefore probable that broad-scale irrigation activities have altered soil pH and redox conditions resulting in release of soluble arsenic within irrigated soils which is then leached and transported directly to streams or indirectly to shallow aquifers.

**Table 5 – Summary of evidence used in the causal analysis of most probable arsenic source(s) and cause(s) within the five Horse Creek assessment zones.**

***Above 85*** **T. Arsenic: 2-4 µg/L (mean = 2.8 µg/L)** **Exceedance of 10 µg/L arsenic criterion? No**

| | pH Enhanced Oxidative Desorption | Evaporative Enrichment | Competitive Ion Displacement | Reductive Dissolution | Sediment Transport |
|---|---|---|---|---|---|
| **Descriptive Chemistry** | ●*Above 85* serves as a least-impacted As reference condition for the Horse Creek watershed<br>●Average 98% of T. As in dissolved form<br>●Average 56% of T. Al. and T. Fe in dissolved form<br><br>●T. As in surface water (mean = 4.4 µg/L) similar to groundwater in the Arikaree and White River (Brule Member) (mean = 5.8 µg/L) | | | | |
| **Spearman Correlations** | ●No correlations of T. As with other parameters in surface water - similar to groundwater. | | | | |
| **PCA** | ●No strong associations of T. As with other parameters - does not suggest arsenic release through broad-scale pH enhanced oxidative desorption, evaporative enrichment, competitive ion displacement or reductive dissolution<br>● Dispersed overlap of surface water samples with groundwater samples - suggests groundwater contributions partially influence T. As in *Above 85* | | | | ●Surface water T. As marginally associated with T. Fe and T. Al that are correlated with TSS - suggests mobilization of sediment-bound As |
| **Piper Diagram** | ●Major ionic chemistry of surface water similar to groundwater of the Arikaree and White River formations both within Horse Creek and throughout SE Wyoming based on current and historic Piper diagrams. Suggests groundwater contributions primarily influence T. As in *Above 85* | | | | |
| **Hydrology** | ●Horse Creek and perennial tributaries are spring-fed | | | | |

| | |
|---|---|
| **Conclusions** | The evidence supports that concentrations of As in segments of Horse and Bear Creeks within the *Above 85* assessment zone are predominantly tied to groundwater contributions with the assumption of limited influence from legacy arsenical pesticide application. Arsenic may also be mobilized when attached to sediment. Considering landuses in the watershed, sediment-bound arsenic is largely presumed to be associated with runoff from uplands and bank erosion. |

**Table 5 (cont.) - Summary of evidence used in the causal analysis of most probable arsenic source(s) and cause(s) within the five Horse Creek assessment zones.**

***Above Hawk*** **T. Arsenic: 2-7 µg/L (mean = 4.4 µg/L)** **Exceedance of 10 µg/L arsenic criterion? No**

| | pH Enhanced Oxidative Desorption | Evaporative Enrichment | Competitive Ion Displacement | Reductive Dissolution | Sediment Transport |
|---|---|---|---|---|---|
| **Descriptive Chemistry** | ●Surface water T. As (2-7 µg/L) similar to least-impacted *Above 85* reference condition (2-4 µg/L)<br>●Average 97% of T. As in dissolved form<br>●Average 17% of T. Al. and T. Fe in dissolved form<br><br>●T. As in surface water (mean = 4.4 µg/L) similar to groundwater in the Arikaree and White River (Brule Member) (mean = 5.8 µg/L) | | | | |
| **Spearman Correlations** | ●Surface water T. As correlated with Na and HCO3 - suggest co-occurrence and mobilization under similar conditions<br>●Dissimilar to groundwater which showed no correlations of T. As with other parameters | | | | ●Surface water T. As corrleated with T. Fe, T. Al, TP and TSS<br>●T.Fe, T. Al and TP correlated to TSS<br><br>●Combined correlations suggests T.As bound to metal oxides in sediments |
| **PCA** | ●No strong associations of T. As with other parameters - does not suggest arsenic release through large-scale pH enhanced oxidative desorption, evaporative enrichment, competitive ion displacement or reductive dissolution<br>● Dispersed overlap of surface water samples with groundwater samples - suggests groundwater contributions partially influence T. As in *Above Hawk* | | | | ●Surface water T. As marginally associated with T. Fe and T. Al which are also both correlated with TSS - suggests mobilization of sediment-bound As |
| **Piper Diagram** | ●Major ionic chemistry of surface water similar to groundwater of the Arikaree and White River formations both within Horse Creek and throughout SE Wyoming based on current and historic Piper diagrams. Suggests groundwater contributions primarily influence T. As in *Above Hawk* | | | | |
| **Hydrology** | ●Horse Creek and perennial tributaries are spring-fed<br>●Flows in Horse Creek and lower Bear Creek may be minorly augmented from seepage along ditches, streams, and wetlands associated with artificial recharge. Irrigation return flows and runoff from fields presumed minor. Horse Creek flows are also influenced by multiple diversions. | | | | |

| | |
|---|---|
| **Conclusions** | The evidence indicates that concentrations of As in segments of Horse and Bear Creeks within the *Above Hawk* assessment zone are largely tied to groundwater contributions with the assumption of limited influence from legacy arsenical pesticide application. Arsenic can also be mobilized when attached to sediment. Potential causes of sediment transport include runoff from uplands and bank erosion. There is insufficient evidence to conclude broad-scale arsenic release or transport due to oxidative desorption, competitive ion displacement or evaporative enrichment in soils. |

**Table 5 (cont.) - Summary of evidence used in the causal analysis of most probable arsenic source(s) and cause(s) within the five Horse Creek assessment zones.**

***Hawk-Fl*** **T. Arsenic: 7-14 µg/L (mean = 10.1 µg/L)** **Exceedance of 10 µg/L arsenic criterion? Yes**

| | pH Enhanced Oxidative Desorption | Evaporative Enrichment | Competitive Ion Displacement | Reductive Dissolution | Sediment Transport |
|---|---|---|---|---|---|
| **Descriptive Chemistry** | ●Surface water T. As (7-14 µg/L) greater than for least-impacted *Above 85* reference condition (2-4 µg/L)<br>●Average 96% of T. As in dissolved form<br>●Average 10% of T. Al. and T. Fe in dissolved form<br><br>●T. As in surface water (mean = 10.1 µg/L) greater than in groundwater in the White River (Chadron Member) and Lance (mean = 5.5 µg/L) | | | | |
| **Spearman Correlations** | ●Surface water T. As correlated with pH, Cl, Na and SO4 - suggest co-occurrence and mobilization under similar conditions<br>●Dissimilar to groundwater which showed no correlations of T. As with other parameters | | | | |
| | | ● Surface water T. As negatively correlated with stream flow - suggests dilution or evaporative enrichment. | | | |
| **PCA** | ● Surface water T. As strongly associated with Cl, Na, K, HCO3 and SO4 - suggests arsenic release through large-scale oxidative desorption, evaporative enrichment and/or competitive ion displacement with HCO3.<br>● Dispersed overlap of surface water samples with groundwater samples - suggests groundwater contributions partially influence T. As in *Hawk-Fl* | | | | ●Surface water T. As marginally associated with T. Fe and T. Al that are correlated with TSS - suggests mobilization of sediment-bound As |
| **Piper Diagram** | ●Surface water with T. As <10 µg/L similar to groundwater. Some surface water samples with T. As >10 µg/L plot close to groundwater samples while others exhibit a divergence from the same groundwater samples. Suggests groundwater contributions only partially responsible for elevated T. As.<br>●Major ion chemistry for several surface water samples with T. As >10 µg/L exhibit greater proportions of Cl, K, Na and SO4 relative to groundwater samples - suggests broad-scale arsenic release and transport by non-groundwater factors | | | | |
| **Hydrology** | ●Horse Creek and perennial tributaries are spring-fed<br>●Seepage along canals, ditches, streams, wetlands and below reservoirs associated with artificial recharge combined with irrigation return flows and runoff from fields augments flows in Horse Creek. Horse Creek flows are also influenced by multiple diversions including storage in reservoirs. | | | | |

| | |
|---|---|
| **Conclusions** | The evidence indicates that elevated concentrations of As in the *Hawk-Fl* segment of Horse Creek are linked to a combination of natural groundwater contributions and arsenic release via broad-scale oxidative desorption, evaporative enrichment and/or competitive ion displacement mechanisms not associated with groundwater. It is suspected these mechanisms are promoted through artificial recharge of soils that contain arsenic, application of water elevated in arsenic and bicarbonate to those soils, and frequent saturation-drying cycles of irrigated soils and shallow water tables. Seepage areas and irrigation return flows are suspected to transport the arsenic leached from soils to surface waters. Leached arsenic may also include any residual contamination bound to soils from legacy pesticide application. Diversions and storage of water may also contribute to evaporative enrichment of arsenic. There is some evidence to indicate sediment is a transport mechanism of arsenic to surface waters. Potential natural causes of sediment transport include runoff from uplands and bank erosion. Human causes of sediment transport include resuspension of sediment in ditches and canals, runoff from fields and/or reservoir releases high in suspended sediment. |

**Table 5 (cont.) - Summary of evidence used in the causal analysis of most probable arsenic source(s) and cause(s) within the five Horse Creek assessment zones.**

***Below Fl*** **T. Arsenic: 2-16 µg/L (mean = 7.5 µg/L)** **Exceedance of 10 µg/L arsenic criterion? Yes**

| | pH Enhanced Oxidative Desorption | Evaporative Enrichment | Competitive Ion Displacement | Reductive Dissolution | Sediment Transport |
|---|---|---|---|---|---|
| **Descriptive Chemistry** | ●Surface water T. As (2-16 µg/L) greater than for least-impacted *Above 85* reference condition (2-4 µg/L)<br>●With augmentation, surface water T. As 2-9 µg/L, mean = 4 µg/L<br>●Without augmentation, surface water T. As 9-16 µg/L, mean = 11 µg/L<br>●Average 94% of T. As in dissolved form<br>●Average 18% of T. Al. and T. Fe in dissolved form<br>●T. As in surface water without augmentation (mean = 11 µg/L) greater than in groundwater in the White River (Chadron Member) and Lance (mean = 5.5 µg/L) | | | | |
| **Spearman Correlations** | ●With augmentation, T. As correlated with Cl, K, Na, HCO3 and TN. Suggests co-occurrence and mobilization under similar conditions<br>●Without augmentation, T. As negatively correlated with NO3 - suggests arsenic release partially mediated by NO3. NO3 concentrations higher without augmentation (mean = 273 µg/L) compared to with augmentation (130 µg/L). Dissimilar to groundwater which showed no correlations with T. As. | | | | |
| | | ● Surface water T. As negatively correlated with stream flow - suggests dilution or evaporative enrichment | | | |
| **PCA** | ● Surface water T. As strongly associated with Cl, Na, K, HCO3 and SO4 - suggests arsenic release through large-scale oxidative desorption, evaporative enrichment and/or competitive ion displacement with HCO3.<br>● Dispersed overlap of surface water samples with groundwater samples - suggests groundwater contributions partially influence T. As in *Below Fl* | | | | ●Surface water T. As marginally associated with T. Fe and T. Al that are correlated with TSS - suggests mobilization of sediment-bound As |
| **Piper Diagram** | ●Surface water with T. As <10 µg/L similar to groundwater. Some surface water samples with T. As >10 µg/L plot close to groundwater samples while others exhibit a divergence from the same groundwater samples. Suggests groundwater contributions only partially responsible for elevated T. As.<br>●Major ion chemistry for several surface water samples with T. As >10 µg/L exhibit greater proportions of Cl, K, Na and SO4 relative to groundwater samples - suggests broad-scale arsenic release and transport by non-groundwater factors<br>●Major ion chemistry for most surface water samples influenced by augmentation exhibit T. As <10 µg/L with lesser proportions of Na and K and dissimilar to groundwater samples | | | | |
| **Hydrology** | ●Horse Creek and perennial tributaries are spring-fed<br>●Seepage along canals, ditches, streams, wetlands and below reservoirs associated with artificial recharge combined with irrigation return flows, runoff from fields and inputs of North Platte River water from the Fort Laramie Canal, augments flows in Horse Creek. Horse Creek flows are also influenced by multiple diversions including storage in reservoirs. | | | | |

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|---|---|
| **Conclusions** | The evidence indicates that elevated concentrations of As in the *Below Fl* segment of Horse Creek are linked to a combination of natural groundwater contributions and arsenic release via broad-scale oxidative desorption, evaporative enrichment and/or competitive ion displacement mechanisms not associated with groundwater. It is suspected these mechanisms are promoted through artificial recharge of soils naturally elevated in arsenic, application of water elevated in arsenic and bicarbonate to those soils, and frequent saturation-drying cycles in irrigated soils and shallow water tables. Seepage areas and irrigation return flows are suspected to transport the arsenic leached from soils to surface waters. Leached arsenic may also include any residual contamination bound to soils from legacy pesticide application. Diversions and storage of water may also contribute to evaporative enrichment of arsenic. There is some evidence to indicate sediment is a transport mechanism of arsenic to surface waters. Potential natural causes of sediment transport include runoff from uplands and bank erosion. Human causes of sediment transport include resuspension of sediment in ditches and canals, runoff from fields and/or reservoir releases high in suspended sediment. Inputs of North Platte River water from the Fort Laramie Canal have a dilution effect resulting in lower T. As concentrations in *Below Fl* during the irrigation season. |

**Table 5 (cont.) - Summary of evidence used in the causal analysis of most probable arsenic source(s) and cause(s) within the five Horse Creek assessment zones.**

***Dry*** **T. Arsenic: 15-52 µg/L (mean = 31.6 µg/L)** **Exceedance of 10 µg/L arsenic criterion? Yes**

| | pH Enhanced Oxidative Desorption | Evaporative Enrichment | Competitive Ion Displacement | Reductive Dissolution | Sediment Transport |
|---|---|---|---|---|---|
| Descriptive Chemistry | ●Surface water T. As (15-52 µg/L) greater than for least-impacted *Above 85* reference condition (2-4 µg/L)<br>●With augmentation, surface water T. As 15-42 µg/L, mean = 27 µg/L; Without augmentation, surface water T. As 30-52 µg/L, mean = 40 µg/L<br>●Average 99% of T. As in dissolved form; Average 26% of T. Al. and 21% of T. Fe in dissolved form<br>●Average T. Fe (1,375 µg/L) 2 times concentration in other zones<br>●Average SO4 (258 mg/L) and T.As (32 µg/L) at least 4 times concentrations in other zones<br>●T. As in surface water (mean = 31.6 µg/L) greater than in groundwater in the White River (Chadron Member) and Lance (mean = 5.5 µg/L) | | | | |
| Spearman Correlations | ●With augmentation, surface water T. As correlated with Cl, K, Na, D. Al, HCO3 and TN. Suggests co-occurrence and mobilization under similar conditions<br>● Surface water T. As also correlated with T. Fe which was correlated with D. Fe though neither iron fraction was correlated to TSS - indicates sediment is not a transport mechanism but rather oxidative desorption of metal oxides and/or sulfide minerals (pyrite)<br>●Detectable levels of D. Fe (mean = 213 µg/L) along with pH conditions no different than other zones indicates Fe(II) from reduced areas<br>●Without augmentation, T. As correlated with stream discharge suggests arsenic mobilization increases with stream flow. SO4 and T. As orders of magnitude greater compared to other zones indicating a large source of both parameters presumably linked to oxidation of arsenopyrite.<br>●Dissimilar to groundwater which showed no correlations of T. As with other parameters | | | | |
| PCA | ● Surface water T. As strongly associated with Cl, Na, K, HCO3 and SO4 - suggests arsenic mobilization through large-scale oxidative desorption, evaporative enrichment and/or competitive ion displacement with HCO3.<br>● Dispersed overlap of surface water samples with groundwater samples - suggests groundwater contributions partially influence T. As in *Dry* | | | | ●Surface water T. As weakly associated with T. Fe and T. Al that are correlated with TSS - suggests minor mobilization of sediment-bound As |
| Piper Diagram | ●Some surface water samples with T. As >10 µg/L plot close to groundwater samples while others exhibit a divergence from the same groundwater samples. Suggests groundwater contributions only partially responsible for elevated T. As.<br>●Major ion chemistry for several surface water samples with T. As >10 µg/L exhibit greater proportions of Cl, K, Na and SO4 relative to groundwater samples - suggests broad-scale arsenic release and transport by non-groundwater factors | | | | |
| Hydrology | ●Dry Creek is spring-fed<br>●Seepage along canals, ditches, streams, wetlands and below reservoirs associated with artificial recharge combined with irrigation return flows, managed wetland outflows, runoff from fields and inputs of North Platte River water from the Fort Laramie Canal, augments flows in Dry Creek. Dry Creek flows are also influenced by multiple diversions including storage in managed wetlands. | | | | |

| | |
|---|---|
| Conclusions | The evidence indicates that elevated concentrations of As in the *Dry* segment are linked to a combination of natural groundwater contributions and arsenic release via broad-scale oxidative desorption of metal oxides, evaporative enrichment, competitive ion displacement and/or reductive dissolution mechanisms not associated with groundwater. Arsenic release may also be tied to oxidation of sulfide minerals (pyrite) considering the markedly high concentrations of SO4 and As relative to other assessment zones. It is suspected these mechanisms are promoted through artificial recharge of soils naturally elevated in arsenic, application of water elevated in arsenic and bicarbonate to those soils, frequent saturation-drying cycles in irrigated soils and shallow water tables, creation of saturated anaerobic areas, and contact of artifically applied water with shallow bedrock that contains pyrite. Seepage areas, irrigation return flow, and managed wetland releases are suspected to transport arsenic leached from soils and shallow geology to surface waters. Leached arsenic may also include any residual contamination bound to soils from legacy pesticide application. Diversions and storage of water may also contribute to evaporative enrichment of arsenic. There is little evidence to indicate sediment is a major transport mechanism of arsenic in Dry Creek. Inputs of North Platte River water from the Fort Laramie Canal have a dilution effect resulting in lower T. As concentrations in *Dry* during the irrigation season. |

Arsenic in irrigation water along with frequent saturation-drying cycles of irrigated soils and shallow water tables may also influence the accumulation and release of arsenic in soils which in turn can be leached to surface waters. The development of saturated anaerobic soils and oxidation of pyrite from application of water appears to be two additional factors promoting arsenic release specific to the Dry Creek watershed. Because pyrite is not expected in the alkaline soils of the study area, it is presumed pyrite oxidation is occurs along shallow shale lenses of the Lance formation. Leached soil arsenic may also include any residual contamination bound to soils from legacy arsenical pesticide application. Possible human influenced transport mechanisms for leached soil arsenic to reach surface waters include seepage areas, irrigation return flows and reservoir releases. Leached soil arsenic that reaches surface waters as well as existing arsenic within surface waters may be subject to further evaporative enrichment through diversions and/or storage of water in reservoirs or ponds. Lastly, sediment bound arsenic may also be at least partially responsible for the elevated arsenic in Horse Creek, the causes of which appear to be both natural and human. Natural sediment transport mechanisms include runoff from uplands and bank erosion. Possible human influenced sediment transport mechanisms include resuspension of sediment in ditches and canals, runoff from fields and reservoir releases high in suspended sediment.

