Jugari
Conceptual hydrogeological model

30 May 2024

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Introduction

Background

This report provides a summary of the hydrogeological data and conceptualisation of the Jugari area. This has been produced to support the E8 approval submission.

Dewatering has been ongoing at the BHP Jugari mine for over 30 years, having started in 1991. The Jugari orebody is hosted by a Channel Iron Deposit (CID) that stretches over 50 km from the BHP Upper Marillana tenement in the west to Weeli Wolli Creek in the east. The CID follows a sinuous route and has multiple tributaries however, and its true length is potentially in the order of 100 km. The Jugari mine is located roughly in the central eastern part of this system, with the Rio Tinto Jugaricoogina mine directly to the east (Figure 1). There is currently no mining / dewatering directly to the west.

The Jugari mine is divided into three main areas:

- Western
- Central
- Eastern

These areas are further divided into numbered segments (Figure 2); Western 0 to 7, Central 1 to 5 and Eastern 1 to 8. The Eastern 8 (E8) pit is situated east of the western most Rio Tinto Jugaricoogina pit (Mungadoo). Therefore, the Mungadoo pit sits between the Jugari E7 and E8 orebodies.

Objectives

The objectives of the conceptualisation were to:

- Collate all available and relevant hydrogeological data.
- Identify and describe the main hydrogeological processes and phenomenon relevant to the:
    - Prediction of future dewatering requirements.
    - Prediction of drawdown magnitude and migration within the CID and beyond.

Hydrogeology and hydrology

Stratigraphy

Surficial geology is shown in Figure 3 and a geological cross section along strike in the CID in Figure 4.

The Jugari stratigraphy is comprised of two main units; a basement (Weeli Wolli Formation) with a meandering palaeochannel system (filled with the Marillana Formation) incised through it. The Marillana Formation is composed of the Munjina, Barimunya and Eastern Members. The Barimunya Member is the main ore-bearing unit and comprises the Channel Iron Deposits (CID). The Eastern Member is unsaturated in this area.

The channel deposits (Barimunya Member) are comprised of:

- Upper Channel Iron Deposits (UCID)
- Ochreous Clay (OK)
- Lower Channel Iron Deposits (LCID)

Two relatively thin rock types of the Munjina Member separate the Barimunya Member and the Weeli Wolli Formation and are known as the Basal Clay and Basal Conglomerate (BG/BK). The UCID and the LCID are both mined for their iron ore.

Marillana Creek runs through the Jugari mine area, generally following the direction of the palaeochannel, but crisscrossing and running parallel to it in several places. The creek is associated with an alluvial deposit which varies in thickness from 2 to 20 m in this area.

In general terms the UCID thickens to the east and the LCID thins in that direction. The alluvium is also generally thicker in the east.

Approximately 3 km to the south of the southeastern most part of the BHP Jugari CID lies the Ministers North orebody. The orebody is located within the mineralised Dales Gorge and Joffre Members of the Brockman Iron Formation and is separated from the Jugari CID by Whaleback Shale, Jugaricoogina Shale and the Weeli Wolli Formation.

Groundwater dataset

There are a vast amount of abstraction and water level data at Jugari (Figure 5). There are:

- 197 monitoring bores with at least 10 observations;
- 29,296 observations at the weekly timescale;
- 166 production bores and 2 main sumps (plus several smaller ones);
- Two surplus water creek discharge points (a permanent discharge and a supplementary discharge) (Figure 6);
- Observations since 1991.

Much of the data is focussed on the CID aquifer as this also makes up the Jugari Orebody. There is however a significant amount of data encompassing the Weeli Wolli Formation and Weeli Wolli Creek alluvium. These datasets will be considered in order below.

The data availability and accuracy reduce prior to 2002 for the abstraction and 2014 for discharge. This data has been infilled with data from the Annual and Triannual Aquifer Reviews (AARs and TARs (BHP, 1996, 1997, 1998, 1999, 2000, 2001, 2002, 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014)) and data from a previous groundwater modelling study (BHP, 2017).

In addition to this there are 36 monitoring bores with transient groundwater data in the Ministers North aquifer (Figure 5).

CID data

The water level in the Jugari CID prior to dewatering (Figures 7 and 8) ranged from approximately 613 mAHD in the west (to the west of Flat Rocks) to approximately 507 mAHD in the east (6 km east of E8). The data show that the gradient is very consistent from west to east, falling 106 m over 48 km (2.2 m/km). The data suggest that there are no major flow barriers perpendicular to the flow direction / CID strike throughout this entire area. Figure 8 shows the water levels in 2023 compared to the water levels prior to dewatering and Figure 9 shows the drawdown since 1991.

The time variant data have been broken into groups (Figure 10) to assist in the analysis of such a large dataset and are shown in Figures 11 to 15. These data are most useful in understanding the effect of dewatering on the groundwater levels. The historical dewatering is shown in Figure 16 and grouped into Western, Central and Eastern locations in Figures 17 to 19. Dewatering commenced at Jugari in 1991 in E2 and E3456.

The data show that to the west of W0 (Figure 11 and 15):

- Water levels varied by just over 6 m prior to dewatering in the Western pits (which started in 2010). This was due to natural variations in short term (i.e. the 1999/2000 high rainfall events) and long term climatic conditions. At HYW0003M for example, the maximum water level between 1994 and 2005 was 606.5 mAHD and the minimum was 600.1 mAHD. Over the same period, the variation at HYW0002M was 5 m, between 617.8 and 612.8 mAHD.
- Based on the observed water level in 1995, the drawdown observed at the most westerly Jugari bore (HYM0002M) was 3.6 m in August 2023. Over almost the same period the drawdown at HYW0003M (just to the west of W0) was 29 m (up to July 2023).
- There has been a recovery of water levels adjacent to W0 (in HYW0005M) since November 2022 in response to a recent reduction in abstraction in W0.

The data show that in W0, W1 and W2 (Figure 11):

- Dewatering commenced in:
    - 2009 in W0. Since then, abstraction increased to reach a maximum of approximately 5 ML/d at the end of 2020. In 2023 the rate has been reduced significantly to reduce pressure on groundwater levels in the CID upstream.
    - W1 in 2010, with a significant spike at just over 20 ML/d in 2012 but then quickly reducing to 10 ML/d and linearly decreasing with time since then.
    - W2 in 2017 and W3 in 2022. Dewatering in these pits has been insignificant.
- Prior to dewatering, observed water levels varied naturally between 589.0 and 582.0 mAHD (7 m), as recorded at YM0105M.
- Water levels started declining in the southern part of W1 in 2006, in response to dewatering in W4.
- Drawdown accelerates in W1 south in 2010 and in W1 north in 2011. These dates coincide with the commencement of dewatering in these locations, respectively.
- Drawdown in W1 south and W2 plateaued at between 50 and 60 m by approximately 2016. In W1 north and W0 drawdown has been markedly lower.

The data show that in W3 and W4 (Figure 12):

- Dewatering commenced in W3 in 2022. In March 2022 the rate was 8 ML/d.

- Dewatering in W4 started in 1995 at a rate less than 1 ML/d, but ramped up significantly in 2006 to about 18 ML/d. From then it declined at a linear rate to reach approximately 5 ML/d in 2010. Between 2010 and 2022 dewatering has remained between 3 and 8 ML/d.
- Prior to noticeable drawdown in these areas (i.e. in the observed data between 1992 and 2005) the natural variation in water level was between 570.6 and 564.3 (6.3 m) (YM0104M).
- Dewatering started in 2006 and resulted in rapid drawdown at all monitoring bores.
- Drawdown was very rapid in the first 2 years. Since then, it has plateaued to some extent and is currently around 50 m.

The data show that in W5, W6 and W7 (Figure 12):

- Dewatering started in W5 in 2015 and has averaged 2 ML/d since then.
- Dewatering commenced in W6 in 1996 (according to the historical AAR reports). The highest abstraction was between 1996 and 2002, averaging approximately 10 ML/d. Abstraction has fallen since then and has averaged less than 1 ML/d since 2017.
- There has been no dewatering at W7.
- Until 2012 data is only available around W6. Drawdown is first observed here in 1996 in response to dewatering of this pit (and the adjacent C1).
- After an initial, rapid, drawdown rate, drawdown has continued at a gradual rate for most of the observation period. By 2023 drawdown was about 50 m.

The data show that in C1, C2 and C3 (Figure 13):

- Dewatering commenced in C1 in 1996. Between then and 2002, dewatering has been constant but has only rarely exceeded 5 ML/d. The average abstraction through this time has been 2 ML/d. Pumping from in-pit sumps has occurred occasionally at C1. Two major pumping periods were in 2000 and 2006, with peaks of almost 10 ML/d in both.
- Dewatering at C2 commenced in 2010 but has not exceeded 2 ML/d since that time and has averaged less than 1 ML/d.
- Dewatering at C3 commenced in 2012 and has averaged 0.3 ML/d up to 2022.
- The water level in C1 and C2 varies between 554.2 and 550.4 mAHD (3.8 m) between 1992 and 1996.
- Dewatering here causes a rapid decrease in water levels in 1996, from approximately 549 mAHD to between 520 and 526 mAHD at the start of 1997.
- Water levels in C1 and C2 have declined a further 30 or 35 m since then to reach 495 mAHD in 2023.
- Water levels in C3 have only been monitored since 2015 (YC0022RDM). They have been stable during this time, even though the water level in C1 and C2 has fallen approximately 11 m between 2015 and 2023.
- Water levels in C3 are approximately 530 mAHD, 35 m higher than the levels in C1.

The data show that in C4, C5 and E1 (Figure 13):

- There has been no dewatering in C4.
- Apart from a small amount of dewatering between 1991 and 1996, dewatering commenced in C5 in 2002. After peaking at just over 10 ML/d in 2003, dewatering has averaged 3 ML/d until 2022.
- Dewatering at E1 has been minimal. It started in 2020 and has averaged 1 ML/d since then.
- Observations are available in C4 and C5 from 1992 and in E1 from 2002.

- It appears that the water levels in C4 and C5 are subject to drawdown almost immediately after the initial observations in 1992 and they decline from then on. The initial drawdown was likely from a combination of C5 and E2 dewatering.
- The E1 levels appear to be quite similar to the levels in C4 and C5.
- All data here return a gradual decline from 1992 to 2023; from levels between 535 to 541 mAHD in 1992 to levels between 484 and 493 mAHD in 2023.

The data show that in E2 to E7 (Figure 14):

- Dewatering at Jugari started in 1991 in the Eastern orebodies; E2 and E356.
- Between 1996 and 2001 (inclusive) the data comes from AAR and TAR reports and does not differentiate between sumps and dewatering bores.
- At E2, dewatering increased from about 2 ML/d in 1991 to reach a peak of 13 ML/d for the year 2000. Given that the data post 2001 shows that the abstraction from E2 was exclusively from sumps between 2003 and 2012 (averaging 7 ML/d over this period), this suggests that the abstraction prior to this was also dominated by sump pumping. From 2012 to 2022 sump pumping has been replaced by dewatering via wells at an average rate of 1.8 ML/d
- At E356 dewatering is mostly via wells. The rate peaked at just over 18 ML/d in 1998. The abstraction rate has been variable, but since 2008 it has averaged almost 5 ML/d.
- At E7 dewatering commenced in 2015 at just under 8 ML/d. Since then, the rate has reduced and averaged 2 ML/d between 2018 and 2022.
- After rapid drawdown in 1991, water levels were roughly stable until 2007. All monitoring bores experienced drawdown in this period, but the variation between the locations was relatively high. The highest water levels (528 mAHD) were in the south (E7) and the lowest (503 mAHD) in the north (E2). This represents a greater variation in stable water levels (over a relatively short distance) seen at other locations in Jugari.
- From 2007 water levels in E6 fell rapidly in response to nearby abstraction and the drawdown migrated to the north so that very quickly water levels in the whole E2 to E6 area were quite similar. Only E7 at this time appears to have significantly different water levels, even though it too is impacted by the dewatering.
- Also from 2007 water levels in E2 to E7 gradually decline to reach a minimum in 2023.

The data show that in E8 (Figure 14):

- Up to 2023 there has been no dewatering at E8. A small amount of abstraction occurred between 2003 and 2012 (average less than 0.1 ML/d) for water supply purposes.
- Water level observations are available between 1992 and 2003, then between 2015 and 2018 and then finally in 2022 and 2023.
- The water level was increasing between 1992 and 2003, most likely because of surplus discharge.
- The water level had fallen by about 10 m between 2003 and 2015, most likely because of dewatering at E7.
- There is a rapid decline (about 12 m) in water levels between March 2017 and August 2017. This is most likely due to dewatering at the RTIO Mungadoo pit situated between E7 and E8.
- There is a continued, gradual, decline from 2018 to 2023 (another 5 m). Water levels are approximately 490 mAHD in June 2023, compared to 523 mAHD in 1992.
- There has been no dewatering in E8 itself up to 2023.

The data show that to the east of E8 (Figure 14):

- There are only two long term water level datasets east of E8.
- YM0120M is in the CID and about 4 km along the flow path east of E8. This shows that water levels increased gradually, and by almost 5 m, between 1992 and 1995. The high in 1995 was 519 mAHD. From 1995 the water levels fell again to reach approximately 513 mAHD in 2011.
- YM0121M is much closer to E8, about 1 km directly northeast. The trends in this location are similar to YM0120M, although the magnitude of the increase between 1992 and 1995 is greater. The data record here is also longer and captures a significant drawdown event between August 2013 and August 2014 (5 m). From August 2014 water levels continue to decline but at a reduced rate and reach 512 mAHD in 2023, a reduction of 10 m compared to the level in 2013. This response seems to be almost identical to that seen in E8 (although the lack of data at key times means that this is uncertain), until the water level reaches 516 mAHD.

Rio Tinto dewatering

Two Jugaricoogina dewatering operations are of relevance to the Jugari groundwater system. These are the Mungadoo and Junction South West pits, which, based on water levels in the adjacent E7 and E8 pits, started dewatering in 2017.

Unfortunately, the exact timing and quantity of dewatering is not known for these operations.

Marillana Creek Alluvium data

Marillana Creek follows the same valley in which the CID palaeochannel developed. It presents an increasing thickness from Flat Rocks (no alluvium) to E7 and E8 (20 m) and probably increasing further to the confluence with Weeli Wolli Creek.

There are numerous monitoring bores in and around Marillana Creek. They were drilled during 2012 to support tree health studies (Golder, 2012). Of these, 12 are screened only within the creek alluvium and 1 is screened in both the alluvium and Weeli Wolli Formation below it. Another 17 are screened in the material beneath the alluvium.

The hydrographs at each of these bores are plotted against the ground surface, base of bore screen and hydrographs from the nearest CID monitoring bores in Figures 20 to 26.

These show that:

- In all cases, when groundwater is recorded at these locations, the CID groundwater level is approximately 30 to 40 m lower than that of the alluvium.
- Even if dry before the wet season, in all cases the water level in these bores rises following flow events.
- The alluvium at most locations records rapid increases in water levels following rainfall / creek flow events. These approach, and sometimes exceed the ground elevation. Depending on the location, the increases range from approximately 3 to 12 m.
- Following these increases, most locations then record a very rapid fall in water levels (i.e. within 3 to 4 months in the case of HYM0033M). These either:
  - Result in a drying out of the bore (e.g. HYM0032M).
  - Result in water levels approaching the base of the screen, but staying a few metres above (i.e. the alluvium retains some saturation at all times (e.g. HYM0025M)).

- The bore close to the E8 discharge remains saturated throughout the monitoring period and does not respond to individual rainfall / creek flow events to the same extent as the other bores (the increase is approximately 1 m). This is as expected with a permanent source of water in this location.
- None of the bores were monitored prior to the adjacent CID being dewatered. However, the long term CID monitoring (as shown in the Figures) shows that prior to dewatering:
  - The CID water levels were close to ground surface at the alluvium bores.
  - The alluvium and CID groundwater levels were probably in equilibrium.
- The alluvium groundwater levels have all been reduced by dewatering (apart from HYM00011M in E8).
- The observed recessions are most likely more rapid than would've occurred prior to dewatering and more often result in complete drying of the Alluvium.

The volume of streamflow required to fill the alluvium is minimal and it is the timing between rainfall / streamflow events that is more critical than the volume of water. There is also evidence of flows from downstream creeks (i.e. from Iowa or Boundary Creeks), which don't register at Flat Rocks, filling the alluvium.

Prior to mining, Marillana Creek may have gained water from the CID in certain circumstances. This is no longer possible in the areas of dewatering where the CID water levels have been lowered significantly.

Marillana Creek discharge data

Excess dewatering water has been discharged to Marillana Creek at three locations (Figures 6 and 27). One in the Central Area and one close to the Eastern 8 orebody. Another discharge location was adjacent to the W3 pit but this has only been used to discharge minimal amounts of water. Total discharge to the creek averaged 22 ML/d between 1997 and 2013, with a peak of 47 ML/d at the end of 2014. The Central location has seen about 20% of the discharge and the Eastern location the rest. Recirculation of the discharged water via seepage from the creek into the CID is likely when the Central discharge point is used. The Central discharge location has not been used consistently since 2013 and is now decommissioned.

Weeli Wolli Formation data

Eighteen boreholes were drilled in the Weeli Wolli Formation to provide a better understanding of this stratigraphy. Fifteen of the bores were drilled in 2015 along 5 transects roughly perpendicular to the CID and a further 3 bores were drilled in the southeast in 2016. The borehole locations are shown in Figure 28 and estimated hydraulic conductivity (K) and measured water level in Table 1.

A limitation to this data is the fact that there are no water levels in the Weeli Wolli Formation prior to 2015. Given that dewatering started in 1991, the water levels at these locations may have already been impacted by the time they were measured.

Table 1. Weeli Wolli Formation drilling campaign.

Home name	Transect	Easting (MGA94)	Northing (MGA94)	Water Level (mRL)	Estimated K (m/d)
HYX0001M	1	704834	7486998	578.9	0.2 to 0.1*
HYX0002M	1	705089	7487502	613.0	0.02 to 0.01
HYX0003M	1	705417	7488976	615.7	0.01
HYX0004M	1	705218	7488003	610.2	0.08 to 0.06
HYX0005M	5	715779	7480148	561.5	1.6 to 1.0
HYX0006M	4	714028	7481621	574.7	1.2
HYX0007M	2	708457	7482483	583.9	0.01
HYX0008M	2	708517	7482757	557.4	-

HYX0009M	5	721781	7480436	525.0	0.04 to 0.05*
HYX0010M	2	708138	7483856	570.4	0.2 to 0.06
HYX0011M	2	708250	7483424	576.4	0.01
HYX0012M	3	713393	7484429	567.2	1.1 to 1.9
HYX0013M	3	713322	7484760	553.5	0.1
HYX0014M	4	713515	7483815	552.5	-
HYX0015M	3	715621	7482607	542.2	0.04
HYX0016M	N/A	721976	7481447	537.1	0.1 to 0.03
HYX0017M	N/A	719817	7481764	547.2	1.3
HYX0018M	N/A	718685	7483368	528.9	0.002

* Described as high confidence estimates (BHP, 2017)

The data at these locations suggest that the hydraulic conductivity of the Weeli Wolli Formation ranges from low to moderate and that drawdown from the dewatering of the CID would be expected to migrate into the Weeli Wolli, although to variable degrees given the variability in hydraulic conductivity.

The groundwater level observations are shown in Figures 29 to 31. These data show that:

- To the north of the W0/W1 north pits (Figure 29):
  - The Weeli Wolli has been depressurised at the closest monitoring bore (HYX0001M), which is now dry. The Weeli Wolli here seemed to respond in the same way as the CID.
  - The furthest bore (HYX0004M) presents a gradually declining trend when observations are available (2015 to 2019). The water levels fell from approximately 610 mAHD to 606 mAHD over this period. These levels are still elevated compared to the adjacent CID though (606 mAHD in 2019 compared to about 564 mAHD (HYW0210M)).
  - Bore HYX0002M is next to HYX0004M has only two observations and these are slightly higher than the adjacent bore and show no decrease between the two readings (2015 and 2023) and therefore the Weeli Wolli at this location does not appear to have been impacted by dewatering.
- To the south of the W3/W4 pits (Figure 29):
  - None of the bores display significant declines over the monitoring period (1995 to 2023). This may be due to the fact that dewatering in this location commenced in 2006.
  - However, at least one of them (HYX0008M) presents lower water levels than what would've been possible prior to dewatering, suggesting that it has been impacted.
- South of the C1/2 pits (Figure 30):
  - The two bores display a steep groundwater gradient towards the CID.
  - The water level at HYX0013M (stable at 550 mAHD) is roughly at the same elevation as the C1/2 CID water levels prior to dewatering. It is however higher than the water levels in C45 and E1 which are directly to the east. It is unknown whether this location has been impacted by dewatering therefore.
  - The water level at HYX0012M displays a small decline (3 m) between 2015 and 2023 (567 mAHD to 564 mAHD) but is still higher than the pre-dewatering levels in the CID surrounding it.
- East of the E2/3/4/5/6 pits (Figure 30):
  - Of the four bores drilled in the Weeli Wolli here, all show strong evidence of being impacted by dewatering.
  - Three have data between 2015/16 and 2022. All three show declines over that period; 7 m at HYX0016M, 11 m at HYX0018M, 4 m at HYX0017M and 8 m HYX0009M.

- HYX0017M, which is the closest to the CID, shows the greatest potential drawdown of the four (given the groundwater level is almost the same as that of the CID).
- HYX0016M, which is the furthest from the CID, shows the lowest potential drawdown (although it is hard to be definitive on this), but the 7 m drawdown over 6 years of monitoring is significant and misses drawdown which is likely to have occurred between 2007 and 2016 (9 years) when monitoring started.

- West of the E2/3/4/5/6 pits (Figure 31) a single Weeli Wooli bore (HYX0006M) shows no signs of being impacted by dewatering. The water levels are much higher than those in the CID (575 mAHD compared to approximately 485 mAHD in the E1 pit) and they did not change appreciably between the first and most recent observations (2015 and 2023).

The data show that the response to dewatering in the Weeli Wolli Formation is very variable. In some places, most notably the four bores east of E2/3/4/5/6, there is evidence that the Weeli Wolli has responded very strongly to dewatering, with water levels falling several metres.

The Ministers North aquifer

Ministers North is directly to the south of the RTIO Mungadoo pit, which sits between the BHP E7 and E8 deposits. The Ministers North aquifer is hosted in mineralised Dales Gorge Member of the Brockman Iron Formation (Figure 32). The aquifer presents very high transmissivity and moderate to low storage and supports the Jugaricoogina Gorge Groundwater Dependent Ecosystem (GDE). The Gorge contains roughly 3.5 km of groundwater dependent vegetation (Biologic, 2022). Since 2018 the groundwater levels in the Ministers North aquifer have declined by approximately 3.5 m (Figure 33).

Two changes have occurred in the hydrological / hydrogeological systems surrounding Ministers North and the Gorge that would have the potential to produce this groundwater level decline. They are lower than average rainfall and dewatering to support mining in nearby aquifers.

The area has experienced lower than average rainfall since 2018 (SILO point 22.85-119.10 returns a long term average (1900 to 2023) yearly rainfall of 329.6 mm compared to 280.1 mm between 2018 and 2023), which correlates exactly with the timing and duration of the observed decline in the Ministers North aquifer groundwater levels. The groundwater monitoring at Ministers North between 2002 and 2018 confirms that the aquifer water levels have varied by at least two metres in response to previous rainfall conditions (where dewatering is very unlikely to have played a part). The Ministers North aquifer is therefore sensitive to variations in rainfall and the lower than average rainfall observed since 2018 is almost certainly the cause of either all, or a proportion, of the observed groundwater level decline over the same period.

Dewatering to support mining is occurring within 15 km to the north, south and east of the Ministers North aquifer. The closest of these being the Jugari / Jugaricoogina mines less than 3 km directly to the north. As was shown above, it is highly likely that the lower than average rainfall since 2018 has contributed to the groundwater level decline, meaning that dewatering may be a contributing factor, but it is unlikely to be the sole reason.

There is a significant amount of climate, groundwater level, downhole logging and geophysical information in the Jugari / Ministers North area, however, the data gaps (most importantly the lack of information between the Ministers North and Jugari / Jugaricoogina CID aquifer systems) mean that there is no existing data that can be used to confidently, and unambiguously, quantify the proportion of the decline that may be due to dewatering, if any at all. This data will take years to collect due to the lack of a baseline between the two aquifer systems and may never be definitive.

Three numerical tools have been used to explore the data and the conceptualisation. They are all documented in detail in the Appendix. They are:

- the Pastas time series analysis open source tool,
- a local scale MODFLOW model of the Ministers North aquifer only, and

- a regional scale MODFLOW model of the entire catchment, including both the Ministers North and Jugari aquifers.

Results from the Pastas model suggest that both rainfall and dewatering could be contributing factors to the Ministers North aquifer water level decline. Results from the local scale MODFLOW model can be used to show that rainfall alone is behind the decline. The regional scale MODFLOW model has been constructed specifically to incorporate the hypothesised hydraulic connection between the Ministers North and Jugari / Jugaricoogina CID aquifers and confirms that this is possible.

The results of the modelling, combined with the ambiguity of the data and the data gaps, clearly demonstrate that it is not currently possible to determine whether the groundwater level decline in the Ministers North aquifer is due to lower than average rainfall or a combination of this and dewatering from nearby mining activities.

Climate

Records at the Marillana Bureau of Meteorology (BOM) weather station (005009) from between 1936 and 2020 indicate a mean annual rainfall of 324 mm/yr. The wettest months are December to March. Although there are several gaps in the data, the highest three single day rainfall observations were:

- 255 mm on the 26th January 2003.
- 177 mm on the 16th December 1999, and
- 172 mm on the 26th March 1942

Between 1936 and 2020 there was one day where the rainfall was greater than 200 mm, 11 days where the rainfall was between 100 and 200 mm, 57 days between 50 and 100 mm and 1936 days between 1 and 50 mm. On 22,397 days, no rainfall was recorded.

Mean Class A pan evaporation at Jigalong and Newman are 4,066 and 3,733 respectively (Luke et al., 1987).

Marillana Creek

Marillana Creek flows to the east, with major tributaries contributing to flow including (moving from west to east) Lamb Creek, Herbert’s Creek and Iowa Creek. Downstream of Jugari, Marillana Creek passes through Rio Tinto's lease where Phil’s Creek and Jugaricoogina Creek enter the creek prior to its confluence with Weeli Wolli Creek. Weeli Wolli Creek flows in a northerly direction for approximately 40 km before discharging into the Fortescue Marsh (BHP, 2016).

A number of creek diversions have been constructed at Jugari. The major creek diversions are the Marillana Creek diversions at E1 and E4 which were completed in 2019. There are two intermediate creek diversions at W3 (Lamb Creek) and Herbert’s Creek (which is a diversion constructed through a mine void via a land bridge structure), and a number of other minor diversions.

Marillana Creek has an ephemeral flow regime, primarily driven by periodic cyclonic storm events and high evaporation rates. The majority of stream flow occurs during the summer months of December through to March. Large stream flows are typically associated with rain-bearing depressions of high intensity rainfall. The gauging station at Flat Rocks (DoW ID 708001), which is located near the western edge of the Jugari mine, (Figure 34) measures surface water flow from the upper sub-catchment (Golder, 2015). Analysis of data from this gauging station between 1967 and 2014 indicates a historical average of four flow events per year with a range of zero to thirteen occurring in a given year.

Flow events in Marillana Creek tend to be “flashy” with steep rises in the flood hydrograph followed by a relatively quick recession. The largest discharge in the gauging record, with a peak hourly discharge of 1,322 m^3/s, was as a result of heavy rainfall associated with tropical cyclone Joan which passed the catchment on 9 December 1975 (BHP, 2016).

While the Marillana Creek is naturally ephemeral, there are a number of semi-permanent and permanent pools known throughout the area including several persistent pools in the lower sub-catchment that are sustained by localised storage in the surrounding alluvium. Persistent pools occur in the vicinity of Flat Rocks gauging station where groundwater ponds behind, and flows over, basement rock at the surface (Golder, 2015).

Conceptual groundwater model

The palaeochannel, which hosts the CID deposits, was incised into an older landscape comprising mostly unmineralised banded iron formations (BIFs) of the Weeli Wolli Formation, with dolerite intrusions. Marillana Creek follows the same broad valley in which the palaeochannel developed. In some locations, the creek flows alongside the palaeochannel and in other locations, it crosses the CID deposit. In locations where the creek is remote from the CID, the creek is incised into BIF bedrock and may, in places, be underlain by recent alluvial material (Figures 35 and 36).

