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Greater Paraburdoo Surface Water Quality – Paraburdoo, Eastern Range and Western Range

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Executive Summary

This report evaluates historical and current geochemical data from surface water monitoring locations in the Greater Paraburdoo region. Surface water quality was evaluated from monitoring sites in pools and creeks, within the Seven Mile Creek and Turee Creek catchments surrounding the Paraburdoo, Eastern Range and Western Range areas. The aim of this report is to summarise available surface water quality data and provide an update to the surface water component of the 2016 Review of Existing Water Quality Data - Greater Paraburdoo (RTIO-PDE-0154092). This work will provide further understanding of background surface water quality and improve knowledge of the hydrological functioning of surface water features.

Surface water in the Greater Paraburdoo region is circum-neutral to mildly alkaline (median lab pH = 8.0) and is generally fresh with TDS <2000 mg/L (median 2017-2018 = 810 mg/L). Metal concentrations were generally low and no obvious trends were identified. Typical water chemistry varied between locations, in particular between the disconnected pools within the Eastern and Western Ranges and the groundwater connected surface features of Ratty Springs and Pirraburdu Spring.

The Western and Eastern Range pools were very fresh; Western Range pools had TDS of <300 mg/L (median = 138 mg/L) and Eastern Range pools of <650 µS/cm (median = 200 mg/L). Major ion compositions of Eastern Range Pools typically ranged from Ca-HCO_3-rich waters to higher proportions of Na-Cl ions. Western Range pools were characterised by higher proportions of Ca ions and generally HCO_3 to SO_4 dominated anions. The very fresh water in Western and Eastern Range pools was also demonstrated by notably low concentrations (<10 mg/L) of major ions (Cl, Mg, Na and SO_4) for numerous samples.

Groundwater connected sites at Pirraburdu and Ratty Springs contained relatively higher proportions of Mg and HCO_3 ions and were more saline. Ratty Springs had TDS <1100 mg/L and median of 750 mg/L.

Surface water from the main drainage course of Seven Mile Creek (including within the Paraburdoo mining area) was characterised by Na-Mg-HCO_3-Cl to Na-Mg-HCO_3-Cl-SO_4 water, with the exception of Kelly's Pool which had slightly higher proportions of Mg. The salinity was variable but typically >1000 mg/L at 7Mile Creek and Kelly's Pool. Increasing trends in salinity and some major ions were observed at 7 Mile Creek monitoring site and downstream in at Joe's Crossing, in the Paraburdoo mining area.

Nitrate concentrations were variable between sites with the highest concentrations occurring at Ratty Springs (median = 30 mg/L). Most sites had nitrate of <10 mg/L. However, surface water from Joe's crossing area had notably higher nitrate than upstream in 7 Mile Creek, with a long term median of 14 mg/L compared to 1.5 mg/L at 7 Mile Creek monitoring site. Nitrate concentrations at Joe's crossing had decreased from initially higher concentrations of >20 mg/L in 2011, but have remained elevated compared to upstream sites. In 2017-2018 nitrate concentrations in the Joe's Crossing area had a median of 8 mg/L and upstream at Kelly's Pool and 7 Mile Creek were <0.5 mg/L.

Based on this updated surface water quality review a number of further or continued actions are recommended:

Regular monitoring of surface water monitoring sites should be continued to build up consistent surface water quality data. This is important to assess the external impacts from mining and for establishing background surface water quality characteristics. Monitoring sites may require biannual sampling (wet and dry season) or annual sampling during wet season to ensure the water quality and natural variation is captured, particularly for ephemeral water bodies. Specific recommendations include:

- Continued sampling of in-pit surface water features that form in the 4E, 4W and 11W pits during the wet season. This is important to support closure planning options to leave pit lakes at closure rather than backfill, particularly as PAF is located on the pit wall.
- The Pirraburdu Springs monitoring sites that are proximal to mining activities (11W) and should be incorporated into the regular monitoring program, to monitor for any changes in water quality.
- Continued opportunistic sampling of Python Pool (23EBP1) when wet should be undertaken due to proximity to mining at Eastern Range's and heritage significance.
- Further monitoring is required to establish baseline water quality in Western Range's pools and Kelly's Pool, all of which only have 2018 data. In particular, continued monitoring of Western Range pools during the study phase will allow for understanding background water quality prior to mining.
- The standard analytical suite should be applied for studies as well as for the regular regional monitoring. This allows for continued build-up of regional background water quality and comparison between sites.
- Future review of surface water data should pay particular attention to; 1) higher nitrate concentrations observed in the Paraburdoo mining area at Joe's crossing that may be associated with mining activities; 2) monitoring of increasing trends in salinity and major ions in Seven Mile. Higher salinity in these regional ephemeral creeks could reflect climate processes over this period. However, impacts from changes in catchment due to mining activities could also result in lower recharge to creek systems. Determining a long term trend is also difficult due to intermittent sampling and variation between wet or dry season.

Table of Contents

Table of Figures

Table of Tables

1 Introduction

The Greater Paraburdoo region is located within the Seven Mile Creek, Six Mile Creek and Turee Creek catchments. The creeks drain west to southwest and join with the Ashburton River. Creek flows are ephemeral, occurring only after significant rainfall events. However, numerous surface water features occur along the creek lines and tributaries. Surface water features include groundwater discharge springs as well as disconnected rainfall-runoff fed pools. The aim of this report is to summarise available surface water quality data and provide an update to the surface water component of the 2016 Review of Existing Water Quality Data - Greater Paraburdoo (RTIO-PDE-0154092). This work will provide further understanding of background surface water quality and improve knowledge of the hydrological functioning of surface water features.

1.1 Background

The Seven Mile Creek catchment drains from Tom Price to Paraburdoo by Bellary Creek, where it merges with Tableland Creek to form Seven Mile Creek immediately downstream of the Paraburdoo Airport (RTIO, 2009). Seven Mile Creek dissects Paraburdoo mine site between the 4W and 4E deposits. Pirraburdu Creek (a major tributary of the Seven Mile Creek) drains through the western portion of the Paraburdoo mine and joins with Seven Mile Creek approximately 12 km south west of the mine site. Ratty Springs, a rights reserved heritage area, occurs where the Pirraburdoo Creek alluvial aquifer intercepts the impermeable upper Nammuldi member of the Marra Mamba Formation, which likely forms a barrier to alluvial flow and groundwater is subsequently expressed at the surface (Dogramaci, 2016).

Eastern and Western Range are elevated ridge lines within the southern extension of the Hamersley Range, located to the east and west of Paraburdoo respectively. Western Range is situated along the catchment divide of Six Mile Creek and Seven Mile Creek. Eastern Range is situated on a catchment divide between the Seven Mile Creek and Turee Creek catchments. Numerous ephemeral to semi-permanent pools occur along gorges within the ranges. The ranges are topographically elevated and the pools are not connected to deeper groundwater, which is estimated to be >100 m below ground level (~346 m RL) (Brunner, 2011). The pools are recharged via direct infiltration or runoff following rainfall and may also receive water from localised surficial alluvial aquifers (Brunner, 2011).

Turee Creek catchment is one of the largest in the Hamersley Basin and extends over ~7000 km^2 (Dogramaci, 2017). Turee Creek headwaters rise from the high relief areas of the Hamersley Range where the Creek drains through the southern portion of the Karijini National Park (RTIO, 2009). The creek drains west and southwest towards the Ashburton River. Stream flow, in addition to rainfall infiltration via alluvium, recharges the shallow alluvial aquifer, which supports the Turee Creek ecosystem.

Surface water features may also develop within pits following rainfall events. Discharge at Joe's Crossing may also result in some runoff and accumulation of surface water within Paraburdoo 4E and 4W pits. Exposures of PAF material on pit walls poses an AMD risk as runoff from the pit walls, following rainfall events, can result in the collection of acidic water in pit. PAF material is currently exposed on the pit walls at 4EN/4EE and 4W and has been exposed for more than ten years (Green et al., 2013; Terrusi, 2016).

2 Surface Water Quality

2.1 Monitoring Sites

Surface water features with available water quality data in the Greater Paraburdoo are detailed below in Table 1. A map of the surface water monitoring sites and creek systems are presented in Figure 3 and in-pit surface water monitoring sites in Figure 4 (Appendix 1).

Table 1: Details of surface water features with water quality data in the Greater Paraburdoo area.

Location	Description	Hydrology comment	Envirosys ID's (ID in bold)	Catchment
Western Range	Pools within gorges	Disconnected from regional groundwater	**SW18WR002**- **G7_8** & **SW18WR002A**- **G7_7** (field site No. WR01-W01) **SW18WR003** (field site No. WR01-W05). **G3_10.** **SW18WR004** (field site No. WR02-WH9, also known as pool 6a). **G8_4.** **SW18WR005** (field site no. WR01-W03, also known as pool 10). **G4_2.** **SW18WR006** (WR01-W06, also known as pool 11a. **G3_3.**	Six Mile/ Seven Mile creeks
Seven Mile Creek	Monitoring sites upstream of Paraburdoo mining area	Main creekline	**7 Mile Creek** **SW18PAR0005** (Kelly's Pool)	Seven Mile Creek
Paraburdoo	Part of Seven Mile Creek	Main creekline	Joe's crossing **SW18PAR0003** **SW18PAR0004**	Seven Mile Creek
Ratty Spring's	Spring in Pirraburdu Creek, eastern side of Western Range	Groundwater connected	**Ratty Springs SW18PAR0001** (upstream of springs)	Seven Mile Creek
Pirraburdu Springs	Spring in Pirraburdu Creek, close to Paraburdoo 11West	Groundwater connected	**Pirra Spring Upper** **Pirra Spring Lower** **RSSW1** **RSSW2**	Seven Mile Creek
Eastern Range	Pools within gorges around Eastern Range mining area. Some difficulties with accessibility for sampling.	Disconnected from regional groundwater	Python Pool – in 24E area **23EBP1** MOC pools - 32E and 37E area **MOCB, MOC-C, MOCD MOC-E, MOC1, MOC2** ERP pools - south of 42E **ERP1, ERP1a, ERP2, ERP3, ERP4, ERP5, ERP6**	Seven Mile/Turee creeks
Paraburdoo Pits s	Surface water pooled within pit voids	Mostly form after rainfall	**MP174ESW0001** **MP1811W0001** **SW154ENW**	Seven Mile Creek

2.2 Stable oxygen and hydrogen isotope compositions

Surface water with stable oxygen and hydrogen isotope data is presented in Figure 1. The local meteoric water and evaporation lines are shown, calculated by Dogramaci et al., (2012). As surface water evaporates, the $\delta^{18}O$ and $\delta^{2}H$ values become increasingly enriched in the remaining surface water. The $\delta^{18}O$ values increase at a higher rate compared to $\delta^{2}H$ during evaporation and surface water isotopic compositions will fall along the local evaporation line.