## 13. CHAPTER 1 CRITERIA ATTAINMENT/NON-ATTAINMENT AND EXTENT

Based on findings from the 2019-2020 study of the Horse Creek watershed, and in accordance with Wyoming's Methods for Determining Surface Water Quality Condition (WDEQ/WQD 2020b), the following conclusions on attainment/non-attainment of applicable criteria, their associated sections in Chapter 1 of the Wyoming Water Quality Rules (WDEQ/WQD 2018), and spatial extent of these conclusions for Horse, Bear and Dry Creeks are described below.

**1. Horse Creek from the Hawk Springs Reservoir supply canal diversion (latitude 41.682092, longitude -104.205316) upstream to a point above the Interstate-25 crossing (latitude 41.450459, longitude -104.941061) (100.5 miles)** attains all applicable numeric and narrative criteria protective of human health and aquatic life as summarized in Table 6.

**Table 6 – Numeric criteria attainment/non-attainment for Horse Creek from the Hawk Springs Reservoir supply canal diversion upstream to a point above the Interstate-25 crossing. Section headings refer to the location of criteria in Chapter 1 of the Wyoming Water Quality Rules. Green boxes with check marks indicate criterion attainment.**

| | [a]Human Health Criteria | [b]Aquatic Life Criteria |
|---|---|---|
| | Section 18 | Section 21 |
| Aluminum | | ✓ |
| Ammonia | | ✓ |
| Arsenic | ✓ | ✓ |
| Chloride | | ✓ |
| Iron | ✓ | ✓ |
| Nitrate+Nitrite-N | ✓ | |

[a]Protective of drinking water and fish consumption

[b]Protective of cold-water fisheries, non-game fisheries and aquatic life other than fish

**2. Horse Creek from the Hawk Springs Reservoir supply canal diversion (latitude 41.682092, longitude -104.205316) downstream to the Wyoming/Nebraska stateline (59.7 miles)** does not attain the numeric human health criterion for arsenic (Section 18) as summarized in Table 7. The most probable sources of the non-attainment of the arsenic criterion protective of drinking water and fish consumption are a combination of natural (e.g. geology and soils), irrigated agriculture, and presumed legacy arsenical pesticide application. All other applicable numeric criteria protective of human health and aquatic life are attained.

**Table 7 - Numeric criteria attainment/non-attainment for Horse Creek from the Hawk Springs Reservoir supply canal diversion downstream to the Wyoming/Nebraska stateline. Section headings refer to the location of criteria in Chapter 1 of the Wyoming Water Quality Rules. Green boxes with check marks indicate criterion attainment whereas red boxes with '≠' indicate criterion non-attainment.**

| | [a]Human Health Criteria | [b]Aquatic Life Criteria |
|---|---|---|
| | Section 18 | Section 21 |
| Aluminum | | ✓ |
| Ammonia | | ✓ |
| Arsenic | ≠ | ✓ |
| Chloride | | ✓ |
| Iron | ✓ | ✓ |
| Nitrate+Nitrite-N | ✓ | |

[a]Protective of drinking water and fish consumption

[b]Protective of cold-water fisheries, non-game fisheries and aquatic life other than fish

**3. Bear Creek from its confluence with Horse Creek upstream to the confluence with Little Bear Creek (latitude 41.616516, longitude -104.610735) (52 miles)** attains all applicable numeric and narrative criteria protective of human health and aquatic life as summarized in Table 8.

**Table 8 - Numeric criteria attainment/non-attainment for Bear Creek from its confluence with Horse Creek upstream to the confluence with Little Bear Creek. Section headings refer to the location of criteria in Chapter 1 of the Wyoming Water Quality Rules. Green boxes with check marks indicate criterion attainment.**

| | [a]Human Health Criteria | [b]Aquatic Life Criteria |
|---|---|---|
| | Section 18 | Section 21 |
| Aluminum | | ✓ |
| Ammonia | | ✓ |
| Arsenic | ✓ | ✓ |
| Chloride | | ✓ |
| Iron | ✓ | ✓ |
| Nitrate+Nitrite-N | ✓ | |

[a]Protective of drinking water and fish consumption

[b]Protective of cold-water fisheries, non-game fisheries and aquatic life other than fish

**4. Dry Creek from its confluence with Horse Creek upstream to its headwaters at Hawk Springs Reservoir north dam (latitude 41.721387, longitude -104.177365) (18 miles)** does not attain the numeric human health criterion for arsenic (Section 18) as summarized in Table 9. The most probable sources of the non-attainment of the arsenic criterion protective of fish consumption are a combination of natural (e.g. geology and soils), irrigated agriculture, and presumed legacy arsenical pesticide application. The numeric human health criteria for iron and nitrate+nitrite-N are not applicable due to Dry Creek's 2C classification. All other applicable numeric criteria protective of aquatic life are attained

**Table 9 – Numeric criteria attainment/non-attainment for Dry Creek from its confluence with Horse Creek upstream to its headwaters at Hawk Springs Reservoir north dam. Section headings refer to the location of criteria in Chapter 1 of the Wyoming Water Quality Rules. Green boxes with check marks indicate criterion attainment whereas red boxes with '≠' indicate criterion non-attainment.**

| | [a]Human Health Criteria | [b]Aquatic Life Criteria |
|---|---|---|
| | Section 18 | Section 21 |
| Aluminum | | ✓ |
| Ammonia | | ✓ |
| Arsenic | ≠ | ✓ |
| Chloride | | ✓ |
| Iron | | ✓ |
| Nitrate+Nitrite-N | | |

[a]Protective of drinking water and fish consumption

[b]Protective of cold-water fisheries, non-game fisheries and aquatic life other than fish

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## Appendix 1 – Physicochemical results at WDEQ/WQD monitoring stations on Horse, Bear and Dry Creeks along with applicable State numeric criteria protective of aquatic life and human health (WDEQ/WQD 2018). Unless otherwise noted, all numeric criteria refer to chronic concentration. Values in red represent an excursion of the applicable numeric criterion.

| Assessment Zone | Above 85 | | | | | | | | | | | Above 85 | | | | | | | | | | | Aquatic Life | Human Health |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Horse Creek - Rd 232 | | | | | | | | | | | Horse Creek - Bullwhacker | | | | | | | | | | | | |
| Collection Year | 2019 | | | | | | | 2020 | | | | 2019 | | | | | | | 2020 | | | | | |
| Collection Date | 6/6 | 6/26 | 8/1 | 8/22 | 9/12 | 10/3 | 10/24 | 5/27 | 6/24 | 7/22 | 10/8 | 6/6 | 6/26 | 8/1 | 8/22 | 9/12 | 10/3 | 10/23 | 5/27 | 6/24 | 7/22 | 10/8 | | |
| Alkalinity, Tot. (mg/L) | 258 | 288 | 276 | 279 | 277 | 327 | 309 | 270 | 228 | 283 | 340 | 177 | 185 | 182 | 171 | 180 | 193 | 191 | 168 | 175 | 166 | 175 | - | - |
| Aluminum, Diss. (µg/L) | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | 750 | - |
| Aluminum, Tot. (µg/L) | 105 | <50 | 70 | 187 | 203 | 162 | 66 | 56 | 102 | 284 | 300 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | | |
| Ammonia-N (mg/L) | <0.05 | NR | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | NR | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | [a] | - |
| Arsenic, Diss. (µg/L) | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 4 | 2 | 3 | 3 | 2 | <1 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | 150 | - |
| Arsenic, Tot. (µg/L) | 3 | 3 | 4 | 3 | 2 | 2 | 2 | 3 | 3 | 4 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 2 | - | 10 |
| Arsenic-III, Tot. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | <5 | <5 | | |
| Arsenic-III, Diss. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | <5 | <5 | | |
| Arsenic-V, Tot. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | <5 | <5 | | |
| Arsenic-V, Diss. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | <5 | <5 | | |
| Bicarbonate, calc. (mg/L) | 315 | 351 | 337 | 340 | 338 | 399 | 377 | 318 | 278 | 345 | 415 | 216 | 216 | 217 | 201 | 213 | 228 | 221 | 190 | 199 | 167 | 175 | | |
| Calcium, Diss. (mg/L) | 86 | 87 | 81 | 81 | 68 | 92 | 102 | 96 | 70 | 91 | 105 | 45 | 47 | 45 | 40 | 43 | 48 | 50 | 49 | 45 | 43 | 47 | - | - |
| Carbonate, calc. (mg/L) | 155 | 173 | 166 | 167 | 166 | 196 | 185 | 162 | 137 | 170 | 204 | 106 | 111 | 109 | 103 | 108 | 116 | 115 | 101 | 105 | 100 | 105 | | |
| Chloride (mg/L) | 7 | 6 | 7 | 9 | 10 | 9 | 9 | 7 | 8 | 10 | 10 | 6 | 6 | 5 | 5 | 5 | 5 | 6 | 5 | 5 | 5 | 6 | 230 | - |
| Hardness, Tot. (mg/L as CaCO3) | 283 | 287 | 263 | 275 | 244 | 304 | 329 | 314 | 253 | 310 | 345 | 177 | 179 | 169 | 157 | 169 | 178 | 187 | 184 | 174 | 165 | 175 | - | - |
| Iron, Diss. (µg/L) | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <30 | <30 | <30 | <30 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <30 | <30 | <30 | <30 | 1000 | 300 |
| Iron, Tot. (µg/L) | 81 | <50 | 57 | 103 | 146 | 154 | <50 | 40 | 78 | 292 | 257 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <30 | 31 | 35 | <30 | | |
| Magnesium, Diss. (mg/L) | 17 | 17 | 15 | 18 | 18 | 18 | 18 | 18 | 19 | 20 | 20 | 15 | 15 | 14 | 14 | 15 | 14 | 15 | 15 | 15 | 14 | 14 | - | - |
| Nitrate+Nitrite-N (µg/L) | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50* | 440 | 410 | 460 | 360 | 590 | 620 | 680 | 420 | 430 | 430 | 510* | - | 10000 |
| Nitrogen, Tot. (µg/L) | 290 | 300 | 330 | 330 | 390 | 270 | 200 | 250 | 410 | 380 | 290* | 680 | 630 | 650 | 510 | 770 | 820 | 760 | 600 | 660 | 550 | 680* | - | - |
| Oxygen, Diss. (% sat.) | - | - | - | - | 64.0 | 45.6 | 93.0 | 163.6 | 78.8 | 27.2 | 77.4 | 184.4 | - | - | - | 133.4 | 123.4 | 129.2 | 157.5 | 171.2 | 186.4 | 154.4 | - | - |
| Oxygen, Diss. (mg/L) | - | - | - | - | 5.5 | 4.5 | 10.7 | 13.1 | 5.8 | 2.2 | 7.1 | 13.5 | - | - | - | 11.3 | 11.8 | 12.9 | 12.2 | 12.5 | 13.8 | 13.8 | [b]CW - 8.0 (ELS) / 4 (OLS)<br>WW+2C - 5.0 (ELS) / 3.0 (OLS) | - |
| pH (s.u.) | - | 8.20 | 8.10 | 7.96 | 7.78 | 7.74 | 8.01 | 8.55 | 7.72 | 7.96 | 7.59 | 8.62 | 8.63 | 8.33 | 8.57 | 8.52 | 8.50 | 8.73 | 8.89 | 8.87 | 9.32 | 9.34 | 6.5 - 9.0 | 6.5 - 9.0 |
| Phosphorus, Tot. (µg/L) | 10 | 20 | 50 | 20 | 20 | 20 | 10 | 10 | 10 | 50 | 20 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | <10 | - | - |
| Potassium, Diss. (mg/L) | 6 | 6 | 5 | 8 | 6 | 5 | 6 | 5 | 6 | 8 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 5 | 5 | 5 | - | - |
| Sodium, Diss. (mg/L) | 22 | 23 | 23 | 25 | 29 | 27 | 26 | 23 | 26 | 30 | 31 | 19 | 17 | 15 | 14 | 17 | 14 | 16 | 15 | 17 | 14 | 15 | - | - |
| Specific Conductivity (µS/cm) | - | 636 | 600 | 594 | 563 | 703 | 666 | 593 | 547 | 566 | 715 | 404 | 400 | 390 | 358 | 366 | 403 | 388 | 370 | 371 | 343 | 367 | - | - |
| Sulfate (mg/L) | 52 | 55 | 42 | 44 | 48 | 52 | 57 | 58 | 56 | 62 | 60 | 32 | 29 | 21 | 22 | 21 | 23 | 23 | 27 | 22 | 20 | 21 | - | - |
| TDS (mg/L) | 420 | 428 | 372 | 344 | 360 | 428 | 420 | 384 | 352 | 412 | 492 | 312 | 272 | 228 | 220 | 252 | 256 | 232 | 212 | 236 | 240 | 252 | - | - |
| Temperature (°C) | - | 15.0 | 18.7 | 18.8 | 13.8 | 8.3 | 2.1 | 16.5 | 20.1 | 19.7 | 10.0 | 21.4 | 18.6 | 17.2 | 18.6 | 14.2 | 9.5 | 8.8 | 18.5 | 21.4 | 20.8 | 11.5 | [c]CW - 20, WW+2C - 30 | - |
| TSS (mg/L) | 2 | 8 | <2 | 7 | 5 | 8 | 9 | 2 | 4 | 8 | 9 | <2 | 4 | <2 | 4 | <2 | <2 | 2 | <2 | 3 | 3 | <2 | - | - |
| Streamflow at Site (cfs) | 3.1 | 6.2 | 2.1 | 0.4 | 0.5 | 0.3 | 1.4 | 1.2 | 0.5 | 0.1 | 0.2 | 14.7 | 7.3 | 8.1 | 8.0 | 10.7 | 6.2 | 8.3 | 9.4 | 6.3 | 6.7 | 6.5 | - | - |
| Ft. Laramie Canal at Diversion (cfs) | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | | |
| Hawk Springs Res. Outflow (cfs) | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | | |
| Sheen | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | No oil sheen | No oil sheen |
| Color | None | None | None | None | None | None | None | None | None | Pl. Grn | None | None | None | None | None | None | None | None | None | None | None | None | - | - |
| Odor | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | - | - |

[a] Criteria are pH and temperature dependent. Table a(ii) of Appendix C, Chapter 1 of the Wyoming Water Quality Rules and Regulations was used to determine attainment with ammonia criteria protective of early life stages for fish.
[b] Criteria protective of cold-water (CW) fisheries is 8 mg/L one-day minimum for early life stages (ELS) and 4 mg/L one-day minimum for other life stages (OLS). Criteria for warm-water (WW) and non-game fisheries is 5 mg/L (ELS) and 3 mg/L (OLS)
[c] The instantaneous criterion protective of cold-water (CW) fisheries is 20 degrees C, for warm-water (WW) and non-game fisheries the criterion is 30 degrees C.
*Values reflect laboratory results minus field blank contamination