The CID deposits comprise an upper CID unit (UCID), which has a high hydraulic conductivity, and a lower CID unit (LCID). The LCID is different to the UCID and it contains a larger proportion of fines, and hence is likely to have a lower hydraulic conductivity. The thickness of the UCID increases from west to east (downstream) and it is about 10 to 30 m thick in western open pits and about 50 to 70 m thick in the central and eastern open pits. The thickness of the LCID decreases from west to east and is 40 to 50 m thick in the western open pits and about 10 to 20 m thick in the central and eastern deposits.

An indurated basal conglomerate, which may have low permeability, is situated at the base of the palaeochannel. The unit seems to occur throughout the palaeochannel length and along the palaeochannel sides. Basal clays also occur sporadically along the base of the palaeochannel.

The Weeli Wolli Formation surrounds the CID and presents extremely variable hydraulic characteristics. Immediately beneath and adjacent to the CID it is likely that the Weeli Wolli Formation presents an elevated hydraulic conductivity due to weathering. However, beyond this zone, the hydraulic conductivity may range from very low to moderate and low storage.

The main source of recharge into this system is from:

- Throughflow from the upstream CID.
- Leakage from the alluvium where it crosses or abuts the CID. This is enhanced during Marillana Creek flow events (it is also enhanced by discharge of surplus dewatering water directly to the creek).

The Marillana Creek is ephemeral, with significant flows in response to high rainfall events but little or no flow in extended dry periods.

A smaller amount of recharge to the CID is also likely to come from direct infiltration of rainfall and from groundwater flow from the surrounding Weeli Wolli Formation.

Discharge to the creek averaged 22 ML/d between 1997 and 2013, with a peak of 47 ML/d at the end of 2014. The Central location has seen about 20% of the discharge and the Eastern location the rest.

Prior to dewatering, discharge from the system was from two main sources:

- Flow within the CID the east.
- Flow into Marillana Creek when water levels were high in the CID.

Groundwater levels in the CID prior to mining at Jugari varied from 615 mAHD near Flat Rocks in the far western area to about 515 mAHD in the east. These levels indicate therefore that groundwater flows from west to east with an average hydraulic gradient of 0.2%. There are no observations of the Weeli Wolli Formation water levels prior to mining.

Dewatering now represents by far the largest outflow from the system and there are no longer any flows into the creek from the CID.

Dewatering commenced in 1991 in the Eastern pits. From 2006 dewatering has occurred concurrently in the Western, Central and Eastern pits.

Dewatering has averaged approximately 27 ML/d between January 1991 and March 2022 and has been achieved through 170 production bores and several sumps. The production bores are installed through the UCID and LCID, but generally don't penetrate below these.

Mining has also required diverting the Marillana Creek in two locations. Once this was complete, the CID beneath the old channel was mined out.

Dewatering of the CID has reduced groundwater levels throughout the Jugari mine site. Dewatering of the RTIO Jugaricoogina mine CID has had the same effect. There is some cumulative drawdown from both operations at the eastern end of Jugari and the western end of Jugaricoogina. Drawdown has occurred in the CID predominantly, but also within the alluvium (especially where the alluvium and CID cross over) and the Weeli Wolli Formation.

Groundwater levels in the CID have been drawdown by approximately 4 m at the westernmost monitoring bore from the Jugari dewatering operation. This monitoring bore is 3.7 km along the flow path from the nearest dewatering bore.

To the east, groundwater levels in the E8 area have been drawdown significantly by dewatering from the RTIO operations to either side (Mungadoo to the west and Junction South West to the east).

The Ministers North aquifer and Jugaricoogina GDE lie directly to the south of the Mungadoo orebody. Groundwater levels in the Ministers North aquifer have been declining since 2018. Without groundwater monitoring between the Ministers North and Jugari / Jugaricoogina CID aquifers it is impossible to tell whether the decline is driven by variations in rainfall or by this combined with drawdown from nearby dewatering activities (Jugari / Jugaricoogina being the closest).

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Figures

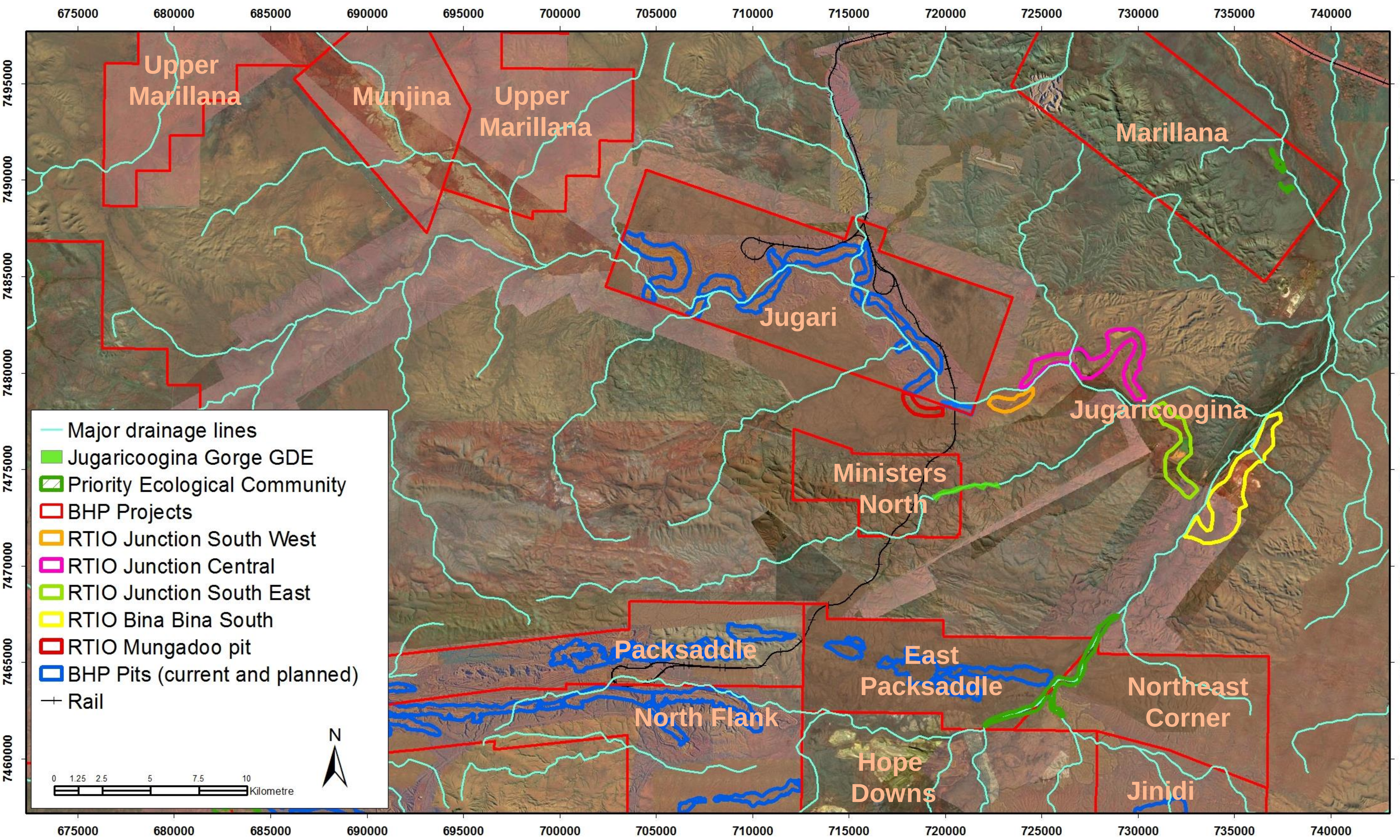

Figure 1
Regional setting

BHP

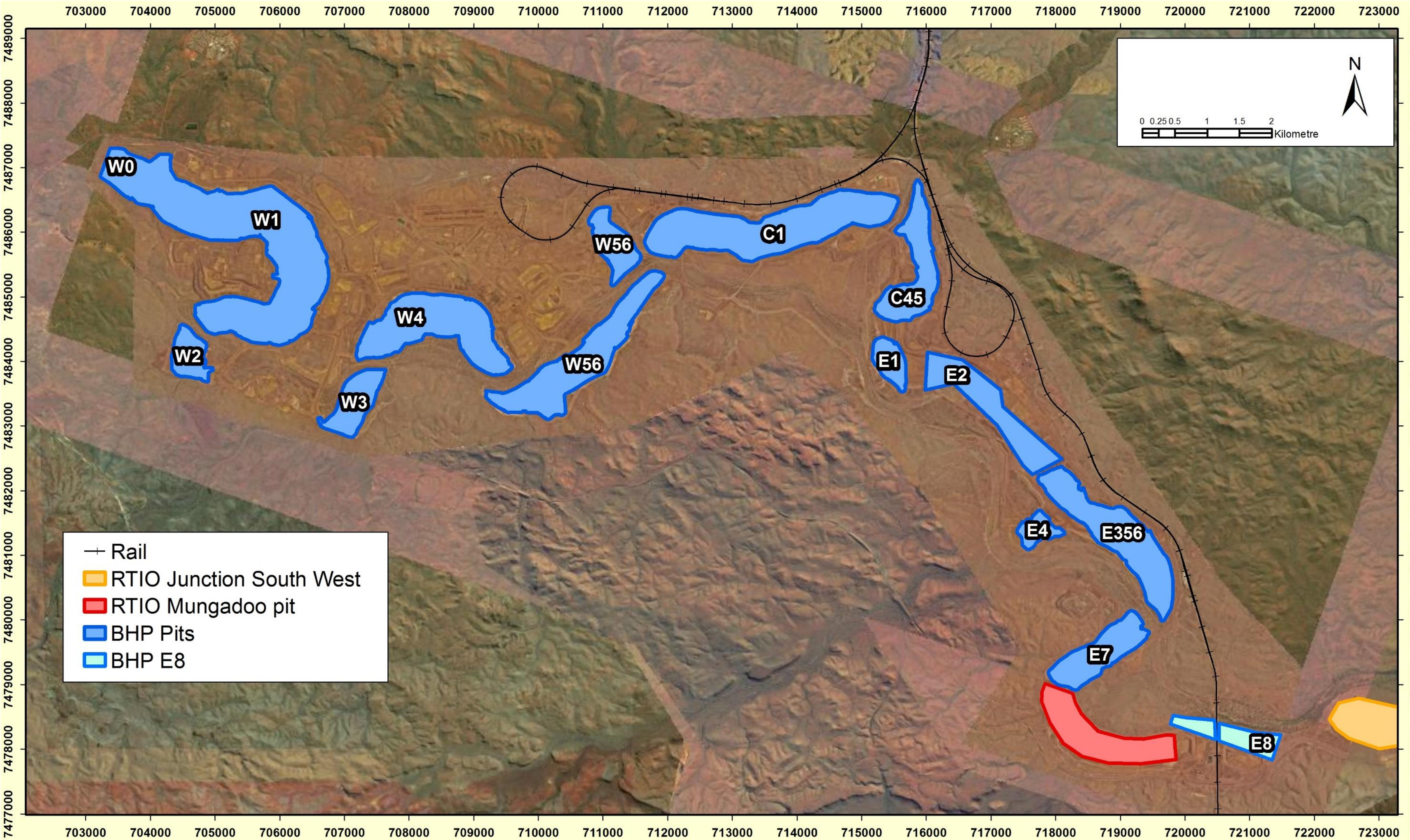

Figure 2
Jugari pit nomenclature

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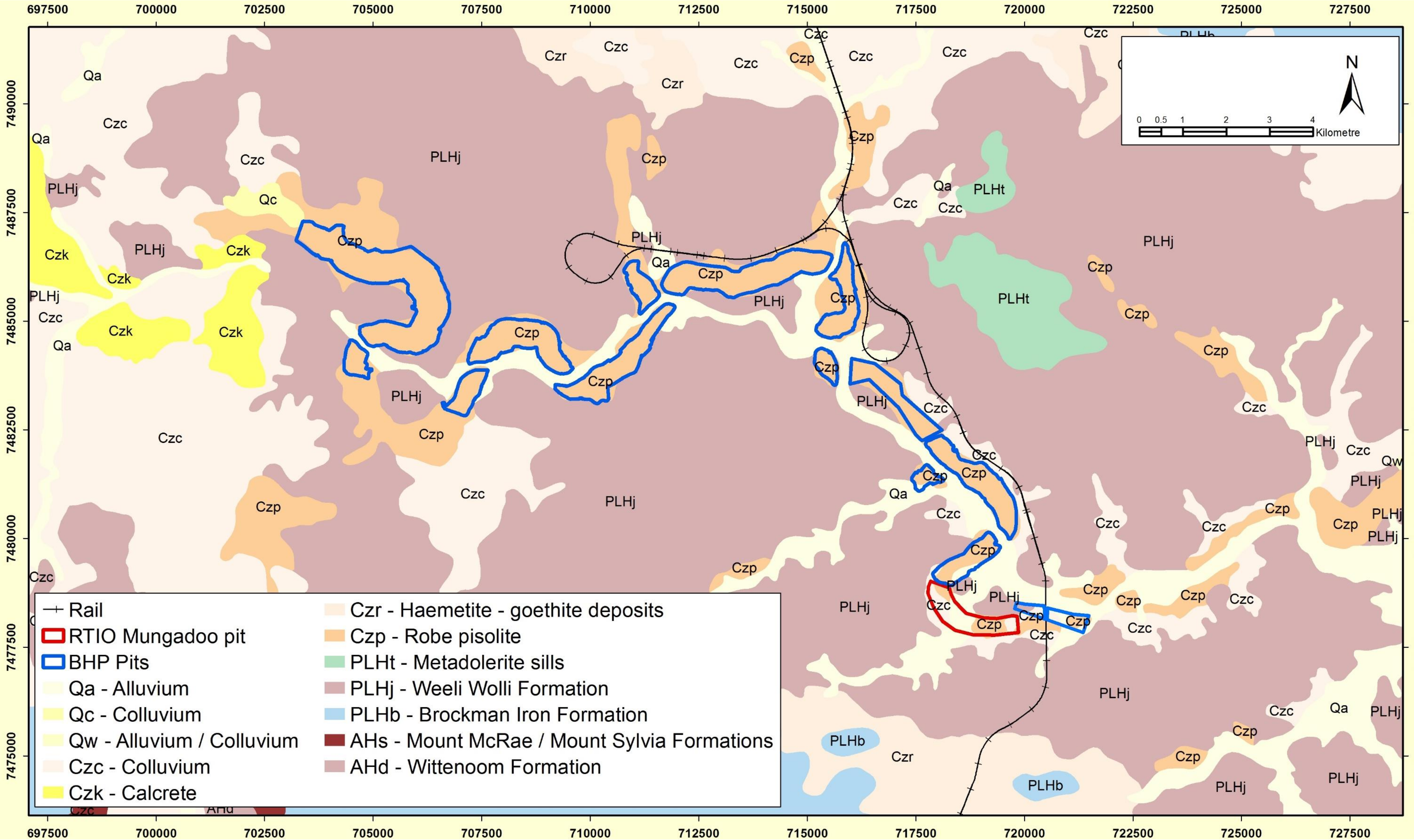

Figure 3
Surface geology

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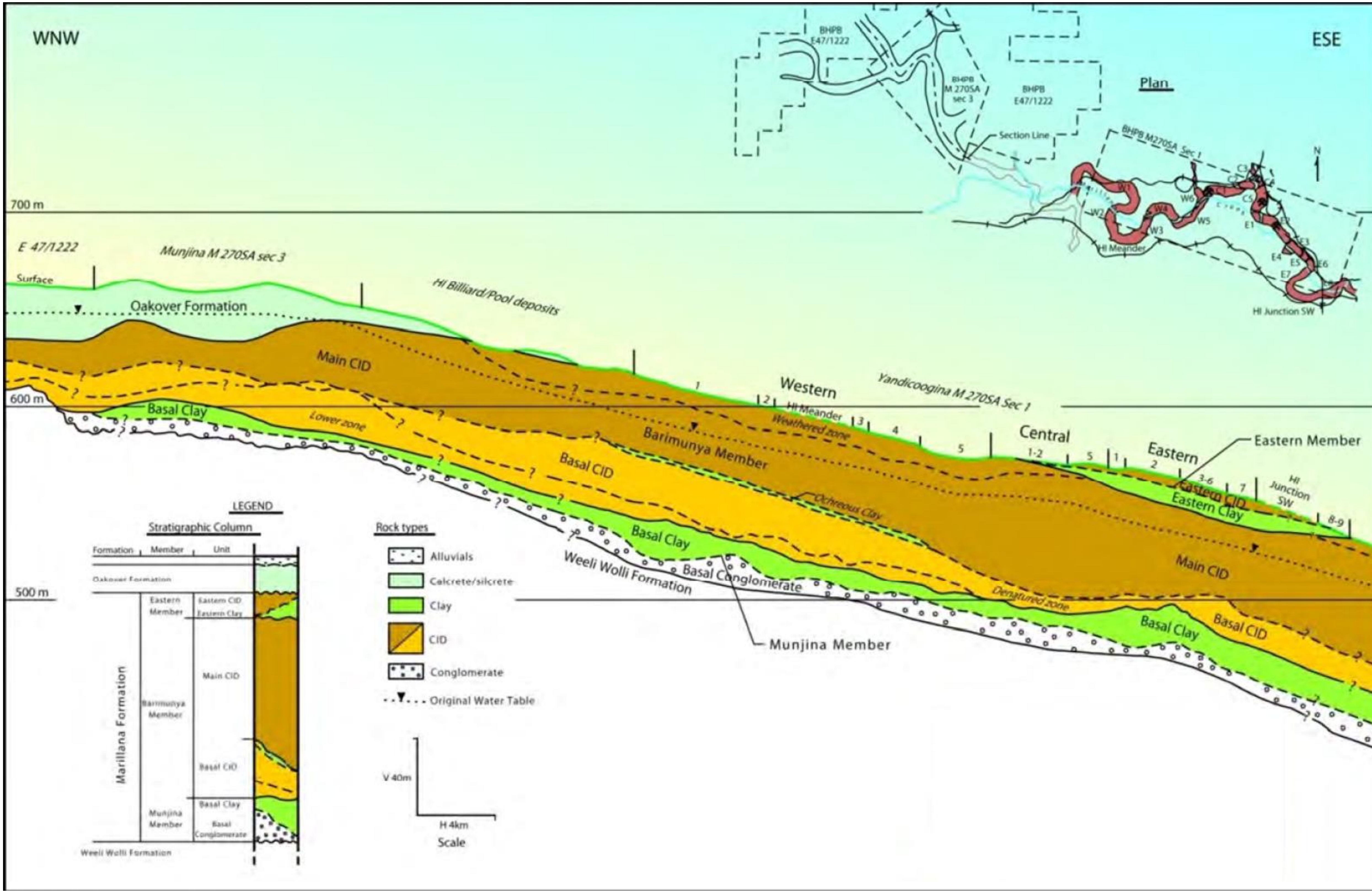