The surface water pools in Eastern and Western Range's had variable and relatively higher $\delta^{18}O$ and $\delta^{2}H$ values indicative of rainfall fed pools, as opposed to groundwater-fed systems

that typically have more depleted and homogenous stable isotope compositions. Western Range pools had the highest range of $\delta^{18}O$ and $\delta^{2}H$ values, ranging from $\delta^{18}O$ of -0.5 to 14.1 ‰, whereas Eastern Range pools had $\delta^{18}O$ values of -4.7 to 7.1. The highest $\delta^{18}O$ values were reported for Western Range pools SW18WR002 and SW18WR004 when sampled in October 2018. The $\delta^{18}O$ values of Western and Eastern Range Pools are relatively enriched compared to regional surface water reported by Dogramaci et al., (2012), which typically has a depleted $\delta^{18}O$ signature associated with recharge by cyclonic rainfall. Whilst higher $\delta^{18}O$ and $\delta^{2}H$ values can suggest more highly evaporated water, the very fresh surface water with Cl concentrations of <25 mg/L of Western Range pools suggests only minor evaporation. Therefore, the WR pools $\delta^{18}O$ values appear to reflect locally derived rainfall with an enriched $\delta^{18}O$ signature. Rainfall with higher $\delta^{18}O$ values is more typical of weather systems developed to the south as oppose to cyclonic systems from the north. The $\delta^{18}O$ and $\delta^{2}H$ value for the Kelly's Pool sample appeared to show evaporated surface water with a notably enriched $\delta^{18}O$ value. Although there is only one sample and no corresponding salinity data.

In contrast, Ratty Springs and Pirraburdu Springs had generally more depleted and less variable $\delta^{18}O$ and $\delta^{2}H$ signatures (Figure 1), consistent with the influence from groundwater connection that reflects the regional lower $\delta^{18}O$ signature. Stable O and H compositions were similar for Ratty Springs and Pirraburdu Springs with a median of $\delta^{18}O$ value of -5.9 ‰. Surface water analysed from Pirraburdu Springs did have some values that indicated some evaporation of surface water.

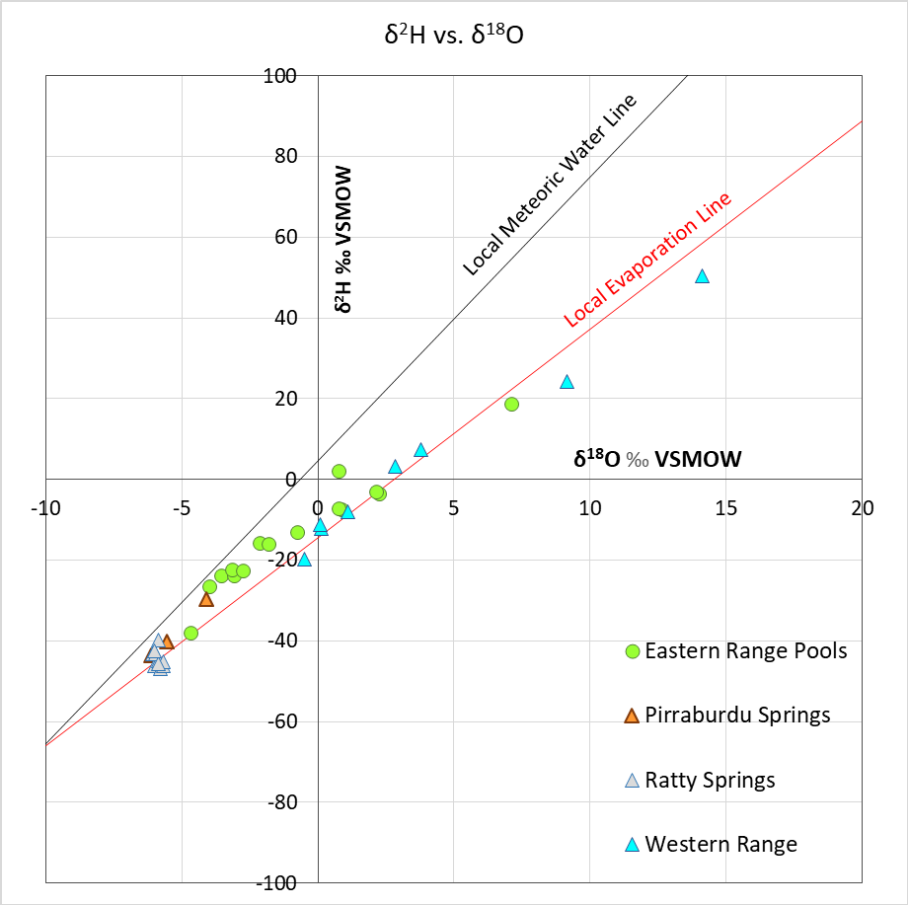

Figure 1: Stable oxygen and hydrogen isotope compositions of Greater Paraburdoo surface water. ERP samples and 2 samples from Pirraburdu collected 2011. The remainder of samples collected in 2017-2018. Local meteoric water line: $\delta^{2}H=7.03\pm0.17\delta^{18}O+4.78\pm1.45$. Local evaporation line: $\delta^{2}H=5.16\pm0.07\ \delta^{18}O-14.37\pm0.49$.

2.3 Water Quality

The major ion chemistry of surface water is presented in Figure 2 and key parameters are plotted in scatter plots, grouped by location, in Appendix 2. Where concentrations are below detection, the data point is shown as a half size icon at half below detection limit. Many monitoring sites have limited data and may only have one water chemistry sample. In particular, water quality data for Kelly's Pool and Western Range pools is from 2017-2018 only. Joe's Crossing, 7 Mile Creek and Ratty Springs have long term monitoring data, but still have temporal gaps in monitoring data.

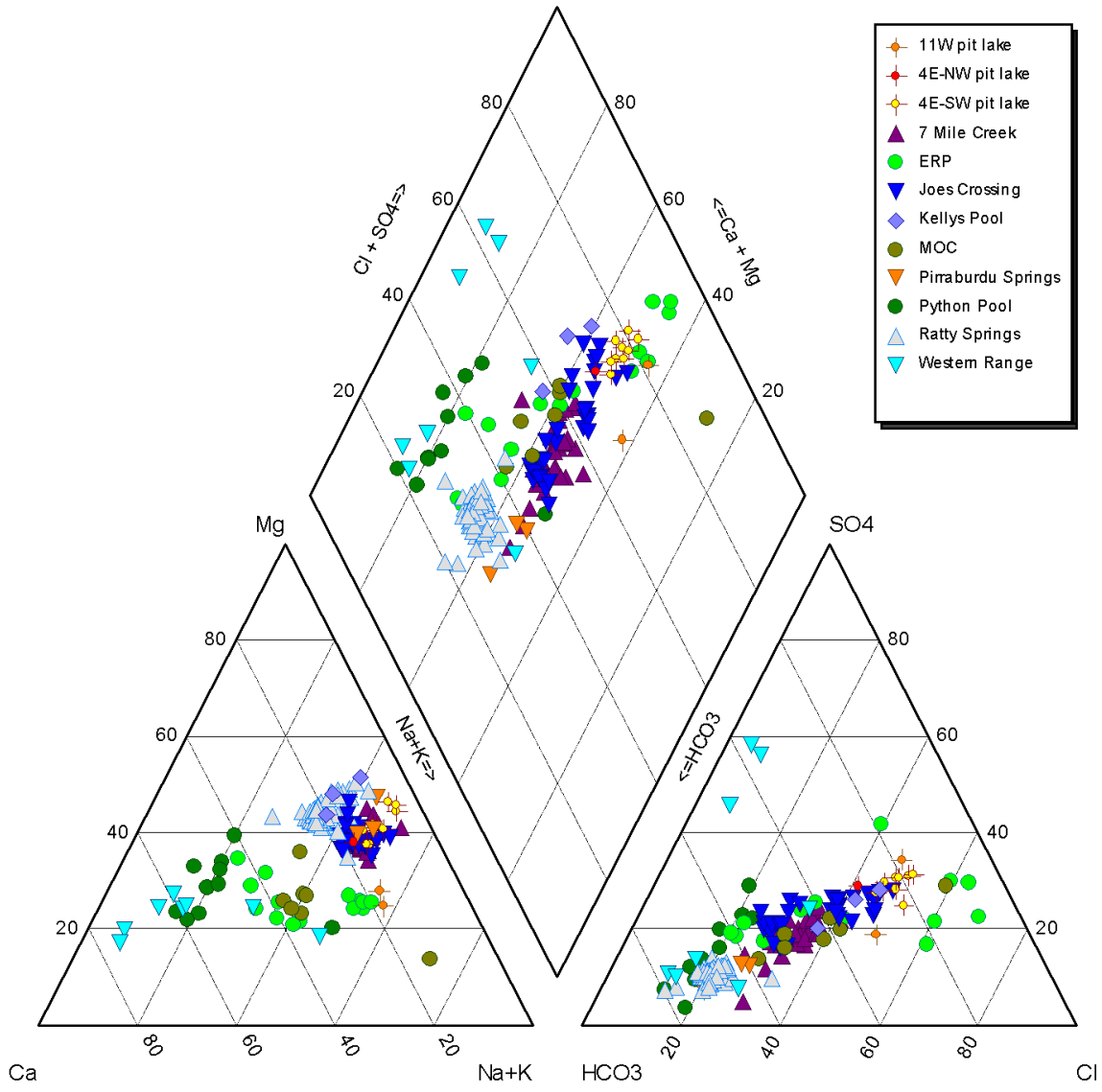

Figure 2: Piper plot of major ions for Greater Paraburdoo surface water.

2.3.1 7 Mile Creek

The 7 Mile Creek monitoring site is located about 3 km northeast of the Paraburdoo mine site towards Paraburdoo township and is shortly downstream of the confluence of Tableland Creek, Bellary Creek and other tributaries into Seven Mile Creek.

The lab pH of the 7 Mile Creek monitoring site ranged from 7.2 to 9 and had generally increased from 2012 to 2015 (Figure 5). However, three samples during 2016-2018 had steady pH values of 8.1-8.3. The field pH data was also variable (6.3-8.3) and was 8.1 when measured in 2018. Historic pH data prior to ~2006-2007 was more variable and then generally decreased during 2008-2010, followed by an increase from 2011-2013. Field pH data was not available for 2013-2017. It may be that older pH data was inputted to Envirosys without discrimination between field and laboratory analysis.

The major ion chemistry of 7 Mile Creek was characterised by Na-Mg-HCO_3-Cl to Na-Mg-HCO_3-Cl-SO_4 water. Salinity mostly ranged between 800 and 2000 mg/L TDS. However, far greater salinity of 3900 mg/L (6000 µS/cm) was measured in August 2016 and highlighted in the previous water quality review (Mather, 2017). Subsequent samples in 2017-2018 had returned to <2000 mg/L TDS. High salinity in August 2016 may reflect evapoconcentration towards the end of the dry season in August. Although rainfall events up to 18 mm measured at Paraburdoo weather station occurred during June and July of 2016 that would have likely recharged some fresher water to the creek and shallow alluvium (Figure 12).

Sulfate concentrations ranged from 59 to 640 mg/L (median = 190 mg/L) and SO_4/Cl was ≤0.7 (Figure 6). Bicarbonate alkalinity increased at 7 Mile Creek over time (R^2=0.33). The HCO_3 concentrations were typically <600 mg/L prior to 2009 and were mostly ~600-800 mg/L during 2011-2015. Samples since 2016 were highly variable with a minimum of 576 mg/L and one elevated concentration of 1805 mg/L corresponding to the highly saline sample from August 2016. A slight increasing trend is also observed for Na concentrations (R^2 = 0.15), which appears to follow a similar pattern. Increases and decreases in the major ions and salinity may partly reflect seasonal changes due to rainfall and evaporation. However, Mann Kendall trend analysis determined increasing trends in TDS, Mg, Na and HCO_3 indicating an overall long term increase in these parameters.