**Appendix 1 (cont.) – Physicochemical results at WDEQ/WQD monitoring stations on Horse, Bear and Dry Creeks along with applicable State numeric criteria protective of aquatic life and human health (WDEQ/WQD 2018). Unless otherwise noted, all numeric criteria refer to chronic concentration. Values in red represent an excursion of the applicable numeric criterion.**

| Assessment Zone | Above Hawk | | | | | | | | | | | Above Hawk | | | | | | | | | | | Aquatic Life | Human Health |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Horse Creek - Hwy 85 | | | | | | | | | | | Horse Creek - County Line | | | | | | | | | | | | |
| Collection Year | 2019 | | | | | | | 2020 | | | | 2019 | | | | | | | 2020 | | | | | |
| Collection Date | 6/6 | 6/25 | 7/31 | 8/21 | 9/11 | 10/2 | 10/23 | 5/27 | 6/23 | 7/21 | 10/7 | 6/6 | 6/25 | 7/31 | 8/21 | 9/11 | 10/2 | 10/23 | 5/27 | 6/23 | 7/21 | 10/7 | - | - |
| Alkalinity, Tot. (mg/L) | 194 | 190 | 192 | 170 | 175 | 189 | 198 | 185 | 195 | 191 | 181 | 194 | 217 | 208 | 204 | 204 | 195 | 202 | 216 | 211 | 209 | 198 | - | - |
| Aluminum, Diss. (µg/L) | <50 | <50 | 60 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | 750 | - |
| Aluminum, Tot. (µg/L) | 832 | 193 | 186 | 102 | 92 | 56 | 118 | 292 | 97 | 199 | 124 | 865 | 959 | 817 | 713 | 490 | 348 | 342 | 1187 | 497 | 279 | 241 | | |
| Ammonia-N (mg/L) | <0.05 | NR | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | NR | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | [a] | - |
| Arsenic, Diss. (µg/L) | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 2 | 3 | 4 | 4 | 4 | 4 | 3 | 3 | 4 | 5 | 5 | 4 | 150 | - |
| Arsenic, Tot. (µg/L) | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 5 | 4 | 4 | 3 | 3 | 4 | 5 | 5 | 4 | - | 10 |
| Arsenic-III, Tot. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | |
| Arsenic-III, Diss. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | |
| Arsenic-V, Tot. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | |
| Arsenic-V, Diss. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | |
| Bicarbonate, calc. (mg/L) | 237 | 232 | 222 | 197 | 205 | 219 | 233 | 218 | 233 | 233 | 214 | 237 | 257 | 234 | 241 | 243 | 238 | 238 | 255 | 248 | 247 | 231 | | |
| Calcium, Diss. (mg/L) | 56 | 48 | 47 | 36 | 36 | 43 | 51 | 56 | 51 | 48 | 50 | 54 | 53 | 50 | 47 | 49 | 44 | 52 | 61 | 51 | 49 | 49 | - | - |
| Carbonate, calc. (mg/L) | 116 | 114 | 115 | 103 | 105 | 113 | 119 | 111 | 117 | 115 | 109 | 116 | 130 | 125 | 122 | 122 | 117 | 121 | 130 | 127 | 125 | 119 | | |
| Chloride (mg/L) | 5 | 6 | 6 | 5 | 5 | 6 | 6 | 5 | 6 | 5 | 5 | 6 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 230 | - |
| Hardness, Tot. (mg/L as CaCO3) | 200 | 178 | 177 | 139 | 143 | 157 | 181 | 197 | 185 | 173 | 174 | 192 | 182 | 165 | 159 | 168 | 151 | 175 | 206 | 177 | 168 | 168 | - | - |
| Iron, Diss. (µg/L) | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <30 | <30 | <30 | <30 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <30 | <30 | <30 | <30 | 1000 | 300 |
| Iron, Tot. (µg/L) | 666 | 162 | 171 | 94 | 77 | <50 | 102 | 238 | 114 | 198 | 115 | 712 | 777 | 736 | 660 | 409 | 292 | 289 | 910 | 438 | 249 | 179 | | |
| Magnesium, Diss. (mg/L) | 14 | 14 | 13 | 12 | 13 | 12 | 13 | 14 | 14 | 13 | 12 | 14 | 12 | 10 | 10 | 11 | 10 | 11 | 13 | 12 | 11 | 11 | - | - |
| Nitrate+Nitrite-N (µg/L) | 320 | 180 | 69 | <50 | 100 | 390 | 570 | 300 | <50 | <50 | 198* | 310 | 460 | 1060 | 1110 | 1010 | 1030 | 1080 | 620 | 710 | 1060 | 778* | - | 10000 |
| Nitrogen, Tot. (µg/L) | 570 | 440 | 320 | 230 | 310 | 560 | 700 | 490 | 360 | 300 | 380* | 580 | 760 | 1300 | 1300 | 1200 | 1270 | 1220 | 840 | 1070 | 1280 | 1020* | - | - |
| Oxygen, Diss. (% sat.) | 105.7 | - | - | - | 114.7 | 119.7 | 106.6 | 117.6 | 122.3 | 88.7 | 117.9 | 104.7 | - | - | - | 105.0 | 112.9 | 105.9 | 112.4 | 122.9 | 118.1 | 116.8 | - | - |
| Oxygen, Diss. (mg/L) | 8.6 | - | - | - | 9.1 | 10.6 | 11.0 | 9.5 | 8.4 | 6.4 | 9.7 | 8.4 | - | - | - | 8.6 | 10.5 | 10.9 | 9.4 | 8.4 | 8.3 | 9.6 | [b]CW - 8.0 (ELS) / 4 (OLS)<br>WW+2C - 5.0 (ELS) / 3.0 (OLS) | - |
| pH (s.u.) | 8.17 | 8.38 | 8.74 | 8.71 | 8.64 | 8.73 | 8.59 | 8.57 | 8.41 | 8.07 | 8.52 | 8.26 | 8.46 | 8.93 | 8.51 | 8.42 | 8.39 | 8.53 | 8.51 | 8.58 | 8.52 | 8.65 | 6.5 - 9.0 | 6.5 - 9.0 |
| Phosphorus, Tot. (µg/L) | 30 | 20 | 10 | <10 | <10 | <10 | <10 | <10 | 10 | 10 | <10 | 20 | 40 | 30 | 30 | 20 | <10 | 20 | 50 | 20 | 20 | 10 | - | - |
| Potassium, Diss. (mg/L) | 6 | 6 | 5 | 6 | 6 | 5 | 6 | 4 | 6 | 6 | 5 | 6 | 6 | 6 | 7 | 7 | 6 | 7 | 5 | 7 | 7 | 6 | - | - |
| Sodium, Diss. (mg/L) | 19 | 18 | 18 | 19 | 20 | 17 | 16 | 15 | 19 | 18 | 15 | 18 | 21 | 24 | 27 | 26 | 21 | 22 | 22 | 30 | 30 | 25 | - | - |
| Specific Conductivity (µS/cm) | 423 | 417 | 404 | 356 | 347 | 387 | 400 | 392 | 409 | 404 | 363 | 460 | 442 | 425 | 409 | 395 | 399 | 410 | 440 | 420 | 368 | 385 | - | - |
| Sulfate (mg/L) | 25 | 25 | 22 | 19 | 18 | 19 | 20 | 22 | 22 | 17 | 18 | 25 | 19 | 15 | 15 | 15 | 15 | 16 | 20 | 17 | 17 | 17 | - | - |
| TDS (mg/L) | 320 | 276 | 244 | 195 | 224 | 264 | 256 | 256 | 256 | 268 | 268 | 332 | 284 | 252 | 225 | 272 | 280 | 256 | 288 | 284 | 292 | 300 | - | - |
| Temperature (˚C) | 16.2 | 21.6 | 27.7 | 27.7 | 19.3 | 14.2 | 7.5 | 17.4 | 25.5 | 23.6 | 14.7 | 16.9 | 21.2 | 22.3 | 22.1 | 17.5 | 11.8 | 7.6 | 15.5 | 25.5 | 25.2 | 15.4 | [c]CW - 20, WW+2C - 30 | - |
| TSS (mg/L) | 34 | 8 | <2 | <2 | 2 | <2 | 6 | 11 | 5 | 5 | <2 | 29 | 32 | 39 | 27 | 21 | 16 | 13 | 60 | 28 | 18 | 7 | - | - |
| Streamflow at Site (cfs) | 26.5 | 15.7 | 1.3 | 1.3 | 1.7 | 2.5 | 8.3 | 18.0 | 0.9 | 0.8 | 3.0 | 46.7 | 49.5 | 22.9 | 21.7 | 22.4 | 29.9 | 32.1 | 33.9 | 17.0 | 12.0 | 21.1 | - | - |
| Ft. Laramie Canal at Diversion (cfs) | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | | |
| Hawk Springs Res. Outflow (cfs) | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | | |
| Sheen | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | No oil sheen | No oil sheen |
| Color | Brown | None | None | None | None | None | None | None | None | None | None | Brown | Brown | Brown | Lt. Brn. | Brown | None | None | Pl. Grn | Pl. Brn | Pl. Grn | None | - | - |
| Odor | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | - | - |

[a] Criteria are pH and temperature dependent. Table a(ii) of Appendix C, Chapter 1 of the Wyoming Water Quality Rules and Regulations was used to determine attainment with ammonia criteria protective of early life stages for fish.

[b] Criteria protective of cold-water (CW) fisheries is 8 mg/L one-day minimum for early life stages (ELS) and 4 mg/L one-day minimum for other life stages (OLS). Criteria for warm-water (WW) and non-game fisheries is 5 mg/L (ELS) and 3 mg/L (OLS)

[c] The instantaneous criterion protective of cold-water (CW) fisheries is 20 degrees C, for warm-water (WW) and non-game fisheries the criterion is 30 degrees C.

*Values reflect laboratory results minus field blank contamination

**Appendix 1 (cont.) – Physicochemical results at WDEQ/WQD monitoring stations on Horse, Bear and Dry Creeks along with applicable State numeric criteria protective of aquatic life and human health (WDEQ/WQD 2018). Unless otherwise noted, all numeric criteria refer to chronic concentration. Values in red represent an excursion of the applicable numeric criterion.**

| Assessment Zone | Above Hawk | | | | | | | | | | | Hawk - FI | | | | | | | | | | | Aquatic Life | Human Health |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Horse Creek - Rd 14 | | | | | | | | | | | Horse Creek - Duroc B | | | | | | | | | | | | |
| Collection Year | 2019 | | | | | | | 2020 | | | | 2019 | | | | | | | 2020 | | | | | |
| Collection Date | 6/5 | 6/25 | 7/31 | 8/21 | 9/11 | 10/2 | 10/23 | 5/26 | 6/23 | 7/21 | 10/7 | 6/5 | 6/25 | 7/31 | 8/21 | 9/11 | 10/2 | 10/23 | 5/26 | 6/23 | 7/21 | 10/7 | - | - |
| Alkalinity, Tot. (mg/L) | 222 | 218 | 264 | 258 | 217 | 206 | 207 | 211 | 225 | 254 | 218 | 285 | 290 | 368 | 183 | 359 | 283 | 383 | 351 | 332 | 331 | 351 | - | - |
| Aluminum, Diss. (µg/L) | <50 | <50 | 79 | <50 | 86 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | 284 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | 750 | - |
| Aluminum, Tot. (µg/L) | 2023 | 1448 | 324 | 359 | 764 | 585 | 292 | 1372 | 2195 | 138 | 102 | 2457 | 784 | 888 | 2829 | 850 | 730 | 90 | 595 | 437 | 631 | 263 | | |
| Ammonia-N (mg/L) | <0.05 | NR | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | - | <0.05 | <0.05 | <0.05 | NR | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | 0.38 | - | <0.05 | <0.05 | [a] | - |
| Arsenic, Diss. (µg/L) | 4 | 4 | 7 | 6 | 4 | 3 | 3 | 4 | 5 | 5 | 4 | 7 | 7 | 10 | 8 | 11 | 7 | 11 | 10 | 11 | 11 | 10 | 150 | - |
| Arsenic, Tot. (µg/L) | 5 | 4 | 7 | 6 | 4 | 3 | 3 | 5 | 6 | 5 | 4 | 8 | 7 | 11 | 9 | 11 | 7 | 11 | 11 | 12 | 10 | 11 | - | 10 |
| Arsenic-III, Tot. (µg/L) | - | - | - | - | - | - | - | - | - | <5 | <5 | - | - | - | - | - | - | - | - | - | <5 | - | | |
| Arsenic-III, Diss. (µg/L) | - | - | - | - | - | - | - | - | - | <5 | <5 | - | - | - | - | - | - | - | - | - | <5 | <5 | | |
| Arsenic-V, Tot. (µg/L) | - | - | - | - | - | - | - | - | - | <5 | <5 | - | - | - | - | - | - | - | - | - | 9 | - | | |
| Arsenic-V, Diss. (µg/L) | - | - | - | - | - | - | - | - | - | <5 | <5 | - | - | - | - | - | - | - | - | - | 7 | 8 | | |
| Bicarbonate, calc. (mg/L) | 271 | 259 | 309 | 307 | 258 | 243 | 253 | 241 | 275 | 310 | 255 | 348 | 354 | 434 | 218 | 427 | 335 | 446 | 404 | 391 | 404 | 409 | | |
| Calcium, Diss. (mg/L) | 55 | 54 | 64 | 60 | 53 | 47 | 54 | 58 | 52 | 59 | 54 | 61 | 60 | 58 | 22 | 57 | 48 | 65 | 63 | 50 | 45 | 57 | - | - |
| Carbonate, calc. (mg/L) | 133 | 131 | 158 | 155 | 130 | 124 | 124 | 127 | 135 | 152 | 131 | 171 | 174 | 221 | 110 | 215 | 170 | 230 | 211 | 199 | 199 | 211 | | |
| Chloride (mg/L) | 6 | 5 | 9 | 7 | 5 | 5 | 6 | 5 | 5 | 6 | 5 | 9 | 8 | 14 | 11 | 15 | 9 | 14 | 13 | 12 | 13 | 14 | 230 | - |
| Hardness, Tot. (mg/L as CaCO3) | 185 | 184 | 212 | 207 | 182 | 159 | 184 | 198 | 179 | 205 | 184 | 217 | 220 | 226 | 87 | 221 | 178 | 241 | 243 | 207 | 195 | 225 | - | - |
| Iron, Diss. (µg/L) | <50 | <50 | 113 | <50 | 79 | <50 | <50 | 121 | <30 | <30 | <30 | <50 | <50 | <50 | 268 | <50 | <50 | <50 | <30 | 30 | <30 | 36 | 1000 | 300 |
| Iron, Tot. (µg/L) | 1705 | 1126 | 321 | 358 | 628 | 488 | 246 | 1175 | 2024 | 126 | 90 | 2069 | 649 | 809 | 2297 | 627 | 616 | 76 | 471 | 395 | 480 | 204 | | |
| Magnesium, Diss. (mg/L) | 12 | 12 | 13 | 14 | 12 | 10 | 12 | 13 | 12 | 14 | 12 | 16 | 17 | 20 | 8 | 19 | 14 | 19 | 21 | 20 | 20 | 20 | - | - |
| Nitrate+Nitrite-N (µg/L) | 450 | 360 | 270 | 460 | 810 | 960 | 1010 | 510 | 340 | <50 | <50* | 470 | 370 | 450 | 400 | 460 | 940 | 840 | 420 | 230 | 230 | 558* | - | 10000 |
| Nitrogen, Tot. (µg/L) | 790 | 650 | 1000 | 730 | 1000 | 1200 | 1160 | 730 | 930 | 410 | 280* | 880 | 810 | 1100 | 1300 | 1200 | 1300 | 1220 | 850 | 800 | 700 | 1060* | - | - |
| Oxygen, Diss. (% sat.) | 102.1 | - | - | - | 99.6 | 107.4 | 104.1 | 114.4 | 121.1 | 194.4 | 155.6 | 100.0 | - | - | - | 116.2 | 107.9 | 130.6 | 151.0 | 155.8 | 160.9 | 138.1 | - | - |
| Oxygen, Diss. (mg/L) | 7.6 | - | - | - | 8.1 | 10.2 | 10.7 | 8.8 | 8.2 | 9.8 | 12.2 | 7.7 | - | - | - | 9.4 | 10.4 | 13.1 | 11.2 | 10.7 | 11.2 | 11.8 | [b]CW - 8.0 (ELS) / 4 (OLS)<br>WW+2C - 5.0 (ELS) / 3.0 (OLS) | - |
| pH (s.u.) | 7.95 | 8.41 | 8.62 | 8.41 | 8.45 | 8.55 | 8.34 | 8.82 | 8.38 | 8.25 | 8.65 | 7.87 | 8.20 | 8.54 | 8.42 | 8.40 | 8.47 | 8.67 | 8.77 | 8.56 | 8.35 | 8.68 | 6.5 - 9.0 | 6.5 - 9.0 |
| Phosphorus, Tot. (µg/L) | 70 | 50 | 60 | 60 | 30 | 20 | 10 | 60 | 120 | 30 | 20 | 60 | 30 | 90 | 420 | 90 | 30 | <10 | 90 | 30 | 80 | 20 | - | - |
| Potassium, Diss. (mg/L) | 7 | 6 | 9 | 10 | 8 | 6 | 7 | 6 | 8 | 8 | 7 | 10 | 10 | 16 | 18 | 17 | 10 | 16 | 14 | 13 | 15 | 13 | - | - |
| Sodium, Diss. (mg/L) | 26 | 21 | 28 | 33 | 26 | 21 | 24 | 23 | 29 | 33 | 25 | 47 | 44 | 83 | 54 | 98 | 47 | 99 | 82 | 87 | 76 | 85 | - | - |
| Specific Conductivity (µS/cm) | 470 | 442 | 536 | 529 | 421 | 412 | 425 | 428 | 446 | 500 | 420 | 589 | 590 | 793 | 427 | 755 | 588 | 811 | 715 | 694 | 724 | 727 | - | - |
| Sulfate (mg/L) | 22 | 19 | 21 | 25 | 17 | 17 | 18 | 20 | 19 | 15 | 18 | 25 | 24 | 45 | 24 | 48 | 28 | 48 | 42 | 39 | 42 | 44 | - | - |
| TDS (mg/L) | 372 | 288 | 336 | 256 | 280 | 296 | 264 | 284 | 312 | 356 | 304 | 432 | 380 | 468 | 235 | 520 | 412 | 480 | 464 | 448 | 480 | 500 | - | - |
| Temperature (˚C) | 22.7 | 21.6 | 23.1 | 22.5 | 17.9 | 11.1 | 7.6 | 20.6 | 26.9 | 27.5 | 16.7 | 20.8 | 20.2 | 24.4 | 18.5 | 18.1 | 10.3 | 8.5 | 22.1 | 26.5 | 25.5 | 15.1 | [c]CW - 20, WW+2C - 30 | - |
| TSS (mg/L) | 92 | 64 | 6 | 14 | 43 | 33 | 12 | 101 | 170 | 5 | <2 | 96 | 37 | 47 | 94 | 33 | 36 | <2 | 33 | 28 | 21 | 13 | - | - |
| Streamflow at Site (cfs) | 38.7 | 23.3 | 2.2 | 2.1 | 9.6 | 15.7 | 15.4 | 24.9 | 3.3 | 0.7 | 2.8 | 72.0 | 50.4 | 10.7 | 71.7 | 12.5 | 27.5 | 9.4 | 12.5 | 8.4 | 4.7 | 7.3 | - | - |
| Ft. Laramie Canal at Diversion (cfs) | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | | |
| Hawk Springs Res. Outflow (cfs) | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.0 | 0.0 | 40.0 | 72.0 | 35.0 | 0.0 | 0.0 | 0.0 | 68.5 | 72.0 | 0.0 | | |
| Sheen | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | No oil sheen | No oil sheen |
| Color | Brown | Brown | Lt. Brn | Lt. Brn | Brown | None | Pl. Brn | Lt. Brn | Brown | Lt. Brn | None | Brown | Brown | Brown | Br/Org | Brown | None | None | Pl. Grn | Pl. Yel | Pl. Grn | None | - | - |
| Odor | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | - | - |

[a] Criteria are pH and temperature dependent. Table a(ii) of Appendix C, Chapter 1 of the Wyoming Water Quality Rules and Regulations was used to determine attainment with ammonia criteria protective of early life stages for fish.

[b] Criteria protective of cold-water (CW) fisheries is 8 mg/L one-day minimum for early life stages (ELS) and 4 mg/L one-day minimum for other life stages (OLS). Criteria for warm-water (WW) and non-game fisheries is 5 mg/L (ELS) and 3 mg/L (OLS)

[c] The instantaneous criterion protective of cold-water (CW) fisheries is 20 degrees C, for warm-water (WW) and non-game fisheries the criterion is 30 degrees C.