Figure 4
Geological cross section from
Munjina to RTIO Junction SW

BHP

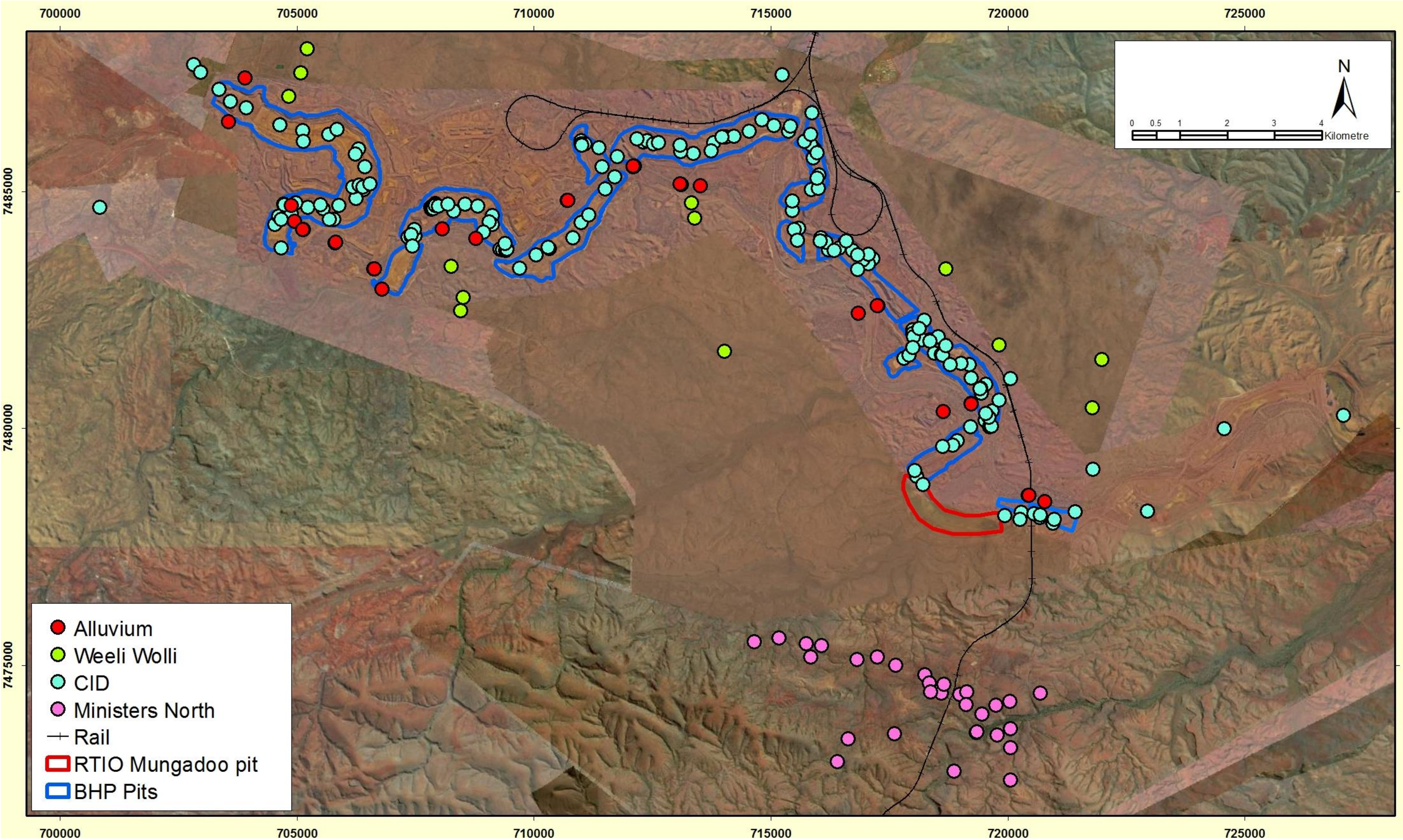


Figure 5
Monitoring bores

BHP

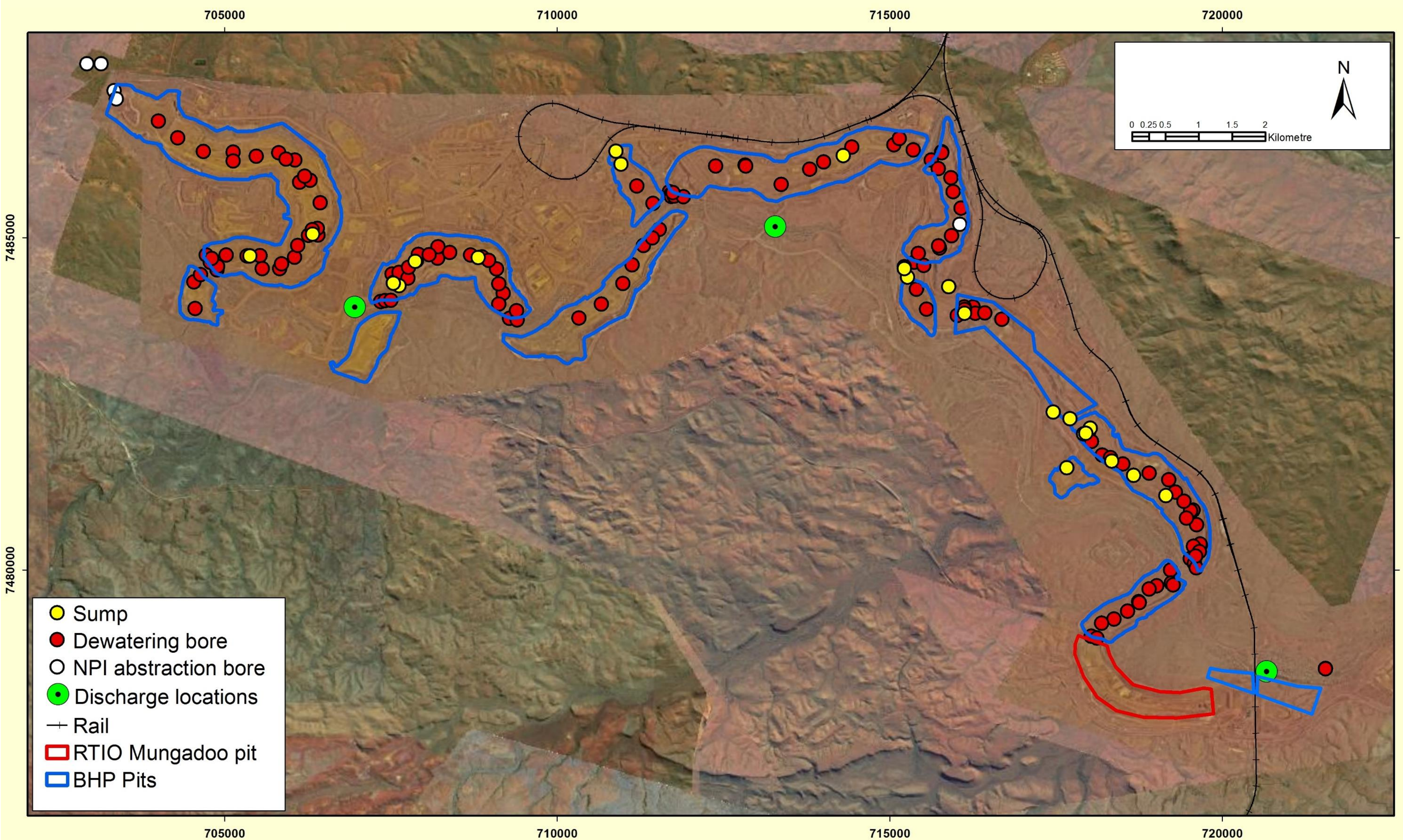


Figure 6
Jugari production bores, sumps
and discharge locations

BHP

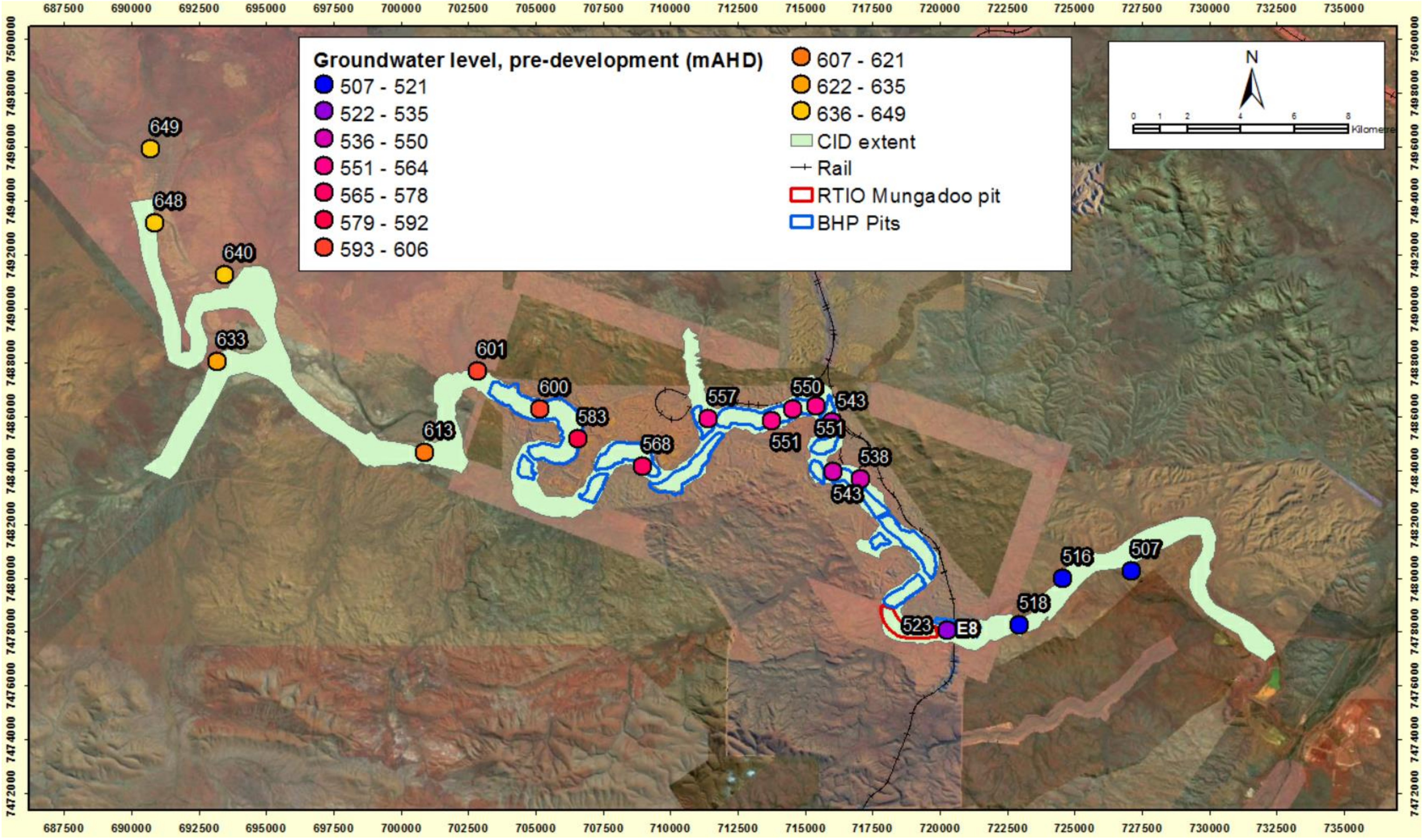


Figure 7
Pre-development groundwater levels

BHP

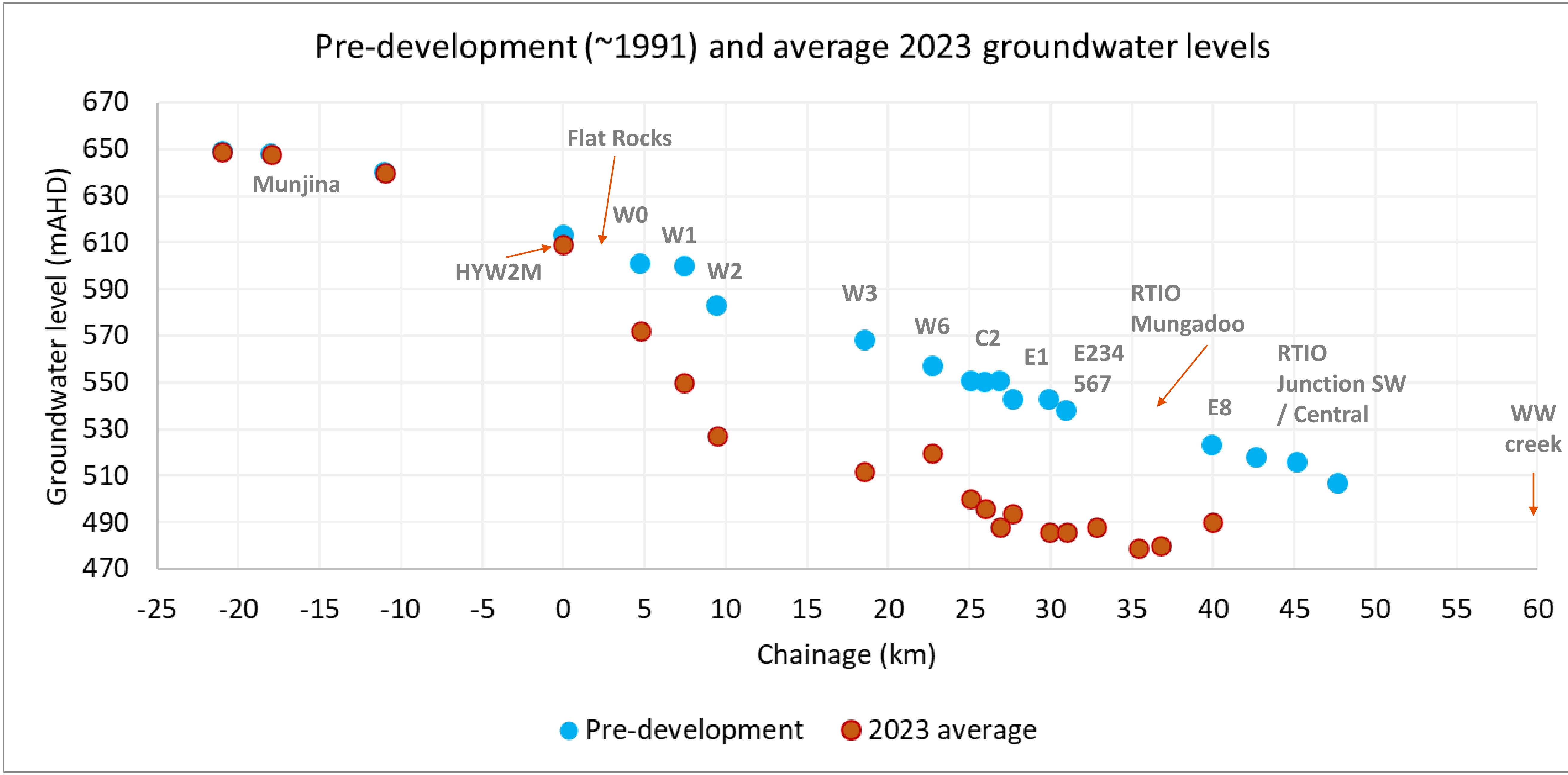


Figure 8
Pre-development and 2023 groundwater levels along the CID

BHP

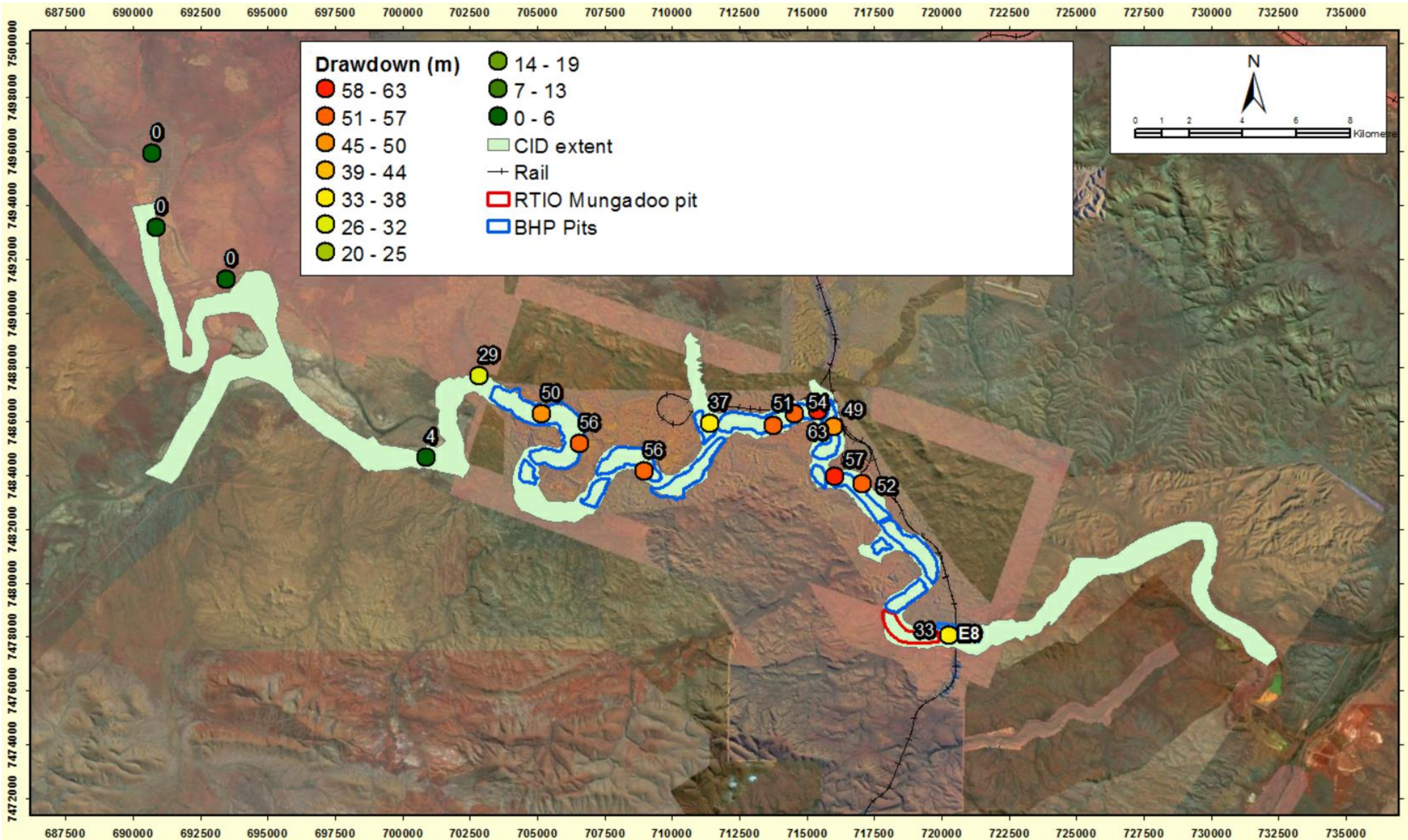


Figure 9
Observed drawdown up to 2023

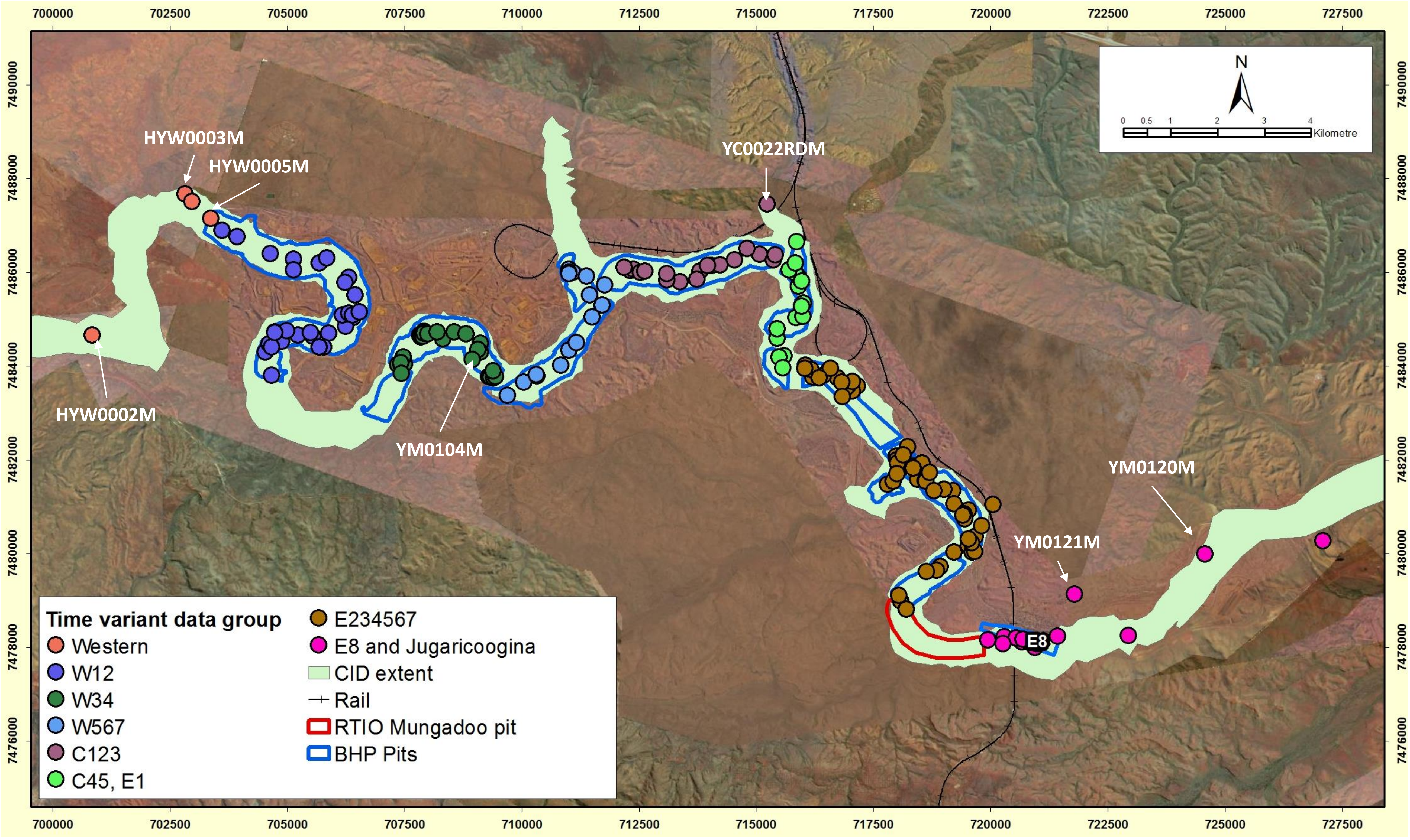


Figure 10
Time variant data groups

BHP

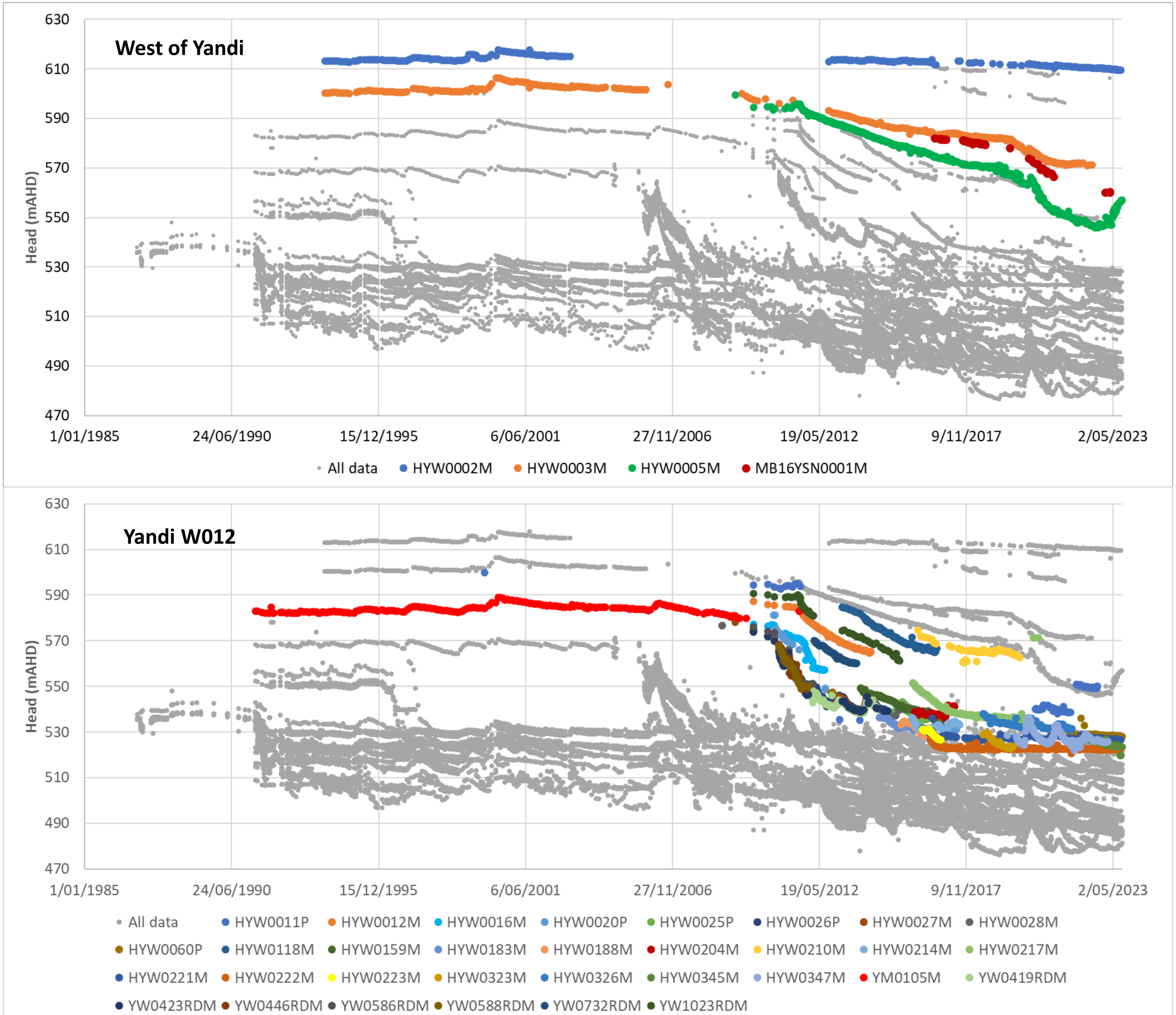


Figure 11
CID groundwater levels west of Jugari and W0/W1/W2

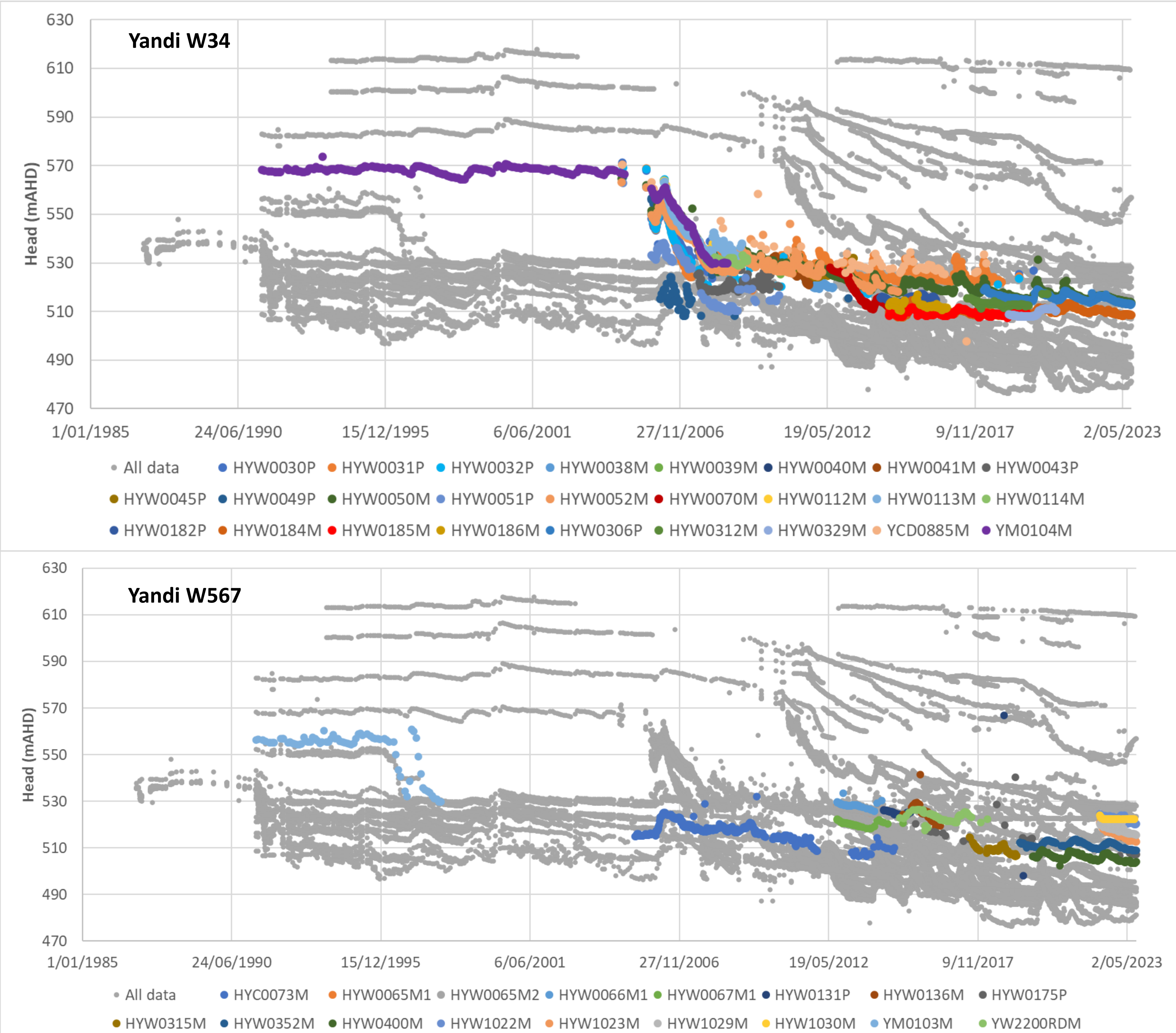
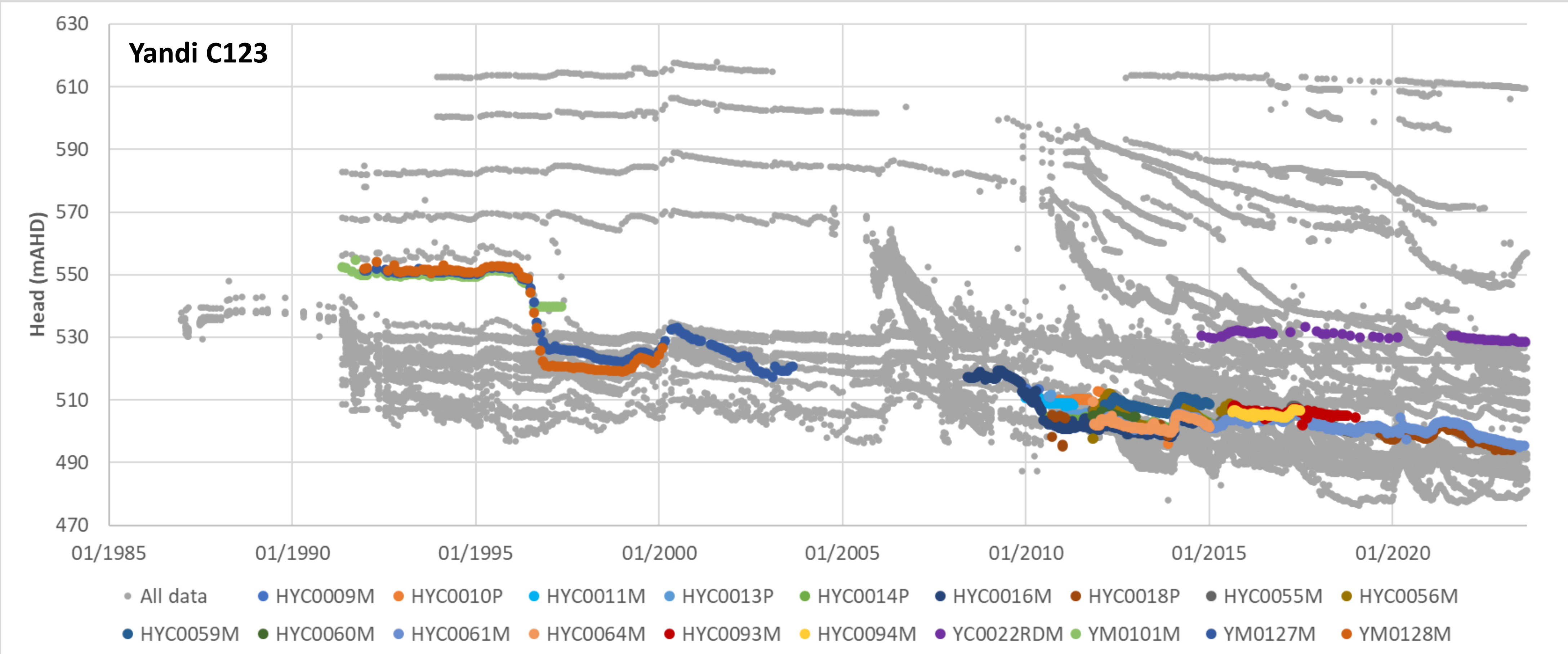


Figure 12
CID groundwater levels W34 and W567



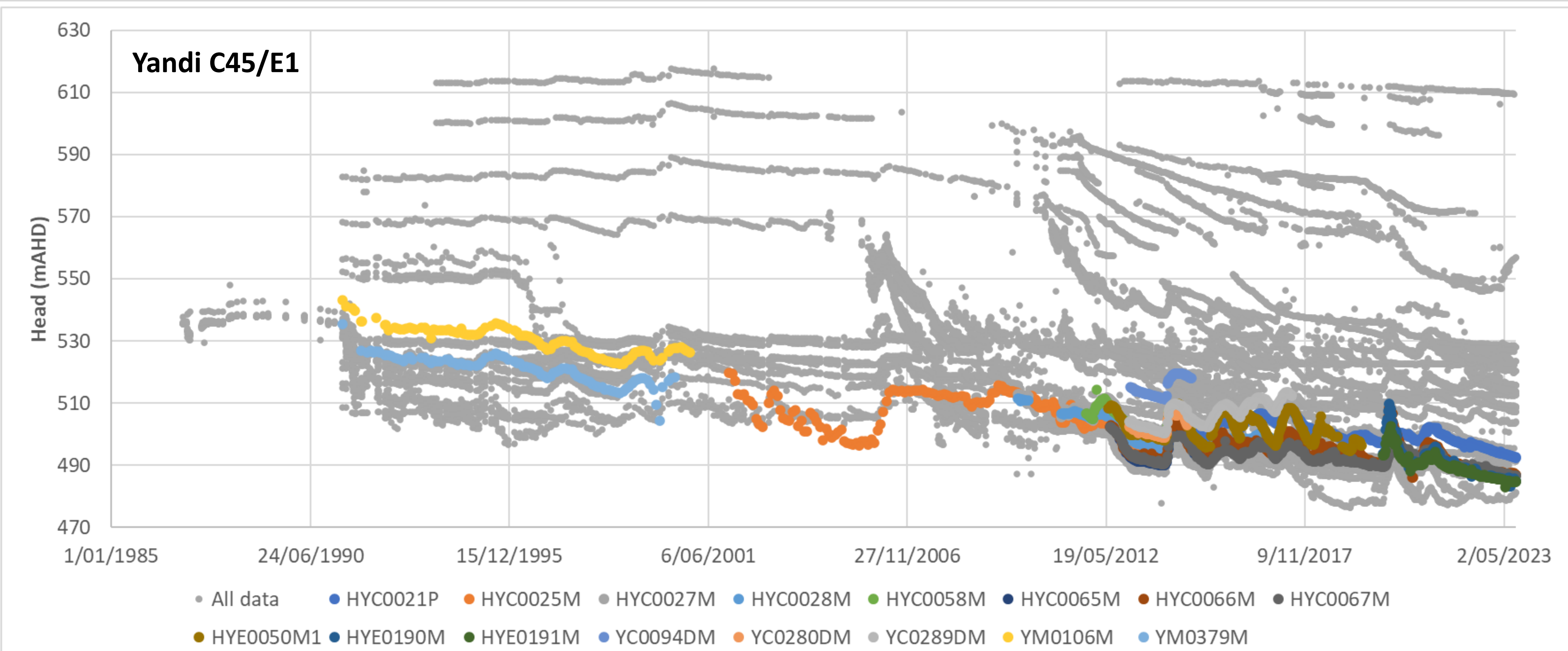


Figure 13
CID groundwater levels C123 and C45/E1

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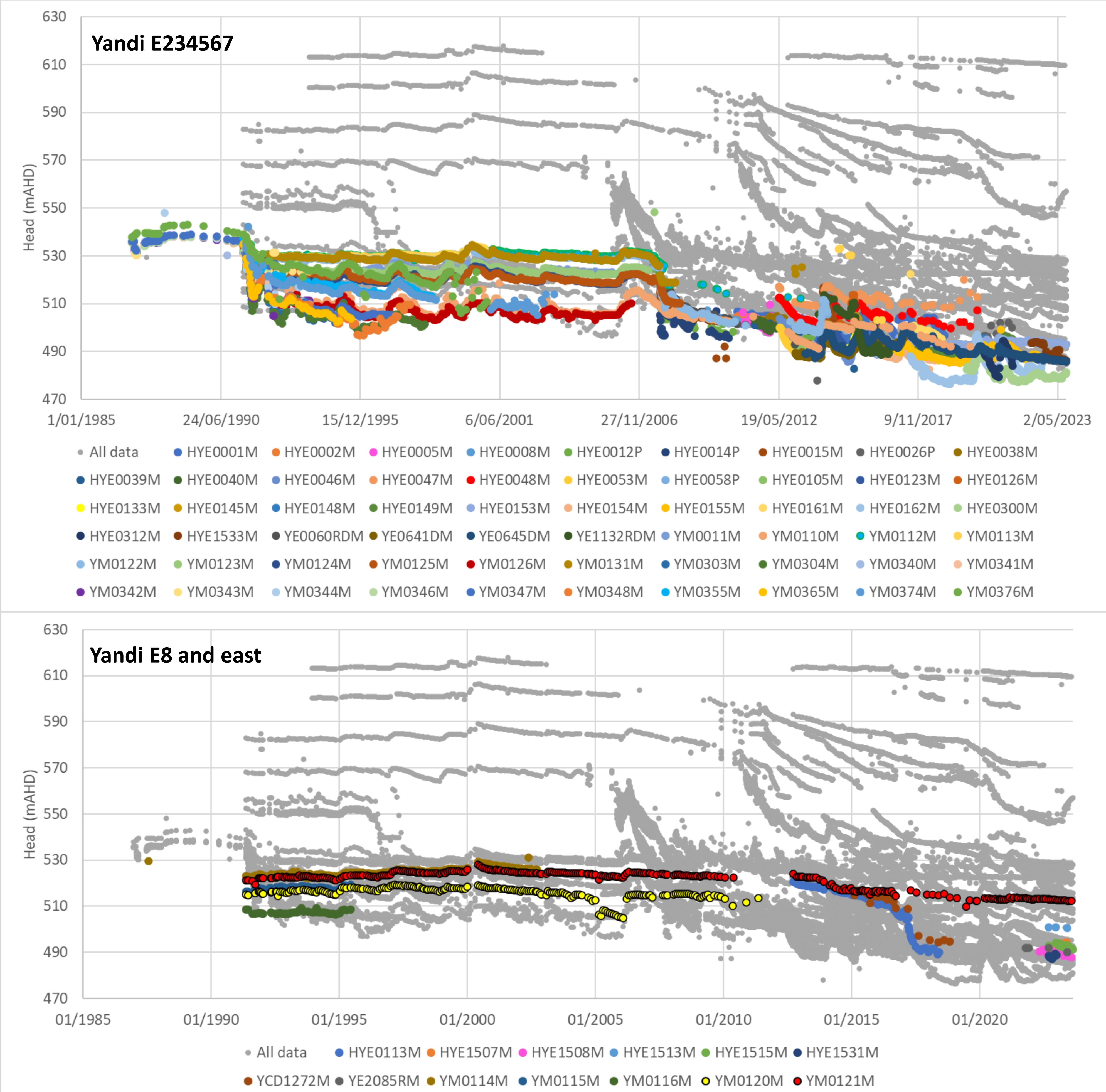