Fe concentrations were variable and ranged from below detection to 1.6 mg/L (median = 0.1 mg/L; Figure 9). The majority of samples were <0.3 mg/L. Mn concentrations ranged from 0.006 to 1.4 mg/L (median = 0.1 mg/L). Al and Zn concentrations decreased over time and were typically <0.1 mg/L. Trace metal concentrations were mostly <0.01 mg/L and frequently below detection. As concentrations ranged from below detection to 0.007 mg/L (Figure 10). Hg was detected for a few samples prior to 2013, with the highest concentration of 0.0006 mg/L reported in December 2007 (Figure 11). However, subsequent samples were below detection.

Nitrate ranged from below detection to 5 mg/L (median = 1.5 mg/L; Figure 7) and did not show any obvious temporal trends. Boron concentrations were steady (median = 0.7 mg/L), except for one elevation concentration of 2.1 mg/L in August 2016.

2.3.2 Kelly's Pool

Kelly's Pool is located just north of Paraburdoo mine site and is downstream of the 7 Mile Creek monitoring site. Kelly's Pool has only been sampled since 2018 onwards so data is limited to 3 samples. Within 2018 the pH was mildly alkaline and ranged between 8.1 and 8.6. Salinity and major ions varied considerably during the year and TDS ranged from 921 to 1530 mg/L and sulfate from 158 to 424 mg/L (Figure 5 and 6). The surface water was sampled twice during February 2018 and had notably fresher water in mid-February compared to early February, likely reflecting dilution from rainfall during this period (Paraburdoo weather station logged 45 mm rainfall 6/2/2018-16/2/2018, with a high intensity event of 21.6 mm on 6/2/2018; Figure 12). Cation chemistry was dominated by Mg then Na and anions were dominated by Cl. Kelly's Pool water displayed a slightly greater influence of Mg ions compared to upstream at 7 Mile Creek (that had Na-Mg type). SO_4/Cl ratios were also ≤0.7.

Al, Fe and Zn concentrations were below detection for all samples and Mn was <0.001 to 0.002 mg/L (Figure 9). As concentrations were 0.001-0.002 mg/L and U concentrations were 0.001-0.004 mg/L (Figure 10). Other trace metals were typically below detection.

Nitrate concentrations were low <0.05 mg/L (Figure 7). However, total N was 0.4-0.6 mg/L, which appeared to be from NH_3 and NH_4. Boron was slightly elevated at Kelly's Pool compared to 7 Mile Creek. The B concentrations ranged from 0.7 to 1.5 mg/L.

2.3.3 Joe's Crossing

Joes Crossing, SW18PAR0003 (Joe's south) and SW18PAR0004 (Joe's north) are located in Seven Mile Creek, directly in the Paraburdoo mine site area between 4W and 4E. Joe's crossing receives occasional dewatering discharge from Paraburdoo pits. Joes Crossing has been monitored since November 2010 although there are some gaps in monitoring, with no sampling conducted in the periods of June 2012 to January 2014 and April 2016 to October 2017. Some samples were only analysed for pH, TDS and TSS. The Joe's north and south monitoring points have data for 2018 only. Infrequent sampling is likely due to intermittent discharge at the site and the typically dry nature of the drainage course.

The lab pH of surface water ranged from 7.6 to 8.9 (median = 8.0) and field pH was similar between 7.0 and 8.7 (median = 7.8) (Figure 5). Salinity ranged from 610 to 1800 mg/L TDS (median = 948 mg/L). Salinity measured at Joe's Crossing in ~2010-2012 was generally lower and had TDS of typically <800 mg/L, compared to increased concentrations since mid-2012 which were most commonly ~900-1100 mg/L (Figure 5). Higher salinity of 1592 mg/L was measured in September 2018 and overall TDS had a positive increasing trend (R^2 = 0.2). Joe's Crossing north (SW18PAR0004) reported the most elevated salinity of for the area 1800 mg/L in February 2018, whereas Joe's Crossing site was <1500 mg/L for the same date. A subsequent sample ten days later at Joe's Crossing north was fresher at 1270 mg/L TDS. Joe's Crossing south (SW18PAR003) was notably fresher at ~710 mg/L TDS. Comparison of Cl concentrations with rainfall data (Figure 12) shows that the lower salinity samples during 2010-2012 have lower Cl concentrations than the bulk of the data for Seven Mile Creek monitoring sites including upstream at 7 Mile Creek. It may be this period reflects dewatering discharge at Joes Crossing with a lower Cl signature.

Similarly to upstream at 7 Mile Creek monitoring site, the Joe's Crossing area was characterised by Na-Mg-HCO_3-Cl to Na-Mg-HCO_3-Cl-SO_4 type water. Sulfate concentrations ranged from 110-352 mg/L (median = 140 mg/L) and HCO_3 concentrations ranged from 178 to 606 mg/L (median = 400 mg/L; Figure 6). SO_4/Cl ratios ranged between 0.5 and 1.0 (median = 0.6).

Metal concentrations were generally low and did not show any obvious temporal trends. Fe concentrations were <0.3 mg/L and Al, Mn and Zn concentrations were <0.15 mg/L (Figure 9). As concentrations ranged from below detection to 0.0036 mg/L (Figure 10).

Nitrate concentrations ranged from 2 to 30 mg/L and were higher than for upstream at 7 Mile Creek and Kelly's Pool (Figure 7). Nitrate concentrations decreased at Joe's Crossing >20 mg/L in 2011 to ~15 mg/L in 2012 and have mostly ranged between 3 and 17 mg/L in subsequent years. The most recent sample for Joe's Crossing in September 2018 had higher nitrate of 25 mg/L. This sample corresponds to aforementioned higher salinity sample from this date. Boron concentrations ranged from 0.3 to 1 mg/L (median = 0.5 mg/L).

2.3.4 Ratty Springs

Ratty Springs is a natural spring located ~2 km west of 11W at Paraburdoo, which feeds a tributary of Seven Mile Creek. Monitoring location SW18PAR0001 is located shortly upstream of Ratty Springs and has water chemistry samples for February and March 2018 only.

The lab pH of Ratty Springs surface water ranged from 6.8 to 8.3 (median 7.95; Figure 5). The median field pH was slightly lower at 7.4 but was mostly in the same range with the exception of one 2005 sample of pH 10, which may reflect a calibration error. Field pH prior to 2006 was more variable. Samples from the 2008-2010 period had slightly lower pH overall and included a number of samples below pH 7. Since 2011 the field pH increased and has mostly been between pH 7 to 8. This pattern was similar for other monitoring sites with long term data and may partly reflect changes in pH measurement and the lack of discrimination of data input between lab and field measurements.

Salinity at Ratty Springs monitoring site ranged from 570 to 1020 mg/L TDS (median = 748 mg/L), whereas the upstream monitoring site had TDS of 1010-1090 mg/L. Ratty Springs was typically characterised by Mg-Na-HCO_3-Cl type surface water (Figure 2). Sulfate and concentrations were <100 mg/L and similar between Ratty Springs and upstream. One sample from September 2008 did had anomalously high sulfate (1200 mg/L) and chloride (514 mg/L) concentrations, which did not make sense as TDS, field electrical conductivity and concentrations of other ions from the same date were within the normal range. Therefore, these values are discounted. HCO_3 concentrations ranged from 460 to 870 mg/L (median = 550 mg/L) and was slightly higher upstream (median = 802 mg/L). Similarly, Cl concentrations were higher upstream (median = 147 mg/L) compared to the springs (median = 96 mg/L) and were generally steady over time, regardless of rainfall (Figure 13). SO_4/Cl ratios have been stable over time and were <0.8 (median = 0.55).

Metals concentrations are variable but generally low. Fe concentrations were frequently below detection and the majority of samples were <0.1 mg/L with an overall median of 0.02 mg/L (Figure 9). Similarly, Mn concentrations ranged from 0.002 to 0.13 mg/L (median = 0.01 mg/L). One sample from May 2012 had elevated metal concentrations notable for Fe (1.8 mg/L) and Al (1.1 mg/L), however, TSS was also elevated and no subsequent samples had Fe and Al below detection. The median Zn and Al concentration was 0.02 mg/L.

Nitrate concentrations ranged from 2 to 34 mg/L and accounted for the majority of N species (Figure 7). Boron concentrations were steady and ranged from 0.3 to 0.7 mg/L.

2.3.5 Pirraburdu Springs

Pirraburdu Springs has a monitoring site located upstream of the confluence between the springs tributary and the main Pirraburdu creek line, in addition to a site at the confluence, both sampled only in April 2018. Two downstream sites (RSSW1-2) were sampled in November 2011. The data is limited to major ions and no pH or salinity measurements were obtained.

Pirra Spring lower had Mg-Na-HCO_3-Cl type water. The major ion concentrations of Pirra Spring Lower was distinct with slightly higher Mg (163 mg/L) and Na (289 mg/L) concentrations and most notably higher HCO_3 (1280 mg/L) concentrations compared to the other monitoring sites (Figure 6 and 8). Pirra Spring Upstream and the RSSW1-2 sites reported Mg concentrations ≤90 mg/L, Na concentrations of ≤200 mg/L and HCO_3 concentrations of 460-660 mg/L. The other major ions were less variable between locations, although Cl was slightly higher at 218 mg/L compared to ≤175 mg/L. However, based on major ions, in particular the elevated alkalinity, the Pirra Spring Lower had higher salinity than the other sites and calculated TDS was 2081 mg/L. RSSW1 was the next most concentrated with a calculated TDS of 1260 mg/L and slightly lower in Pirra Spring Upper at 1100 mg/L. RSSW2 had the lowest calculated TDS of 860 mg/L. SO_4/Cl ratios were all <0.5 and lowest at the Pirra Spring Lower site (0.3). The Pirra Spring Upper had Mg-Na-Ca-HCO_3 type water and RSSW1-2 had Na-Mg-HCO_3-Cl type.

2.3.6 Western Range Pools

Six pools from Western Range were sampled during 2018. Only two pools (SW18WR002 & SW18WR003) were sampled twice. The surface water was circum-neutral (pH of 7.6-8.0) and very fresh with TDS of <300 mg/L (median = 138 mg/L; Figure 5). Western Range pools were characterised by higher proportions of Ca ions and generally dominated by HCO_3 to SO_4 anions (Figure 2). In particular, the Western Range pools had very low Cl concentrations (median = 8 mg/L). Bicarbonate alkalinity (HCO_3) ranged from 32 to 100 mg/L. Sulfate concentrations ranged from 3 to 109 mg/L and were ≤11 mg/L in pools SW18WR002, SW18WR002A and SW18WR004. In general, concentrations of other major ions (Cl, Mg, Na and K) were frequently low <10 mg/L (Figure 8). However, low concentrations did not always correspond for all major ions; for example, sulfate was highest at SW18WR006 (109 mg/L) but the same water sample had Cl of 7 mg/L. SO_4/Cl ratios were highly variable due to the very low but variable Cl and SO_4 concentrations.

Metal concentrations were low; Fe, Mn, Al and Zn concentrations were mostly <0.05 mg/L (Figure 9). One higher Mn concentration of 0.3 mg/L occurred at pool SW18WR005 and a higher Fe concentration of 0.5 mg/L occurred at pool SW18WR004.

Nitrate was variable and ranged from below detection to 6.6 mg/L (Figure 7). The two samples from SW18WR002 indicated variability within pools as concentrations ranged from 0.1 to 6.6 mg/L between the May and October sampling. Boron concentrations were ≤0.05 mg/L.

2.3.7 Eastern Range Pools

Eastern Range's pools include Python Pool, in the 24E area, MOC pools (MOC1, MOC-C and MOC-E), located close to 32E and 37E area and ERP pools (ERP1a, ERP2, ERP3, ERP3B, ERP4 and ERP6), situated just south of 42E. Python Pool is also known as 23EBP1 and has largely been dry in recent years, resulting in very few samples since 2009. Monitoring of the Eastern Ranges Pools (ERP and MOC) commenced in 2011 but is limited as sampling was intermittent. Therefore, plotted data 2003-2010 is Python Pool and 2011-2018 are ERP and MOC pools, except one 2016 sample from Python Pool.