*Values reflect laboratory results minus field blank contamination

**Appendix 1 (cont.) – Physicochemical results at WDEQ/WQD monitoring stations on Horse, Bear and Dry Creeks along with applicable State numeric criteria protective of aquatic life and human health (WDEQ/WQD 2018). Unless otherwise noted, all numeric criteria refer to chronic concentration. Values in red represent an excursion of the applicable numeric criterion.**

| Assessment Zone | Hawk - FI | | | | | | | | | | | Below FI | | | | | | | | | | | Aquatic Life | Human Health |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Horse Creek - Rd 42 | | | | | | | | | | | Horse Creek - Blw EGHD | | | | | | | | | | | | |
| Collection Year | 2019 | | | | | | | 2020 | | | | 2019 | | | | | | | 2020 | | | | | |
| Collection Date | 6/5 | 6/25 | 7/31 | 8/21 | 9/11 | 10/2 | 10/23 | 5/26 | 6/23 | 7/21 | 10/7 | 6/5 | 6/25 | 7/31 | 8/21 | 9/11 | 10/2 | 10/23 | 5/26 | 6/23 | 7/21 | 10/7 | - | - |
| Alkalinity, Tot. (mg/L) | 292 | 303 | 365 | 203 | 345 | 296 | 385 | 351 | 369 | 388 | 350 | 304 | 203 | 362 | 238 | 183 | 181 | 372 | 175 | 145 | 143 | 327 | - | - |
| Aluminum, Diss. (µg/L) | <50 | <50 | 105 | 270 | 58 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | 343 | 1239 | 79 | <50 | <50 | <50 | <50 | <50 | <50 | 750 | - |
| Aluminum, Tot. (µg/L) | 1744 | 1501 | 2448 | 10068 | 1236 | 1087 | 182 | 1151 | 371 | 723 | 907 | 1687 | 944 | 1865 | 4368 | 814 | 680 | 174 | 722 | 449 | 2760 | 193 | | |
| Ammonia-N (mg/L) | <0.05 | NR | <0.05 | 0.077 | <0.05 | <0.05 | <0.05 | <0.05 | - | 0.069 | <0.05 | <0.05 | NR | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | [a] | - |
| Arsenic, Diss. (µg/L) | 8 | 7 | 12 | 7 | 10 | 7 | 10 | 10 | 14 | 15 | 9 | 8 | 3 | 12 | 9 | 3 | 3 | 10 | 3 | 2 | 2 | 12 | 150 | - |
| Arsenic, Tot. (µg/L) | 8 | 8 | 12 | 10 | 10 | 7 | 10 | 11 | 13 | 14 | 10 | 9 | 4 | 13 | 10 | 4 | 3 | 10 | 3 | 2 | 3 | 12 | - | 10 |
| Arsenic-III, Tot. (µg/L) | - | - | - | - | - | - | - | - | - | - | <5 | - | - | - | - | - | - | - | - | - | - | - | | |
| Arsenic-III, Diss. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | |
| Arsenic-V, Tot. (µg/L) | - | - | - | - | - | - | - | - | - | - | 7 | - | - | - | - | - | - | - | - | - | - | - | | |
| Arsenic-V, Diss. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | |
| Bicarbonate, calc. (mg/L) | 356 | 358 | 387 | 241 | 407 | 361 | 453 | 402 | 423 | 448 | 403 | 371 | 248 | 408 | 290 | 214 | 215 | 454 | 200 | 169 | 169 | 387 | | |
| Calcium, Diss. (mg/L) | 63 | 57 | 54 | 28 | 47 | 57 | 50 | 46 | 32 | 31 | 41 | 62 | 56 | 53 | 39 | 53 | 60 | 51 | 54 | 51 | 54 | 47 | - | - |
| Carbonate, calc. (mg/L) | 175 | 182 | 219 | 122 | 207 | 178 | 231 | 211 | 221 | 233 | 210 | 182 | 122 | 217 | 143 | 110 | 109 | 223 | 105 | 87 | 86 | 196 | | |
| Chloride (mg/L) | 10 | 11 | 17 | 14 | 19 | 11 | 18 | 20 | 37 | 41 | 26 | 12 | 14 | 23 | 18 | 12 | 12 | 23 | 15 | 11 | 9 | 38 | 230 | - |
| Hardness, Tot. (mg/L as CaCO3) | 224 | 216 | 200 | 111 | 196 | 208 | 203 | 197 | 170 | 176 | 193 | 215 | 218 | 206 | 158 | 211 | 224 | 214 | 221 | 197 | 205 | 212 | - | - |
| Iron, Diss. (µg/L) | <50 | <50 | 84 | 249 | <50 | <50 | <50 | <30 | <30 | 35 | <30 | <50 | <50 | 302 | 1069 | 58 | <50 | <50 | <30 | <30 | 32 | <30 | 1000 | 300 |
| Iron, Tot. (µg/L) | 1473 | 1279 | 2206 | 9817 | 994 | 893 | 154 | 870 | 375 | 595 | 745 | 1397 | 794 | 1451 | 4504 | 687 | 593 | 137 | 547 | 458 | 2116 | 141 | | |
| Magnesium, Diss. (mg/L) | 16 | 18 | 16 | 10 | 19 | 16 | 19 | 20 | 22 | 24 | 22 | 15 | 19 | 18 | 15 | 19 | 18 | 21 | 21 | 17 | 17 | 23 | - | - |
| Nitrate+Nitrite-N (µg/L) | 390 | 300 | 200 | 680 | 220 | 820 | 730 | 170 | 240 | 180 | 218* | 280 | 76 | <50 | 120 | <50 | 120 | 480 | <50 | <50 | <50 | <50* | - | 10000 |
| Nitrogen, Tot. (µg/L) | 850 | 750 | 840 | 1500 | 820 | 1150 | 1100 | 820 | 1080 | 1060 | 880* | 790 | 380 | 920 | 820 | 350 | 380 | 850 | 280 | 310 | 240 | 430* | - | - |
| Oxygen, Diss. (% sat.) | 125.5 | - | - | - | 112.1 | 105.3 | 115.2 | 169.5 | 254.2 | 217.0 | 166.4 | 120.7 | 116.7 | - | - | 105.8 | 106.6 | 111.1 | 103.6 | 117.6 | 112.9 | 114.9 | - | - |
| Oxygen, Diss. (mg/L) | 9.5 | - | - | - | 9.0 | 10.3 | 11.9 | 12.3 | 16.5 | 14.9 | 14.4 | 9.2 | 9.3 | - | - | 8.3 | 9.9 | 11.5 | 9.8 | 8.9 | 8.1 | 9.8 | [b]CW - 8.0 (ELS) / 4 (OLS)<br>WW+2C - 5.0 (ELS) / 3.0 (OLS) | - |
| pH (s.u.) | 7.95 | 8.50 | 9.18 | 8.46 | 8.54 | 8.35 | 8.57 | 8.81 | 8.80 | 8.75 | 8.78 | 7.96 | 8.34 | 8.91 | 8.38 | 8.63 | 8.45 | 8.34 | 8.84 | 8.66 | 8.51 | 8.48 | 6.5 - 9.0 | 6.5 - 9.0 |
| Phosphorus, Tot. (µg/L) | 60 | 50 | 80 | 560 | 40 | 30 | 10 | 40 | 40 | 40 | 40 | 80 | 40 | 60 | 160 | 40 | 30 | 10 | 30 | 30 | 80 | 20 | - | - |
| Potassium, Diss. (mg/L) | 10 | 12 | 12 | 16 | 19 | 12 | 14 | 15 | 18 | 20 | 16 | <10 | 7 | 13 | 16 | 6 | 6 | 17 | 6 | 5 | 4 | 14 | - | - |
| Sodium, Diss. (mg/L) | 51 | 54 | 101 | 69 | 116 | 64 | 117 | 116 | 185 | 183 | 123 | 71 | 53 | 127 | 98 | 58 | 45 | 138 | 65 | 46 | 37 | 170 | - | - |
| Specific Conductivity (µS/cm) | 614 | 625 | 912 | 540 | 779 | 627 | 846 | 747 | 1037 | 1104 | 827 | 672 | 650 | 920 | 688 | 584 | 588 | 934 | 603 | 541 | 522 | 1126 | - | - |
| Sulfate (mg/L) | 31 | 32 | 59 | 56 | 68 | 34 | 66 | 74 | 125 | 132 | 86 | 46 | 115 | 95 | 100 | 119 | 109 | 104 | 143 | 122 | 115 | 234 | - | - |
| TDS (mg/L) | 464 | 420 | 492 | 325 | 492 | 404 | 512 | 524 | 680 | 724 | 528 | 504 | 416 | 544 | 340 | 380 | 364 | 592 | 420 | 340 | 336 | 772 | - | - |
| Temperature (˚C) | 21.6 | 20.5 | 23.8 | 19.8 | 18.5 | 9.7 | 7.3 | 23.4 | 29.9 | 26.5 | 15.1 | 21.6 | 18.6 | 23.9 | 20.7 | 19.7 | 12.1 | 7.1 | 19.1 | 21.9 | 24.4 | 15.1 | [c]CW - 20, WW+2C - 30 | - |
| TSS (mg/L) | 58 | 60 | 102 | 713 | 53 | 46 | 7 | 42 | 11 | 18 | 55 | 60 | 40 | 64 | 403 | 46 | 32 | 5 | 31 | 31 | 100 | <2 | - | - |
| Streamflow at Site (cfs) | 79.5 | 44.1 | 12.4 | 62.0 | 9.0 | 24.0 | 7.9 | 4.2 | 0.3 | 0.1 | 0.8 | 85.2 | 143.5 | 11.9 | 26.5 | 73.6 | 126.7 | 10.8 | 67.3 | 71.1 | 62.8 | 0.7 | - | - |
| Ft. Laramie Canal at Diversion (cfs) | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | 0.0 | 949.0 | 0.0 | 0.0 | 1240.0 | 1145.0 | 0.0 | 1151.0 | 1203.0 | 1185.0 | 0.0 | | |
| Hawk Springs Res. Outflow (cfs) | 0.0 | 0.0 | 40.0 | 72.0 | 35.0 | 0.0 | 0.0 | 0.0 | 68.5 | 72.0 | 0.0 | 0.0 | 0.0 | 40.0 | 72.0 | 35.0 | 0.0 | 0.0 | 0.0 | 68.5 | 72.0 | 0.0 | | |
| Sheen | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | No oil sheen | No oil sheen |
| Color | Brown | Brown | Brown | Brown | Brown | Pl. Grn | None | Pl. Grn | Pl. Grn | Pl. Grn | Brown | Brown | Brown | Brown | Brown | Brown | Pl. Grn | None | Pl. Grn | Brown | Pl. Grn | None | - | - |
| Odor | Organic | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | - | - |

[a] Criteria are pH and temperature dependent. Table a(ii) of Appendix C, Chapter 1 of the Wyoming Water Quality Rules and Regulations was used to determine attainment with ammonia criteria protective of early life stages for fish.

[b] Criteria protective of cold-water (CW) fisheries is 8 mg/L one-day minimum for early life stages (ELS) and 4 mg/L one-day minimum for other life stages (OLS). Criteria for warm-water (WW) and non-game fisheries is 5 mg/L (ELS) and 3 mg/L (OLS)

[c] The instantaneous criterion protective of cold-water (CW) fisheries is 20 degrees C, for warm-water (WW) and non-game fisheries the criterion is 30 degrees C.

*Values reflect laboratory results minus field blank contamination

**Appendix 1 (cont.) – Physicochemical results at WDEQ/WQD monitoring stations on Horse, Bear and Dry Creeks along with applicable State numeric criteria protective of aquatic life and human health (WDEQ/WQD 2018). Unless otherwise noted, all numeric criteria refer to chronic concentration. Values in red represent an excursion of the applicable numeric criterion.**

| Assessment Zone | Below FI | | | | | | | | | | | Below FI | | | | | | | | | | | Aquatic Life | Human Health |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Horse Creek - Rd 53 | | | | | | | | | | | Horse Creek - Rd 48 | | | | | | | | | | | | |
| Collection Year | 2019 | | | | | | | 2020 | | | | 2019 | | | | | | | 2020 | | | | | |
| Collection Date | 6/5 | 6/25 | 7/31 | 8/21 | 9/11 | 10/2 | 10/23 | 5/26 | 6/23 | 7/21 | 10/7 | 6/5 | 6/25 | 7/31 | 8/21 | 9/11 | 10/2 | 10/23 | 5/26 | 6/23 | 7/21 | 10/7 | | |
| Alkalinity, Tot. (mg/L) | 312 | 212 | 339 | 296 | 195 | 182 | 354 | 172 | 152 | 153 | 312 | 348 | 232 | 415 | 413 | 318 | 216 | 386 | 350 | 265 | 329 | 377 | - | - |
| Aluminum, Diss. (µg/L) | <50 | <50 | 101 | 908 | 97 | <50 | <50 | <50 | <50 | 245 | <50 | 105 | <50 | <50 | <50 | 61 | 95 | <50 | <50 | <50 | <50 | <50 | 750 | - |
| Aluminum, Tot. (µg/L) | 2319 | 2083 | 477 | 2509 | 1445 | 1062 | 146 | 587 | 761 | 2112 | 93 | 723 | 3183 | 79 | 960 | 288 | 1455 | 208 | 203 | 335 | 207 | 96 | | |
| Ammonia-N (mg/L) | <0.05 | NR | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | NR | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | - | <0.05 | 0.17 | [a] | - |
| Arsenic, Diss. (µg/L) | 9 | 5 | 11 | 11 | 4 | 3 | 9 | 3 | 2 | 3 | 7 | 15 | 6 | 10 | 14 | 7 | 4 | 10 | 8 | 6 | 8 | 10 | 150 | - |
| Arsenic, Tot. (µg/L) | 10 | 4 | 12 | 11 | 4 | 4 | 9 | 3 | 2 | 3 | 7 | 16 | <11 | 10 | 14 | 7 | 5 | 10 | 8 | 6 | 8 | 11 | - | 10 |
| Arsenic-III, Tot. (µg/L) | - | - | - | - | - | - | - | - | - | <5 | <5 | - | - | - | - | - | - | - | - | - | - | - | | |
| Arsenic-III, Diss. (µg/L) | - | - | - | - | - | - | - | - | - | <5 | <5 | - | - | - | - | - | - | - | - | - | - | - | | |
| Arsenic-V, Tot. (µg/L) | - | - | - | - | - | - | - | - | - | <5 | <5 | - | - | - | - | - | - | - | - | - | - | - | | |
| Arsenic-V, Diss. (µg/L) | - | - | - | - | - | - | - | - | - | <5 | 6 | - | - | - | - | - | - | - | - | - | - | - | | |
| Bicarbonate, calc. (mg/L) | 381 | 259 | 414 | 361 | 238 | 222 | 432 | 197 | 179 | 187 | 381 | 424 | 283 | 506 | 504 | 388 | 264 | 471 | 412 | 323 | 401 | 448 | | |
| Calcium, Diss. (mg/L) | 58 | 58 | 47 | 30 | 52 | 59 | 50 | 56 | 52 | 58 | 53 | 48 | 53 | 69 | 46 | 61 | 61 | 55 | 64 | 58 | 66 | 58 | - | - |
| Carbonate, calc. (mg/L) | 187 | 127 | 203 | 178 | 117 | 109 | 212 | 103 | 91 | 92 | 187 | 209 | 139 | 249 | 248 | 191 | 130 | 232 | 210 | 159 | 197 | 226 | | |
| Chloride (mg/L) | 15 | 16 | 27 | 23 | 12 | 14 | 25 | 16 | 12 | 10 | 31 | 22 | 19 | 26 | 29 | 19 | 18 | 27 | 22 | 17 | 20 | 29 | 230 | - |
| Hardness, Tot. (mg/L as CaCO3) | 211 | 228 | 191 | 153 | 208 | 221 | 220 | 222 | 200 | 219 | 231 | 180 | 202 | 253 | 184 | 231 | 231 | 228 | 246 | 223 | 247 | 231 | - | - |
| Iron, Diss. (µg/L) | <50 | <50 | 58 | 580 | 85 | <50 | <50 | <30 | <30 | 354 | <30 | 81 | <50 | <50 | <50 | <50 | 88 | <50 | <30 | <30 | 31 | <30 | 1000 | 300 |
| Iron, Tot. (µg/L) | 2063 | 1685 | 392 | 2004 | 1193 | 887 | 125 | 440 | 714 | 1946 | 57 | 681 | 2387 | 76 | 857 | 220 | 1217 | 152 | 153 | 311 | 171 | 65 | | |
| Magnesium, Diss. (mg/L) | 16 | 20 | 18 | 19 | 19 | 18 | 23 | 20 | 17 | 18 | 24 | 15 | 17 | 20 | 17 | 20 | 19 | 22 | 21 | 19 | 20 | 21 | - | - |
| Nitrate+Nitrite-N (µg/L) | 270 | 59 | 130 | 76 | <50 | 100 | 390 | <50 | <50 | 61 | 468* | 150 | <50 | 650 | 310 | 330 | 120 | 450 | 420 | 250 | 410 | 218* | - | 10000 |
| Nitrogen, Tot. (µg/L) | 1500 | 450 | 710 | 570 | 380 | 360 | 770 | 300 | 350 | 370 | 920* | 860 | 520 | 1000 | 860 | 690 | 540 | 840 | 740 | 590 | 730 | 620* | - | - |
| Oxygen, Diss. (% sat.) | 104.1 | 74.4 | - | - | 97.2 | 108.0 | 111.6 | 120.4 | 115.1 | 110.0 | 116.1 | 89.3 | 90.3 | - | - | 95.0 | 98.2 | 100.2 | 152.8 | 138.8 | 139.8 | 132.2 | - | - |
| Oxygen, Diss. (mg/L) | 8.2 | 6.0 | - | - | 7.9 | 9.5 | 11.7 | 10.0 | 9.0 | 8.2 | 10.9 | 7.4 | 7.5 | - | - | 8.1 | 9.4 | 10.4 | 12.4 | 10.9 | 10.8 | 12.3 | [b]CW - 8.0 (ELS) / 4 (OLS)<br>WW+2C - 5.0 (ELS) / 3.0 (OLS) | - |
| pH (s.u.) | 7.92 | 8.38 | 8.21 | 8.30 | 8.30 | 8.23 | 8.14 | 8.80 | 8.56 | 8.38 | 8.31 | 8.07 | 8.04 | 7.87 | 7.97 | 7.78 | 7.56 | 7.41 | 8.56 | 8.38 | 8.26 | 8.43 | 6.5 - 9.0 | 6.5 - 9.0 |
| Phosphorus, Tot. (µg/L) | 90 | 60 | 30 | 60 | 60 | 50 | 10 | 30 | 40 | 70 | 10 | 140 | 100 | 20 | 70 | 30 | 60 | 20 | 30 | 40 | 40 | 10 | - | - |
| Potassium, Diss. (mg/L) | 10 | 8 | 14 | 20 | 8 | 6 | 17 | 6 | 5 | 5 | 15 | 15 | 9 | 13 | 15 | 10 | 8 | 18 | 15 | 10 | 11 | 14 | - | - |
| Sodium, Diss. (mg/L) | 83 | 62 | 153 | 144 | 56 | 46 | 149 | 63 | 48 | 40 | 176 | 147 | 89 | 213 | 246 | 154 | 65 | 185 | 159 | 132 | 147 | 206 | - | - |
| Specific Conductivity (µS/cm) | 741 | 674 | 1020 | 879 | 607 | 599 | 985 | 658 | 567 | 550 | 1146 | 906 | 764 | 1306 | 1290 | 984 | 686 | 1142 | 1031 | 880 | 1071 | 1250 | - | - |
| Sulfate (mg/L) | 68 | 126 | 322 | 132 | 120 | 114 | 141 | 170 | 129 | 120 | 266 | 108 | 143 | 251 | 244 | 192 | 131 | 182 | 212 | 176 | 213 | 266 | - | - |
| TDS (mg/L) | 556 | 440 | 620 | 475 | 392 | 380 | 628 | 432 | 380 | 352 | 776 | 668 | 492 | 844 | 740 | 656 | 452 | 712 | 720 | 580 | 708 | 852 | - | - |
| Temperature (˚C) | 19.3 | 17.8 | 21.9 | 19.8 | 18.3 | 11.5 | 6.7 | 16.5 | 20.0 | 22.0 | 11.7 | 17.5 | 16.9 | 16.5 | 17.0 | 15.9 | 10.6 | 7.1 | 18.1 | 20.0 | 20.1 | 12.1 | [c]CW - 20, WW+2C - 30 | - |
| TSS (mg/L) | 84 | 70 | 5 | 76 | 83 | 55 | 5 | 36 | 47 | 98 | <2 | 76 | 103 | <2 | 40 | 9 | 80 | 8 | 9 | 20 | 5 | <2 | - | - |
| Streamflow at Site (cfs) | 86.7 | 142.7 | 7.5 | 13.9 | 72.2 | 116.6 | 11.1 | 57.7 | 72.1 | 57.8 | 3.0 | 107.7 | 114.5 | 6.4 | 8.6 | 6.2 | 83.8 | 17.7 | 10.7 | 20.9 | 11.3 | 6.9 | - | - |
| Ft. Laramie Canal at Diversion (cfs) | 0.0 | 949.0 | 0.0 | 0.0 | 1240.0 | 1145.0 | 0.0 | 1151.0 | 1203.0 | 1185.0 | 0.0 | 0.0 | 949.0 | 0.0 | 0.0 | 1240.0 | 1145.0 | 0.0 | 1151.0 | 1203.0 | 1185.0 | 0.0 | | |
| Hawk Springs Res. Outflow (cfs) | 0.0 | 0.0 | 40.0 | 72.0 | 35.0 | 0.0 | 0.0 | 0.0 | 68.5 | 72.0 | 0.0 | 0.0 | 0.0 | 40.0 | 72.0 | 35.0 | 0.0 | 0.0 | 0.0 | 68.5 | 72.0 | 0.0 | | |
| Sheen | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | No oil sheen | No oil sheen |
| Color | Brown | Brown | Brown | Brown | Brown | Pl. Grn | None | Lt. Brn | Brown | Pl. Grn | None | Brown | Brown | None | Brown | None | Pl. Grn | None | Pl. Grn | Pl. Brn | Pl. Grn | None | - | - |
| Odor | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | - | - |

[a] Criteria are pH and temperature dependent. Table a(ii) of Appendix C, Chapter 1 of the Wyoming Water Quality Rules and Regulations was used to determine attainment with ammonia criteria protective of early life stages for fish.

[b] Criteria protective of cold-water (CW) fisheries is 8 mg/L one-day minimum for early life stages (ELS) and 4 mg/L one-day minimum for other life stages (OLS). Criteria for warm-water (WW) and non-game fisheries is 5 mg/L (ELS) and 3 mg/L (OLS)

[c] The instantaneous criterion protective of cold-water (CW) fisheries is 20 degrees C, for warm-water (WW) and non-game fisheries the criterion is 30 degrees C.

*Values reflect laboratory results minus field blank contamination

**Appendix 1 (cont.) – Physicochemical results at WDEQ/WQD monitoring stations on Horse, Bear and Dry Creeks along with applicable State numeric criteria protective of aquatic life and human health (WDEQ/WQD 2018). Unless otherwise noted, all numeric criteria refer to chronic concentration. Values in red represent an excursion of the applicable numeric criterion.**

| Assessment Zone | Above 85 | | | | | | | | | | | Above Hawk | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Bear Creek - Blw Little Bear Ck | | | | | | | | | | | Bear Creek - 85/151 | | | | | | | | | | | Aquatic Life | Human Health |
| Collection Year | 2019 | | | | | | | 2020 | | | | 2019 | | | | | | | 2020 | | | | | |
| Collection Date | 6/6 | 6/26 | 8/1 | 8/22 | 9/12 | 10/3 | 10/24 | 5/27 | 6/24 | 7/22 | 10/8 | 6/5 | 6/25 | 7/31 | 8/21 | 9/11 | 10/2 | 10/23 | 5/26 | 6/23 | 7/21 | 10/7 | - | - |
| Alkalinity, Tot. (mg/L) | 200 | 207 | 201 | 214 | 211 | 216 | 220 | 190 | 191 | 193 | 208 | 261 | 257 | 255 | 249 | 249 | 263 | 268 | 253 | 251 | 241 | 243 | - | - |
| Aluminum, Diss. (µg/L) | <50 | <50 | <50 | 50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <50 | 302 | <50 | 72 | <50 | <50 | <50 | 194 | 55 | <50 | 750 | - |
| Aluminum, Tot. (µg/L) | 331 | 311 | 478 | 508 | 419 | 324 | 151 | 616 | 521 | 833 | 432 | 2401 | 3448 | 6007 | 4081 | 2316 | 1201 | 2587 | 1049 | 2069 | 4699 | 1409 | | |
| Ammonia-N (mg/L) | <0.05 | NR | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | NR | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | 0.22 | - | <0.05 | <0.05 | [a] | - |
| Arsenic, Diss. (µg/L) | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 6 | 5 | 6 | 6 | 5 | 6 | 5 | 6 | 7 | 7 | 6 | 150 | - |
| Arsenic, Tot. (µg/L) | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 6 | 5 | 7 | 7 | 6 | 6 | 5 | 6 | 7 | 7 | 6 | - | 10 |
| Arsenic-III, Tot. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | |
| Arsenic-III, Diss. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | |
| Arsenic-V, Tot. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | |
| Arsenic-V, Diss. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | | |
| Bicarbonate, calc. (mg/L) | 244 | 253 | 235 | 261 | 257 | 264 | 268 | 224 | 233 | 223 | 254 | 318 | 314 | 297 | 293 | 295 | 305 | 310 | 290 | 295 | 286 | 284 | | |
| Calcium, Diss. (mg/L) | 52 | 54 | 53 | 54 | 51 | 54 | 61 | 55 | 50 | 50 | 59 | 60 | 61 | 55 | 53 | 58 | 57 | 65 | 63 | 58 | 59 | 58 | - | - |
| Carbonate, calc. (mg/L) | 120 | 124 | 121 | 128 | 127 | 130 | 132 | 114 | 115 | 116 | 125 | 157 | 154 | 153 | 149 | 149 | 158 | 161 | 152 | 151 | 145 | 146 | | |
| Chloride (mg/L) | 6 | 5 | 5 | 6 | 6 | 6 | 6 | 7 | 5 | 6 | 6 | 7 | 7 | 7 | 7 | 8 | 8 | 9 | 9 | 8 | 7 | 7 | 230 | - |
| Hardness, Tot. (mg/L as CaCO3) | 178 | 184 | 177 | 183 | 177 | 180 | 202 | 187 | 174 | 174 | 197 | 211 | 210 | 190 | 185 | 202 | 200 | 228 | 219 | 207 | 205 | 202 | - | - |
| Iron, Diss. (µg/L) | <50 | <50 | <50 | <50 | <50 | <50 | <50 | <30 | <30 | <30 | <30 | <50 | <50 | 220 | <50 | 60 | <50 | <50 | <30 | 155 | 41 | <30 | 1000 | 300 |
| Iron, Tot. (µg/L) | 293 | 280 | 405 | 433 | 308 | 237 | 114 | 447 | 448 | 656 | 317 | 1881 | 2625 | 4722 | 3504 | 1781 | 977 | 1941 | 899 | 1667 | 3438 | 777 | | |
| Magnesium, Diss. (mg/L) | 11 | 12 | 11 | 12 | 12 | 11 | 12 | 12 | 12 | 12 | 12 | 15 | 14 | 13 | 13 | 14 | 14 | 16 | 15 | 15 | 14 | 14 | - | - |
| Nitrate+Nitrite-N (µg/L) | 380 | 530 | 300 | 360 | 490 | 650 | 760 | 440 | 390 | 360 | 490* | 160 | 290 | 320 | 520 | 740 | 790 | 470 | 470 | 540 | 770 | 928* | - | 10000 |
| Nitrogen, Tot. (µg/L) | 650 | 740 | 530 | 600 | 700 | 850 | 880 | 630 | 700 | 560 | 670* | 590 | 590 | 760 | 760 | 1000 | 1080 | 780 | 700 | 960 | 1110 | 1210* | - | - |
| Oxygen, Diss. (% sat.) | 119.8 | - | - | - | 96.2 | 98.6 | 97.2 | 110.1 | 104.3 | 102.7 | 99.3 | 105.0 | - | - | - | 97.6 | 103.2 | 102.3 | 121.0 | 115.9 | 103.5 | 110.4 | - | - |
| Oxygen, Diss. (mg/L) | 9.3 | - | - | - | 8.6 | 10.0 | 10.9 | 8.4 | 8.3 | 8.3 | 9.5 | 8.2 | - | - | - | 8.0 | 9.9 | 10.6 | 9.9 | 8.6 | 7.7 | 9.9 | [b]CW - 8.0 (ELS) / 4 (OLS)<br>WW+2C - 5.0 (ELS) / 3.0 (OLS) | - |
| pH (s.u.) | 8.37 | 8.11 | 8.65 | 8.18 | 8.39 | 7.11 | 7.27 | 8.53 | 8.33 | 8.75 | 8.24 | 7.66 | 8.25 | 8.69 | 8.55 | 8.46 | 8.71 | 8.73 | 8.80 | 8.57 | 8.44 | 8.65 | 6.5 - 9.0 | 6.5 - 9.0 |
| Phosphorus, Tot. (µg/L) | 10 | 10 | 20 | 20 | 10 | <10 | <10 | 10 | 20 | 20 | 20 | 40 | 80 | 170 | 120 | 70 | 30 | 60 | 30 | 50 | 90 | 20 | - | - |
| Potassium, Diss. (mg/L) | 6 | 5 | 5 | 7 | 7 | 6 | 6 | 5 | 5 | 5 | 6 | 7 | 5 | 6 | 7 | 7 | 6 | 8 | 5 | 6 | 6 | 6 | - | - |
| Sodium, Diss. (mg/L) | 17 | 16 | 16 | 19 | 20 | 16 | 17 | 17 | 17 | 17 | 17 | 31 | 27 | 30 | 31 | 35 | 35 | 35 | 33 | 40 | 31 | 34 | - | - |
| Specific Conductivity (µS/cm) | 401 | 408 | 399 | 409 | 396 | 427 | 431 | 377 | 374 | 372 | 405 | 515 | 499 | 492 | 489 | 476 | 517 | 536 | 485 | 491 | 489 | 476 | - | - |
| Sulfate (mg/L) | 10 | 9 | 9 | 10 | 10 | 11 | 11 | 10 | 10 | 10 | 10 | 13 | 12 | 13 | 15 | 16 | 17 | 20 | 16 | 17 | 19 | 17 | - | - |
| TDS (mg/L) | 308 | 260 | 232 | 200 | 272 | 284 | 236 | 224 | 252 | 264 | 264 | 388 | 336 | 316 | 360 | 324 | 356 | 328 | 320 | 340 | 352 | 360 | - | - |
| Temperature (˚C) | 18.9 | 14.5 | 19.0 | 16.4 | 12.3 | 6.8 | 2.9 | 19.5 | 17.4 | 18.1 | 9.2 | 20.1 | 19.0 | 22.3 | 20.7 | 17.3 | 10.5 | 7.4 | 17.1 | 22.1 | 22.6 | 12.2 | [c]CW - 20, WW+2C - 30 | - |
| TSS (mg/L) | 16 | 24 | 38 | 48 | 26 | 17 | 12 | 35 | 43 | 62 | 31 | 78 | 130 | 280 | 226 | 105 | 39 | 111 | 44 | 91 | 186 | 26 | - | - |
| Streamflow at Site (cfs) | 13.1 | 8.4 | 10.2 | 9.8 | 10.0 | 9.1 | 12.3 | 9.2 | 6.0 | 6.4 | 8.3 | 28.3 | 27.3 | 15.8 | 11.9 | 9.9 | 7.9 | 20.9 | 12.6 | 5.0 | 6.4 | 4.8 | - | - |
| Ft. Laramie Canal at Diversion (cfs) | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | | |
| Hawk Springs Res. Outflow (cfs) | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | | |
| Sheen | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | No oil sheen | No oil sheen |
| Color | Lt. Brn | None | Brown | Brown | Lt. Brn | None | None | Lt. Brn | Pl. Brn | None | None | Brown | Brown | Brown | Brown | Brown | Grey | Cream | Pl. Grn | Lt. Brn | Lt. Grn. | Grn/Gry | - | - |
| Odor | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | - | - |

[a] Criteria are pH and temperature dependent. Table a(ii) of Appendix C, Chapter 1 of the Wyoming Water Quality Rules and Regulations was used to determine attainment with ammonia criteria protective of early life stages for fish.

[b] Criteria protective of cold-water (CW) fisheries is 8 mg/L one-day minimum for early life stages (ELS) and 4 mg/L one-day minimum for other life stages (OLS). Criteria for warm-water (WW) and non-game fisheries is 5 mg/L (ELS) and 3 mg/L (OLS)

[c] The instantaneous criterion protective of cold-water (CW) fisheries is 20 degrees C, for warm-water (WW) and non-game fisheries the criterion is 30 degrees C.

*Values reflect laboratory results minus field blank contamination

**Appendix 1 (cont.) – Physicochemical results at WDEQ/WQD monitoring stations on Horse, Bear and Dry Creeks along with applicable State numeric criteria protective of aquatic life and human health (WDEQ/WQD 2018). Unless otherwise noted, all numeric criteria refer to chronic concentration. Values in red represent an excursion of the applicable numeric criterion.**