Figure 14
CID groundwater levels E234567 and E8

BHP

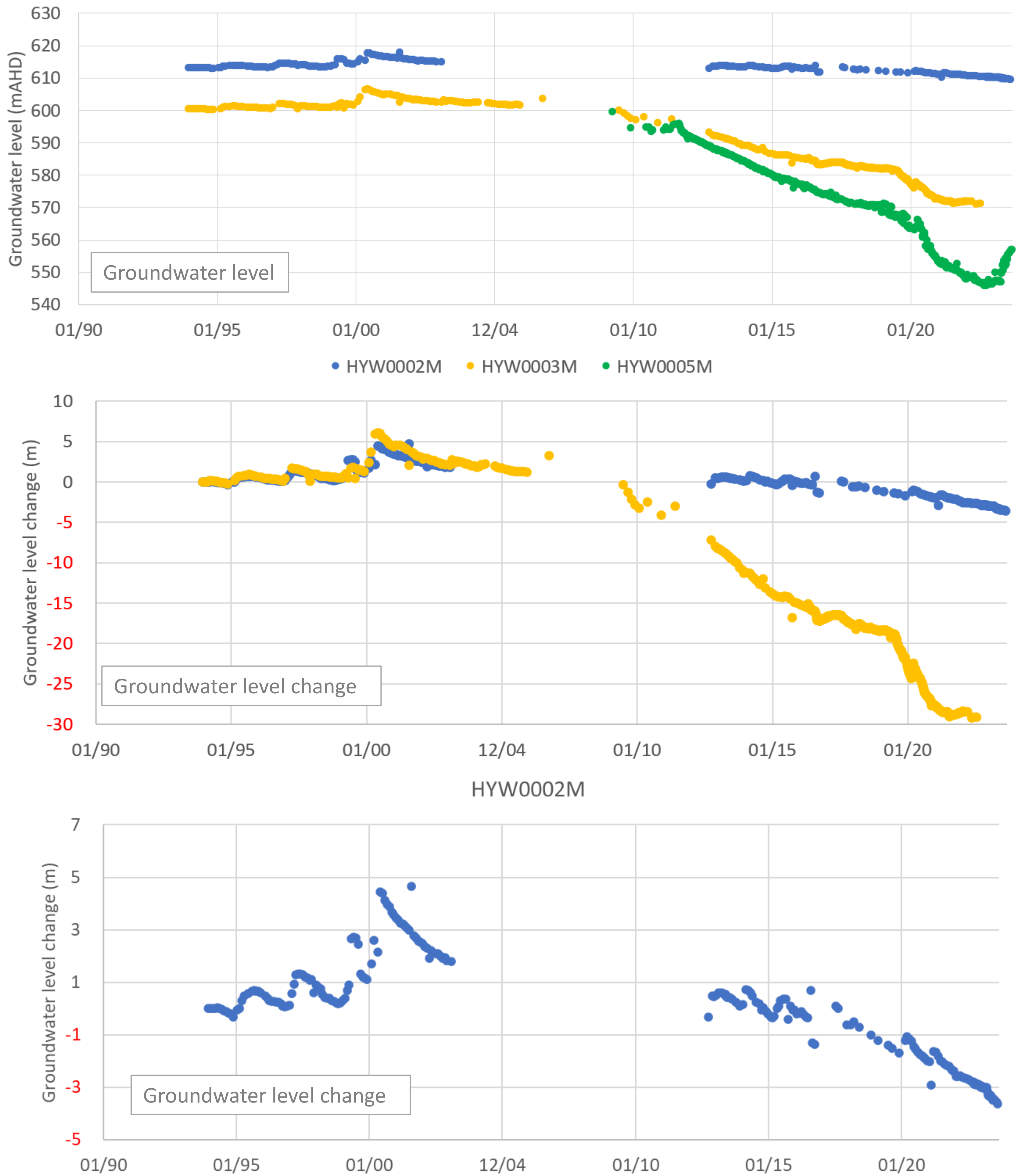

Figure 15
Groundwater levels and change – west of Jugari

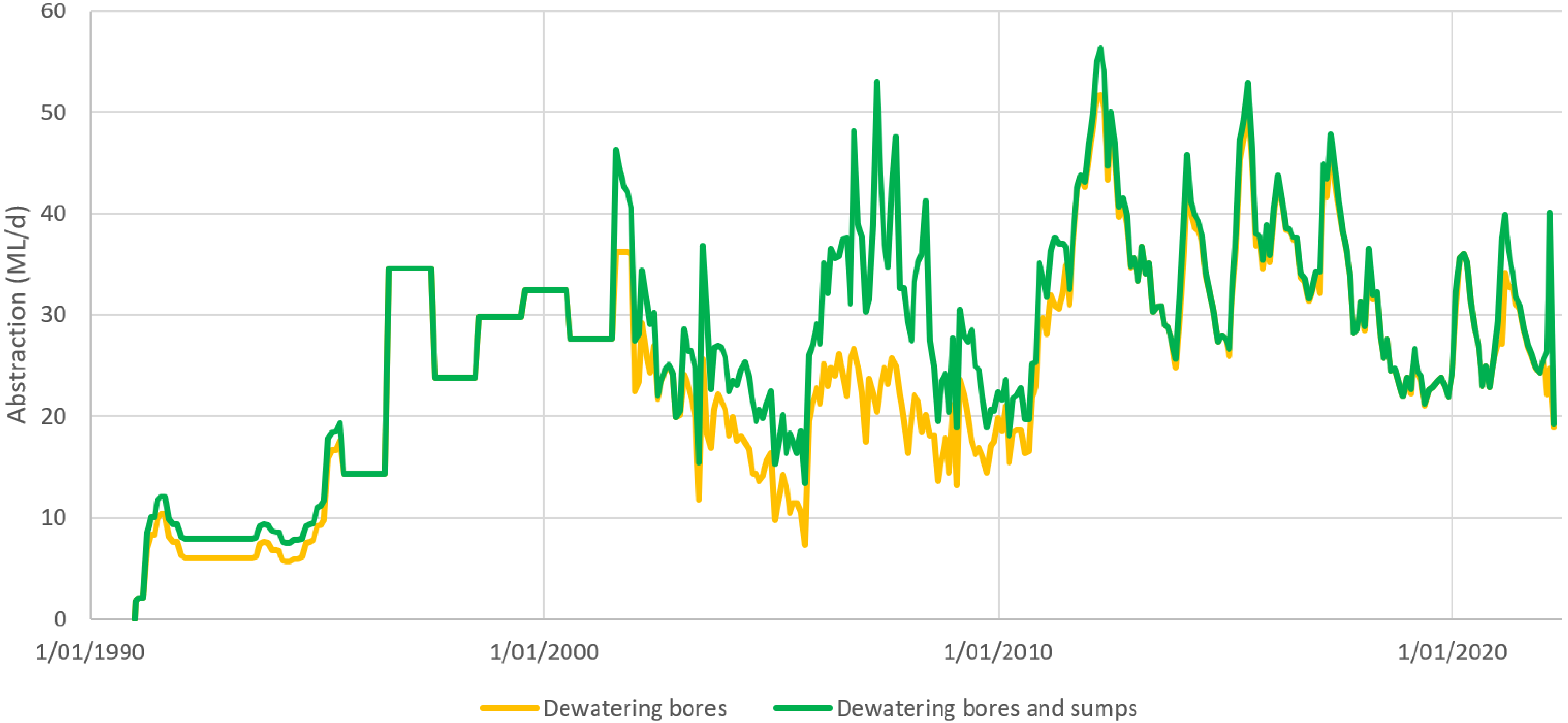

Figure 16
Total Jugari dewatering rates

BHP

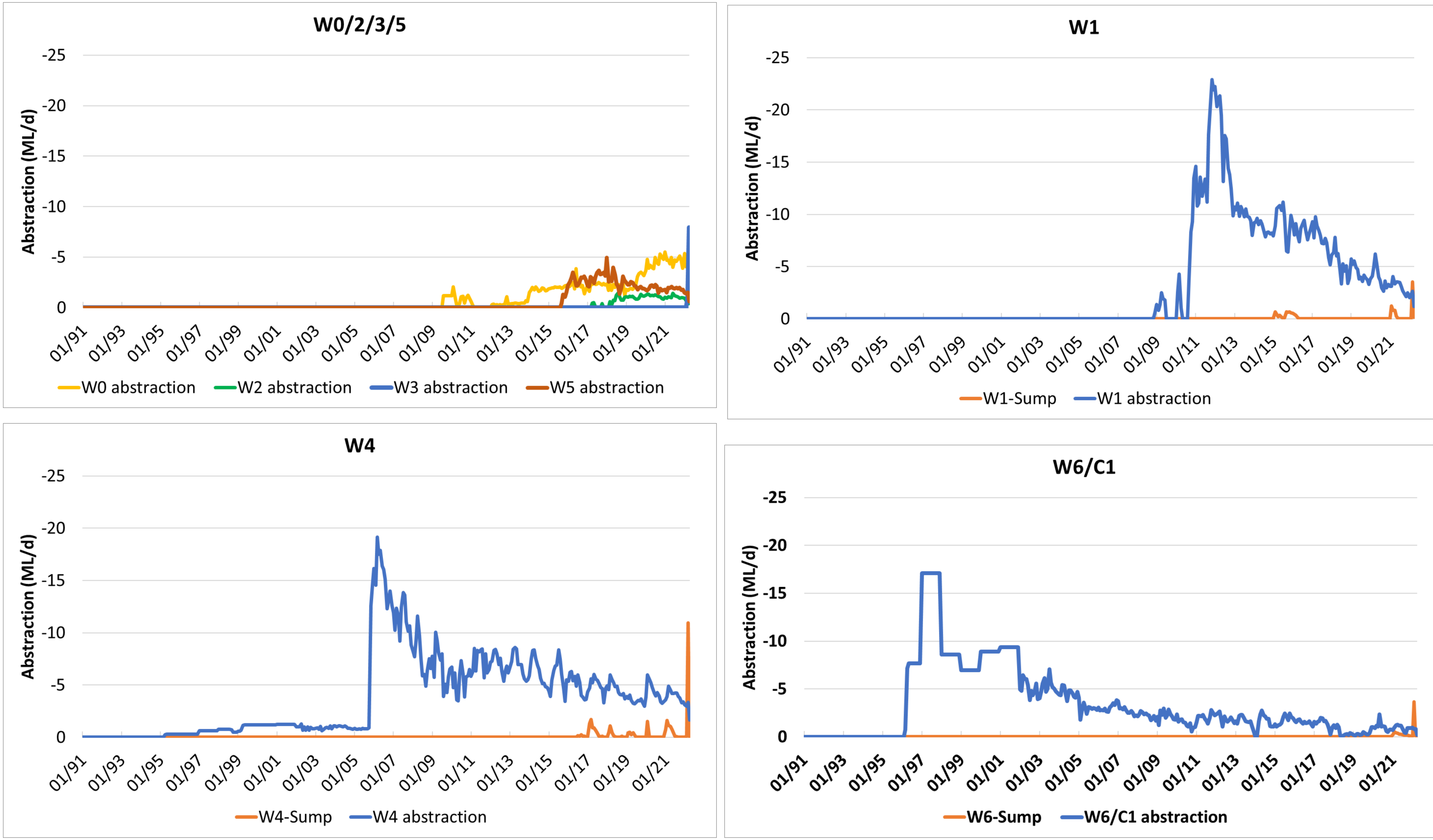

Figure 17
Western pits – dewatering rates

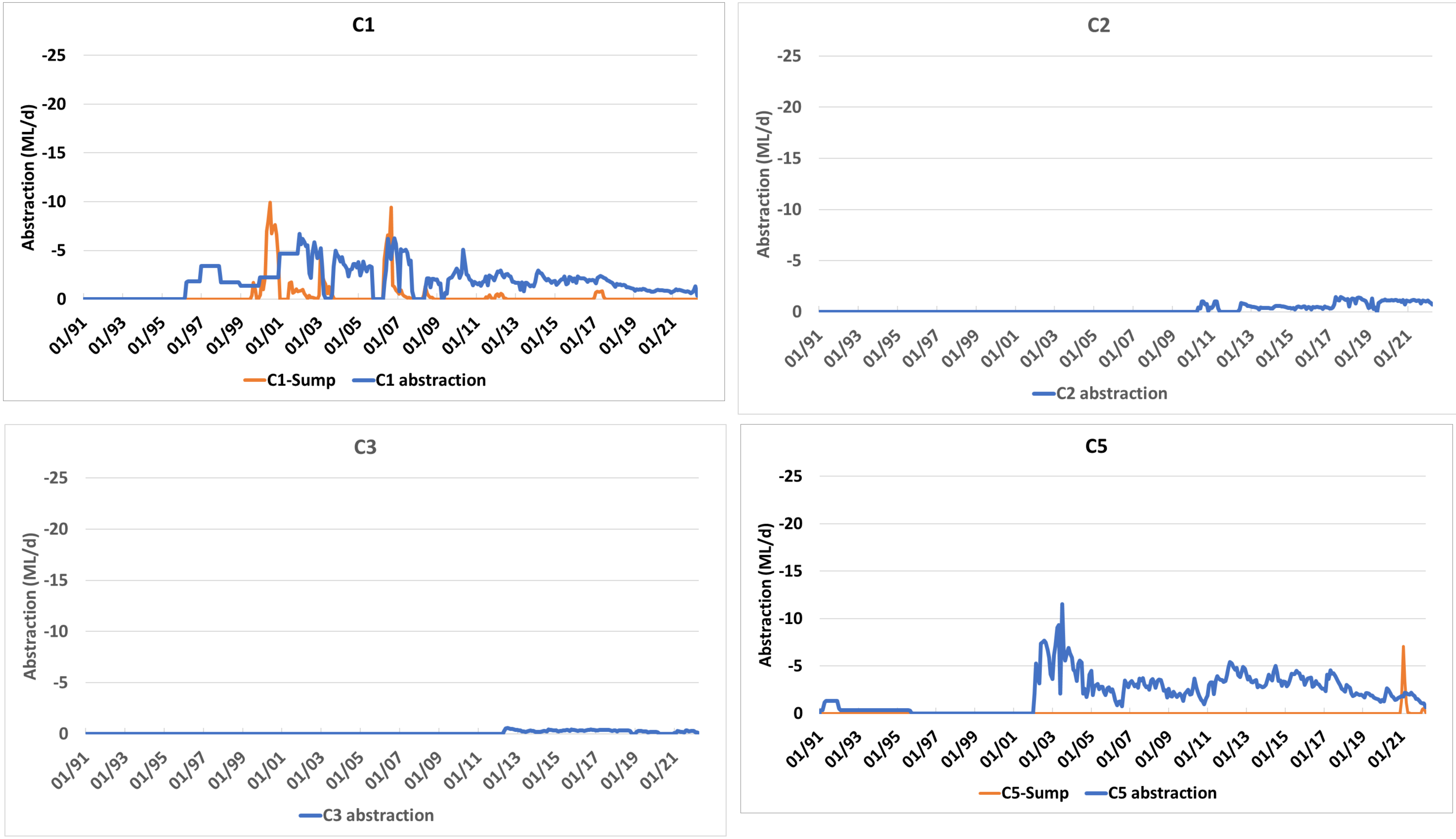

Figure 18
Central pits – dewatering rates

BHP

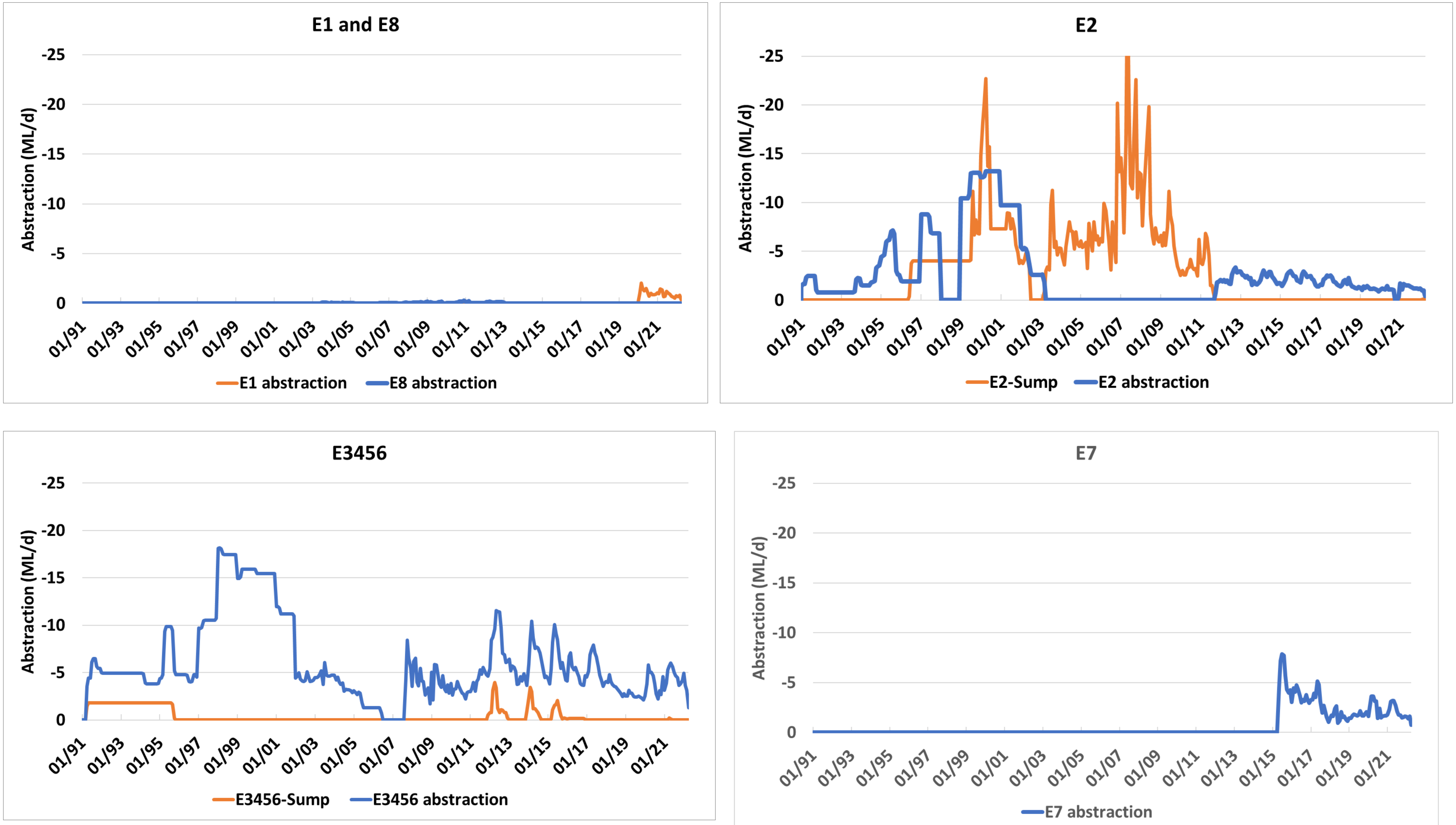

Figure 19
Eastern pits – dewatering rates

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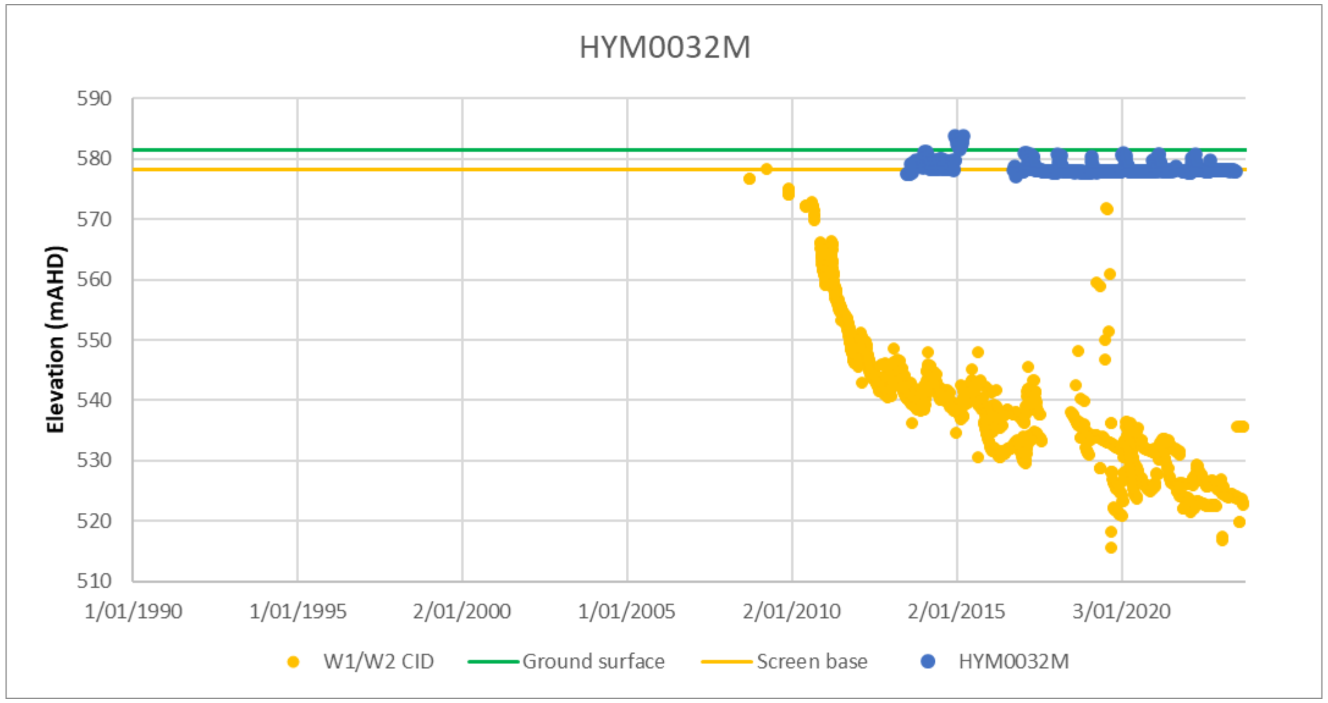
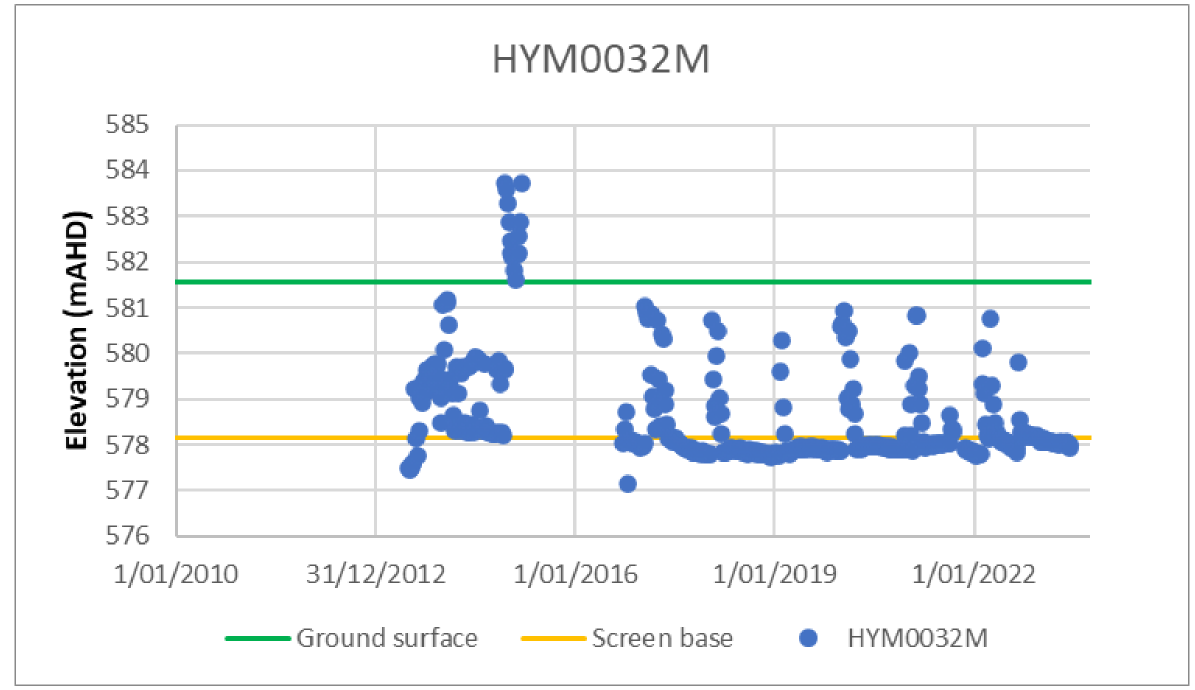
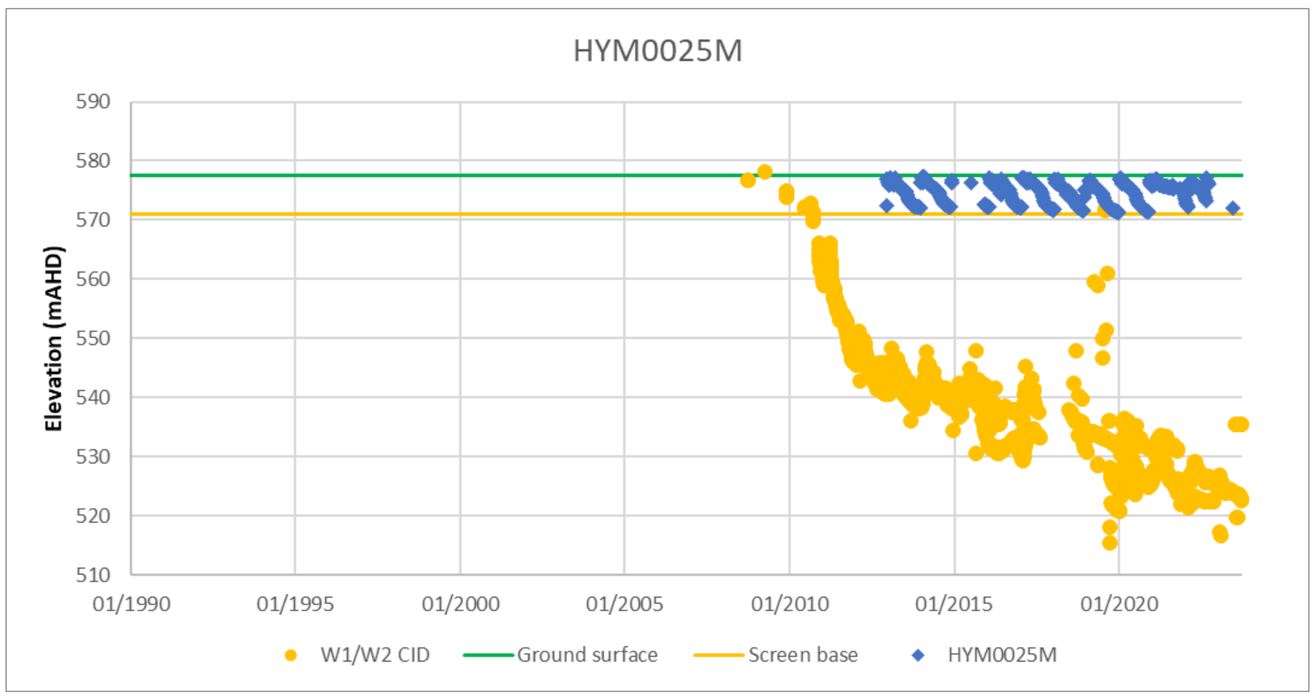
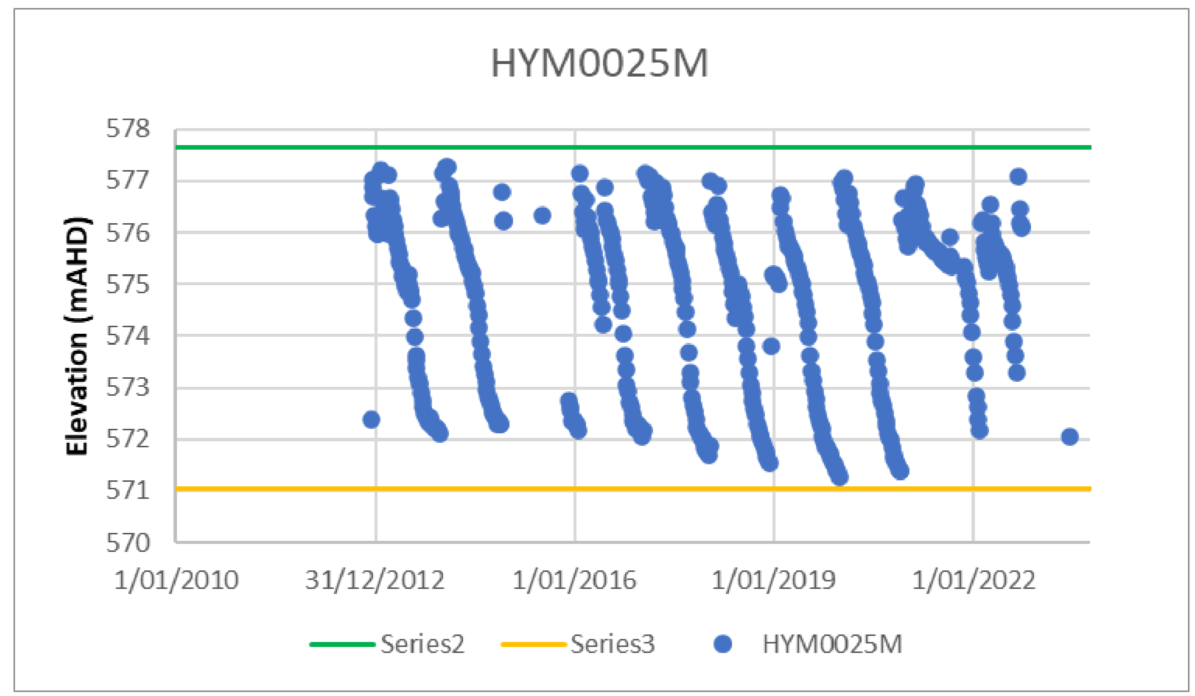