Python pool mostly has field pH data and ranged from 6.0 to 8.6 with a median of 7.5 (Figure 5). The field pH data was highly variable as also observed at other regional monitoring sites and may be due to the lack of discrimination of data input between lab and field measurements. The MOC/ERP pools had a slightly higher field pH range of 6.4 to 8.9, but with the same median of 7.5. Lab pH data for MOC/ERP pools was less variable than field data and ranged from 6.7 to 7.6 (median = 7.1).

Surface water was fresh and TDS ranged from 32 to 620 mg/L (median = 200 mg/L). The composition of Eastern Range Pools typically ranged from Ca-HCO_3-rich water to higher proportions of Na-Cl ions. Sulfate concentrations ranged from 2 to 175 mg/L (median = 22 mg/L) and HCO_3 concentrations ranged from 7 to 260 mg/L (median = 42 mg/L; Figure 6). One sample from September 2008 (the same as Ratty Springs sample issue) was discounted due to highly elevated sulfate and chloride concentrations of >1000 mg/L in conjunction with generally low TDS and other ions within the normal range. The variability in Cl concentrations is compared to rainfall data in Figure 14; the range of concentrations observed in pools is consistent with periodic recharge by dilute rainwaters and evapoconcentration during dry periods.

Metal concentrations were generally low; Fe concentrations ranged from below detection to 0.6 mg/L and Mn concentrations ranged from 0.001 to 0.2 mg/L (Figure 9). Metal concentrations were mostly higher at Python Pool whereas MOC/ERP pools had Fe and Mn concentrations typically <0.1 mg/L.

Nitrate concentrations were variable and ranged from below detection to 60 mg/L in Python Pool, but were dominantly <5 mg/L (Figure 7). Nitrate concentrations ranged from 0.8 to 5.5 mg/L in ERP pools and from 6-24 mg/L in MOC pools. Nitrite and NH3_N was mostly below detection. B ranged from 0.02 to 0.2 mg/L (median = 0.1 mg/L), which was more variable than that recorded for Western Range Pools but both were lower than observed at other regional sites, such as 7 Mile Creek.

2.4 Surface water collected in pit voids

Surface water from Paraburdoo pit voids were sampled at 4E pit SW area (MP174ESW0001) and the northern area of 11W pit (MP1811W0001) in 2017-2018. The 11W pit only has 2 data points from sampling in 2018. Other available data includes one 4E pit NW area sample (SW154ENW) from 2015.

Paraburdoo pit surface water had mildly alkaline lab pH of 8.3 to 8.9 and was similar at both the 4E and 11W pits. The 4E pit water had Na-Mg-Cl-SO4-HCO_3 type water and had TDS of 724-1310 mg/L. Sulfate concentrations ranged from 170 to 304 mg/L and SO_4/Cl ratios were <0.7. Nitrate concentrations ranged from 0.1 to 10 mg/L and were lower when sampled in late 2017 and early 2018. The 11W pit surface water also had a pH between 8.3-8.9 but was fresher with TDS of 208-338 mg/L. Sulfate concentrations were ~50 mg/L and SO_4/Cl ratios were ≤0.75. Metal concentrations were generally low for both Paraburdoo pit lakes; Fe concentrations were <0.05 to 0.2 mg/L and Mn concentrations were ≤0.02 mg/L. Trace metals were typically below detection.

2.5 Comparison to ANZECC Guidelines

Water quality data of full analytical suites from 2017-2018 have been compared to ANZECC guidelines for 95% protection of aquatic ecosystems. Comparison of pH is not included as Pilbara waters have naturally mildly alkaline pH, which frequently is out of the range of ANZECC guidelines.

Table 2 (Appendix 4) displays ANZECC guideline values and the number of exceedances for Greater Paraburdoo surface water. Many water quality parameters have few or no exceedances. Surface water in Kelly's Pool exceeded TDS guideline of 1500 mg/L for 2/3 samples. One sample from Joe's Crossing north (SW18PAR0004) also exceeded the TDS guideline, but a second sample ten days later was fresher and <1500 mg/L. A few samples also exceeded guideline values for Fe and Al, but overall concentrations were low and exceedances were <5% of all 2017-2018 samples.

A number of parameters exceed the guideline values for the majority of samples as are naturally occurring within the Pilbara at a higher range of concentrations. Boron, nitrate, total phosphorus and uranium all have >50% exceedances. However, the median values of all long term background water quality for the region also exceed the guidelines. Similarly, Cu, Mo and Zn have a number of exceedances ≥10% but also have regional medians that exceed the guideline value. Therefore, if further monitoring of water quality parameters in relation to aquatic ecosystems is required it may be appropriate to develop site specific trigger values for these parameters.

2.6 Summary

Surface water in the Greater Paraburdoo region is circum-neutral to mildly alkaline (median lab pH = 8.0) and is generally fresh with TDS <2000 mg/L (median 2017-2018 = 810 mg/L). Typical water chemistry varied between locations, in particular between the disconnected pools within the Eastern and Western Ranges and the groundwater connected surface

features of Ratty Springs and Pirraburdu Springs. The Western and Eastern Range pools were very fresh; Western Range pools had TDS of <300 mg/L (median = 138 mg/L) and Eastern Range pools of <650 µS/cm (median = 200 mg/L). Major ion compositions of Eastern Range Pools typically ranged from Ca-HCO_3-rich waters to higher proportions of Na-Cl ions. Western Range pools were characterised by higher proportions of Ca ions and generally HCO_3 to SO_4 dominated anions. The very fresh water in Western and Eastern Range pools was also demonstrated by notably low concentrations (<10 mg/L) of major ions (Cl, Mg, Na and SO_4) for numerous samples. Groundwater connected sites at Pirraburdu and Ratty Springs contained relatively higher proportions of Mg and HCO_3 ions and were more saline. Ratty Springs had TDS <1100 mg/L and median of 750 mg/L. Surface water from the main drainage course of Seven Mile Creek (including within the Paraburdoo mining area) was characterised by Na-Mg-HCO_3-Cl to Na-Mg-HCO_3-Cl-SO_4 water, with the exception of Kelly's Pool which had slightly higher proportions of Mg. The salinity was variable but typically >1000 mg/L at 7Mile Creek and Kelly's Pool.

Increasing trends in salinity and some major ions were observed at 7 Mile Creek monitoring site and downstream in Seven Mile Creek at Joe's Crossing, in the Paraburdoo mining area. Major metal concentrations of Al, Fe, Mn and Zn were typically <0.1 mg/L in 2017-2018 for Greater Paraburdoo surface water. Trace metals do not display any obvious trends. In 2017-2018 As, Cu and Ni are <0.01 mg/L, Cr is <0.001 mg/L. Cd, Pb, Sb, Se and Hg are below detection.

Nitrate concentrations were variable between sites with the highest concentrations occurring at Ratty Springs (median = 30 mg/L). Most sites had nitrate of <10 mg/L. However, surface water from Joe's crossing area had notably higher nitrate than upstream in 7 Mile Creek, with a long term median of 14 mg/L compared to 1.5 mg/L at 7 Mile Creek monitoring site. Nitrate concentrations at Joe's crossing had decreased from initially higher concentrations of >20 mg/L in 2011, but have remained elevated compared to upstream sites. In 2017-2018 nitrate concentrations in the Joe's Crossing area had a median of 8 mg/L and upstream at Kelly's Pool and 7 Mile Creek were <0.5 mg/L.

2.7 Recommendations

Since the 2016 water quality review a number of recommendations have been actioned:

1. *Kelly's Pool added to regional monitoring.*
2. *Resumption of regular regional surface water sampling.*

   Regional monitoring sites have been sampled a number of times since the previous water quality review. However, the sampling dates and regularity are variable between locations.

3. *Implementation of standardised analytical suite to build up consistent long term data sets, comparable over time and between sites.*

   This has been implemented for standard regional monitoring. However, was not completed where sampling was completed for other studies, such as the stable isotope sampling collection. In particular, even key water quality parameters such as pH were missing for some samples.

4. *Opportunistic sampling of Python Pool was resumed.*

   For Python Pool (23EBP1) this was only one sample from 2016, although this is likely due to dry conditions predominating.

5. *Sampling from 7 Mile Creek to determine whether the high salinity sample from 2016 was a one off sample or a concerning increasing trend.*

   This review has demonstrated it was a one off sample.

6. *Sampling of pit lakes that form in the 4E and 4W pit during the wet season.*

   There has been multiple samples collected from the 4E-SW area (MP174ESW0001). No data from 4W pit. There has also been a few samples collected from a pit lake formed in 11W (MP1811W0001).

Based on this updated surface water quality review a number of further or continued actions are recommended:

Regular monitoring of surface water monitoring sites should be continued to build up consistent surface water quality data. This is important to assess the external impacts from mining and for establishing background surface water quality characteristics. Monitoring sites may require biannual sampling (wet and dry season) or annual sampling during wet season to ensure the water quality and natural variation is captured, particularly for ephemeral water bodies. Specific recommendations include:

- Continued sampling of pit lakes that form in the 4E, 4W and 11W pits during the wet season. This is important to support closure planning options to leave pit lakes at closure rather than backfill, particularly as PAF is located on the pit wall.
- The Pirraburdu Springs monitoring sites that are proximal to mining activities (11W) and should be incorporated into the regular monitoring program, to monitor for any changes in water quality.
- Continued opportunistic sampling of Python Pool (23EBP1) when wet should be undertaken due to proximity to mining at Eastern Range's and heritage significance.
- Further monitoring is required to establish baseline water quality in Western Range's pools and Kelly's Pool, all of which only have 2018 data. In particular, continued monitoring of Western Range pools during the study phase will allow for understanding background water quality prior to mining.
- The standard analytical suite should be applied for studies as well as for the regular regional monitoring. This allows for continued build-up of regional background water quality and comparison between sites.
- Future review of surface water data should pay particular attention to; 1) higher nitrate concentrations observed in the Paraburdoo mining area at Joe's crossing that may be associated with mining activities; 2) monitoring of increasing trends in salinity and major ions in Seven Mile Creek sites. Higher salinity in these regional ephemeral creeks could reflect climate processes over this period. However, impacts from changes in catchment due to mining activities could also result in lower recharge to creek systems. Determining a long term trend is also difficult due to intermittent sampling and variation between wet or dry season.