| Assessment Zone | Dry | Dry | | | | Dry | | | | | | | | | | | Aquatic Life | Human Health |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Dry Creek - Rd 32 | Dry Creek - Rd 40 | | | | Dry Creek - Mouth | | | | | | | | | | | | |
| Collection Year | 2020 | 2020 | | | | 2019 | | | | | | | 2020 | | | | | |
| Collection Date | 5/26 | 5/26 | 6/23 | 7/21 | 10/7 | 6/5 | 6/25 | 7/31 | 8/21 | 9/11 | 10/2 | 10/23 | 5/26 | 6/23 | 7/21 | 10/7 | - | - |
| Alkalinity, Tot. (mg/L) | 530 | 534 | 272 | 302 | 515 | 522 | 472 | 647 | 611 | 412 | 395 | 738 | 530 | 369 | 390 | 685 | - | - |
| Aluminum, Diss. (µg/L) | 846 | 301 | <50 | <50 | 186 | 749 | 381 | 351 | 566 | 146 | 237 | 115 | 272 | 110 | <50 | 232 | 750 | - |
| Aluminum, Tot. (µg/L) | 2821 | 1072 | 87 | 568 | 1392 | 5930 | 3422 | 3932 | 3212 | 1645 | 1151 | 807 | 997 | 178 | 884 | 725 | | |
| Ammonia-N (mg/L) | <0.05 | <0.05 | - | 0.087 | <0.05 | 0.058 | NR | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | <0.05 | - | 0.13 | <0.05 | [a] | - |
| Arsenic, Diss. (µg/L) | 23 | 43 | 15 | 23 | 43 | 45 | 33 | 49 | 35 | 26 | 22 | 29 | 32 | 22 | 26 | 30 | 150 | - |
| Arsenic, Tot. (µg/L) | 25 | 42 | 15 | 22 | 43 | 49 | 32 | 52 | 36 | 27 | 23 | 30 | 33 | 21 | 25 | 30 | - | 10 |
| Arsenic-III, Tot. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | <5 | <5 | | |
| Arsenic-III, Diss. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | <5 | <5 | | |
| Arsenic-V, Tot. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 23 | 29 | | |
| Arsenic-V, Diss. (µg/L) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 22 | 29 | | |
| Bicarbonate, calc. (mg/L) | 647 | 627 | 332 | 368 | 628 | 637 | 576 | 757 | 723 | 503 | 482 | 900 | 617 | 450 | 476 | 813 | | |
| Calcium, Diss. (mg/L) | 28 | 42 | 62 | 55 | 47 | 24 | 30 | 45 | 32 | 48 | 58 | 61 | 40 | 55 | 52 | 64 | - | - |
| Carbonate, calc. (mg/L) | 318 | 320 | 163 | 181 | 309 | 313 | 283 | 388 | 367 | 247 | 237 | 443 | 318 | 221 | 234 | 411 | | |
| Chloride (mg/L) | 33 | 48 | 24 | 20 | 34 | 54 | 56 | 43 | 41 | 33 | 29 | 50 | 40 | 32 | 27 | 46 | 230 | - |
| Hardness, Tot. (mg/L as CaCO3) | 156 | 179 | 233 | 207 | 171 | 106 | 137 | 165 | 133 | 186 | 215 | 243 | 178 | 216 | 200 | 255 | - | - |
| Iron, Diss. (µg/L) | 507 | 188 | <30 | 54 | 150 | 540 | 343 | 275 | 441 | 112 | 223 | 94 | 174 | 83 | 43 | 154 | 1000 | 300 |
| Iron, Tot. (µg/L) | 2022 | 728 | 96 | 437 | 939 | 4034 | 2532 | 3614 | 2725 | 1274 | 947 | 653 | 678 | 183 | 668 | 470 | | |
| Magnesium, Diss. (mg/L) | 21 | 18 | 19 | 17 | 13 | 11 | 15 | 13 | 13 | 16 | 17 | 22 | 19 | 19 | 17 | 23 | - | - |
| Nitrate+Nitrite-N (µg/L) | <50 | <50 | <50 | <50 | 198* | <50 | <50 | 170 | 130 | 76 | 140 | 500 | <50 | <50 | 57 | 298* | - | 10000 |
| Nitrogen, Tot. (µg/L) | 1160 | 1260 | 780 | 740 | 770* | 790 | 1400 | 1300 | 1200 | 840 | 720 | 1320 | 1120 | 850 | 940 | 1110* | - | - |
| Oxygen, Diss. (% sat.) | 65.0 | 127.0 | 99.8 | 73.1 | 95.2 | 94.7 | 99.0 | - | - | 104.0 | 99.5 | 129.1 | 140.4 | 128.6 | 111.3 | 126.1 | - | - |
| Oxygen, Diss. (mg/L) | 5.8 | 10.9 | 8.2 | 5.8 | 9.8 | 7.2 | 7.9 | - | - | 8.5 | 9.8 | 13.1 | 11.9 | 10.2 | 8.3 | 11.9 | [b]CW - 8.0 (ELS) / 4 (OLS)<br>WW+2C - 5.0 (ELS) / 3.0 (OLS) | - |
| pH (s.u.) | 8.28 | 8.60 | 8.10 | 7.90 | 8.35 | 7.75 | 8.11 | 8.63 | 8.49 | 8.30 | 8.13 | 8.37 | 8.68 | 8.39 | 8.31 | 8.44 | 6.5 - 9.0 | 6.5 - 9.0 |
| Phosphorus, Tot. (µg/L) | 270 | 180 | 140 | 260 | 70 | 390 | 270 | 310 | 250 | 180 | 120 | 170 | 190 | 110 | 180 | 160 | - | - |
| Potassium, Diss. (mg/L) | 21 | 23 | 12 | 13 | 16 | 22 | 25 | 18 | 23 | 19 | 17 | 34 | 21 | 15 | 16 | 24 | - | - |
| Sodium, Diss. (mg/L) | 254 | 318 | 132 | 147 | 305 | 354 | 292 | 402 | 358 | 266 | 201 | 464 | 311 | 228 | 203 | 374 | - | - |
| Specific Conductivity (µS/cm) | 1216 | 1588 | 933 | 815 | 1552 | 1657 | 1478 | 1927 | 1703 | 1302 | 1250 | 2216 | 1527 | 1224 | 1261 | 1926 | - | - |
| Sulfate (mg/L) | 122 | 288 | 206 | 196 | 304 | 235 | 195 | 322 | 268 | 232 | 230 | 407 | 259 | 248 | 246 | 364 | - | - |
| TDS (mg/L) | 856 | 1092 | 636 | 660 | 1040 | 1220 | 1028 | 1264 | 1045 | 888 | 840 | 1492 | 1068 | 832 | 812 | 1364 | - | - |
| Temperature (˚C) | 13.8 | 13.1 | 17.6 | 19.3 | 7.4 | 21.6 | 18.7 | 21.4 | 19.5 | 17.8 | 9.2 | 7.8 | 15.5 | 19.0 | 22.0 | 10.3 | [c]CW - 20, WW+2C - 30 | - |
| TSS (mg/L) | 26 | 6 | 4 | 49 | 8 | 60 | 37 | 175 | 96 | 49 | 36 | 23 | 11 | 7 | 36 | 3 | - | - |
| Streamflow at Site (cfs) | 0.1 | 1.9 | 3.4 | 1.0 | 0.6 | 22.8 | 12.0 | 1.6 | 1.9 | 1.0 | 4.0 | 0.4 | 3.3 | 2.9 | 1.3 | 0.4 | - | - |
| Ft. Laramie Canal at Diversion (cfs) | NA | 1151.0 | 1203.0 | 1185.0 | 0.0 | 0.0 | 949.0 | 0.0 | 0.0 | 1240.0 | 1145.0 | 0.0 | 1151.0 | 1203.0 | 1185.0 | 0.0 | | |
| Hawk Springs Res. Outflow (cfs) | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | NA | | |
| Sheen | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | No oil sheen | No oil sheen |
| Color | Lt. Brn | Lt. Brn | Pl. Yel | Brown | Pl. Grn | Brown | Brown | Brown | Brown | Brown | Pl. Grn | Pl. Grn | Lt. Brn | Pl. Brn | Lt. Grn | Pl. Grn | - | - |
| Odor | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | None | - | - |

[a] Criteria are pH and temperature dependent. Table a(ii) of Appendix C, Chapter 1 of the Wyoming Water Quality Rules and Regulations was used to determine attainment with ammonia criteria protective of early life stages for fish.

[b] Criteria protective of cold-water (CW) fisheries is 8 mg/L one-day minimum for early life stages (ELS) and 4 mg/L one-day minimum for other life stages (OLS). Criteria for warm-water (WW) and non-game fisheries is 5 mg/L (ELS) and 3 mg/L (OLS)

[c] The instantaneous criterion protective of cold-water (CW) fisheries is 20 degrees C, for warm-water (WW) and non-game fisheries the criterion is 30 degrees C.

*Values reflect laboratory results minus field blank contamination

**Appendix 2 – Spearman correlations (r) between 19 water quality parameters for all five assessment zones (*Above 85*, *Above Hawk*, *Hawk-Fl*, *Below Fl*, and *Dry*) and groundwater wells identified in Table 1. For the *Below Fl* and *Dry* zones, correlations are provided for samples collected when the Fort Laramie Canal was active (Aug) and inactive (No Aug). Values in red are significant at p<0.05. Strong correlation values (r >0.7) are shaded in gray. For variables with no variation in data, correlations cannot be calculated.**

**Above 85**

| | pH | Chloride | Sulfate | Calcium | Magnes-ium | Potass-ium | Sodium | D. Alum-inum | T. Alum-inum | D. Arsenic | T. Arsenic | D. Iron | T. Iron | Bicarb-onate | Nitrate+ Nitrite-N | TSS | Dis-charge | T. Nitro-gen | T. Phos-phorus |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1.000 | -0.574 | -0.290 | -0.712 | -0.234 | -0.671 | -0.607 | | -0.363 | -0.073 | -0.124 | -0.273 | -0.400 | -0.840 | 0.286 | -0.311 | 0.344 | 0.197 | -0.366 |
| Chloride | -0.574 | 1.000 | 0.627 | 0.809 | 0.606 | 0.573 | 0.853 | | 0.273 | 0.134 | 0.157 | -0.052 | 0.221 | 0.772 | -0.613 | 0.077 | -0.597 | -0.608 | 0.384 |
| Sulfate | -0.290 | 0.627 | 1.000 | 0.504 | 0.948 | 0.189 | 0.621 | | -0.452 | -0.087 | -0.090 | -0.050 | -0.457 | 0.498 | -0.622 | -0.530 | -0.722 | -0.654 | 0.133 |
| Calcium | -0.712 | 0.809 | 0.504 | 1.000 | 0.461 | 0.557 | 0.788 | | 0.399 | 0.283 | 0.271 | -0.020 | 0.322 | 0.942 | -0.624 | 0.255 | -0.568 | -0.625 | 0.472 |
| Magnesium | -0.234 | 0.606 | 0.948 | 0.461 | 1.000 | 0.158 | 0.656 | | -0.417 | -0.122 | -0.145 | -0.121 | -0.421 | 0.448 | -0.622 | -0.500 | -0.748 | -0.652 | 0.178 |
| Potassium | -0.671 | 0.573 | 0.189 | 0.557 | 0.158 | 1.000 | 0.590 | | 0.410 | 0.317 | 0.286 | 0.173 | 0.412 | 0.664 | -0.323 | 0.391 | -0.206 | -0.202 | 0.310 |
| Sodium | -0.607 | 0.853 | 0.621 | 0.788 | 0.656 | 0.590 | 1.000 | | 0.279 | 0.244 | 0.256 | -0.010 | 0.263 | 0.823 | -0.715 | 0.145 | -0.575 | -0.626 | 0.508 |
| D. Aluminum | | | | | | | | 1.000 | | | | | | | | | | | |
| T. Aluminum | -0.363 | 0.273 | -0.452 | 0.399 | -0.417 | 0.410 | 0.279 | | 1.000 | 0.382 | 0.421 | -0.136 | 0.952 | 0.389 | -0.140 | 0.868 | 0.041 | -0.020 | 0.469 |
| D. Arsenic | -0.073 | 0.134 | -0.087 | 0.283 | -0.122 | 0.317 | 0.244 | | 0.382 | 1.000 | 0.819 | -0.238 | 0.297 | 0.185 | -0.216 | 0.375 | 0.071 | -0.105 | 0.162 |
| T. Arsenic | -0.124 | 0.157 | -0.090 | 0.271 | -0.145 | 0.286 | 0.256 | | 0.421 | 0.819 | 1.000 | -0.257 | 0.373 | 0.201 | -0.265 | 0.317 | 0.064 | -0.113 | 0.300 |
| D. Iron | -0.273 | -0.052 | -0.050 | -0.020 | -0.121 | 0.173 | -0.010 | | -0.136 | -0.238 | -0.257 | 1.000 | 0.007 | 0.192 | 0.107 | -0.074 | 0.281 | 0.116 | -0.090 |
| T. Iron | -0.400 | 0.221 | -0.457 | 0.322 | -0.421 | 0.412 | 0.263 | | 0.952 | 0.297 | 0.373 | 0.007 | 1.000 | 0.374 | -0.087 | 0.857 | 0.086 | 0.053 | 0.510 |
| Bicarbonate | -0.840 | 0.772 | 0.498 | 0.942 | 0.448 | 0.664 | 0.823 | | 0.389 | 0.185 | 0.201 | 0.192 | 0.374 | 1.000 | -0.612 | 0.281 | -0.565 | -0.566 | 0.534 |
| Nitrate+Nitrite-N | 0.286 | -0.613 | -0.622 | -0.624 | -0.622 | -0.323 | -0.715 | | -0.140 | -0.216 | -0.265 | 0.107 | -0.087 | -0.612 | 1.000 | -0.037 | 0.688 | 0.932 | -0.537 |
| TSS | -0.311 | 0.077 | -0.530 | 0.255 | -0.500 | 0.391 | 0.145 | | 0.868 | 0.375 | 0.317 | -0.074 | 0.857 | 0.281 | -0.037 | 1.000 | 0.152 | 0.054 | 0.394 |
| Discharge | 0.344 | -0.597 | -0.722 | -0.568 | -0.748 | -0.206 | -0.575 | | 0.041 | 0.071 | 0.064 | 0.281 | 0.086 | -0.565 | 0.688 | 0.152 | 1.000 | 0.680 | -0.449 |
| T. Nitrogen | 0.197 | -0.608 | -0.654 | -0.625 | -0.652 | -0.202 | -0.626 | | -0.020 | -0.105 | -0.113 | 0.116 | 0.053 | -0.566 | 0.932 | 0.054 | 0.680 | 1.000 | -0.425 |
| T. Phosphorus | -0.366 | 0.384 | 0.133 | 0.472 | 0.178 | 0.310 | 0.508 | | 0.469 | 0.162 | 0.300 | -0.090 | 0.510 | 0.534 | -0.537 | 0.394 | -0.449 | -0.425 | 1.000 |

**Appendix 2 (cont.) - Spearman correlations (r) between 19 water quality parameters for all five assessment zones (*Above 85*, *Above Hawk*, *Hawk-Fl*, *Below Fl*, and *Dry*) and groundwater wells identified in Table 1. For the *Below Fl* and *Dry* zones, correlations are provided for samples collected when the Fort Laramie Canal was active (Aug) and inactive (No Aug). Values in red are significant at p<0.05. Strong correlation values (r >0.7) are shaded in gray.**

**Above Hawk**

| | pH | Chloride | Sulfate | Calcium | Magnes-ium | Potass-ium | Sodium | D. Alum-inum | T. Alum-inum | D. Arsenic | T. Arsenic | D. Iron | T. Iron | Bicarb-onate | Nitrate+ Nitrite-N | TSS | Dis-charge | T. Nitro-gen | T. Phos-phorus |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1.000 | 0.079 | -0.036 | -0.093 | -0.086 | -0.262 | 0.066 | 0.151 | -0.097 | 0.073 | 0.093 | 0.098 | -0.119 | -0.084 | 0.156 | -0.121 | -0.214 | 0.074 | -0.130 |
| Chloride | 0.079 | 1.000 | -0.027 | 0.613 | 0.720 | 0.100 | 0.570 | 0.387 | 0.394 | 0.575 | 0.552 | 0.280 | 0.389 | 0.563 | -0.109 | 0.317 | -0.210 | -0.012 | 0.422 |
| Sulfate | -0.036 | -0.027 | 1.000 | 0.049 | 0.234 | -0.122 | -0.447 | -0.060 | -0.270 | -0.338 | -0.336 | -0.046 | -0.273 | -0.201 | -0.364 | -0.253 | -0.107 | -0.401 | -0.133 |
| Calcium | -0.093 | 0.613 | 0.049 | 1.000 | 0.677 | 0.171 | 0.592 | 0.216 | 0.621 | 0.666 | 0.644 | 0.080 | 0.578 | 0.681 | -0.062 | 0.534 | 0.160 | 0.041 | 0.661 |
| Magnesium | -0.086 | 0.720 | 0.234 | 0.677 | 1.000 | -0.116 | 0.318 | 0.193 | 0.302 | 0.381 | 0.335 | 0.030 | 0.273 | 0.349 | -0.435 | 0.236 | -0.187 | -0.411 | 0.290 |
| Potassium | -0.262 | 0.100 | -0.122 | 0.171 | -0.116 | 1.000 | 0.526 | 0.091 | 0.159 | 0.393 | 0.383 | 0.171 | 0.147 | 0.588 | 0.181 | 0.143 | -0.084 | 0.330 | 0.355 |
| Sodium | 0.066 | 0.570 | -0.447 | 0.592 | 0.318 | 0.526 | 1.000 | 0.284 | 0.630 | 0.915 | 0.887 | 0.108 | 0.618 | 0.824 | 0.321 | 0.572 | -0.044 | 0.464 | 0.653 |
| D. Aluminum | 0.151 | 0.387 | -0.060 | 0.216 | 0.193 | 0.091 | 0.284 | 1.000 | 0.258 | 0.372 | 0.393 | 0.517 | 0.260 | 0.319 | -0.001 | 0.235 | -0.247 | 0.111 | 0.332 |
| T. Aluminum | -0.097 | 0.394 | -0.270 | 0.621 | 0.302 | 0.159 | 0.630 | 0.258 | 1.000 | 0.687 | 0.729 | 0.277 | 0.991 | 0.623 | 0.238 | 0.963 | 0.446 | 0.342 | 0.850 |
| D. Arsenic | 0.073 | 0.575 | -0.338 | 0.666 | 0.381 | 0.393 | 0.915 | 0.372 | 0.687 | 1.000 | 0.975 | 0.102 | 0.679 | 0.808 | 0.160 | 0.609 | -0.030 | 0.353 | 0.748 |
| T. Arsenic | 0.093 | 0.552 | -0.336 | 0.644 | 0.335 | 0.383 | 0.887 | 0.393 | 0.729 | 0.975 | 1.000 | 0.149 | 0.730 | 0.790 | 0.157 | 0.666 | -0.014 | 0.353 | 0.804 |
| D. Iron | 0.098 | 0.280 | -0.046 | 0.080 | 0.030 | 0.171 | 0.108 | 0.517 | 0.277 | 0.102 | 0.149 | 1.000 | 0.307 | 0.186 | 0.142 | 0.316 | 0.201 | 0.151 | 0.357 |
| T. Iron | -0.119 | 0.389 | -0.273 | 0.578 | 0.273 | 0.147 | 0.618 | 0.260 | 0.991 | 0.679 | 0.730 | 0.307 | 1.000 | 0.602 | 0.287 | 0.969 | 0.461 | 0.396 | 0.864 |
| Bicarbonate | -0.084 | 0.563 | -0.201 | 0.681 | 0.349 | 0.588 | 0.824 | 0.319 | 0.623 | 0.808 | 0.790 | 0.186 | 0.602 | 1.000 | 0.171 | 0.553 | 0.010 | 0.333 | 0.696 |
| Nitrate+Nitrite-N | 0.156 | -0.109 | -0.364 | -0.062 | -0.435 | 0.181 | 0.321 | -0.001 | 0.238 | 0.160 | 0.157 | 0.142 | 0.287 | 0.171 | 1.000 | 0.336 | 0.413 | 0.929 | 0.089 |
| TSS | -0.121 | 0.317 | -0.253 | 0.534 | 0.236 | 0.143 | 0.572 | 0.235 | 0.963 | 0.609 | 0.666 | 0.316 | 0.969 | 0.553 | 0.336 | 1.000 | 0.498 | 0.403 | 0.844 |
| Discharge | -0.214 | -0.210 | -0.107 | 0.160 | -0.187 | -0.084 | -0.044 | -0.247 | 0.446 | -0.030 | -0.014 | 0.201 | 0.461 | 0.010 | 0.413 | 0.498 | 1.000 | 0.384 | 0.260 |
| T. Nitrogen | 0.074 | -0.012 | -0.401 | 0.041 | -0.411 | 0.330 | 0.464 | 0.111 | 0.342 | 0.353 | 0.353 | 0.151 | 0.396 | 0.333 | 0.929 | 0.403 | 0.384 | 1.000 | 0.239 |
| T. Phosphorus | -0.130 | 0.422 | -0.133 | 0.661 | 0.290 | 0.355 | 0.653 | 0.332 | 0.850 | 0.748 | 0.804 | 0.357 | 0.864 | 0.696 | 0.089 | 0.844 | 0.260 | 0.239 | 1.000 |