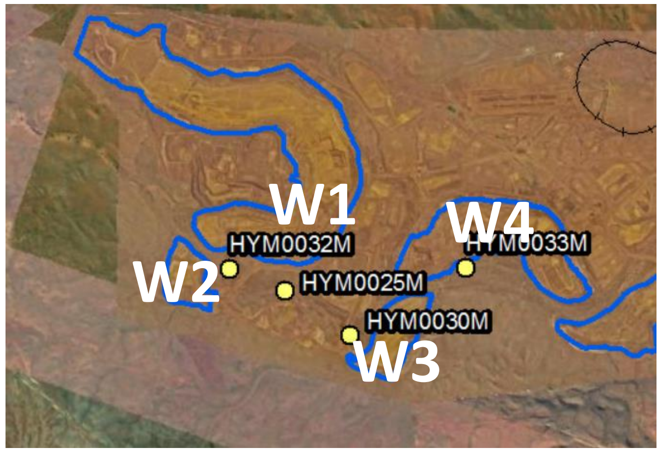
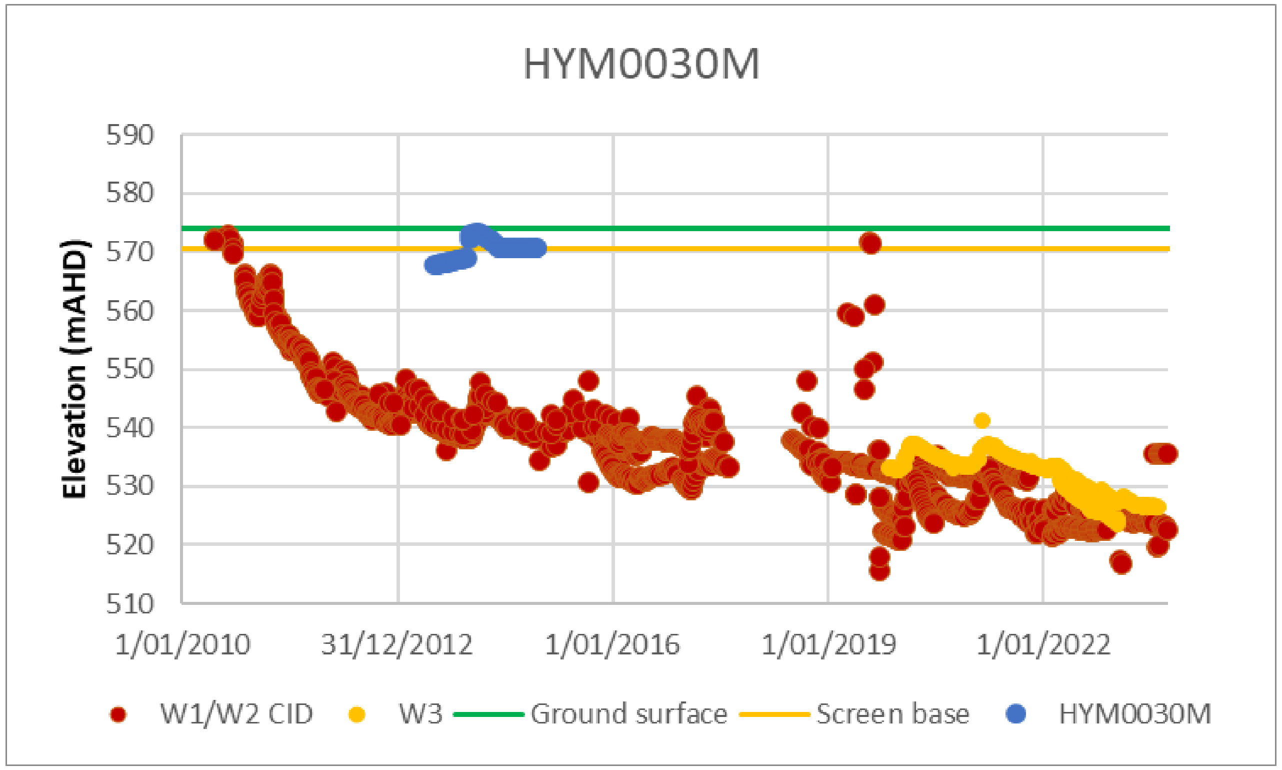
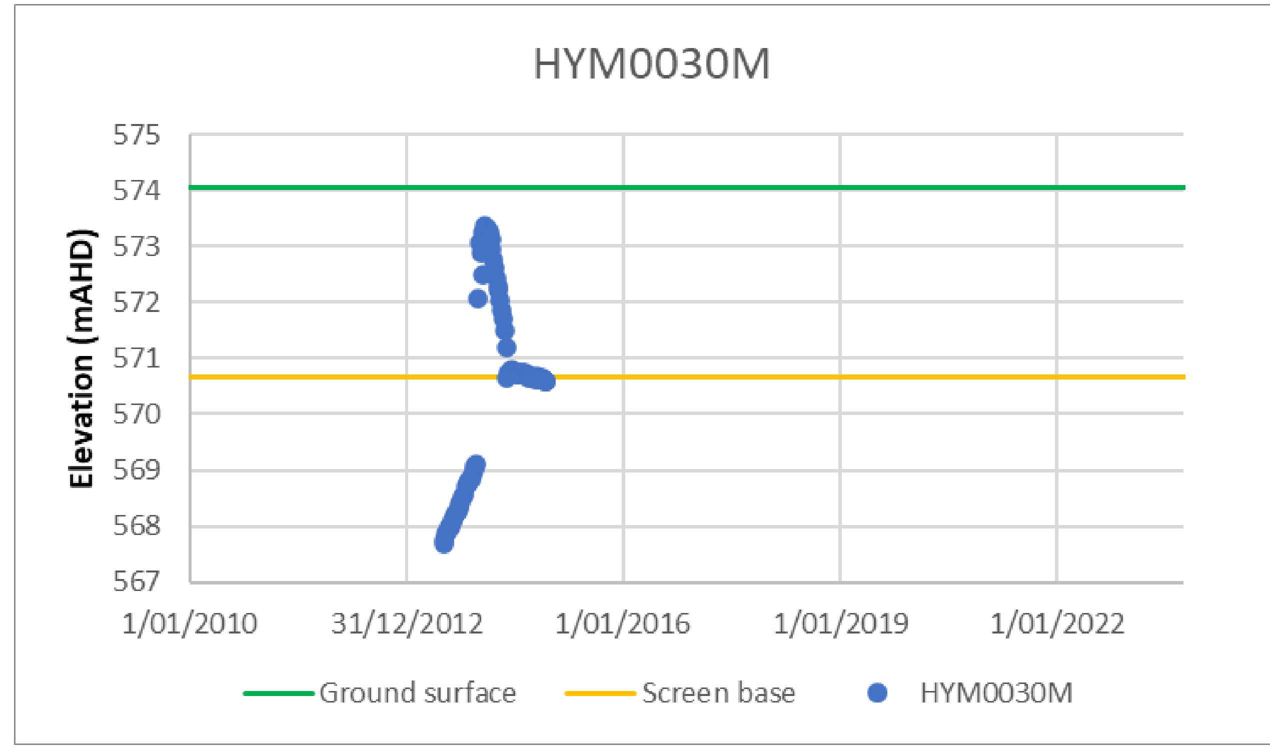
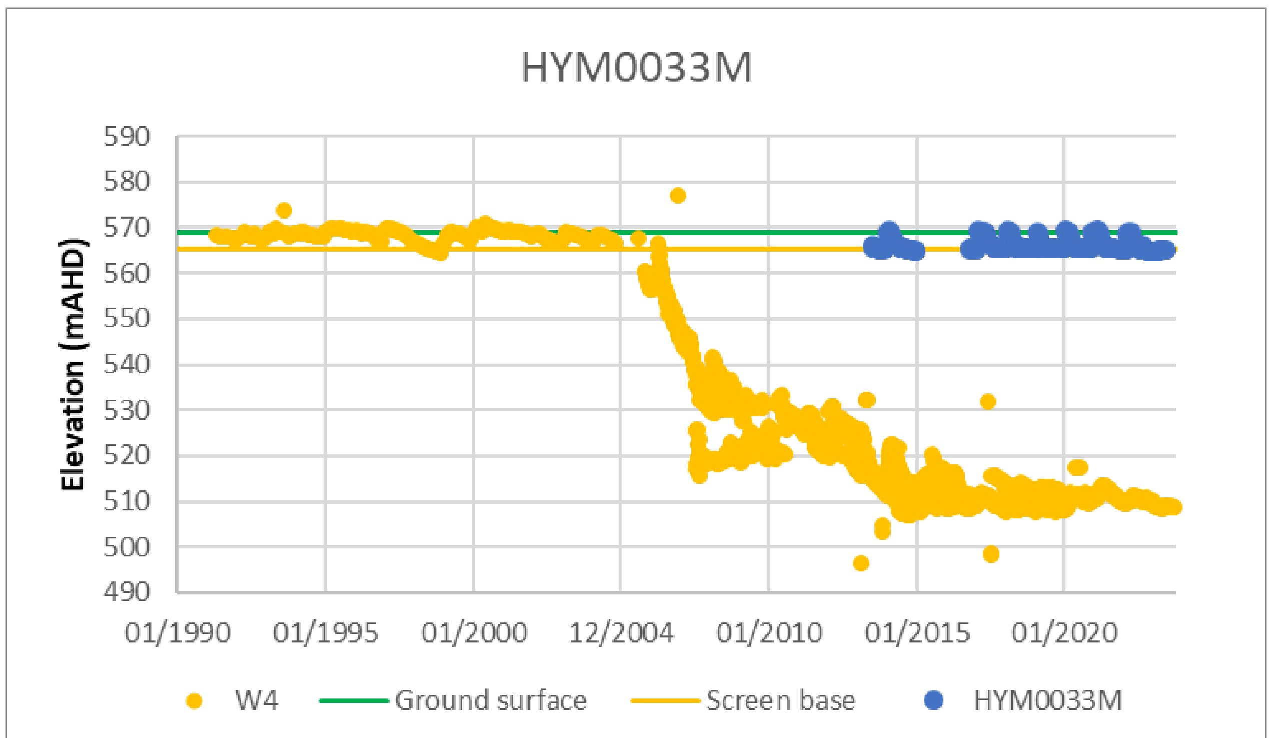
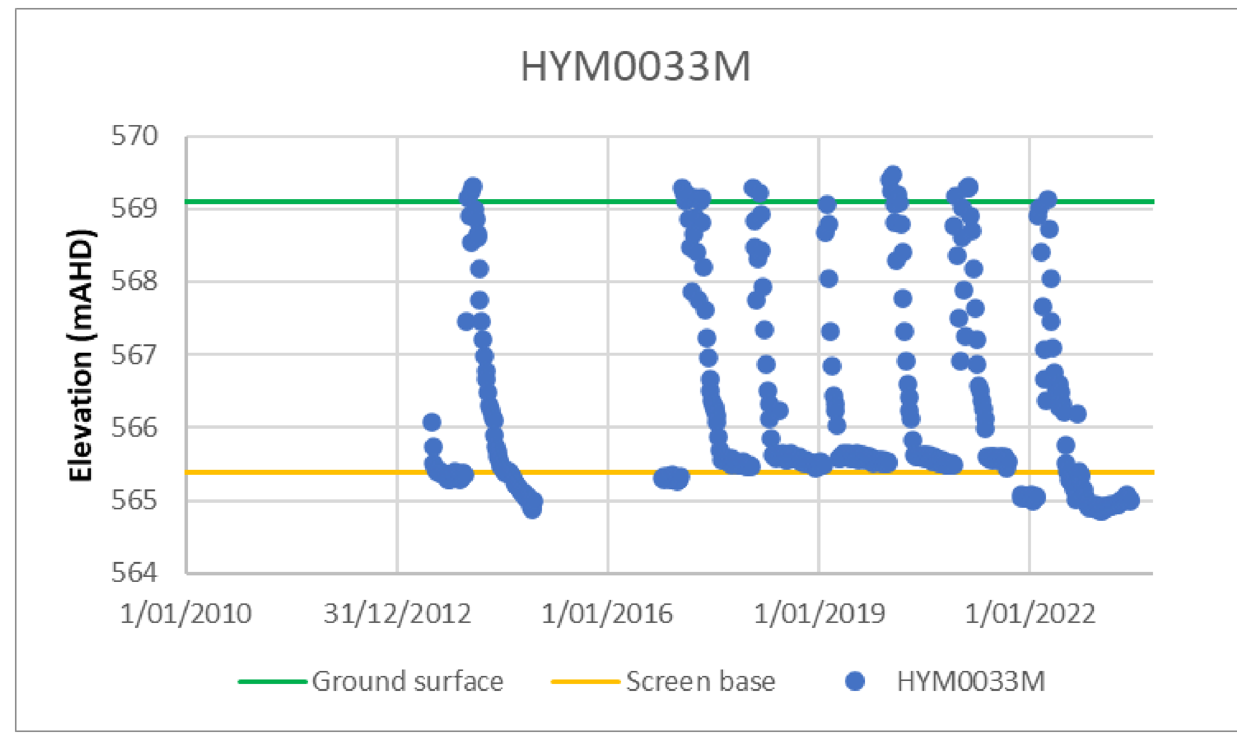


Figure 20
Alluvial groundwater levels – Western area (1)









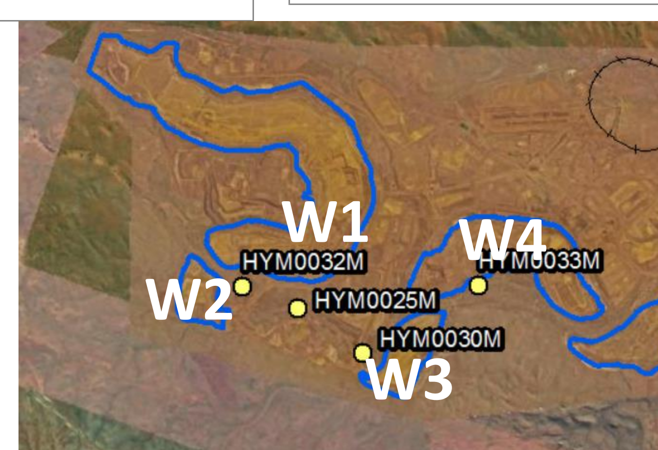


Figure 21
Alluvial groundwater levels – Western area (2)

BHP

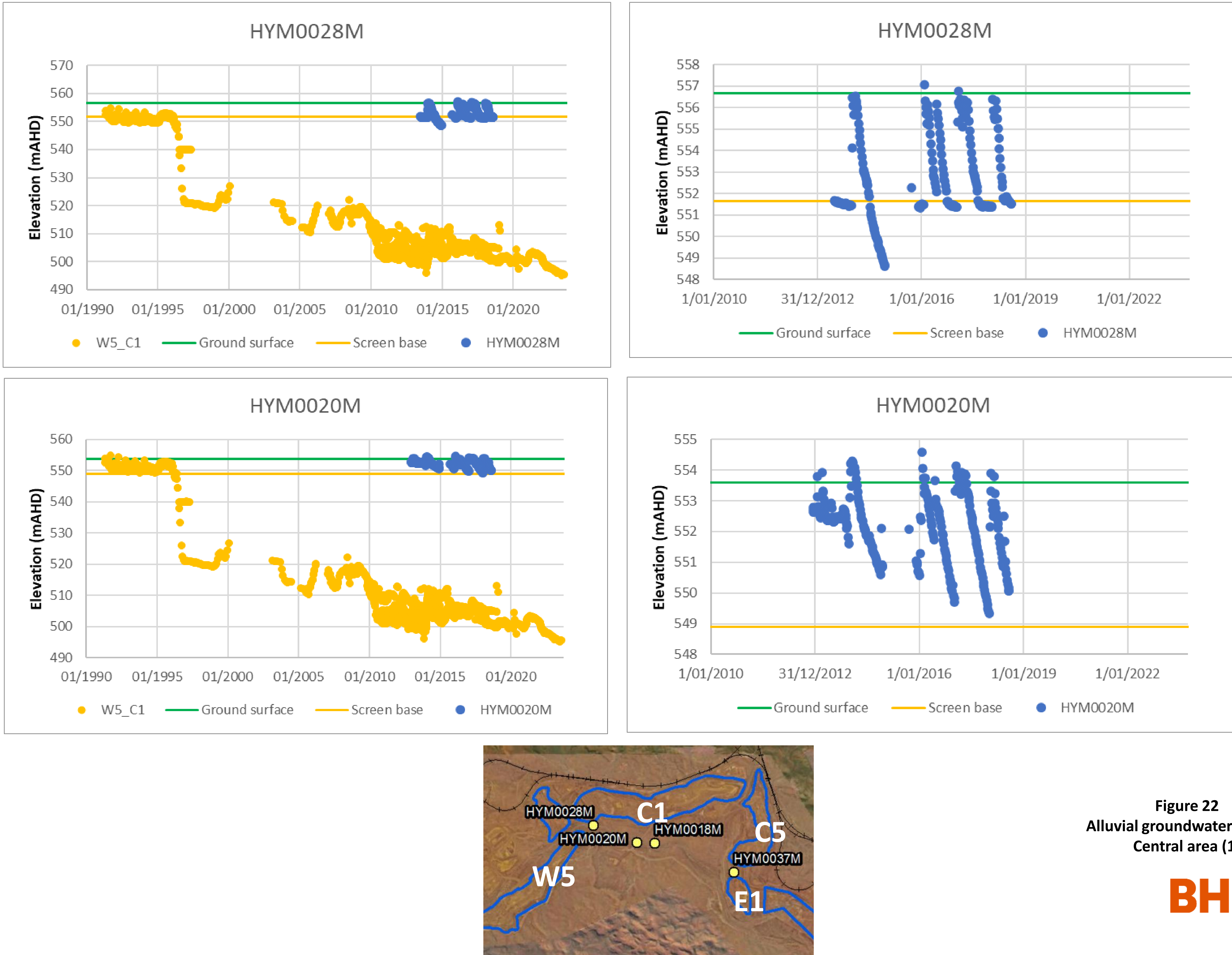
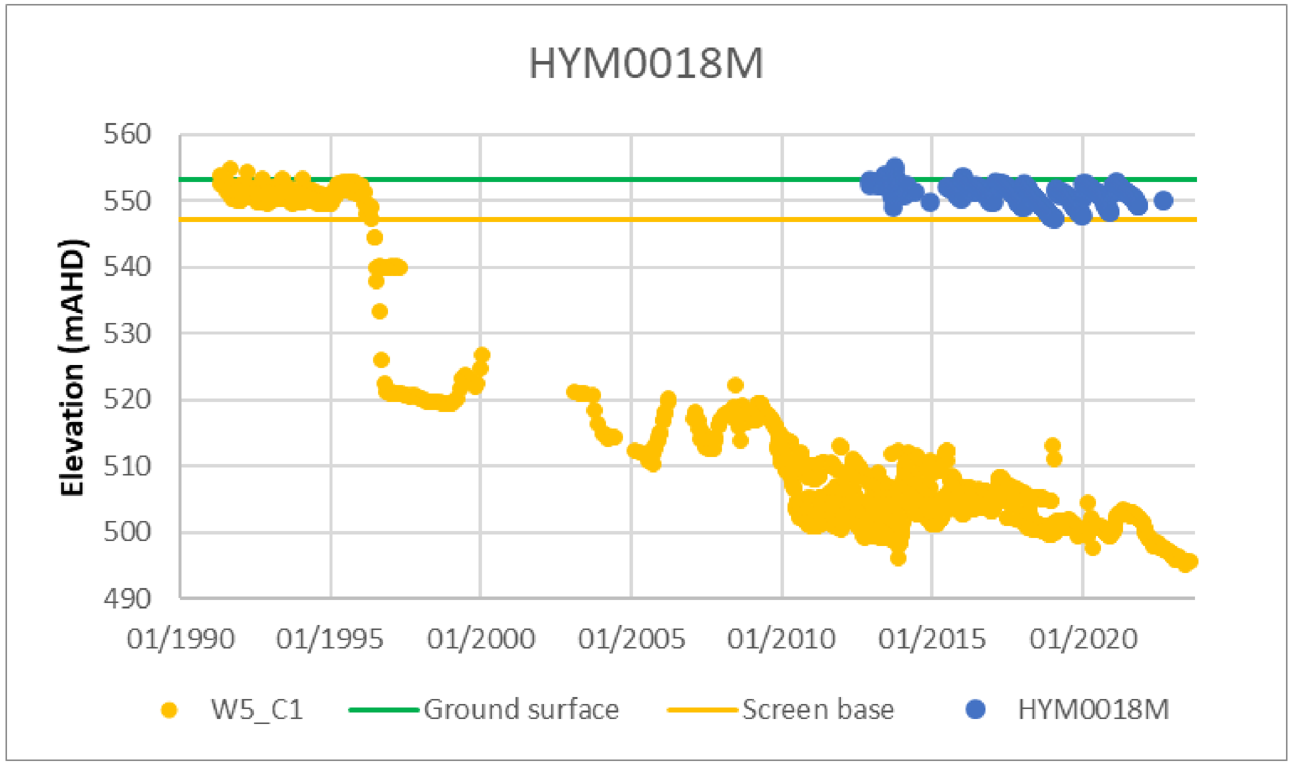
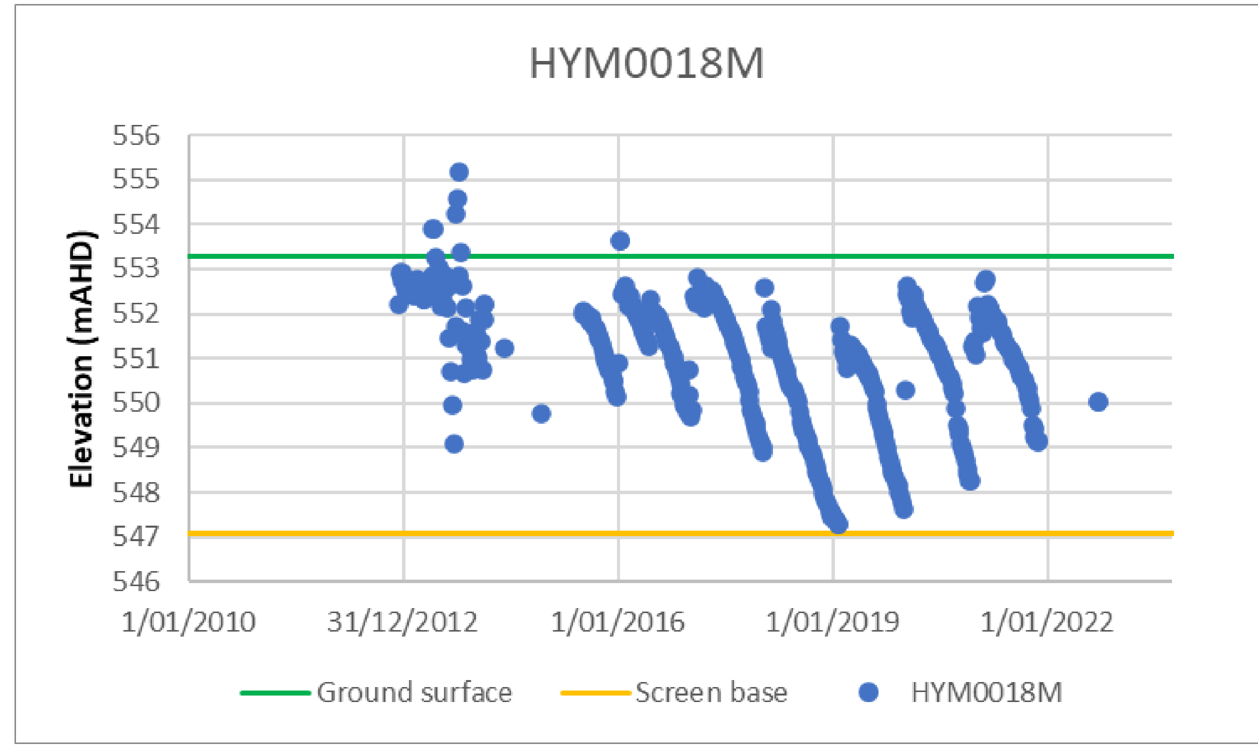
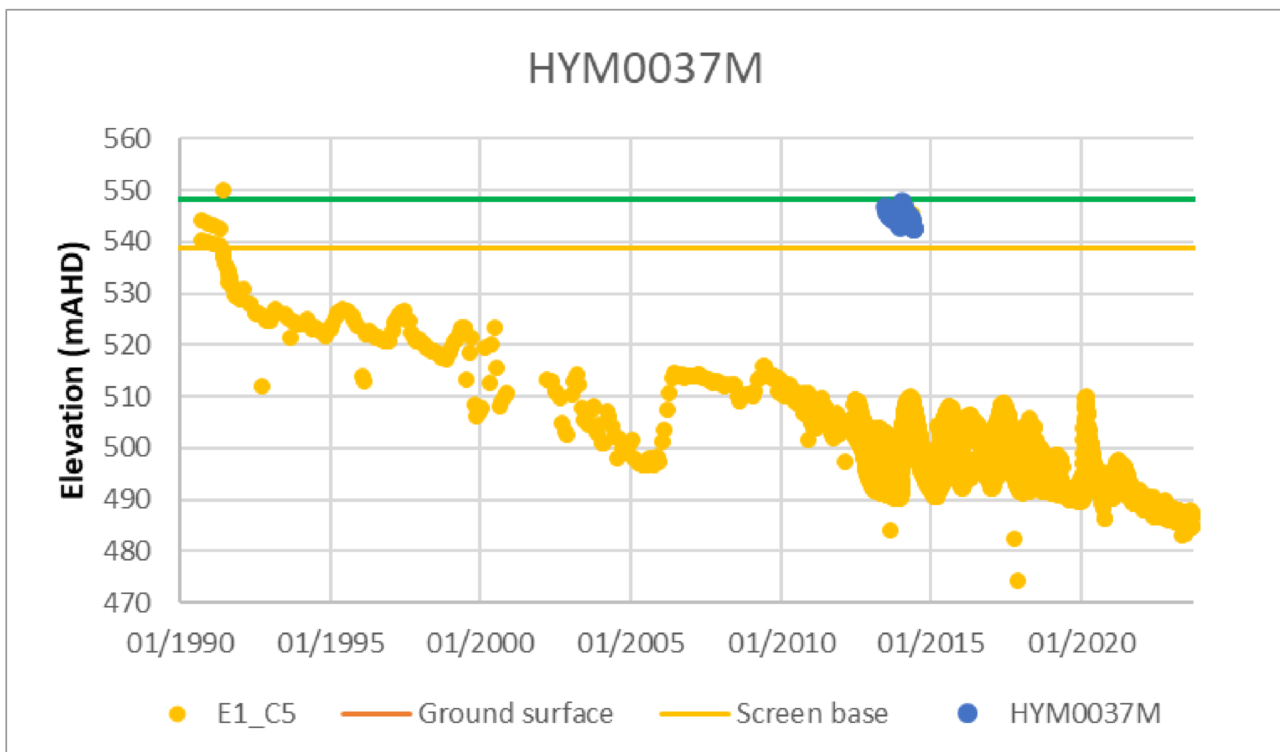
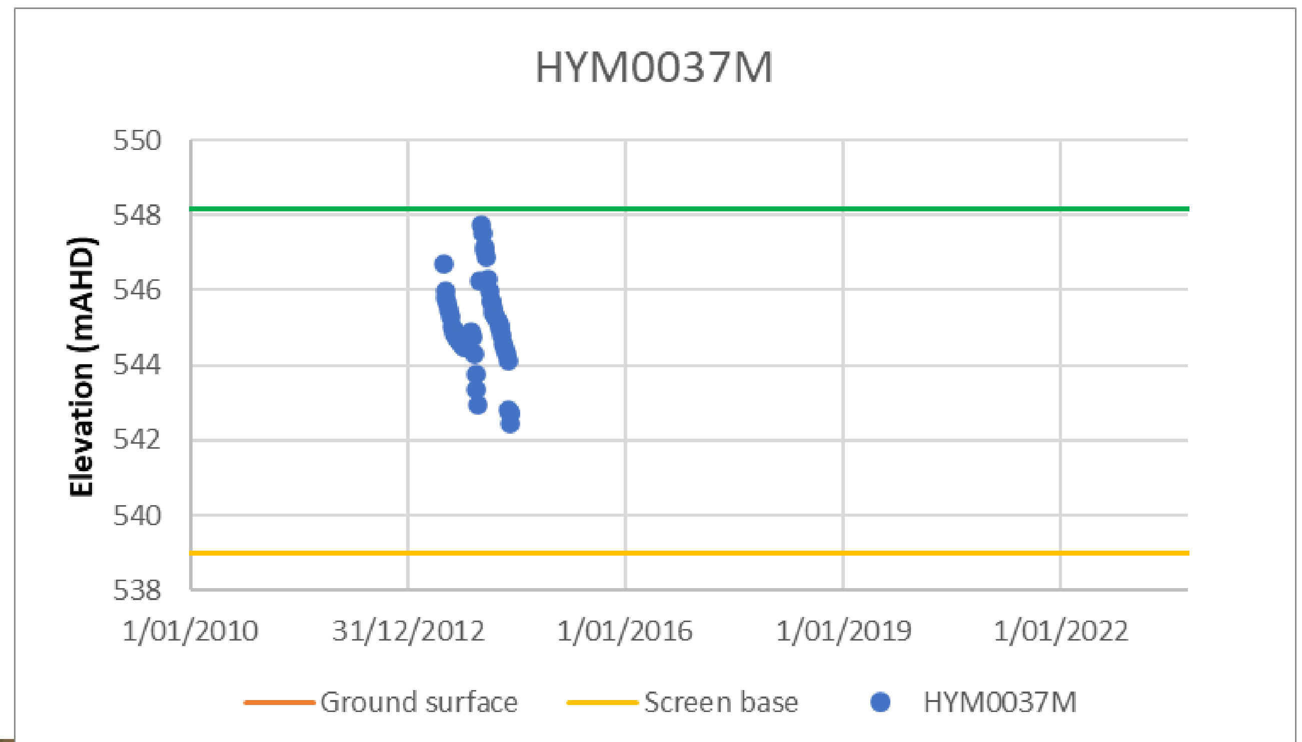