3 References

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APPENDIX 1: **Maps of surface water monitoring sites**

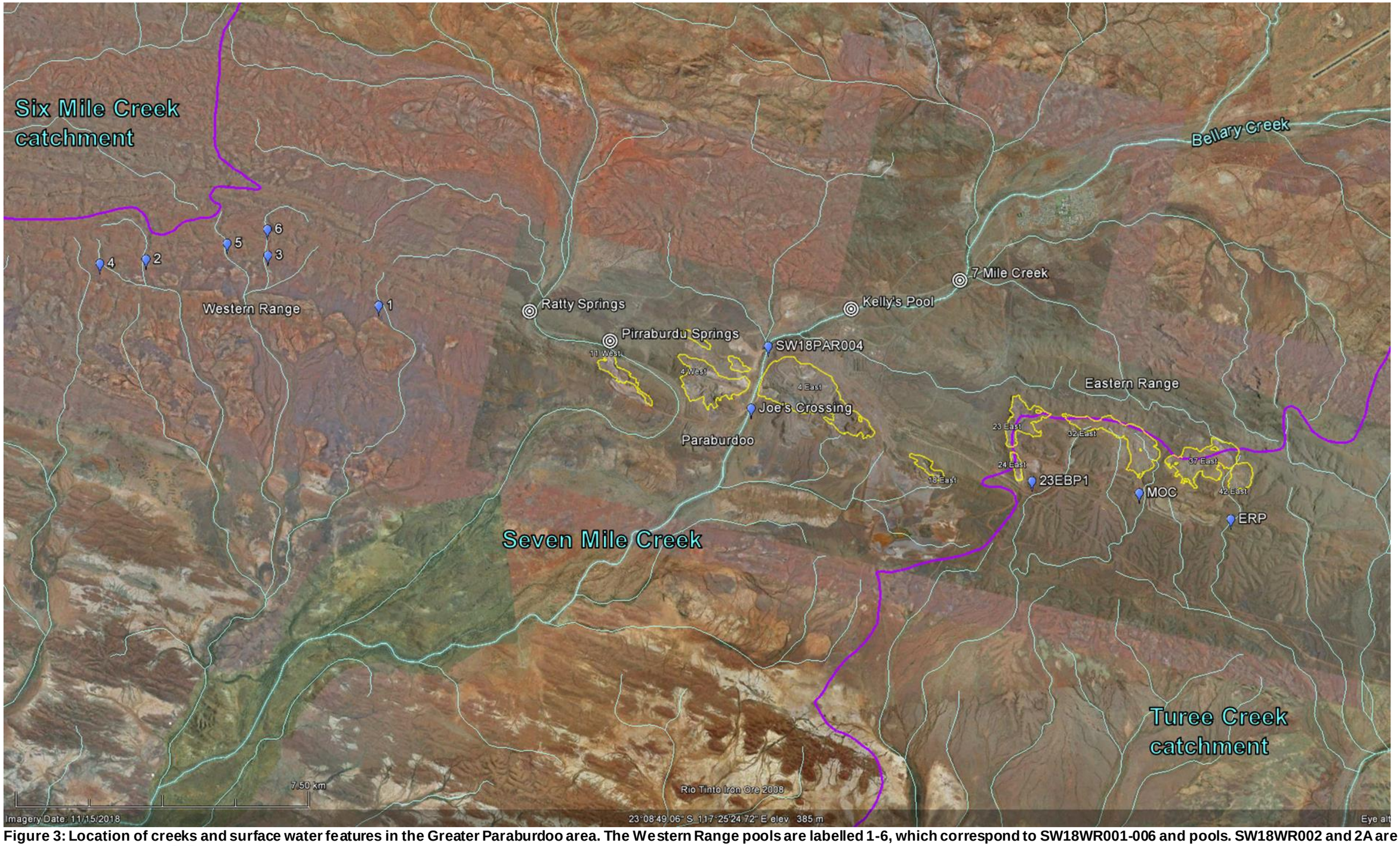

Figure 3: Location of creeks and surface water features in the Greater Paraburdoo area. The Western Range pools are labelled 1-6, which correspond to SW18WR001-006 and pools. SW18WR002 and 2A are closely located and marked as 2. Purple lines delineate catchment boundaries.

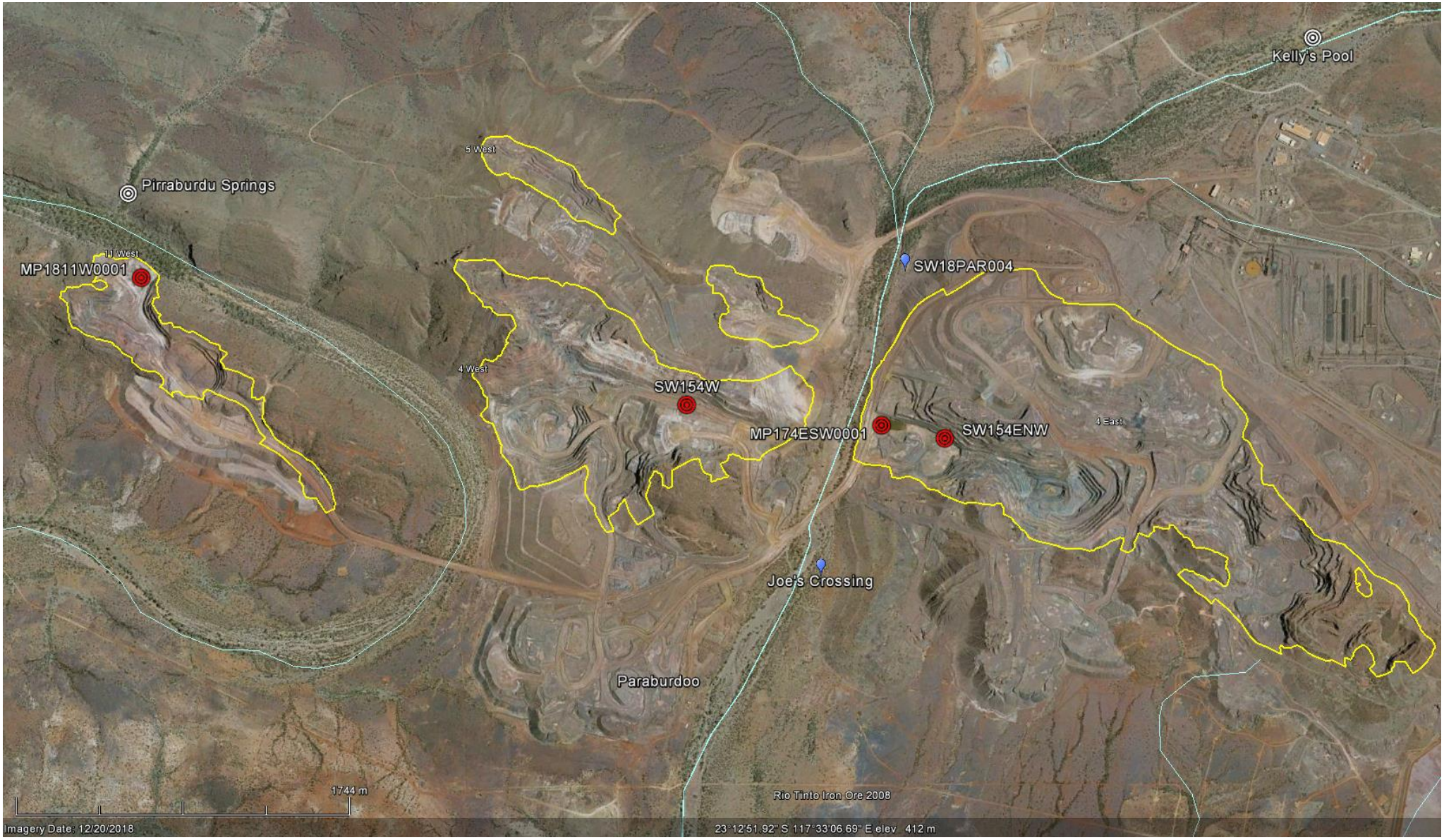

Figure 4: Maps showing location of pit lake monitoring at Paraburdoo.

APPENDIX 2: **Surface Water Quality Graphs**

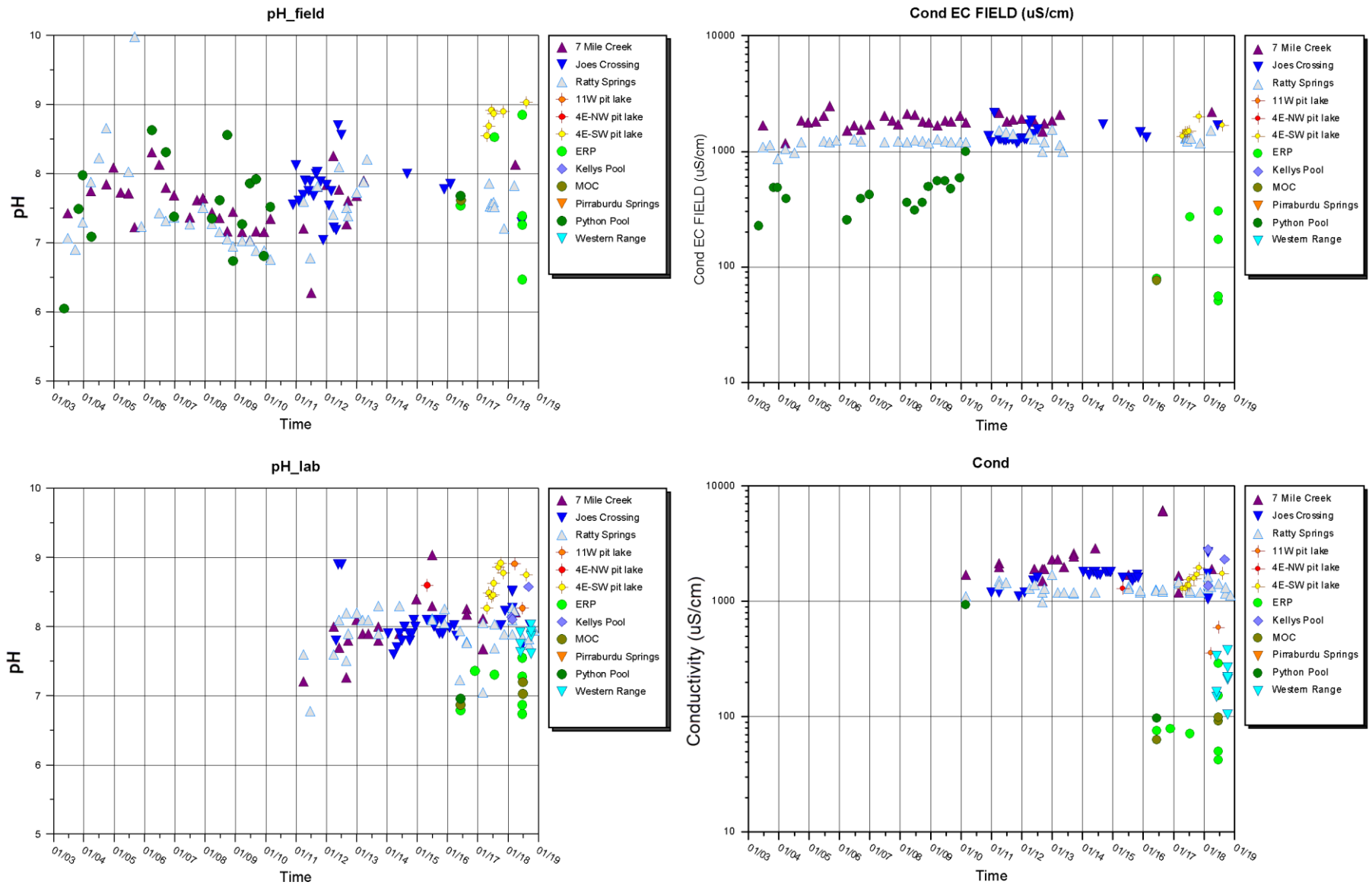

Figure 5: Field and laboratory pH and conductivity of surface water.