**Appendix 2 (cont.) - Spearman correlations (r) between 19 water quality parameters for all five assessment zones (*Above 85*, *Above Hawk*, *Hawk-Fl*, *Below Fl*, and *Dry*) and groundwater wells identified in Table 1. For the *Below Fl* and *Dry* zones, correlations are provided for samples collected when the Fort Laramie Canal was active (Aug) and inactive (No Aug). Values in red are significant at p<0.05. Strong correlation values (r >0.7) are shaded in gray.**

**Hawk - Fl**

| | pH | Chloride | Sulfate | Calcium | Magnes-ium | Potass-ium | Sodium | D. Alum-inum | T. Alum-inum | D. Arsenic | T. Arsenic | D. Iron | T. Iron | Bicarb-onate | Nitrate+ Nitrite-N | TSS | Dis-charge | T. Nitro-gen | T. Phos-phorus |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1.000 | 0.754 | 0.736 | -0.259 | 0.598 | 0.373 | 0.787 | 0.023 | -0.347 | 0.591 | 0.737 | -0.417 | -0.354 | 0.484 | -0.417 | -0.293 | -0.713 | -0.068 | -0.186 |
| Chloride | 0.754 | 1.000 | 0.979 | -0.472 | 0.638 | 0.734 | 0.963 | 0.087 | -0.237 | 0.686 | 0.731 | -0.341 | -0.260 | 0.690 | -0.460 | -0.296 | -0.804 | 0.054 | -0.040 |
| Sulfate | 0.736 | 0.979 | 1.000 | -0.428 | 0.618 | 0.656 | 0.939 | 0.041 | -0.241 | 0.639 | 0.692 | -0.352 | -0.263 | 0.668 | -0.420 | -0.289 | -0.786 | 0.045 | -0.088 |
| Calcium | -0.259 | -0.472 | -0.428 | 1.000 | -0.100 | -0.561 | -0.388 | -0.452 | -0.172 | -0.171 | -0.191 | 0.076 | -0.154 | 0.085 | 0.391 | -0.081 | 0.402 | -0.146 | -0.172 |
| Magnesium | 0.598 | 0.638 | 0.618 | -0.100 | 1.000 | 0.443 | 0.692 | -0.515 | -0.615 | 0.645 | 0.668 | -0.860 | -0.636 | 0.735 | -0.471 | -0.597 | -0.848 | -0.333 | -0.189 |
| Potassium | 0.373 | 0.734 | 0.656 | -0.561 | 0.443 | 1.000 | 0.672 | 0.302 | -0.112 | 0.543 | 0.554 | -0.125 | -0.133 | 0.516 | -0.282 | -0.222 | -0.520 | 0.281 | 0.241 |
| Sodium | 0.787 | 0.963 | 0.939 | -0.388 | 0.692 | 0.672 | 1.000 | -0.018 | -0.392 | 0.762 | 0.768 | -0.429 | -0.413 | 0.751 | -0.444 | -0.431 | -0.856 | -0.006 | -0.204 |
| D. Aluminum | 0.023 | 0.087 | 0.041 | -0.452 | -0.515 | 0.302 | -0.018 | 1.000 | 0.606 | -0.074 | -0.006 | 0.641 | 0.623 | -0.392 | -0.118 | 0.583 | 0.292 | 0.217 | 0.471 |
| T. Aluminum | -0.347 | -0.237 | -0.241 | -0.172 | -0.615 | -0.112 | -0.392 | 0.606 | 1.000 | -0.512 | -0.402 | 0.573 | 0.995 | -0.697 | -0.182 | 0.964 | 0.602 | 0.006 | 0.628 |
| D. Arsenic | 0.591 | 0.686 | 0.639 | -0.171 | 0.645 | 0.543 | 0.762 | -0.074 | -0.512 | 1.000 | 0.895 | -0.421 | -0.516 | 0.733 | -0.435 | -0.562 | -0.720 | -0.136 | -0.044 |
| T. Arsenic | 0.737 | 0.731 | 0.692 | -0.191 | 0.668 | 0.554 | 0.768 | -0.006 | -0.402 | 0.895 | 1.000 | -0.413 | -0.410 | 0.645 | -0.419 | -0.415 | -0.677 | -0.051 | 0.056 |
| D. Iron | -0.417 | -0.341 | -0.352 | 0.076 | -0.860 | -0.125 | -0.429 | 0.641 | 0.573 | -0.421 | -0.413 | 1.000 | 0.606 | -0.419 | 0.424 | 0.555 | 0.710 | 0.469 | 0.271 |
| T. Iron | -0.354 | -0.260 | -0.263 | -0.154 | -0.636 | -0.133 | -0.413 | 0.623 | 0.995 | -0.516 | -0.410 | 0.606 | 1.000 | -0.701 | -0.170 | 0.966 | 0.618 | 0.005 | 0.620 |
| Bicarbonate | 0.484 | 0.690 | 0.668 | 0.085 | 0.735 | 0.516 | 0.751 | -0.392 | -0.697 | 0.733 | 0.645 | -0.419 | -0.701 | 1.000 | -0.090 | -0.726 | -0.733 | 0.011 | -0.301 |
| Nitrate+Nitrite-N | -0.417 | -0.460 | -0.420 | 0.391 | -0.471 | -0.282 | -0.444 | -0.118 | -0.182 | -0.435 | -0.419 | 0.424 | -0.170 | -0.090 | 1.000 | -0.150 | 0.466 | 0.685 | -0.189 |
| TSS | -0.293 | -0.296 | -0.289 | -0.081 | -0.597 | -0.222 | -0.431 | 0.583 | 0.964 | -0.562 | -0.415 | 0.555 | 0.966 | -0.726 | -0.150 | 1.000 | 0.625 | -0.043 | 0.606 |
| Discharge | -0.713 | -0.804 | -0.786 | 0.402 | -0.848 | -0.520 | -0.856 | 0.292 | 0.602 | -0.720 | -0.677 | 0.710 | 0.618 | -0.733 | 0.466 | 0.625 | 1.000 | 0.196 | 0.368 |
| T. Nitrogen | -0.068 | 0.054 | 0.045 | -0.146 | -0.333 | 0.281 | -0.006 | 0.217 | 0.006 | -0.136 | -0.051 | 0.469 | 0.005 | 0.011 | 0.685 | -0.043 | 0.196 | 1.000 | 0.058 |
| T. Phosphorus | -0.186 | -0.040 | -0.088 | -0.172 | -0.189 | 0.241 | -0.204 | 0.471 | 0.628 | -0.044 | 0.056 | 0.271 | 0.620 | -0.301 | -0.189 | 0.606 | 0.368 | 0.058 | 1.000 |

**Appendix 2 (cont.) - Spearman correlations (r) between 19 water quality parameters for all five assessment zones (*Above 85*, *Above Hawk*, *Hawk-Fl*, *Below Fl*, and *Dry*) and groundwater wells identified in Table 1. For the *Below Fl* and *Dry* zones, correlations are provided for samples collected when the Fort Laramie Canal was active (Aug) and inactive (No Aug). Values in red are significant at p<0.05. Strong correlation values (r >0.7) are shaded in gray.**

**Below Fl (No Aug)**

| | pH | Chloride | Sulfate | Calcium | Magnes-ium | Potass-ium | Sodium | D. Alum-inum | T. Alum-inum | D. Arsenic | T. Arsenic | D. Iron | T. Iron | Bicarb-onate | Nitrate+ Nitrite-N | TSS | Dis-charge | T. Nitro-gen | T. Phos-phorus |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1.000 | 0.633 | 0.536 | -0.452 | 0.405 | -0.068 | 0.333 | -0.137 | -0.650 | 0.264 | 0.255 | -0.652 | -0.650 | 0.084 | -0.217 | -0.817 | -0.800 | -0.533 | -0.560 |
| Chloride | 0.633 | 1.000 | 0.929 | -0.444 | 0.836 | 0.297 | 0.833 | -0.274 | -0.733 | 0.179 | 0.102 | -0.783 | -0.733 | 0.285 | -0.067 | -0.877 | -0.867 | -0.433 | -0.568 |
| Sulfate | 0.536 | 0.929 | 1.000 | -0.282 | 0.725 | 0.281 | 0.937 | -0.138 | -0.795 | 0.120 | 0.085 | -0.730 | -0.795 | 0.298 | -0.075 | -0.821 | -0.728 | -0.335 | -0.562 |
| Calcium | -0.452 | -0.444 | -0.282 | 1.000 | -0.394 | -0.434 | -0.159 | -0.413 | 0.243 | -0.586 | -0.410 | -0.056 | 0.243 | -0.239 | 0.226 | 0.274 | 0.276 | 0.192 | 0.057 |
| Magnesium | 0.405 | 0.836 | 0.725 | -0.394 | 1.000 | 0.438 | 0.608 | -0.485 | -0.734 | -0.220 | -0.362 | -0.651 | -0.734 | 0.178 | 0.304 | -0.750 | -0.785 | -0.228 | -0.691 |
| Potassium | -0.068 | 0.297 | 0.281 | -0.434 | 0.438 | 1.000 | 0.415 | 0.070 | -0.415 | 0.216 | -0.087 | 0.218 | -0.415 | 0.783 | 0.559 | -0.182 | -0.110 | 0.000 | -0.431 |
| Sodium | 0.333 | 0.833 | 0.937 | -0.159 | 0.608 | 0.415 | 1.000 | -0.137 | -0.683 | 0.213 | 0.153 | -0.578 | -0.683 | 0.527 | -0.033 | -0.681 | -0.567 | -0.367 | -0.507 |
| D. Aluminum | -0.137 | -0.274 | -0.138 | -0.413 | -0.485 | 0.070 | -0.137 | 1.000 | 0.274 | 0.560 | 0.560 | 0.612 | 0.274 | 0.000 | -0.411 | 0.420 | 0.548 | 0.274 | 0.575 |
| T. Aluminum | -0.650 | -0.733 | -0.795 | 0.243 | -0.734 | -0.415 | -0.683 | 0.274 | 1.000 | 0.153 | 0.264 | 0.634 | 1.000 | -0.318 | -0.333 | 0.877 | 0.767 | 0.283 | 0.901 |
| D. Arsenic | 0.264 | 0.179 | 0.120 | -0.586 | -0.220 | 0.216 | 0.213 | 0.560 | 0.153 | 1.000 | 0.943 | 0.228 | 0.153 | 0.517 | -0.545 | 0.022 | 0.060 | -0.306 | 0.290 |
| T. Arsenic | 0.255 | 0.102 | 0.085 | -0.410 | -0.362 | -0.087 | 0.153 | 0.560 | 0.264 | 0.943 | 1.000 | 0.152 | 0.264 | 0.316 | -0.724 | 0.091 | 0.119 | -0.247 | 0.424 |
| D. Iron | -0.652 | -0.783 | -0.730 | -0.056 | -0.651 | 0.218 | -0.578 | 0.612 | 0.634 | 0.228 | 0.152 | 1.000 | 0.634 | 0.112 | 0.056 | 0.857 | 0.894 | 0.410 | 0.587 |
| T. Iron | -0.650 | -0.733 | -0.795 | 0.243 | -0.734 | -0.415 | -0.683 | 0.274 | 1.000 | 0.153 | 0.264 | 0.634 | 1.000 | -0.318 | -0.333 | 0.877 | 0.767 | 0.283 | 0.901 |
| Bicarbonate | 0.084 | 0.285 | 0.298 | -0.239 | 0.178 | 0.783 | 0.527 | 0.000 | -0.318 | 0.517 | 0.316 | 0.112 | -0.318 | 1.000 | 0.268 | -0.197 | -0.117 | -0.243 | -0.400 |
| Nitrate+Nitrite-N | -0.217 | -0.067 | -0.075 | 0.226 | 0.304 | 0.559 | -0.033 | -0.411 | -0.333 | -0.545 | -0.724 | 0.056 | -0.333 | 0.268 | 1.000 | -0.077 | -0.100 | 0.383 | -0.542 |
| TSS | -0.817 | -0.877 | -0.821 | 0.274 | -0.750 | -0.182 | -0.681 | 0.420 | 0.877 | 0.022 | 0.091 | 0.857 | 0.877 | -0.197 | -0.077 | 1.000 | 0.962 | 0.553 | 0.795 |
| Discharge | -0.800 | -0.867 | -0.728 | 0.276 | -0.785 | -0.110 | -0.567 | 0.548 | 0.767 | 0.060 | 0.119 | 0.894 | 0.767 | -0.117 | -0.100 | 0.962 | 1.000 | 0.500 | 0.743 |
| T. Nitrogen | -0.533 | -0.433 | -0.335 | 0.192 | -0.228 | 0.000 | -0.367 | 0.274 | 0.283 | -0.306 | -0.247 | 0.410 | 0.283 | -0.243 | 0.383 | 0.553 | 0.500 | 1.000 | 0.324 |
| T. Phosphorus | -0.560 | -0.568 | -0.562 | 0.057 | -0.691 | -0.431 | -0.507 | 0.575 | 0.901 | 0.290 | 0.424 | 0.587 | 0.901 | -0.400 | -0.542 | 0.795 | 0.743 | 0.324 | 1.000 |

**Appendix 2 (cont.) - Spearman correlations (r) between 19 water quality parameters for all five assessment zones (*Above 85*, *Above Hawk*, *Hawk-Fl*, *Below Fl*, and *Dry*) and groundwater wells identified in Table 1. For the *Below Fl* and *Dry* zones, correlations are provided for samples collected when the Fort Laramie Canal was active (Aug) and inactive (No Aug). Values in red are significant at p<0.05. Strong correlation values (r >0.7) are shaded in gray.**

**Below Fl (Aug)**

| | pH | Chloride | Sulfate | Calcium | Magnes-ium | Potass-ium | Sodium | D. Alum-inum | T. Alum-inum | D. Arsenic | T. Arsenic | D. Iron | T. Iron | Bicarb-onate | Nitrate+ Nitrite-N | TSS | Dis-charge | T. Nitro-gen | T. Phos-phorus |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1.000 | -0.452 | -0.410 | -0.211 | 0.004 | -0.414 | -0.408 | -0.098 | -0.004 | -0.435 | -0.503 | -0.343 | 0.000 | -0.533 | -0.596 | 0.036 | 0.179 | -0.475 | -0.004 |
| Chloride | -0.452 | 1.000 | 0.608 | 0.005 | 0.223 | 0.899 | 0.936 | 0.166 | -0.211 | 0.926 | 0.902 | 0.180 | -0.240 | 0.935 | 0.596 | -0.355 | -0.654 | 0.845 | -0.169 |
| Sulfate | -0.410 | 0.608 | 1.000 | 0.202 | 0.442 | 0.412 | 0.726 | -0.257 | -0.600 | 0.431 | 0.361 | -0.367 | -0.625 | 0.533 | 0.526 | -0.644 | -0.625 | 0.358 | -0.469 |
| Calcium | -0.211 | 0.005 | 0.202 | 1.000 | 0.603 | -0.112 | 0.065 | -0.400 | -0.492 | -0.088 | -0.134 | -0.292 | -0.494 | 0.134 | 0.489 | -0.416 | -0.013 | 0.113 | -0.320 |
| Magnesium | 0.004 | 0.223 | 0.442 | 0.603 | 1.000 | 0.161 | 0.355 | -0.174 | -0.534 | 0.127 | -0.007 | -0.262 | -0.575 | 0.241 | 0.288 | -0.526 | -0.177 | 0.077 | -0.369 |
| Potassium | -0.414 | 0.899 | 0.412 | -0.112 | 0.161 | 1.000 | 0.876 | 0.357 | -0.071 | 0.955 | 0.913 | 0.355 | -0.093 | 0.920 | 0.615 | -0.186 | -0.594 | 0.894 | 0.033 |
| Sodium | -0.408 | 0.936 | 0.726 | 0.065 | 0.355 | 0.876 | 1.000 | 0.112 | -0.384 | 0.874 | 0.820 | 0.037 | -0.414 | 0.910 | 0.649 | -0.480 | -0.760 | 0.816 | -0.231 |
| D. Aluminum | -0.098 | 0.166 | -0.257 | -0.400 | -0.174 | 0.357 | 0.112 | 1.000 | 0.431 | 0.385 | 0.358 | 0.858 | 0.410 | 0.188 | -0.051 | 0.394 | -0.233 | 0.289 | 0.451 |
| T. Aluminum | -0.004 | -0.211 | -0.600 | -0.492 | -0.534 | -0.071 | -0.384 | 0.431 | 1.000 | -0.045 | 0.064 | 0.601 | 0.996 | -0.263 | -0.495 | 0.958 | 0.429 | -0.163 | 0.671 |
| D. Arsenic | -0.435 | 0.926 | 0.431 | -0.088 | 0.127 | 0.955 | 0.874 | 0.385 | -0.045 | 1.000 | 0.951 | 0.412 | -0.071 | 0.945 | 0.578 | -0.184 | -0.655 | 0.920 | 0.064 |
| T. Arsenic | -0.503 | 0.902 | 0.361 | -0.134 | -0.007 | 0.913 | 0.820 | 0.358 | 0.064 | 0.951 | 1.000 | 0.441 | 0.035 | 0.918 | 0.507 | -0.078 | -0.549 | 0.873 | 0.055 |
| D. Iron | -0.343 | 0.180 | -0.367 | -0.292 | -0.262 | 0.355 | 0.037 | 0.858 | 0.601 | 0.412 | 0.441 | 1.000 | 0.584 | 0.253 | 0.026 | 0.529 | 0.008 | 0.353 | 0.514 |
| T. Iron | 0.000 | -0.240 | -0.625 | -0.494 | -0.575 | -0.093 | -0.414 | 0.410 | 0.996 | -0.071 | 0.035 | 0.584 | 1.000 | -0.285 | -0.497 | 0.962 | 0.448 | -0.168 | 0.671 |
| Bicarbonate | -0.533 | 0.935 | 0.533 | 0.134 | 0.241 | 0.920 | 0.910 | 0.188 | -0.263 | 0.945 | 0.918 | 0.253 | -0.285 | 1.000 | 0.734 | -0.382 | -0.637 | 0.943 | -0.108 |
| Nitrate+Nitrite-N | -0.596 | 0.596 | 0.526 | 0.489 | 0.288 | 0.615 | 0.649 | -0.051 | -0.495 | 0.578 | 0.507 | 0.026 | -0.497 | 0.734 | 1.000 | -0.543 | -0.538 | 0.718 | -0.117 |
| TSS | 0.036 | -0.355 | -0.644 | -0.416 | -0.526 | -0.186 | -0.480 | 0.394 | 0.958 | -0.184 | -0.078 | 0.529 | 0.962 | -0.382 | -0.543 | 1.000 | 0.489 | -0.247 | 0.656 |
| Discharge | 0.179 | -0.654 | -0.625 | -0.013 | -0.177 | -0.594 | -0.760 | -0.233 | 0.429 | -0.655 | -0.549 | 0.008 | 0.448 | -0.637 | -0.538 | 0.489 | 1.000 | -0.608 | 0.094 |
| T. Nitrogen | -0.475 | 0.845 | 0.358 | 0.113 | 0.077 | 0.894 | 0.816 | 0.289 | -0.163 | 0.920 | 0.873 | 0.353 | -0.168 | 0.943 | 0.718 | -0.247 | -0.608 | 1.000 | 0.032 |
| T. Phosphorus | -0.004 | -0.169 | -0.469 | -0.320 | -0.369 | 0.033 | -0.231 | 0.451 | 0.671 | 0.064 | 0.055 | 0.514 | 0.671 | -0.108 | -0.117 | 0.656 | 0.094 | 0.032 | 1.000 |