Figure 22
Alluvial groundwater levels – Central area (1)









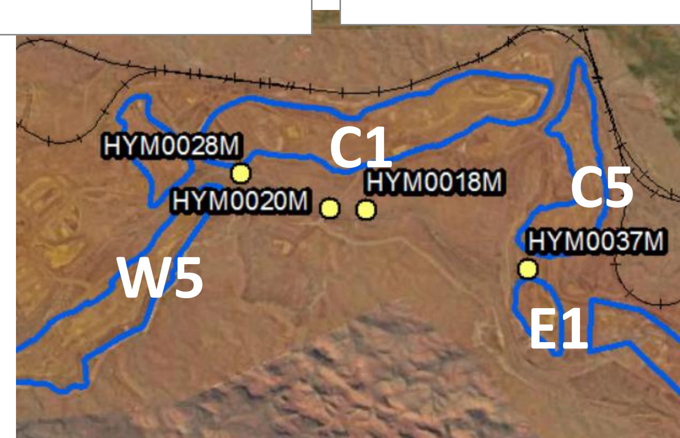


Figure 23
Alluvial groundwater levels – Central area (2)

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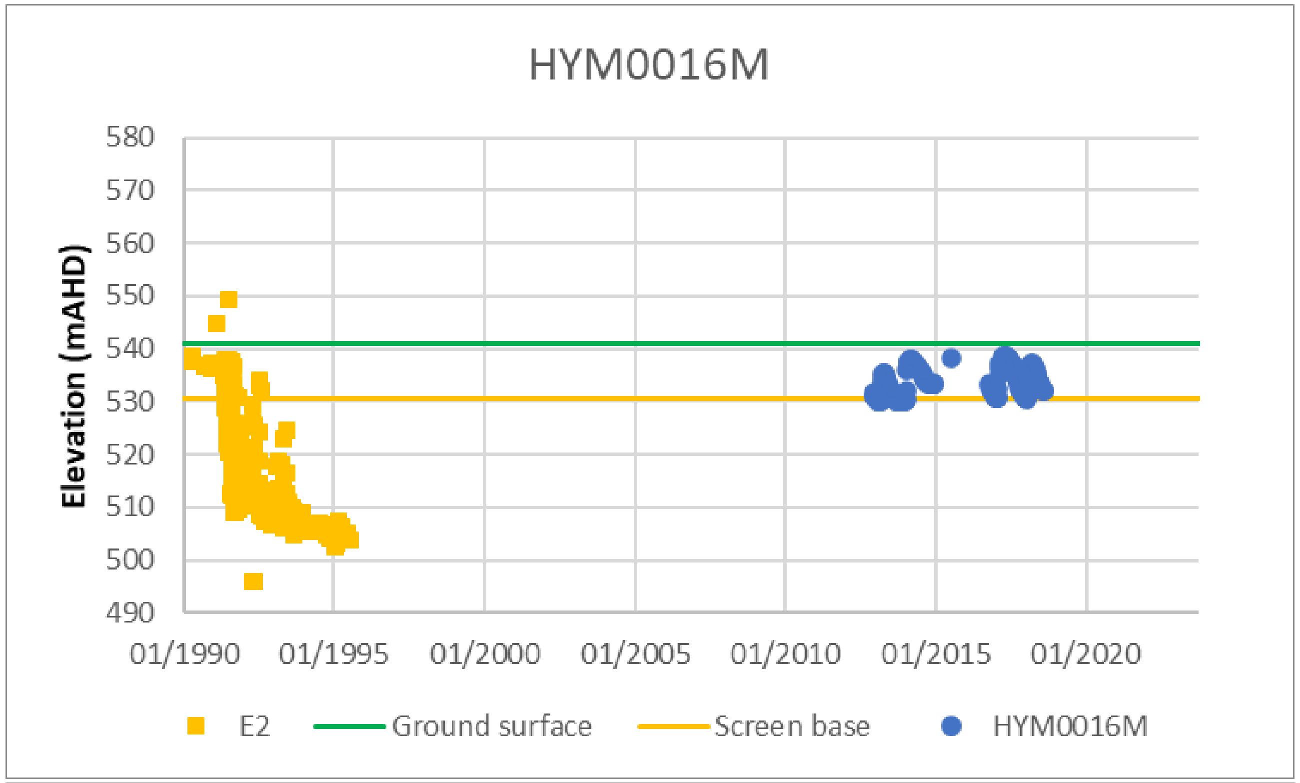
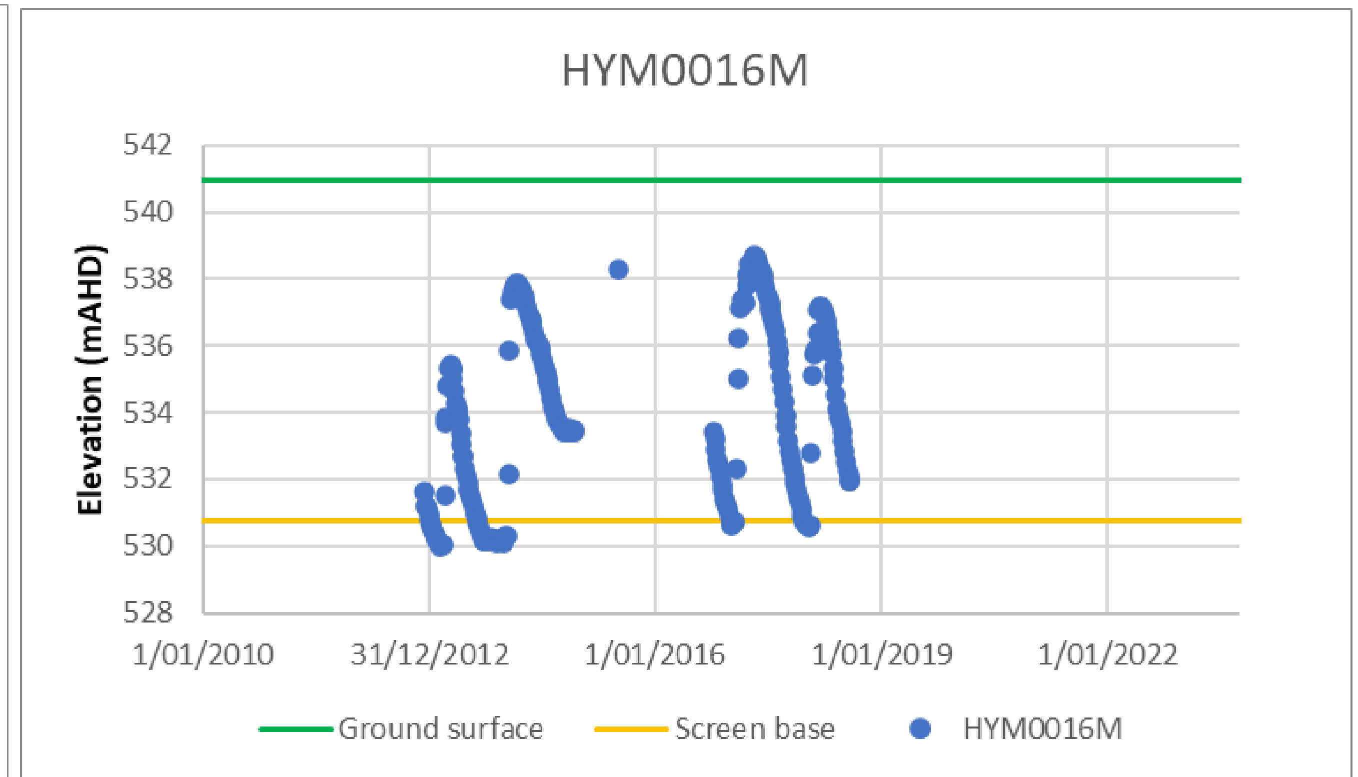
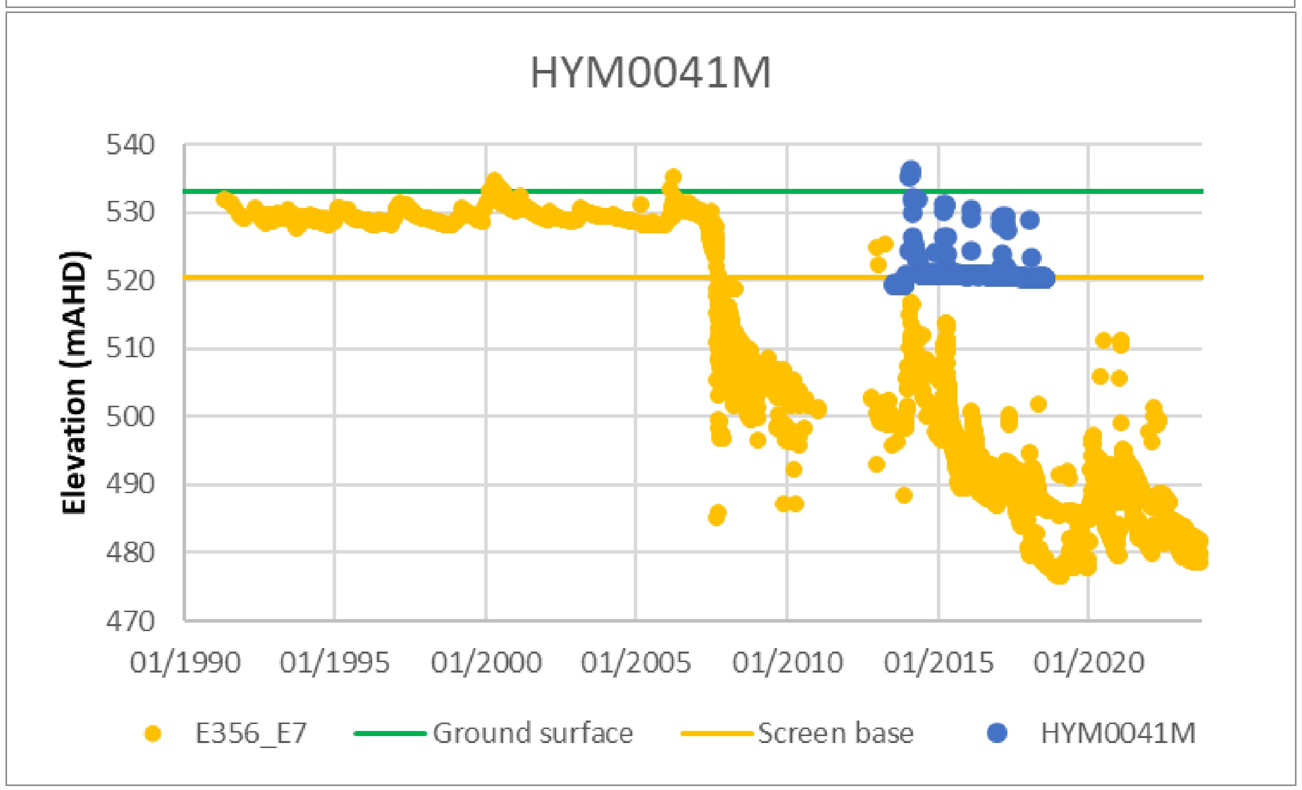






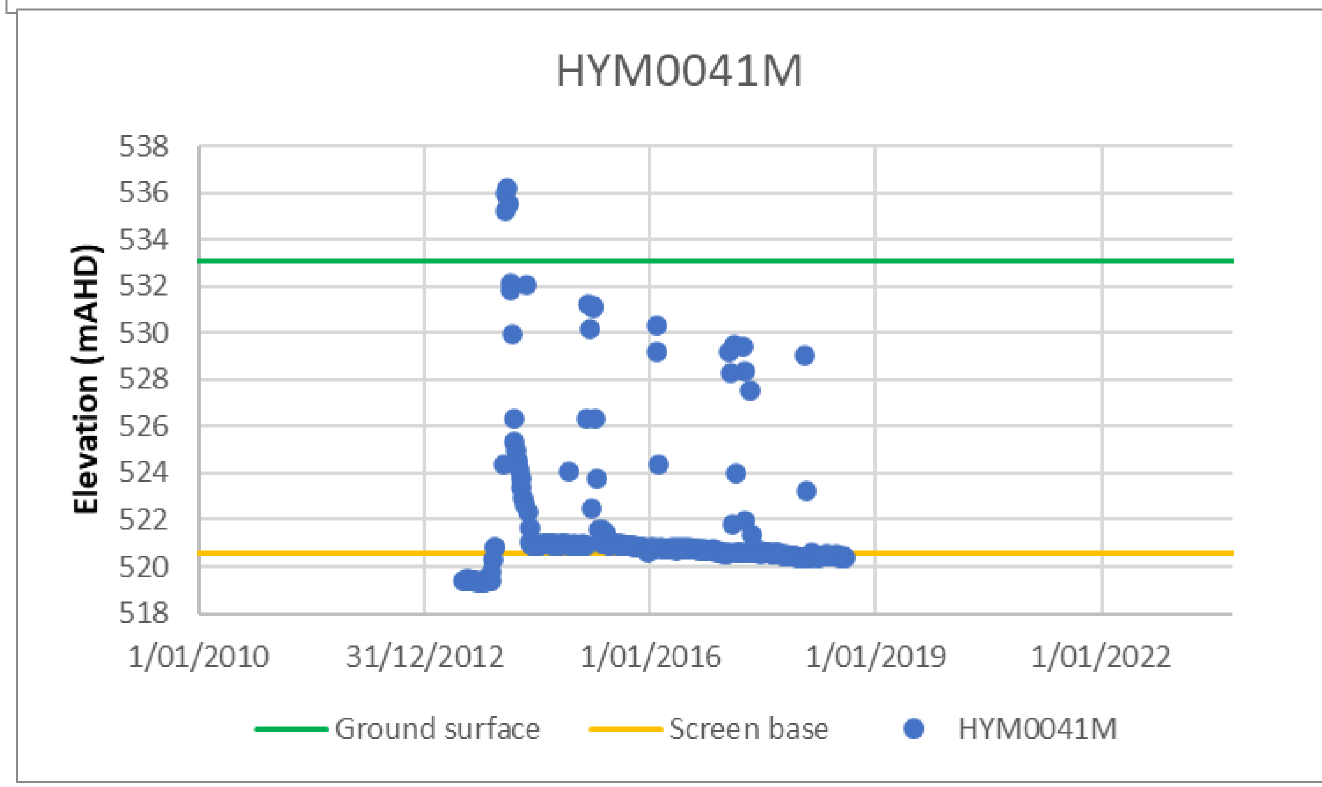
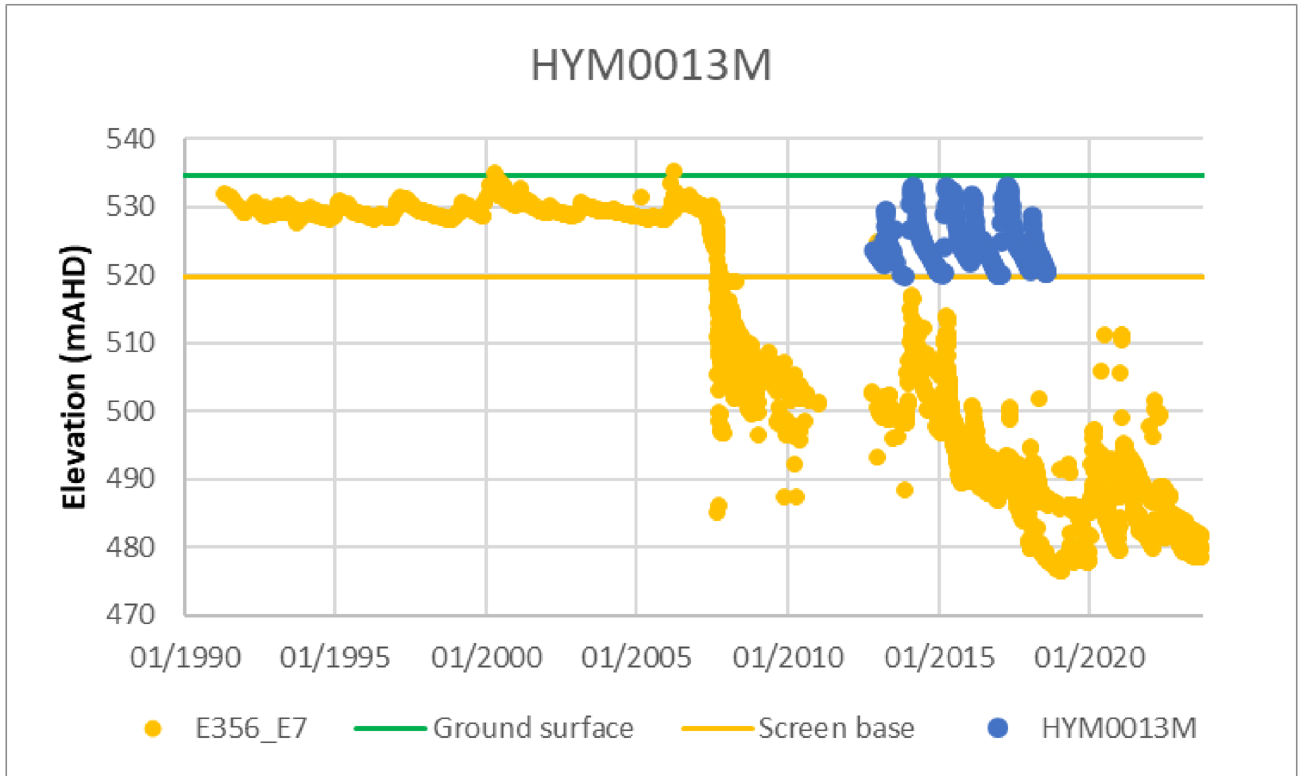
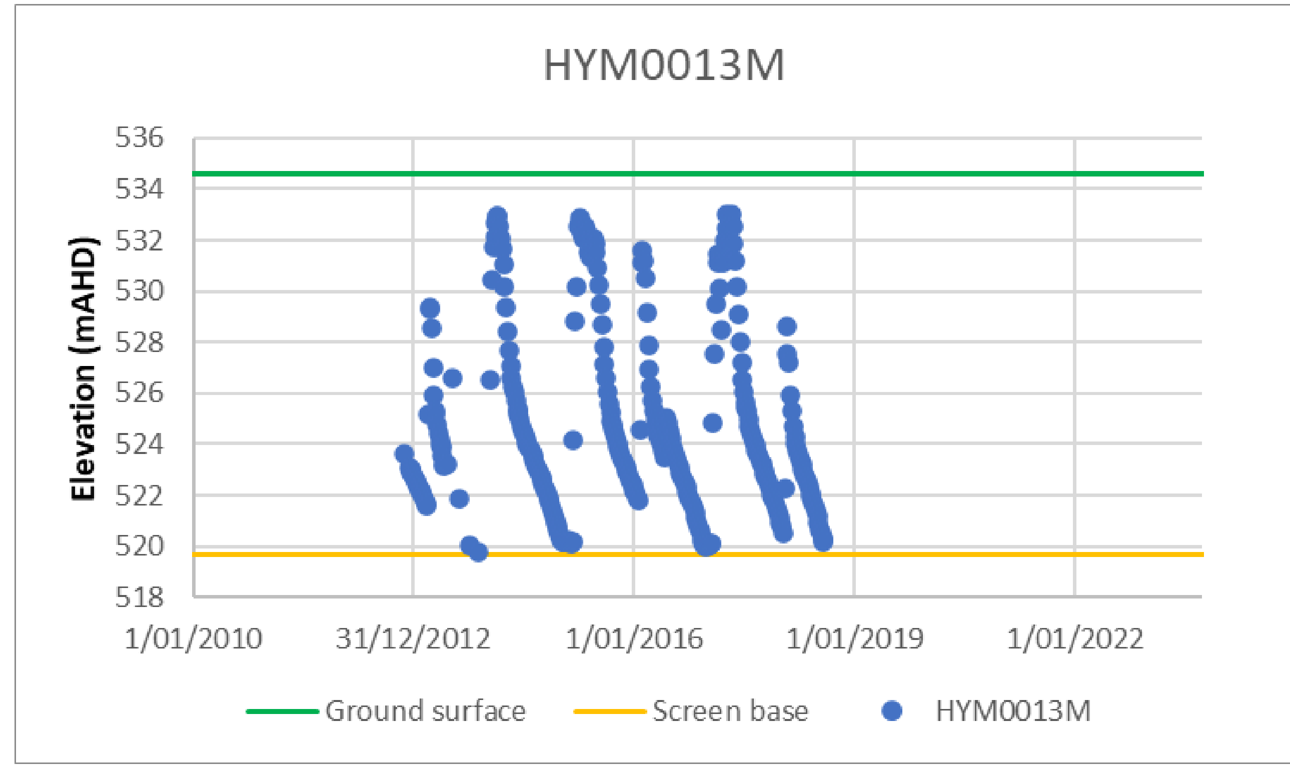
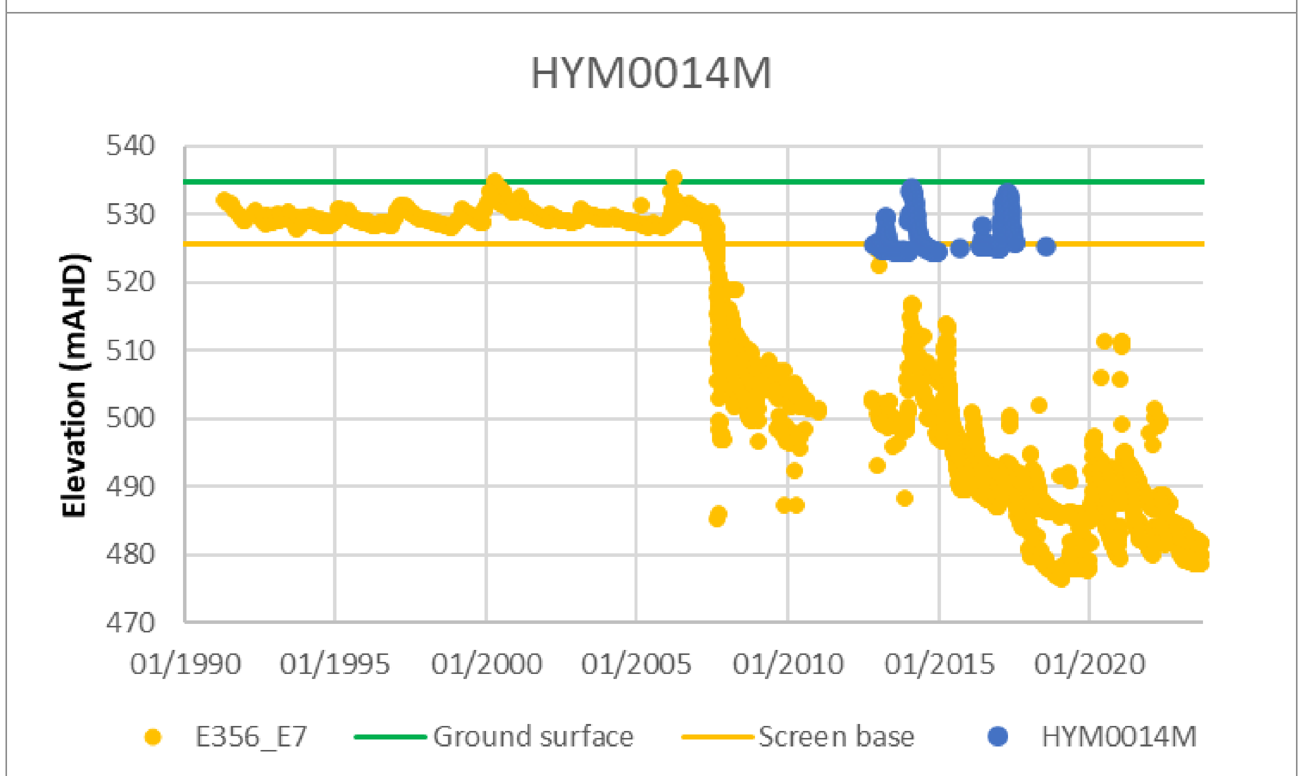
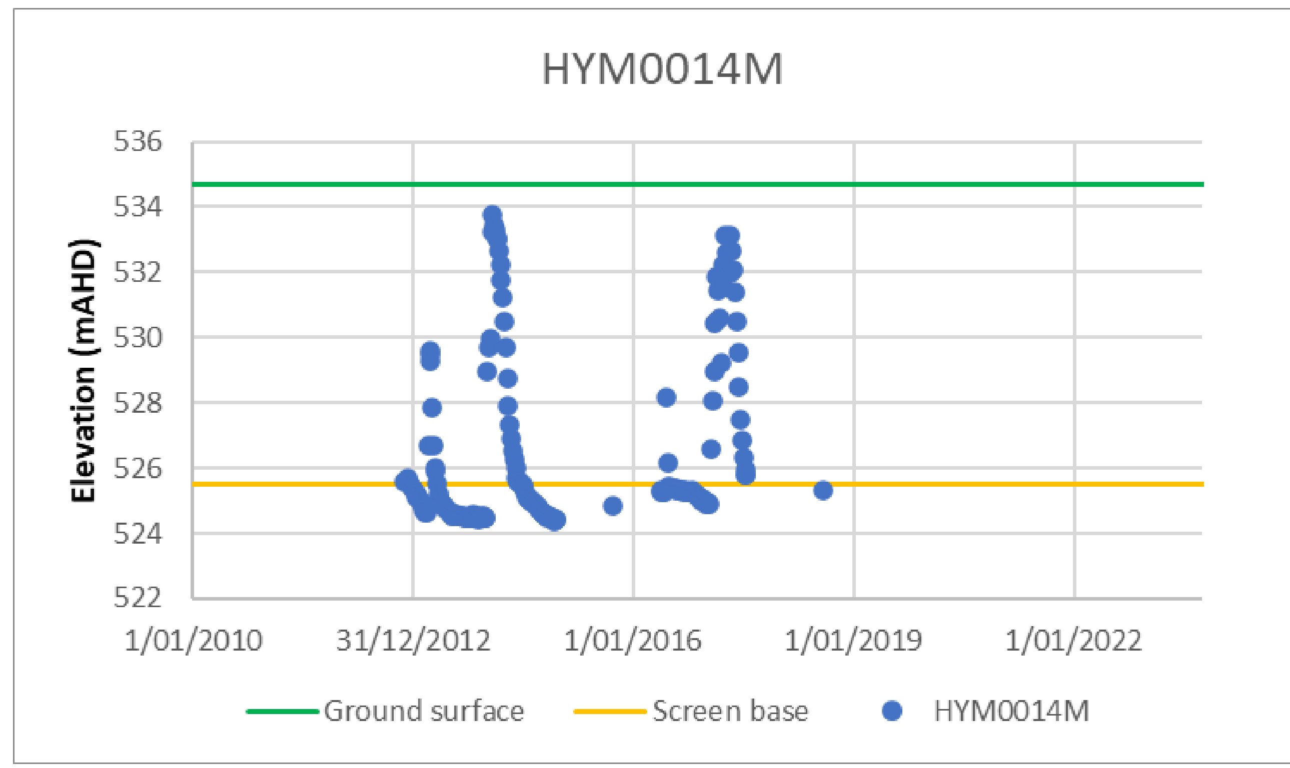