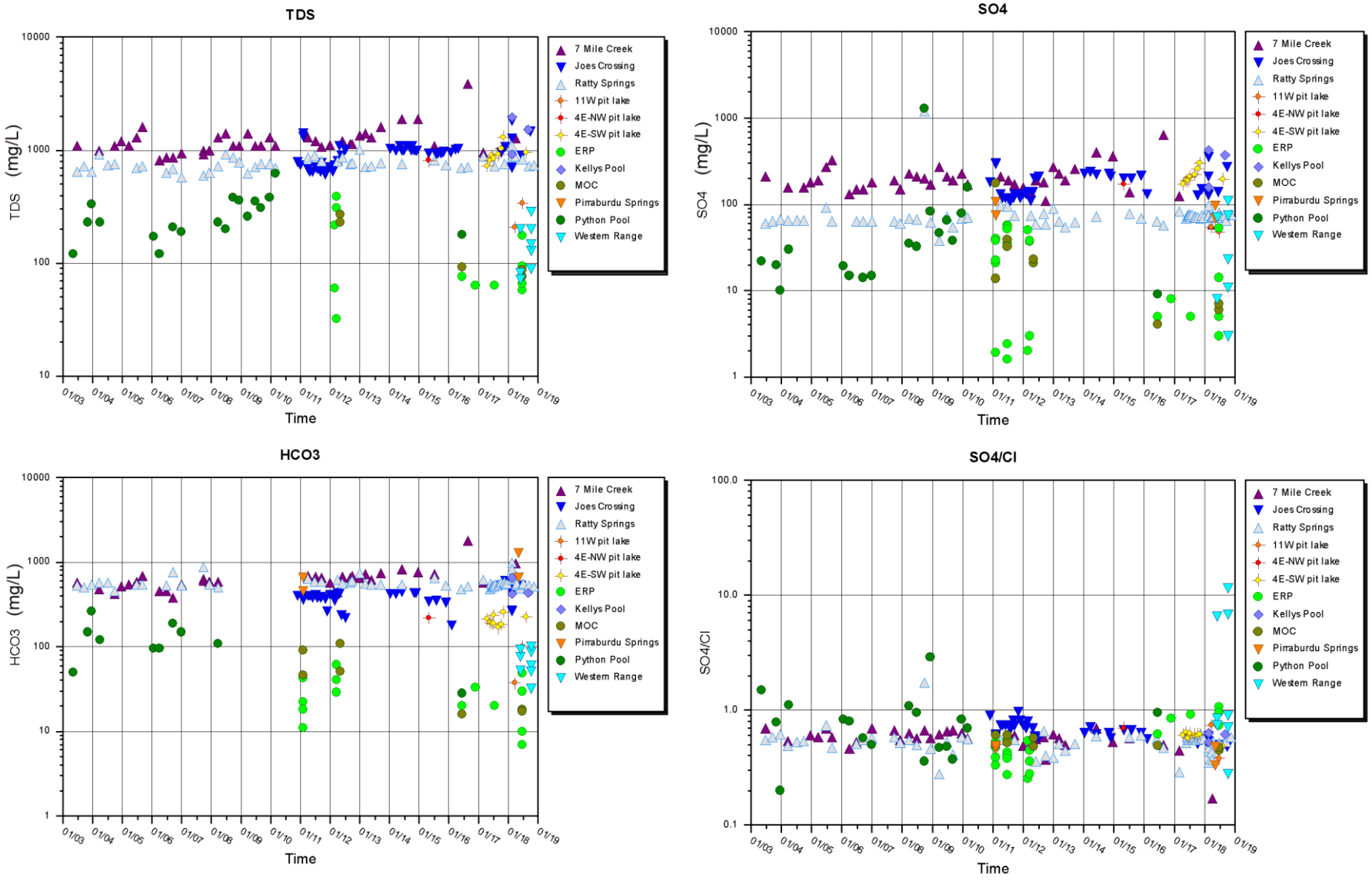

Figure 6: Total dissolved solids (TDS), bicarbonate (HCO_3) and sulfate concentration and sulfate/chloride ratios (calculated from mEq/L) of surface water.

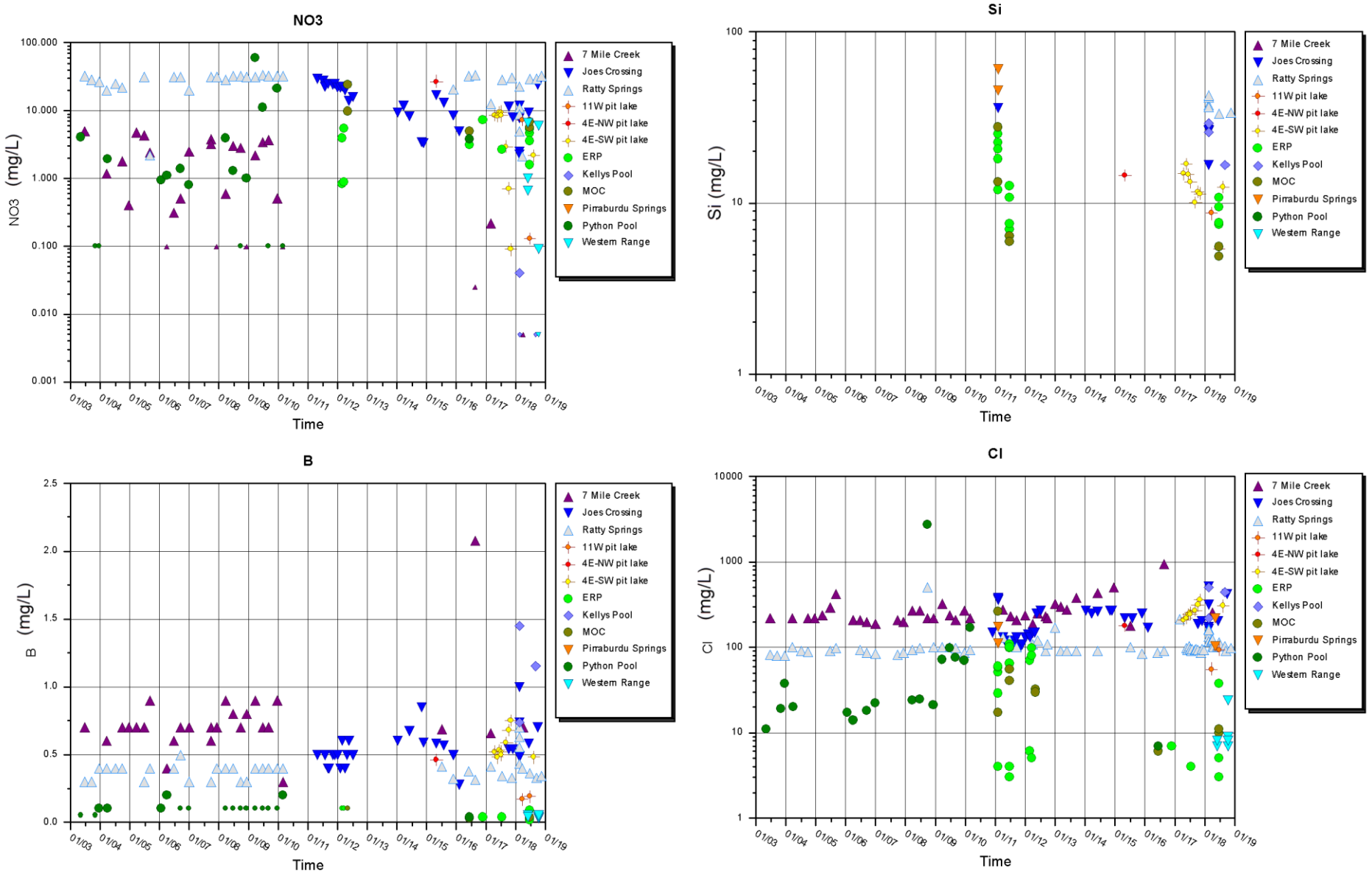

Figure 7: Nitrate, boron, silica and chloride concentrations of surface water. Small icons are below detection values, indicated at half below detection.

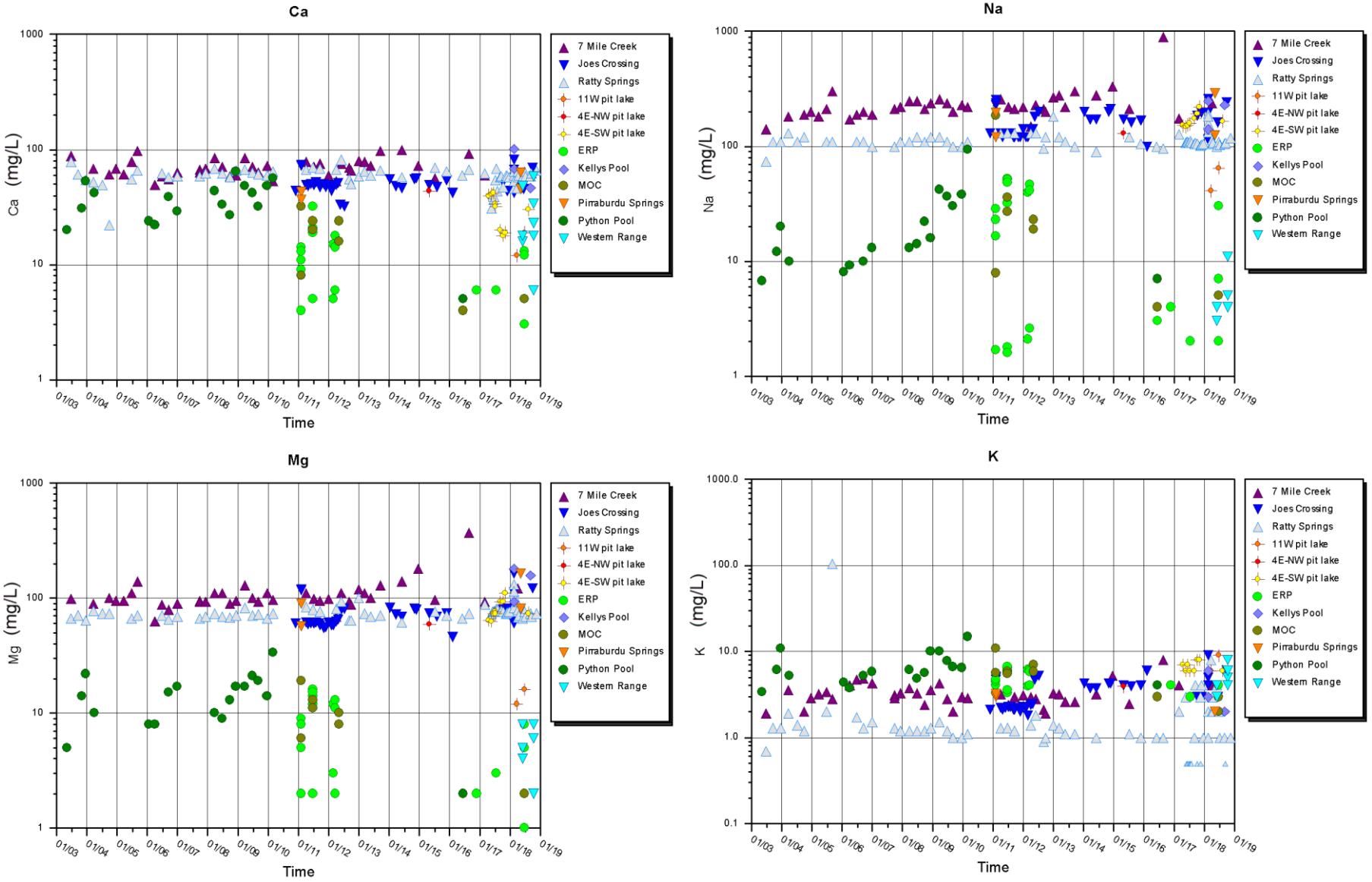

Figure 8: Calcium, magnesium, sodium and potassium concentrations of surface water. Small icons are below detection values, indicated at half below detection.