**Appendix 2 (cont.) - Spearman correlations (r) between 19 water quality parameters for all five assessment zones (*Above 85*, *Above Hawk*, *Hawk-Fl*, *Below Fl*, and *Dry*) and groundwater wells identified in Table 1. For the *Below Fl* and *Dry* zones, correlations are provided for samples collected when the Fort Laramie Canal was active (Aug) and inactive (No Aug). Values in red are significant at p<0.05. Strong correlation values (r >0.7) are shaded in gray.**

**Dry (No Aug)**

| | pH | Chloride | Sulfate | Calcium | Magnes-ium | Potass-ium | Sodium | D. Alum-inum | T. Alum-inum | D. Arsenic | T. Arsenic | D. Iron | T. Iron | Bicarb-onate | Nitrate+ Nitrite-N | TSS | Dis-charge | T. Nitro-gen | T. Phos-phorus |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1.000 | -0.071 | 0.536 | 0.464 | 0.222 | 0.107 | 0.643 | -0.321 | -0.107 | 0.250 | 0.234 | -0.357 | -0.107 | 0.486 | 0.414 | 0.321 | 0.107 | 0.571 | -0.143 |
| Chloride | -0.071 | 1.000 | 0.429 | 0.107 | -0.074 | 0.571 | 0.607 | -0.250 | 0.107 | 0.286 | 0.306 | -0.036 | 0.107 | 0.143 | 0.252 | 0.000 | 0.393 | 0.143 | 0.286 |
| Sulfate | 0.536 | 0.429 | 1.000 | 0.893 | 0.556 | 0.464 | 0.857 | -0.893 | -0.607 | 0.000 | 0.018 | -0.857 | -0.607 | 0.943 | 0.955 | -0.357 | -0.214 | 0.429 | -0.500 |
| Calcium | 0.464 | 0.107 | 0.893 | 1.000 | 0.741 | 0.357 | 0.571 | -0.857 | -0.857 | -0.214 | -0.234 | -0.893 | -0.857 | 0.943 | 0.955 | -0.643 | -0.429 | 0.179 | -0.786 |
| Magnesium | 0.222 | -0.074 | 0.556 | 0.741 | 1.000 | 0.556 | 0.334 | -0.408 | -0.889 | -0.741 | -0.767 | -0.556 | -0.889 | 0.754 | 0.636 | -0.630 | -0.815 | 0.334 | -0.556 |
| Potassium | 0.107 | 0.571 | 0.464 | 0.357 | 0.556 | 1.000 | 0.571 | -0.250 | -0.429 | -0.500 | -0.487 | -0.214 | -0.429 | 0.600 | 0.414 | -0.250 | -0.179 | 0.464 | -0.107 |
| Sodium | 0.643 | 0.607 | 0.857 | 0.571 | 0.334 | 0.571 | 1.000 | -0.607 | -0.214 | 0.143 | 0.180 | -0.536 | -0.214 | 0.886 | 0.685 | 0.107 | 0.036 | 0.714 | -0.036 |
| D. Aluminum | -0.321 | -0.250 | -0.893 | -0.857 | -0.408 | -0.250 | -0.607 | 1.000 | 0.643 | 0.000 | -0.036 | 0.964 | 0.643 | -0.943 | -0.955 | 0.500 | 0.214 | -0.179 | 0.714 |
| T. Aluminum | -0.107 | 0.107 | -0.607 | -0.857 | -0.889 | -0.429 | -0.214 | 0.643 | 1.000 | 0.643 | 0.667 | 0.750 | 1.000 | -0.714 | -0.775 | 0.857 | 0.714 | -0.036 | 0.857 |
| D. Arsenic | 0.250 | 0.286 | 0.000 | -0.214 | -0.741 | -0.500 | 0.143 | 0.000 | 0.643 | 1.000 | 0.991 | 0.179 | 0.643 | -0.200 | -0.162 | 0.500 | 0.821 | -0.214 | 0.357 |
| T. Arsenic | 0.234 | 0.306 | 0.018 | -0.234 | -0.767 | -0.487 | 0.180 | -0.036 | 0.667 | 0.991 | 1.000 | 0.144 | 0.667 | -0.174 | -0.145 | 0.541 | 0.811 | -0.144 | 0.378 |
| D. Iron | -0.357 | -0.036 | -0.857 | -0.893 | -0.556 | -0.214 | -0.536 | 0.964 | 0.750 | 0.179 | 0.144 | 1.000 | 0.750 | -1.000 | -0.955 | 0.536 | 0.429 | -0.250 | 0.786 |
| T. Iron | -0.107 | 0.107 | -0.607 | -0.857 | -0.889 | -0.429 | -0.214 | 0.643 | 1.000 | 0.643 | 0.667 | 0.750 | 1.000 | -0.714 | -0.775 | 0.857 | 0.714 | -0.036 | 0.857 |
| Bicarbonate | 0.486 | 0.143 | 0.943 | 0.943 | 0.754 | 0.600 | 0.886 | -0.943 | -0.714 | -0.200 | -0.174 | -1.000 | -0.714 | 1.000 | 0.986 | -0.429 | -0.429 | 0.657 | -0.771 |
| Nitrate+Nitrite-N | 0.414 | 0.252 | 0.955 | 0.955 | 0.636 | 0.414 | 0.685 | -0.955 | -0.775 | -0.162 | -0.145 | -0.955 | -0.775 | 0.986 | 1.000 | -0.559 | -0.360 | 0.288 | -0.721 |
| TSS | 0.321 | 0.000 | -0.357 | -0.643 | -0.630 | -0.250 | 0.107 | 0.500 | 0.857 | 0.500 | 0.541 | 0.536 | 0.857 | -0.429 | -0.559 | 1.000 | 0.536 | 0.429 | 0.786 |
| Discharge | 0.107 | 0.393 | -0.214 | -0.429 | -0.815 | -0.179 | 0.036 | 0.214 | 0.714 | 0.821 | 0.811 | 0.429 | 0.714 | -0.429 | -0.360 | 0.536 | 1.000 | -0.250 | 0.429 |
| T. Nitrogen | 0.571 | 0.143 | 0.429 | 0.179 | 0.334 | 0.464 | 0.714 | -0.179 | -0.036 | -0.214 | -0.144 | -0.250 | -0.036 | 0.657 | 0.288 | 0.429 | -0.250 | 1.000 | 0.214 |
| T. Phosphorus | -0.143 | 0.286 | -0.500 | -0.786 | -0.556 | -0.107 | -0.036 | 0.714 | 0.857 | 0.357 | 0.378 | 0.786 | 0.857 | -0.771 | -0.721 | 0.786 | 0.429 | 0.214 | 1.000 |

**Appendix 2 (cont.) - Spearman correlations (r) between 19 water quality parameters for all five assessment zones (*Above 85*, *Above Hawk*, *Hawk-Fl*, *Below Fl*, and *Dry*) and groundwater wells identified in Table 1. For the *Below Fl* and *Dry* zones, correlations are provided for samples collected when the Fort Laramie Canal was active (Aug) and inactive (No Aug). Values in red are significant at p<0.05. Strong correlation values (r >0.7) are shaded in gray.**

**Dry (Aug)**

| | pH | Chloride | Sulfate | Calcium | Magnes-ium | Potass-ium | Sodium | D. Alum-inum | T. Alum-inum | D. Arsenic | T. Arsenic | D. Iron | T. Iron | Bicarb-onate | Nitrate+ Nitrite-N | TSS | Dis-charge | T. Nitro-gen | T. Phos-phorus |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1.000 | 0.550 | 0.933 | -0.469 | 0.414 | 0.467 | 0.750 | 0.407 | -0.050 | 0.471 | 0.583 | 0.233 | 0.100 | 0.650 | -0.040 | -0.387 | -0.067 | 0.533 | -0.186 |
| Chloride | 0.550 | 1.000 | 0.317 | -0.837 | -0.207 | 0.933 | 0.917 | 0.932 | 0.433 | 0.773 | 0.800 | 0.783 | 0.700 | 0.883 | -0.158 | -0.050 | 0.343 | 0.800 | 0.288 |
| Sulfate | 0.933 | 0.317 | 1.000 | -0.226 | 0.552 | 0.233 | 0.583 | 0.186 | -0.333 | 0.319 | 0.433 | 0.017 | -0.117 | 0.483 | -0.040 | -0.496 | -0.259 | 0.333 | -0.339 |
| Calcium | -0.469 | -0.837 | -0.226 | 1.000 | 0.346 | -0.879 | -0.879 | -0.732 | -0.510 | -0.932 | -0.879 | -0.577 | -0.644 | -0.828 | 0.239 | -0.249 | -0.029 | -0.862 | -0.689 |
| Magnesium | 0.414 | -0.207 | 0.552 | 0.346 | 1.000 | -0.414 | -0.069 | -0.246 | -0.759 | -0.348 | -0.276 | -0.414 | -0.759 | -0.207 | -0.461 | -0.818 | 0.087 | -0.069 | -0.491 |
| Potassium | 0.467 | 0.933 | 0.233 | -0.879 | -0.414 | 1.000 | 0.883 | 0.932 | 0.583 | 0.874 | 0.917 | 0.850 | 0.850 | 0.950 | 0.020 | 0.160 | 0.268 | 0.733 | 0.458 |
| Sodium | 0.750 | 0.917 | 0.583 | -0.879 | -0.069 | 0.883 | 1.000 | 0.814 | 0.283 | 0.874 | 0.900 | 0.633 | 0.567 | 0.933 | -0.198 | -0.059 | 0.033 | 0.817 | 0.322 |
| D. Aluminum | 0.407 | 0.932 | 0.186 | -0.732 | -0.246 | 0.932 | 0.814 | 1.000 | 0.475 | 0.709 | 0.780 | 0.932 | 0.763 | 0.881 | -0.101 | -0.009 | 0.485 | 0.627 | 0.310 |
| T. Aluminum | -0.050 | 0.433 | -0.333 | -0.510 | -0.759 | 0.583 | 0.283 | 0.475 | 1.000 | 0.345 | 0.400 | 0.617 | 0.833 | 0.417 | 0.485 | 0.740 | 0.184 | 0.150 | 0.424 |
| D. Arsenic | 0.471 | 0.773 | 0.319 | -0.932 | -0.348 | 0.874 | 0.874 | 0.709 | 0.345 | 1.000 | 0.950 | 0.563 | 0.630 | 0.874 | -0.195 | 0.174 | -0.080 | 0.824 | 0.658 |
| T. Arsenic | 0.583 | 0.800 | 0.433 | -0.879 | -0.276 | 0.917 | 0.900 | 0.780 | 0.400 | 0.950 | 1.000 | 0.650 | 0.700 | 0.967 | -0.020 | 0.118 | -0.008 | 0.717 | 0.525 |
| D. Iron | 0.233 | 0.783 | 0.017 | -0.577 | -0.414 | 0.850 | 0.633 | 0.932 | 0.617 | 0.563 | 0.650 | 1.000 | 0.833 | 0.767 | 0.119 | 0.202 | 0.485 | 0.383 | 0.254 |
| T. Iron | 0.100 | 0.700 | -0.117 | -0.644 | -0.759 | 0.850 | 0.567 | 0.763 | 0.833 | 0.630 | 0.700 | 0.833 | 1.000 | 0.733 | 0.416 | 0.521 | 0.192 | 0.350 | 0.407 |
| Bicarbonate | 0.650 | 0.883 | 0.483 | -0.828 | -0.207 | 0.950 | 0.933 | 0.881 | 0.417 | 0.874 | 0.967 | 0.767 | 0.733 | 1.000 | 0.020 | 0.025 | 0.134 | 0.683 | 0.356 |
| Nitrate+Nitrite-N | -0.040 | -0.158 | -0.040 | 0.239 | -0.461 | 0.020 | -0.198 | -0.101 | 0.485 | -0.195 | -0.020 | 0.119 | 0.416 | 0.020 | 1.000 | 0.404 | -0.124 | -0.455 | -0.332 |
| TSS | -0.387 | -0.050 | -0.496 | -0.249 | -0.818 | 0.160 | -0.059 | -0.009 | 0.740 | 0.174 | 0.118 | 0.202 | 0.521 | 0.025 | 0.404 | 1.000 | -0.371 | -0.176 | 0.530 |
| Discharge | -0.067 | 0.343 | -0.259 | -0.029 | 0.087 | 0.268 | 0.033 | 0.485 | 0.184 | -0.080 | -0.008 | 0.485 | 0.192 | 0.134 | -0.124 | -0.371 | 1.000 | 0.184 | -0.094 |
| T. Nitrogen | 0.533 | 0.800 | 0.333 | -0.862 | -0.069 | 0.733 | 0.817 | 0.627 | 0.150 | 0.824 | 0.717 | 0.383 | 0.350 | 0.683 | -0.455 | -0.176 | 0.184 | 1.000 | 0.458 |
| T. Phosphorus | -0.186 | 0.288 | -0.339 | -0.689 | -0.491 | 0.458 | 0.322 | 0.310 | 0.424 | 0.658 | 0.525 | 0.254 | 0.407 | 0.356 | -0.332 | 0.530 | -0.094 | 0.458 | 1.000 |

**Appendix 2 (cont.) - Spearman correlations (r) between 19 water quality parameters for all five assessment zones (*Above 85*, *Above Hawk*, *Hawk-Fl*, *Below Fl*, and *Dry*) and groundwater wells identified in Table 1. For the *Below Fl* and *Dry* zones, correlations are provided for samples collected when the Fort Laramie Canal was active (Aug) and inactive (No Aug). Values in red are significant at p<0.05. Strong correlation values (r >0.7) are shaded in gray. For variables with no variation in data, correlations cannot be calculated.**

## Wells

| | pH | Chloride | Sulfate | Calcium | Magnes-ium | Potass-ium | Sodium | D. Alum-inum | T. Alum-inum | D. Arsenic | T. Arsenic | D. Iron | T. Iron | Bicarb-onate | Nitrate+ Nitrite-N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| pH | 1.000 | 0.236 | 0.017 | -0.666 | -0.551 | 0.070 | 0.729 | | 0.469 | 0.097 | -0.304 | | 0.469 | 0.621 | -0.390 |
| Chloride | 0.236 | 1.000 | 0.907 | 0.336 | 0.500 | 0.868 | 0.637 | | -0.309 | 0.463 | 0.194 | | -0.309 | 0.369 | 0.622 |
| Sulfate | 0.017 | 0.907 | 1.000 | 0.404 | 0.533 | 0.923 | 0.484 | | -0.463 | 0.393 | 0.238 | | -0.463 | 0.289 | 0.635 |
| Calcium | -0.666 | 0.336 | 0.404 | 1.000 | 0.872 | 0.270 | -0.319 | | -0.425 | 0.210 | 0.358 | | -0.425 | -0.499 | 0.741 |
| Magnesium | -0.551 | 0.500 | 0.533 | 0.872 | 1.000 | 0.418 | -0.143 | | -0.386 | 0.157 | 0.200 | | -0.386 | -0.248 | 0.724 |
| Potassium | 0.070 | 0.868 | 0.923 | 0.270 | 0.418 | 1.000 | 0.599 | | -0.386 | 0.262 | 0.226 | | -0.386 | 0.418 | 0.561 |
| Sodium | 0.729 | 0.637 | 0.484 | -0.319 | -0.143 | 0.599 | 1.000 | | 0.309 | 0.157 | -0.122 | | 0.309 | 0.869 | -0.028 |
| D. Aluminum | | | | | | | | 1.000 | | | | | | | |
| T. Aluminum | 0.469 | -0.309 | -0.463 | -0.425 | -0.386 | -0.386 | 0.309 | | 1.000 | -0.123 | -0.220 | | 1.000 | 0.464 | -0.425 |
| D. Arsenic | 0.097 | 0.463 | 0.393 | 0.210 | 0.157 | 0.262 | 0.157 | | -0.123 | 1.000 | 0.707 | | -0.123 | 0.066 | 0.577 |
| T. Arsenic | -0.304 | 0.194 | 0.238 | 0.358 | 0.200 | 0.226 | -0.122 | | -0.220 | 0.707 | 1.000 | | -0.220 | -0.218 | 0.486 |
| D. Iron | | | | | | | | | | | | 1.000 | | | |
| T. Iron | 0.469 | -0.309 | -0.463 | -0.425 | -0.386 | -0.386 | 0.309 | | 1.000 | -0.123 | -0.220 | | 1.000 | 0.464 | -0.425 |
| Bicarbonate | 0.621 | 0.369 | 0.289 | -0.499 | -0.248 | 0.418 | 0.869 | | 0.464 | 0.066 | -0.218 | | 0.464 | 1.000 | -0.212 |
| Nitrate+Nitrite-N | -0.390 | 0.622 | 0.635 | 0.741 | 0.724 | 0.561 | -0.028 | | -0.425 | 0.577 | 0.486 | | -0.425 | -0.212 | 1.000 |