Figure 24
Alluvial groundwater levels – Eastern area (1)









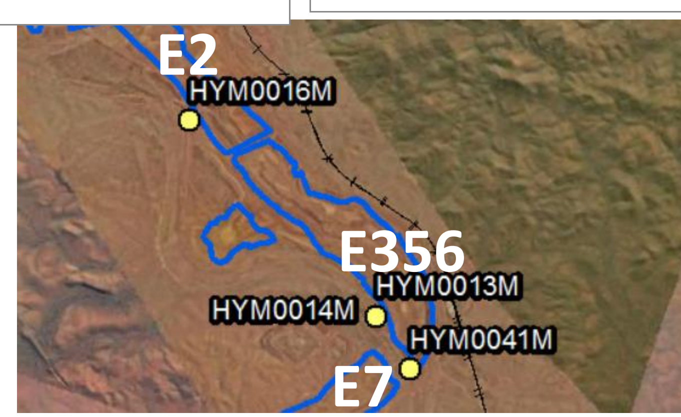


Figure 25
Alluvial groundwater levels – Eastern area (2)

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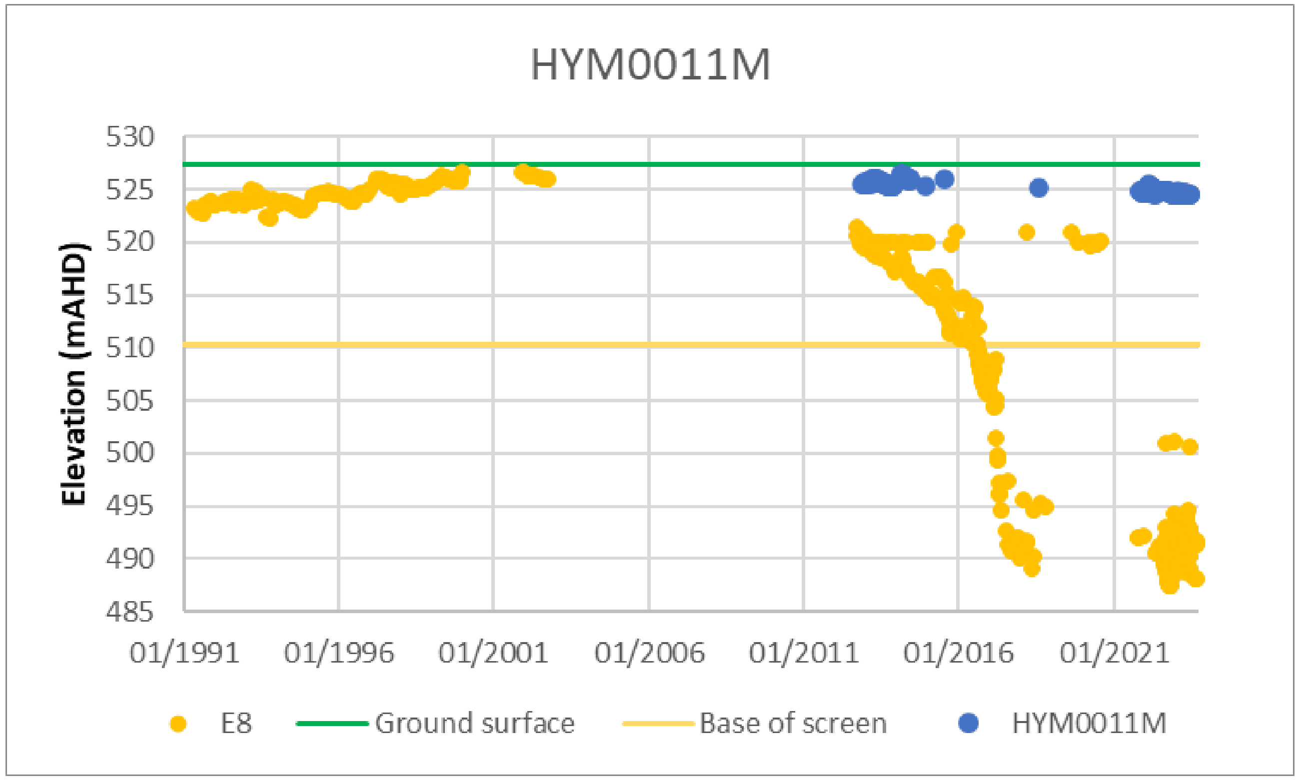


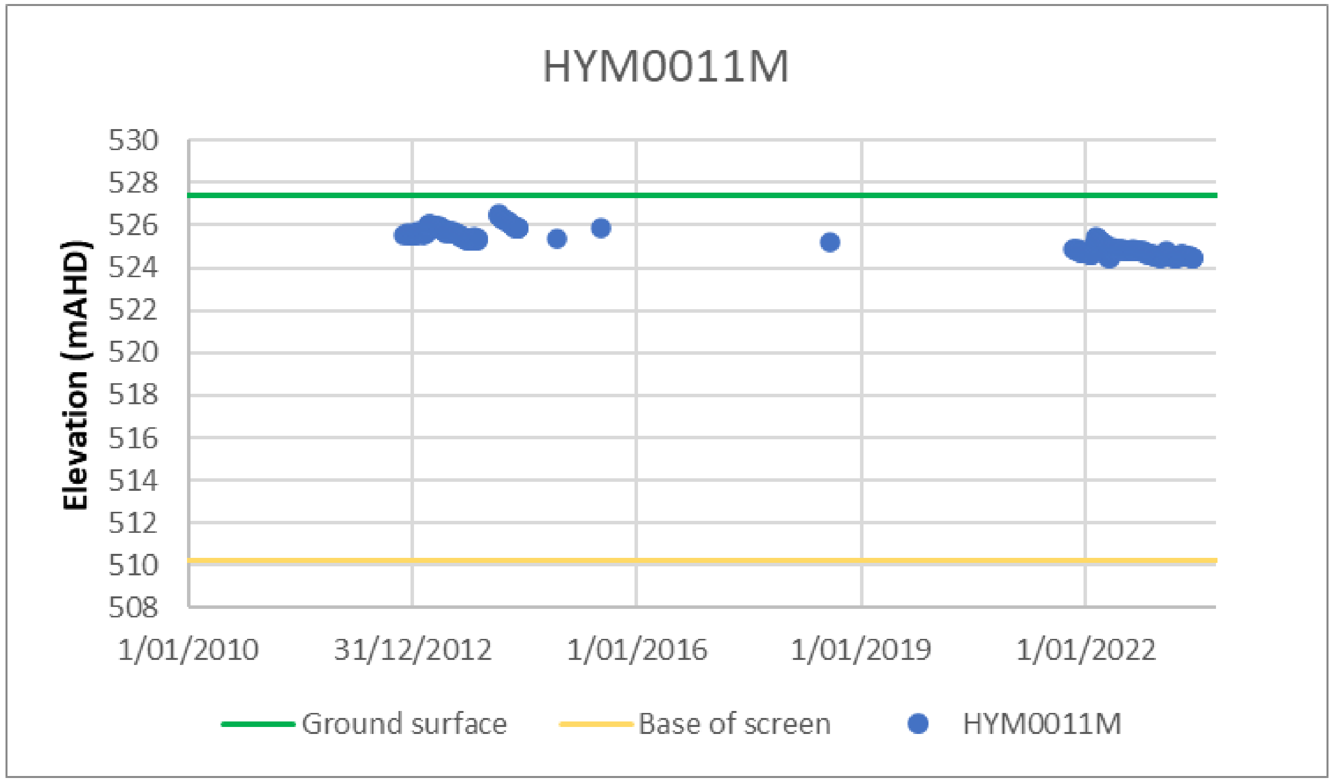


Figure 26
Alluvial groundwater levels – Eastern area (3)

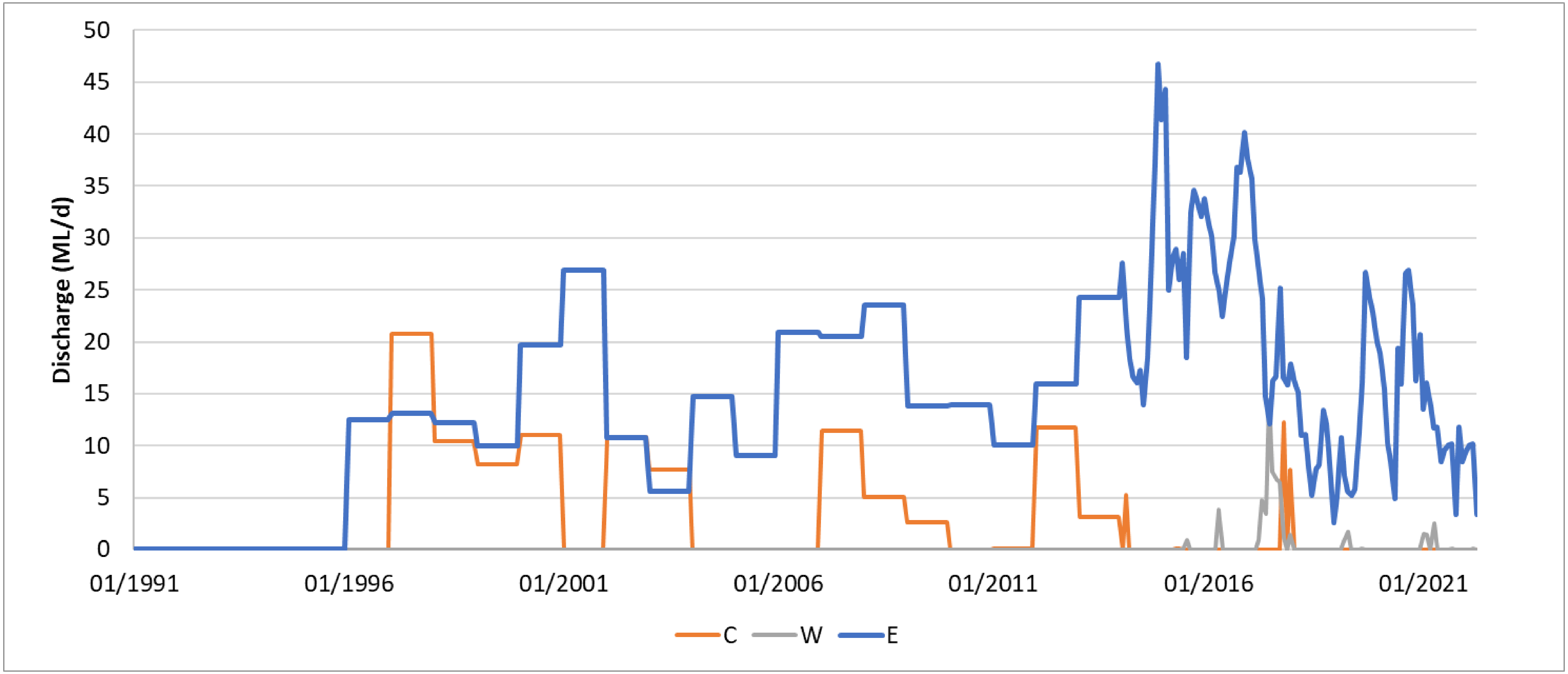


Figure 27
Surplus water discharge

BHP

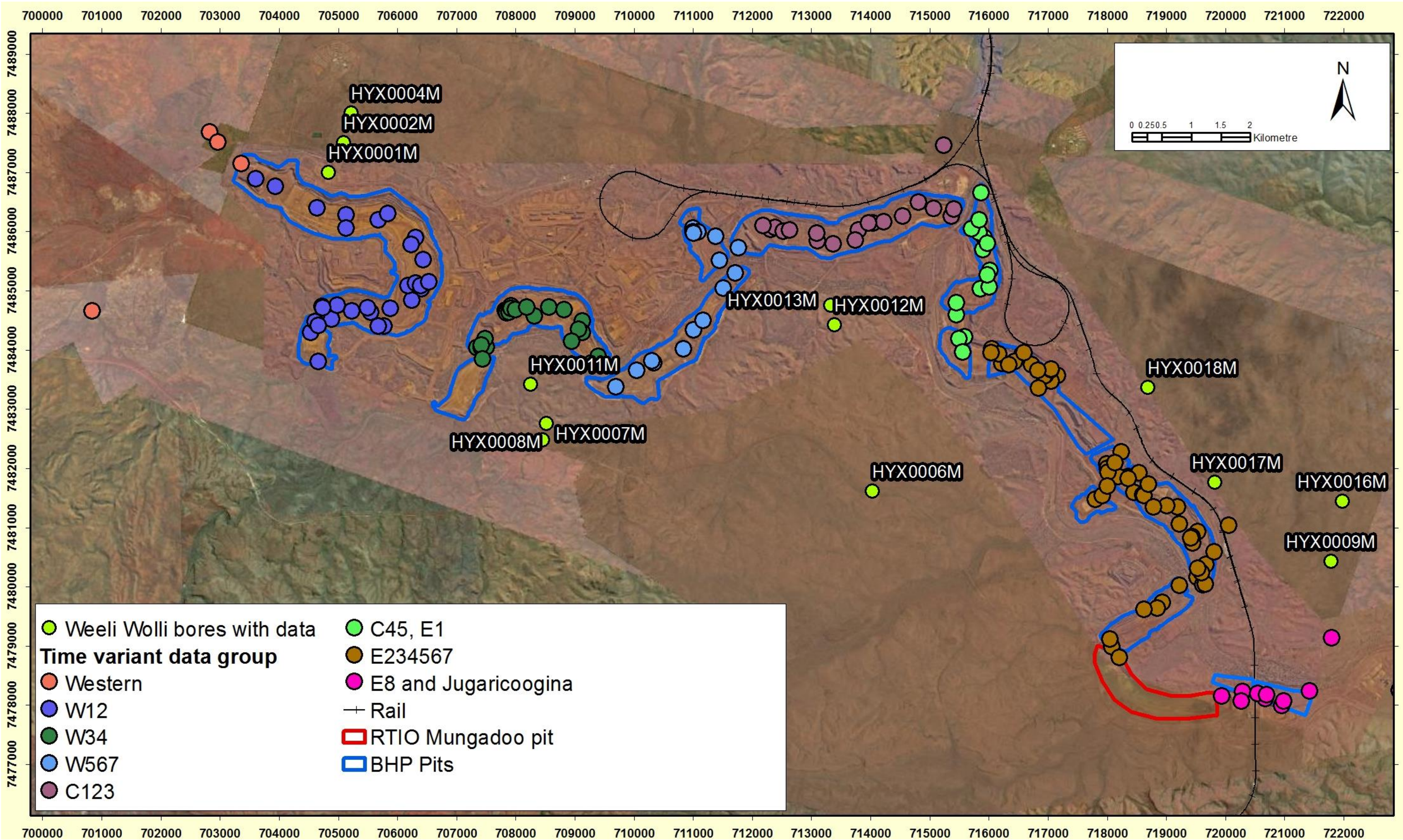
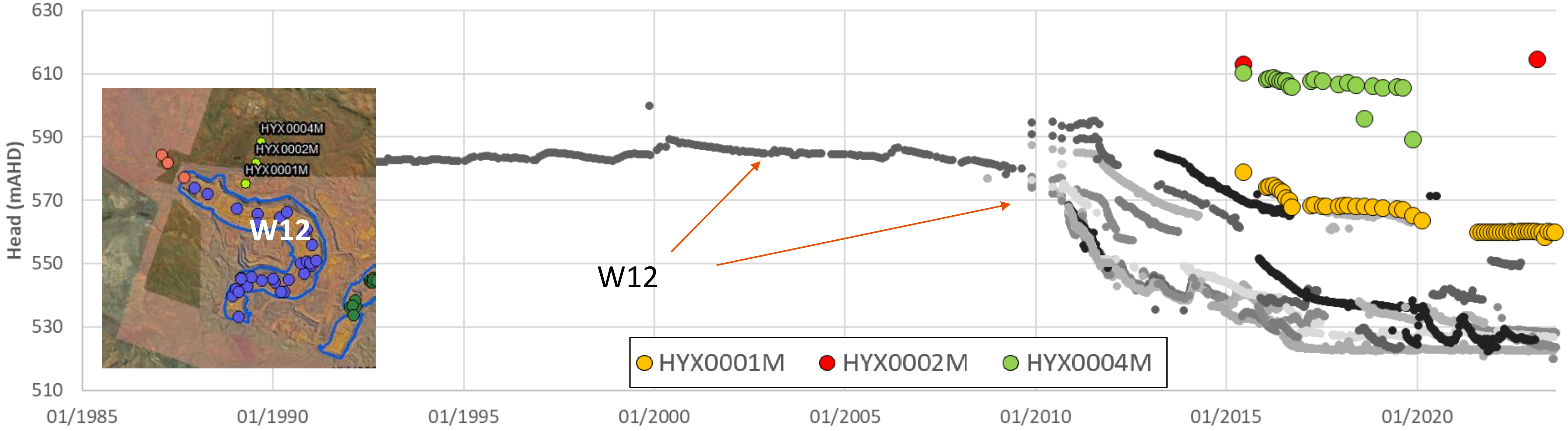


Figure 28
Weeli Wolli Formation
monitoring bores



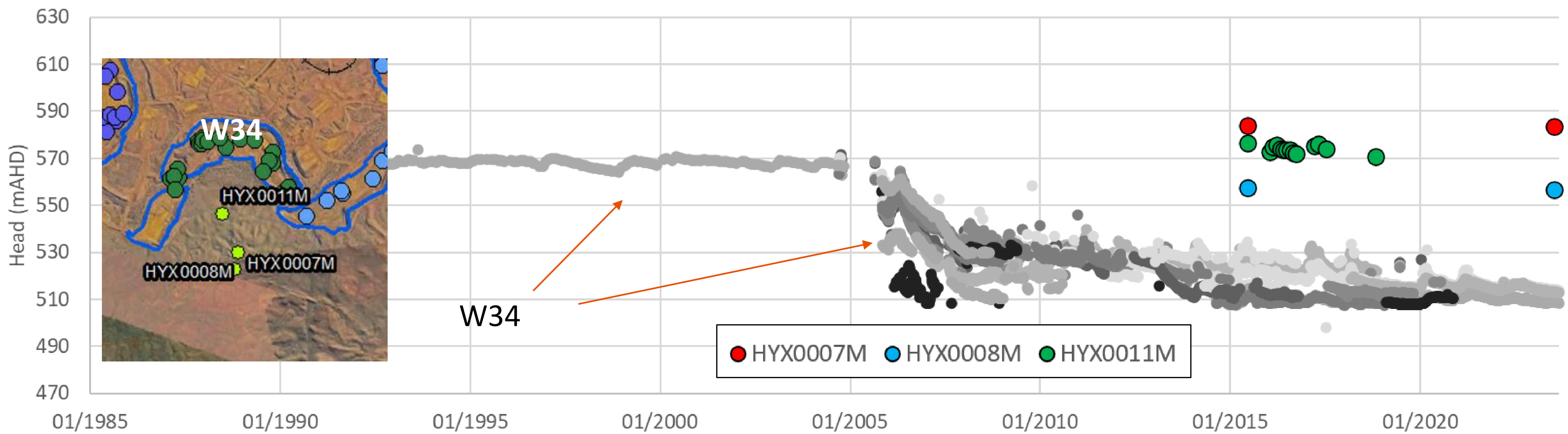


Figure 29
Weeli Wolli Monitoring data (1)

BHP

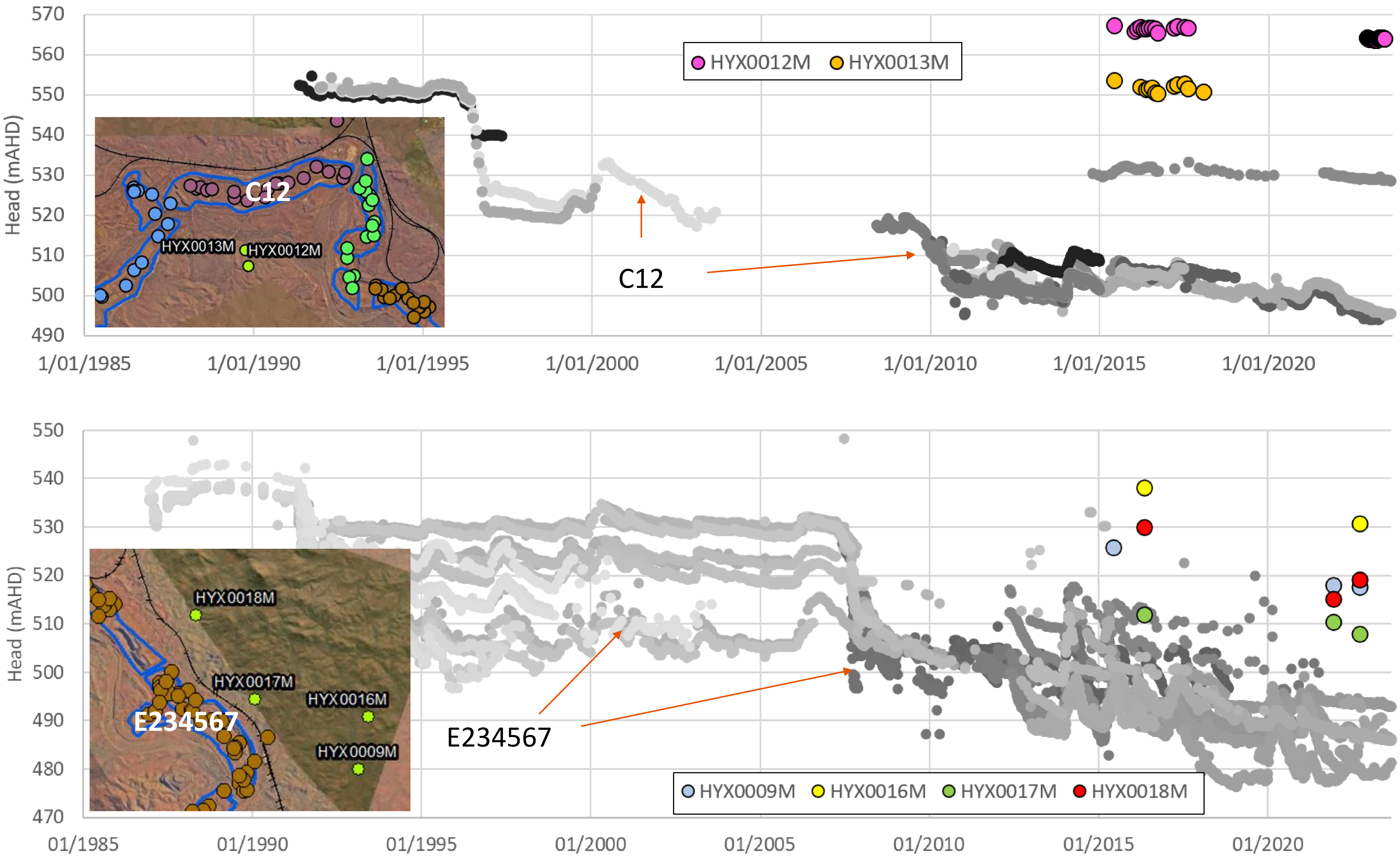
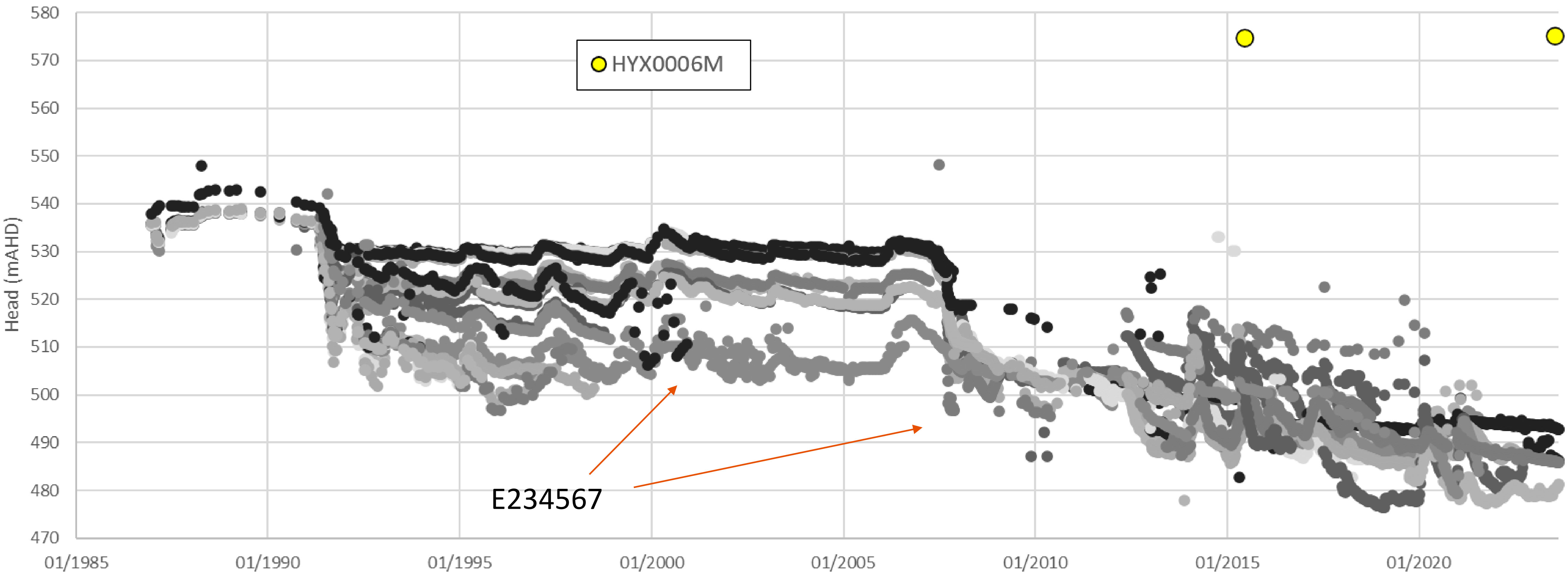