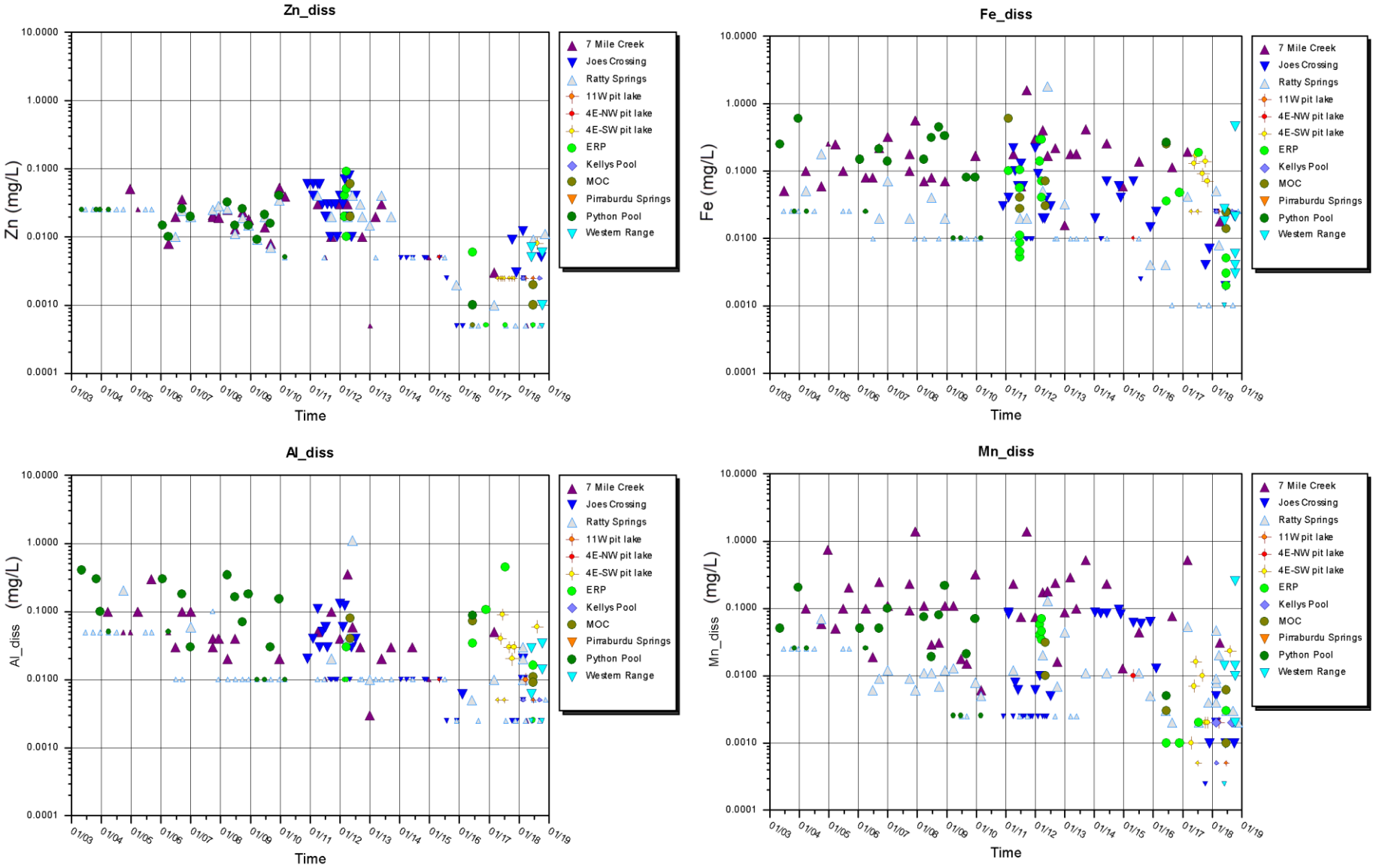

Figure 9: Aluminium, iron, manganese and zinc concentrations of surface water. Small icons are below detection values, indicated at half below detection.

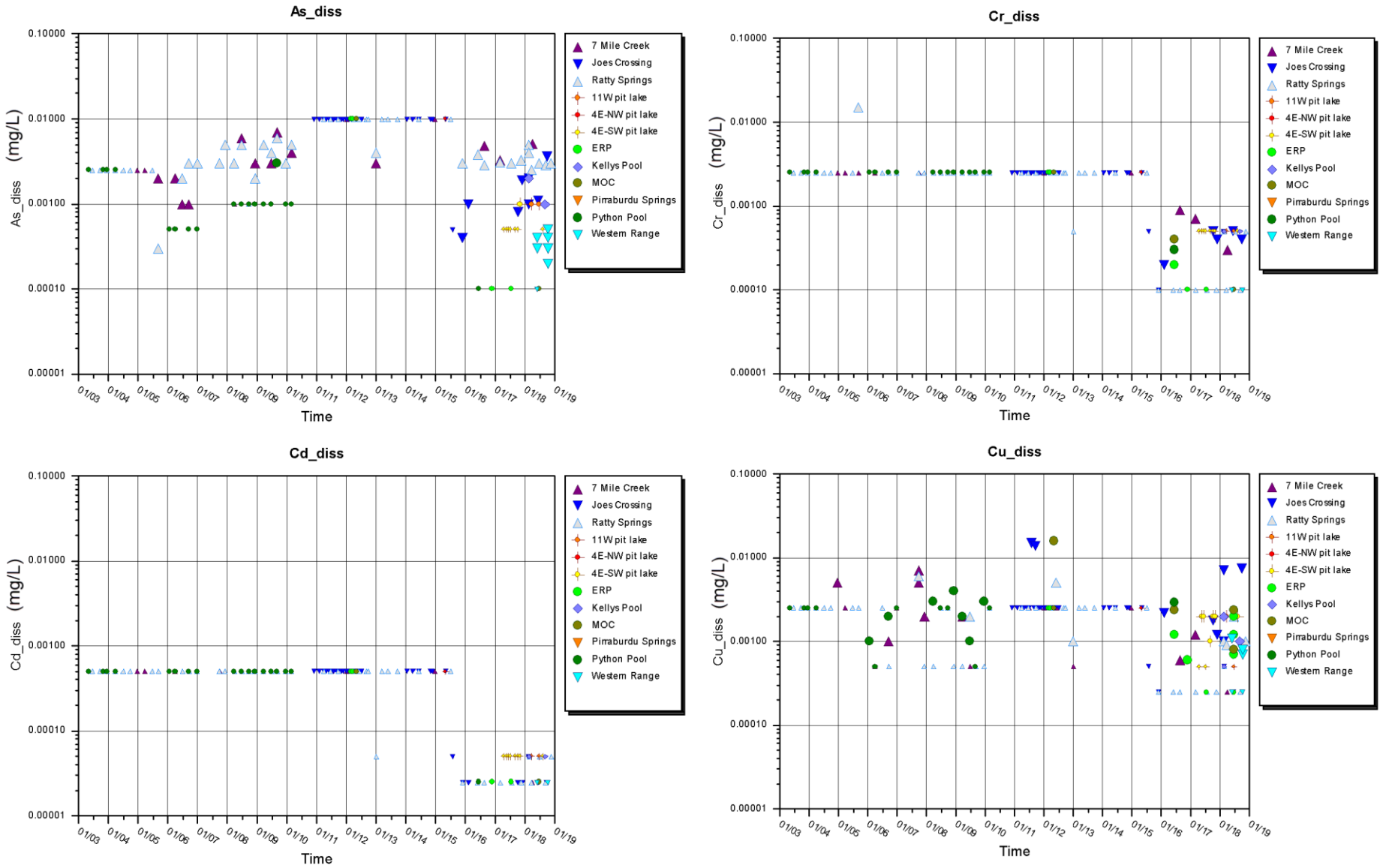

Figure 10: Arsenic, cadmium, chromium and copper concentrations of surface water. Small icons are below detection values, indicated at half below detection.

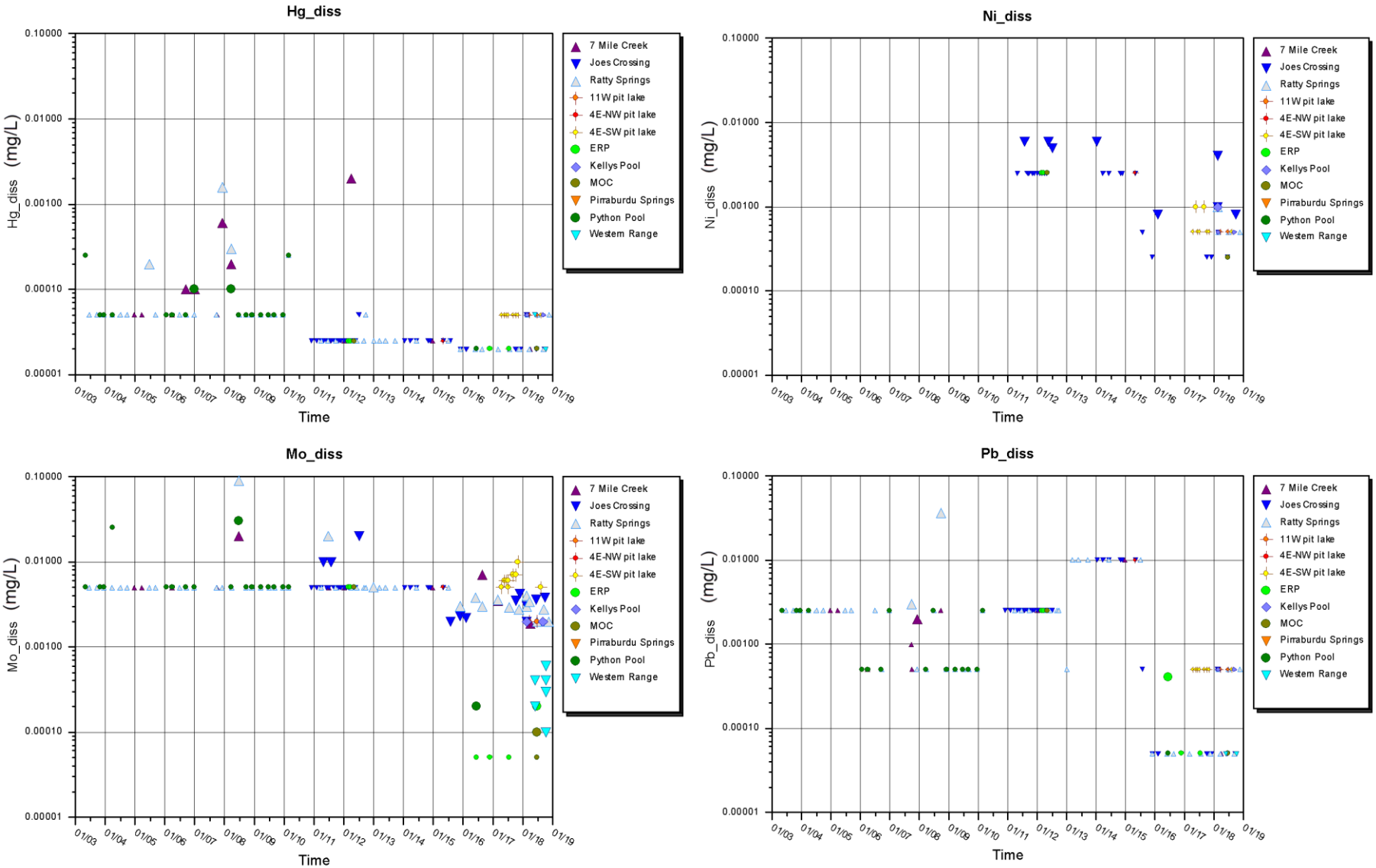

Figure 11: Mercury, molybdenum, nickel and lead concentrations of surface water. Small icons are below detection values, indicated at half below detection.