Figure 30
Weeli Wolli Monitoring data (2)



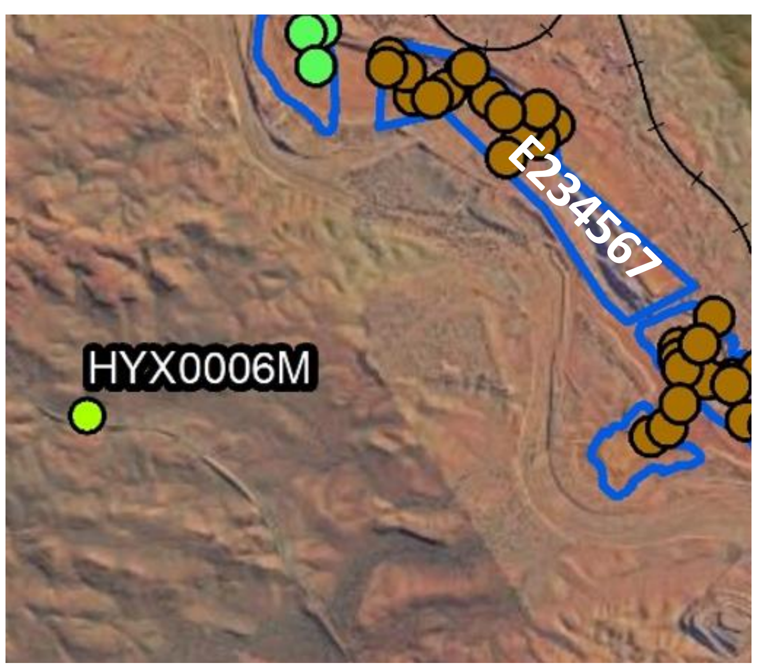
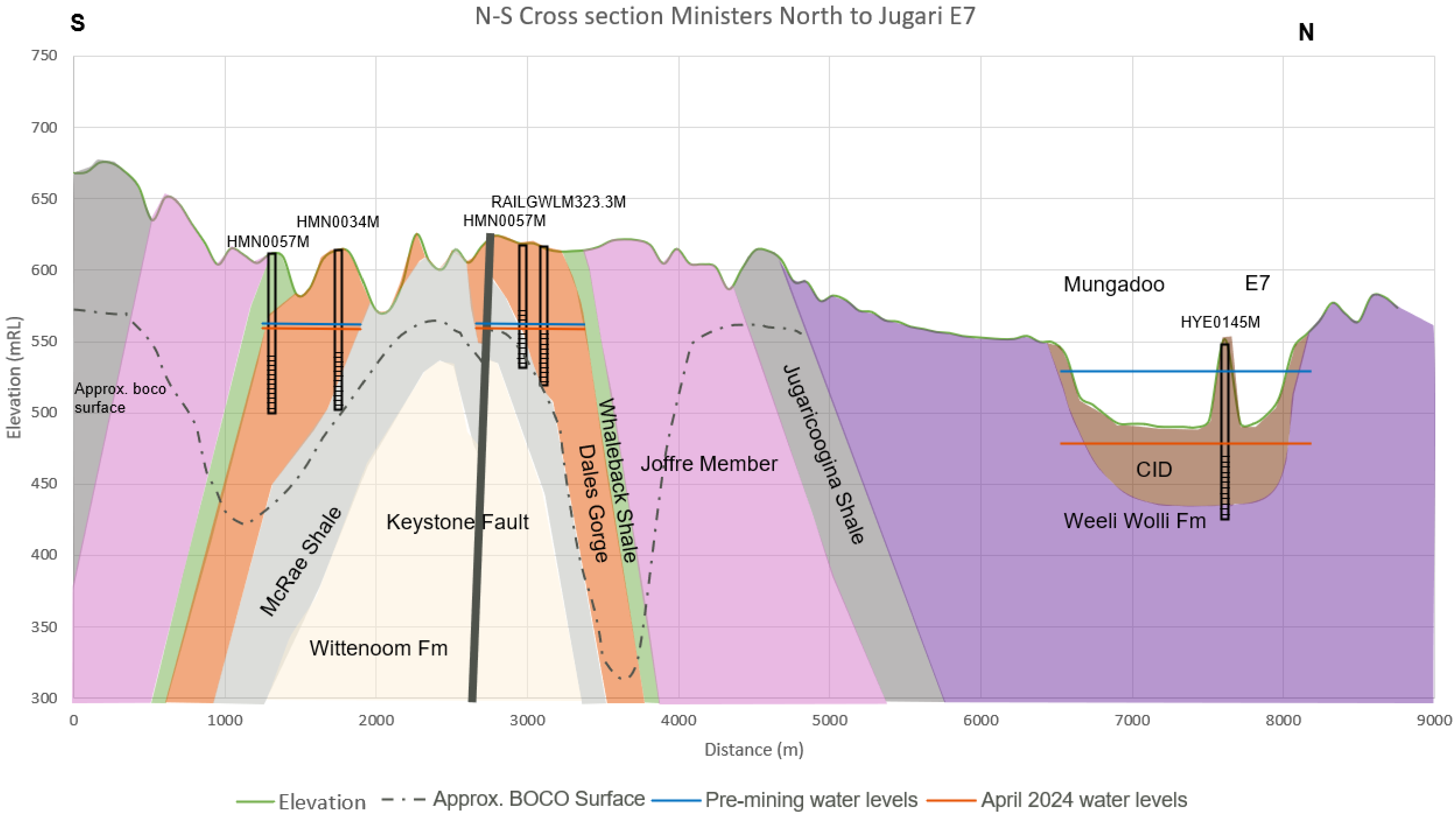


Figure 31
Weeli Wolli Monitoring data (3)



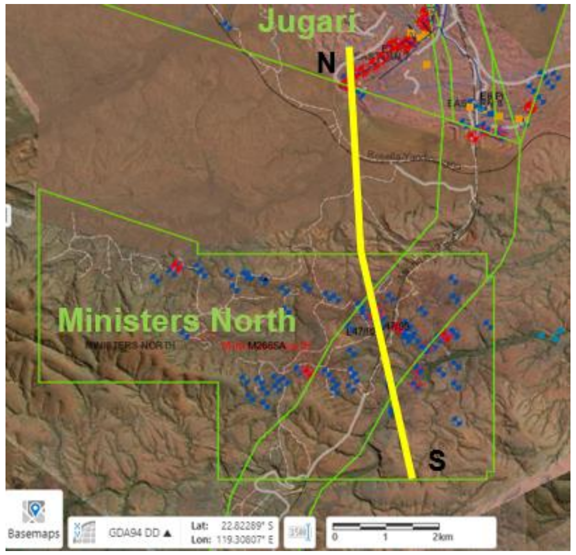
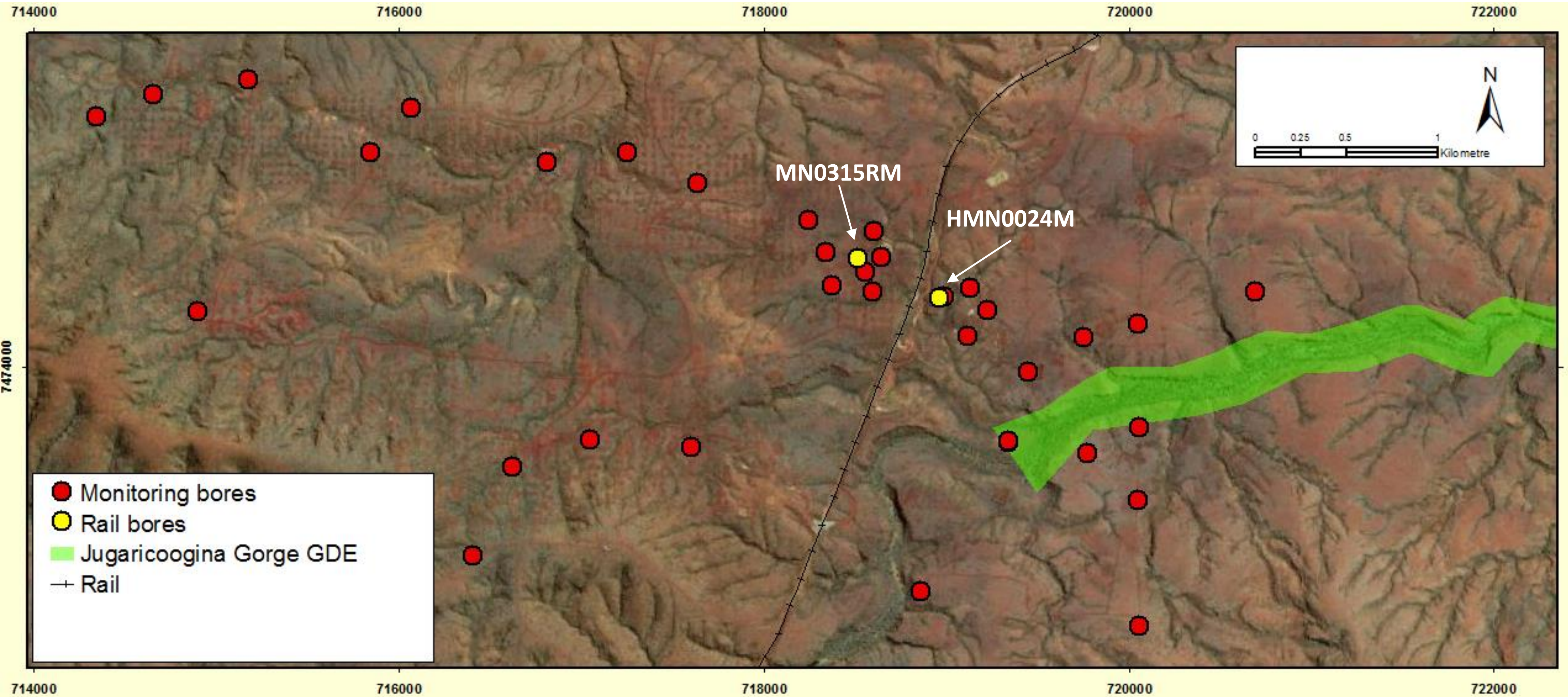


Figure 32
Ministers North / Jugari CID cross section

BHP



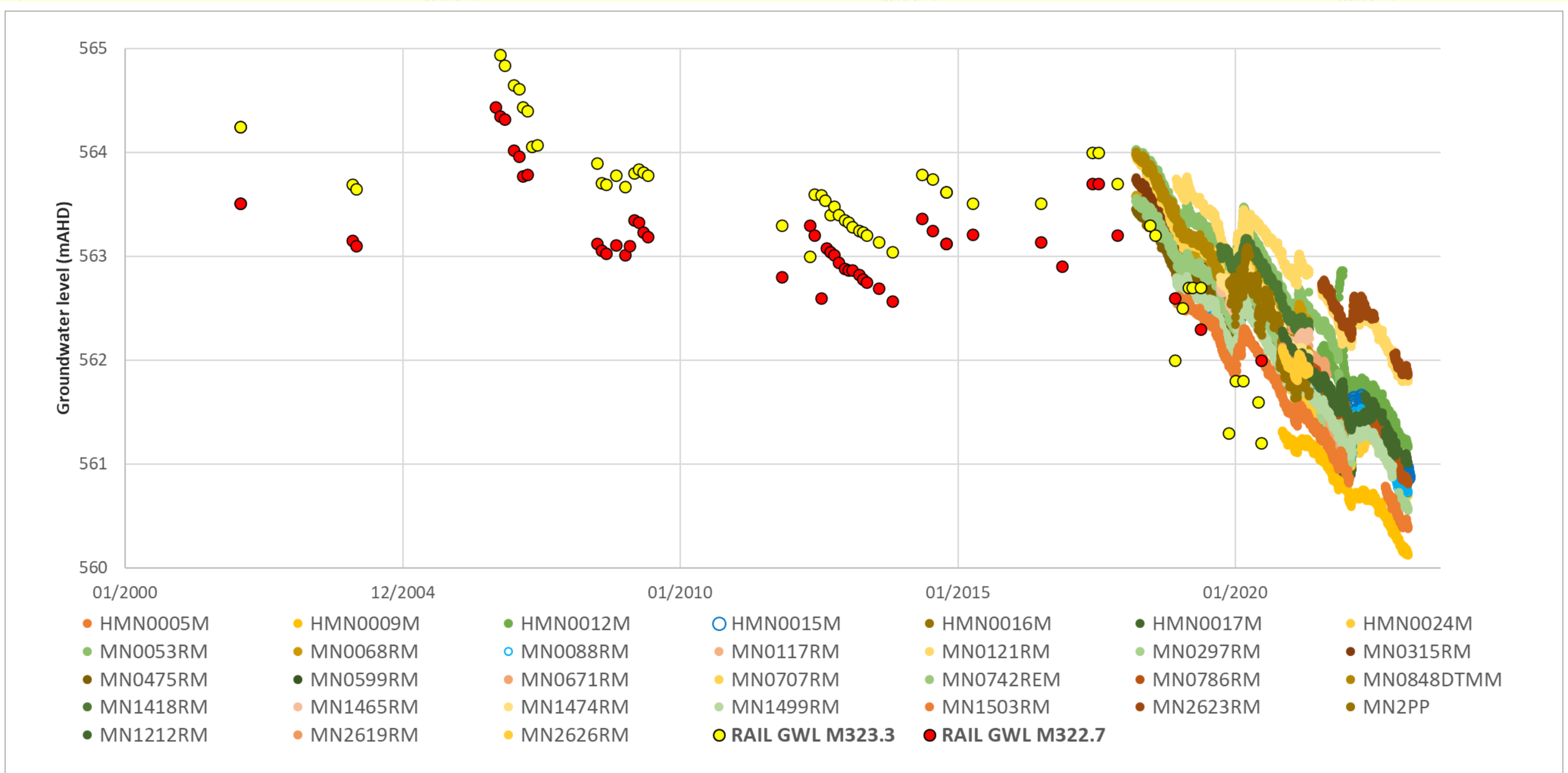


Figure 33
Ministers North aquifer groundwater levels

BHP

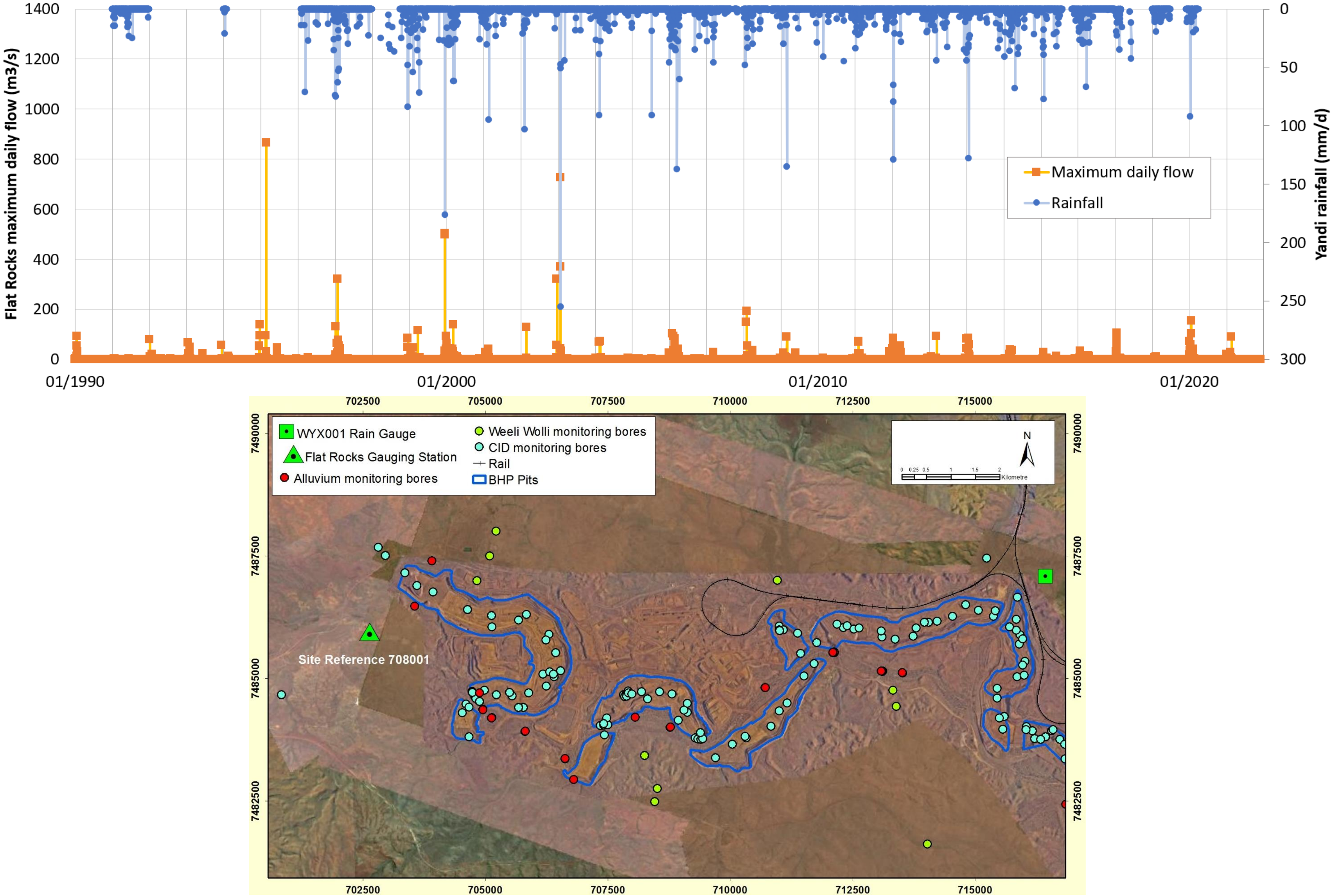


Figure 34
Surface water flows at Flat Rocks gauging station

BHP

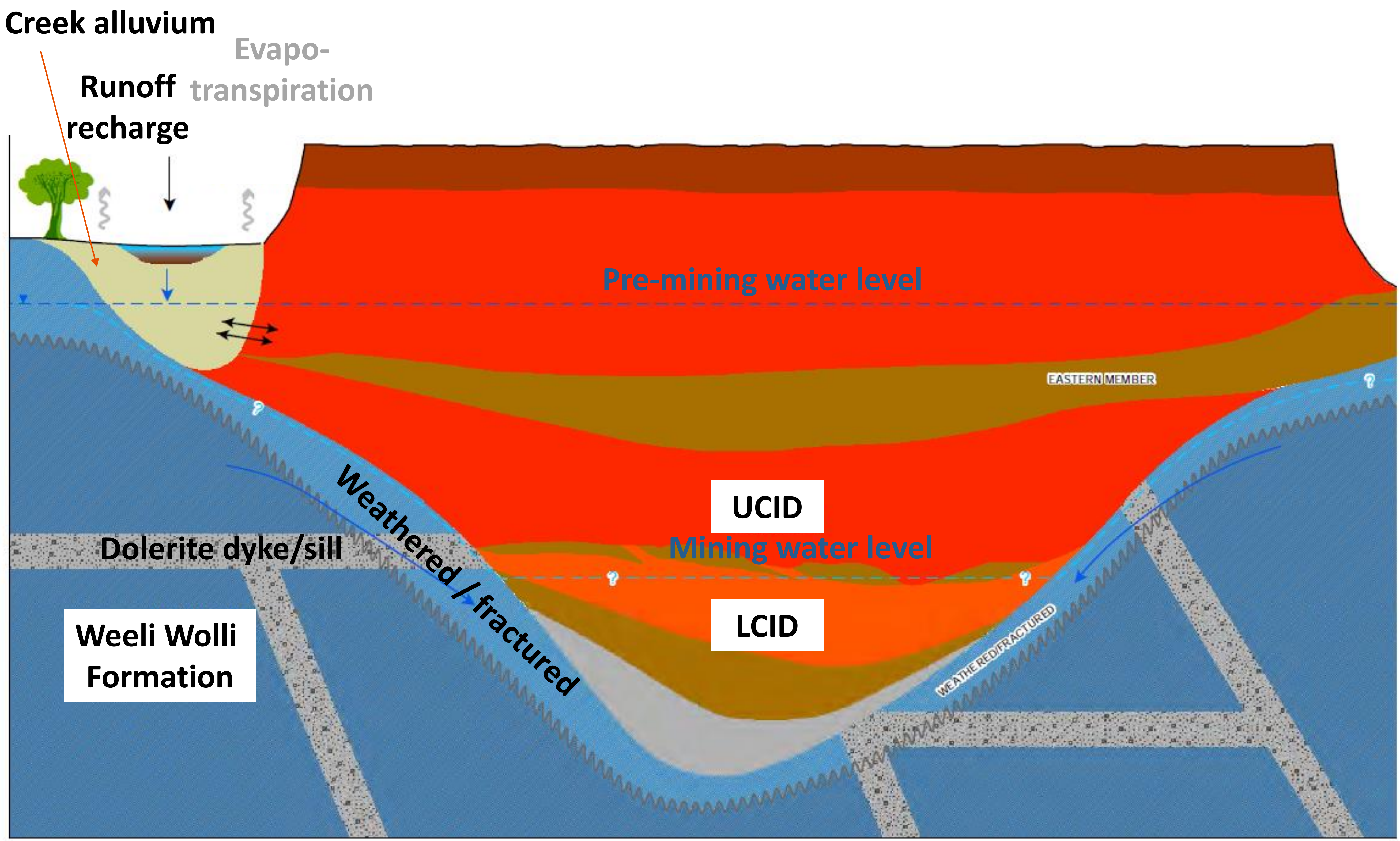


Figure 35
Jugari CID conceptual cross section (1)

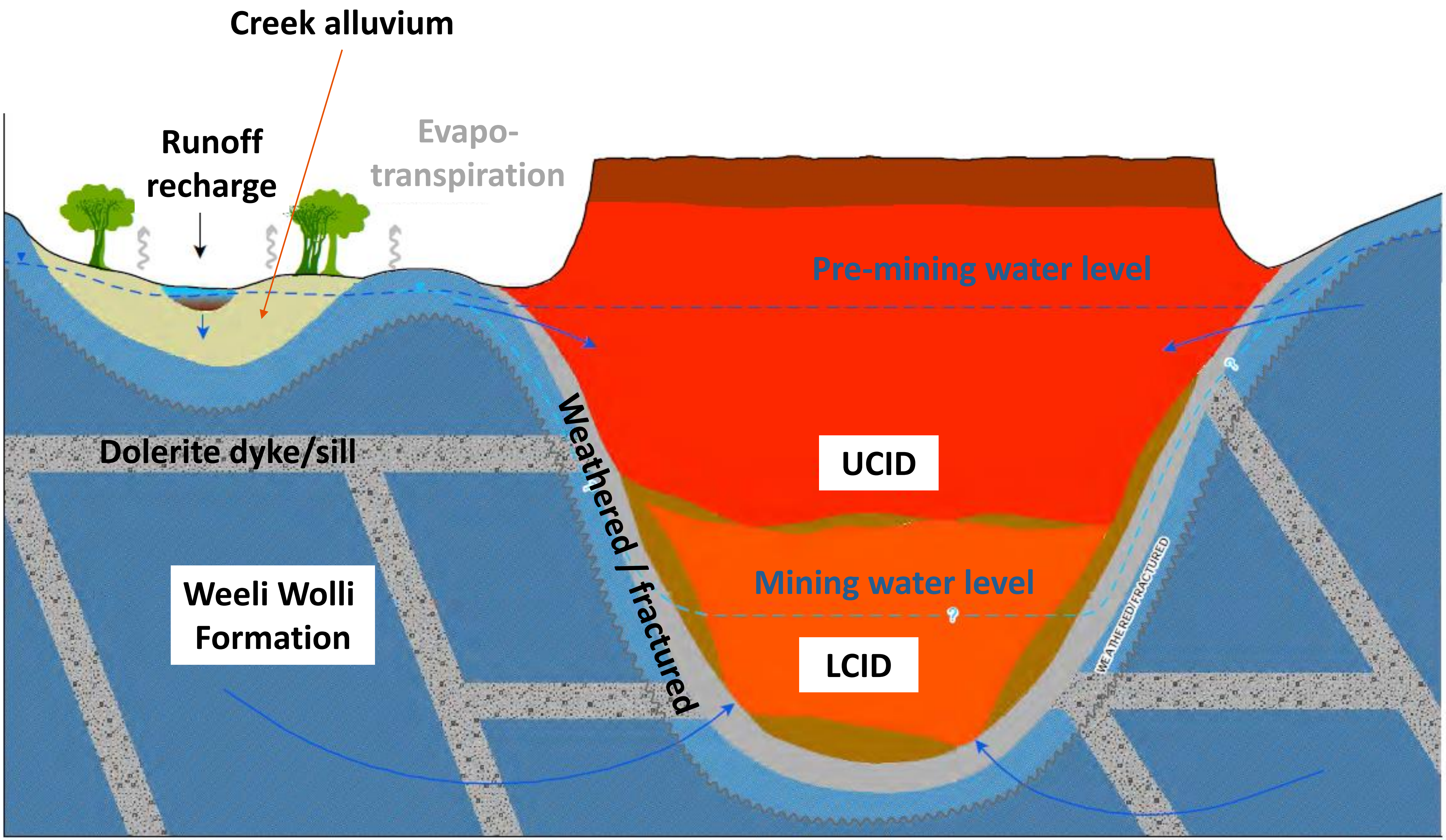


Figure 36
Jugari CID conceptual cross section (2)