APPENDIX 3– **Daily rainfall graphs**

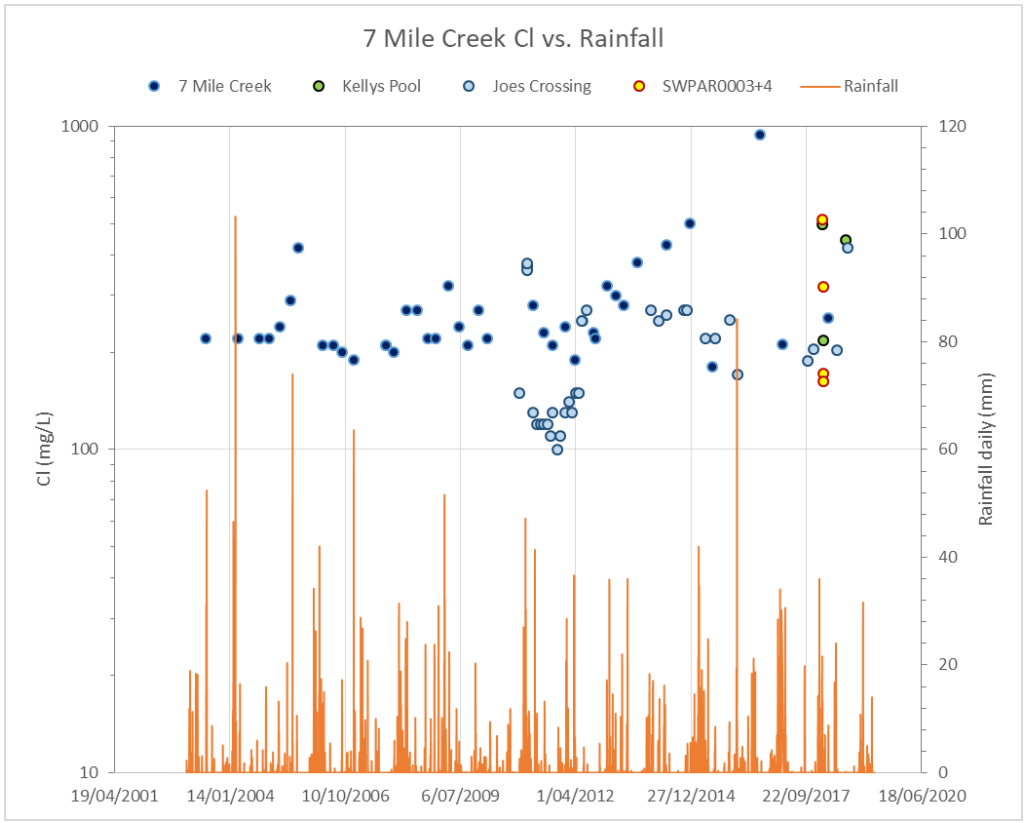

Figure 12: Cl concentrations versus daily rainfall for monitoring sites in Seven Mile Creek.

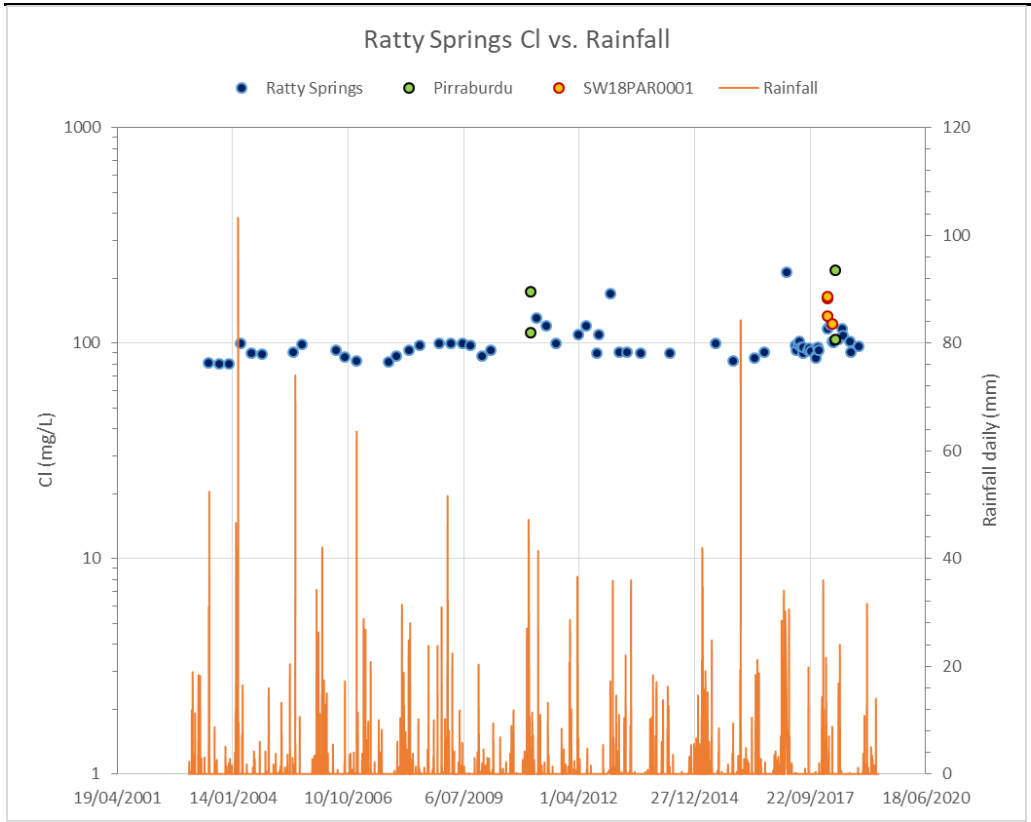

Figure 13: Cl concentrations versus daily rainfall for Ratty Springs monitoring sites.

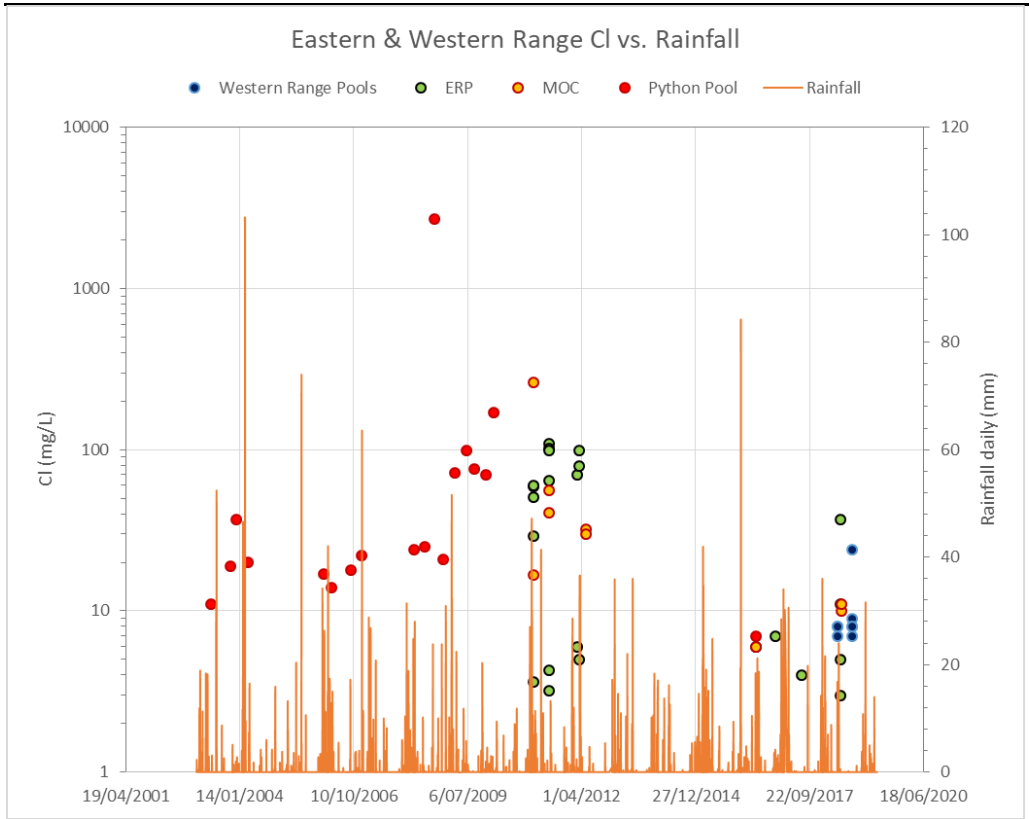

Figure 14: Cl concentrations versus daily rainfall for surface water pools across Western Range and Eastern Range.

APPENDIX 4 **– Tables**

Table 2: The number of exceedances of ANZECC guideline values for Greater Paraburdoo surface water samples during 2017-2018. The count of exceedances is highlighted in green.

Parameter	ANZECC GUIDELINE (mg/L)	7 Mile Creek		Kelly's Pool		Eastern Range		Joe's Crossing		Ratty Springs		Western Range		Paraburdoo in-pit surface water	
		Exceedances	No. samples	Exceedances	No. samples	Exceedances	No. samples	Exceedances	No. samples	Exceedances	No. samples	Exceedances	No. samples	Exceedances	No. samples
TDS	>1500	0	2	2	3	0	7	1	8	0	11	0	8	0	10
TSS	>80	0	2	0	3	0	7	0	8	0	11	0	8	1	10
Al	0.055	0	2	0	3	1	7	0	8	0	11	0	8	1	11
Sb	0.009	n/a	0	0	3	n/a	0	0	4	0	6		0	0	11
As	0.013	0	2	0	3	0	7	0	8	0	11	0	8	0	11
B	0.370	2	2	3	3	0	7	8	8	6	11	0	8	9	11
Cd	0.0002	0	2	0	3	0	7	0	8	0	11	0	8	0	11
Cr	0.001	0	2	0	3	0	7	0	8	0	11	0	8	0	11
Co	0.003	n/a	0	0	3	0	6	0	4	0	6		0	0	11
Cu	0.001	0	2	1	3	2	7	3	8	1	11	0	8	6	11
Fe	0.300	0	2	0	3	0	7	0	8	0	11	1	8	0	11
Pb	0.003	0	2	0	3	0	7	0	8	0	11	0	8	0	11
Mn	1.700	0	2	0	3	0	7	0	8	0	11	0	8	0	11
Hg	0.006	0	2	0	3	0	7	0	8	0	11	0	8	0	11
Mo	0.003	1	2	0	3	0	7	4	8	3	11	0	8	9	11
Ni	0.011	n/a	0	0	3	0	6	0	8	0	6		0	0	11
NO3	0.700	0	2	0	3	7	7	8	8	11	11	3	8	9	11
NH3_N	0.900	n/a	0	0	3	0	6	0	4	0	6		0	0	10
P Total	0.010	n/a	0	3	3	3	6	4	4	4	6		0	8	10
Se Total	0.011	n/a	0	0	3	0	6	0	4	0	6		0	0	8
Sn	0.003	n/a	0	0	3	n/a	0	0	8	0	6		0	0	10
U	0.0005	n/a	0	3	3	0	6	4	4	6	6		0	9	11
Zn_diss	0.008	0	2	0	3	0	7	2	8	2	11	0	8	0	10