Fortescue
The New Force in Iron Ore

Report

Surface Water Impact Assessment

Eliwana Mine Project

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	Surface Water Impact Assessment		
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1. INTRODUCTION

The Eliwana Mine Project ('the project') is located in the Pilbara region of Western Australia, approximately 120 km West South West of Fortescue's Solomon Mine and 100km West North West of the town of Tom Price, as shown in Figure 1. The project contains includes two deposits, Eliwana and Flying Fish, which span a distance of approximately 50km east to west, along a series of similarly oriented valleys, as shown by the indicative project footprint in Figure 2. The project includes a series of pits, stockpiles, waste rock landforms and topsoil storage areas that form the Eliwana and Flying Fish deposits. The proposed pits will be linked by conveyor and/or haul road alignments to process infrastructure, from which the ore is conveyed to a train load out onto the proposed Eliwana railway. The operation will be supported by non-process infrastructure including but not limited to roads, airstrip and camps.

This report outlines the current hydrological regime in a regional and local content, and presents modelling undertaken for present conditions and to quantify the impacts to surface water as a result of the proposed action for the project. The report is supported by the *Eliwana Mine Project Hydrology Study*, which details the development of the hydrologic and hydraulic modelling approach used in this impact assessment.

A proposed rail alignment linking the Eliwana project to FMG's Hamersley railway (the Eliwana Rail Project) is not part of this impact assessment.

2. CURRENT HYDROLOGICAL REGIME

2.1 Catchment Description

2.1.1 Regional Catchments

The project is located in the Hamersley Ranges within the Duck Creek catchment, a tributary of the Ashburton River. The Ashburton River basin has a total area of 78 777 km^2 and is shown in Figure 1. The Duck Creek catchment area is approximately 6800km^2 at the confluence with the Ashburton River.

Major tributaries of Duck Creek include Boolgeeda Creek, Caves Creek, with Barnett Creek and Wackilina Creek forming the upper section of Caves Creek. These catchments boundaries are presented in Figure 2 and areas are summarised in Table 1. The majority of the project disturbance (including the vast majority of mine pits and waste rock landforms) are located within the Boolgeeda Creek subcatchment. The remainder of disturbance, consisting of process and non-process infrastructure and a small number of mine pits and waste rock landforms, is located in the the Duck Creek catchment between the Caves Creek confluence and Boolgeeda Creek confluence. This distribution of the disturbance across the regional catchment areas is shown in Figure 2.

Table 1: Eliwana Surface Water Catchment Areas

Catchment Description	Area (sq. km)
Ashburton River Basin	78 777
Duck Creek (at confluence with Ashburton River)	6800
Duck Creek (upstream of Boolgeeda Creek confluence)[1]	3692
Boolgeeda Creek	1658
Duck Creek (upstream of Caves Creek confluence)[2]	578
Caves Creek	1535
Barnett Creek	520
Wackilina Creek	210

The Duck Creek catchment includes a variety of physiographic types. In the eastern parts of the catchment, the upper sections of Caves Creek include parts of the Weelamurra flats and other low relief terrain areas north of Tom Price, where banded vegetation types indicative of sheetflow

[1] This area excludes the Boolgeeda Creek catchment area

[2] This area excludes Caves Creek catchment area

and flat cracking clay grasslands are common. In the central Duck Creek catchment around the proposed mine areas, terrain becomes more undulating and channels more confined, with numerous gorges in the area. Pools are common along Duck Creek in this area, suggesting regular outcropping of bedrock. The confluence of Duck Creek and Ashburton River is beyond the western extent of Hammersley range where low relief terrain dominates.

2.1.2 Project Catchments

The project disturbance is focussed along the catchment divide between Duck Creek and Boolgeeda Creek, as shown in Figure 3 Mineralisation occurs within two parallel ridges near the catchment divide, with an east-west line of strike orientation and that runs approximately 70km measured from Duck Creek to Mt Brockman. The main valley segments that form between these two ridges, (referred to as the strike valley), drain either east to west or west to east, with varying channel morphology types controlled either by the valley grade, the width between the two ridges or localised instances of bedrock outcropping.

The strike valley catchments typically traverse the southern ridge and drain southwards to Boolgeeda Creek. This includes Pinarra Creek, a named tributary of Boolgeeda Creek and several other catchments informally named as Strike East, Flying Fish 1 and Flying Fish 2. The exception is the western extent of the Eliwana deposit where the strike valley (part of the informally named West Creek catchment) drains directly to Duck Creek upstream of the Boolgeeda confluence. The project subcatchments are shown in Figure 3 and catchment areas are summarised in Table 2, in accordance with their receiving subcatchment.

Many gorges are present throughout the project area and are associated with the strike valley. This includes instances where the northern and southern parallel ridges move close together (as seen in West Creek and Pinarra Creek) and where drainage lines cross either or both of the parallel ridges.

Table 2: Eliwana Sub-Catchment Areas – Total Area to Downstream Project Boundary

Sub-Catchment	Area (sq. km)	Area (Ha)
Duck Creek Sub-Catchments		
West Creek	68.9	6885
Combined Infrastructure Areas	39.8	3981
Boolgeeda Subcatchments		
Pinarra Creek	60.3	6033
Strike East	45.7	4569
Flying Fish 1	60.1	6013
Flying Fish 2	60.0	5998

A more detailed description of each of the project subcatchment areas is provided below.

West Creek

The western most section of the project area including 15km of the strike valley is referred to (informally) as the West Creek catchment (refer Figure 4). The catchment is typically steep and undulating throughout with deeply dissected drainage and hydraulic controls imposed by the parallel ridges and other topographic features. The main branch of West Creek flows 15km before crossing through the northern parallel ridge where a gorge has formed. The creek flows 2km along the strike valley before entering another gorge where the two parallel ridges have moved closer together. This gorge runs for 2km, is up to 70 metres deep with a typical channel width of 25 metres. West Creek runs a further 7.5km before discharging to Duck Creek.

Pinarra Creek

Pinarra Creek, shown in Figure 5, runs east to west through a 19km section of the strike valley. The catchment contains the majority of the Eliwana deposit. From an indistinct divide with the Strike East catchment, the valley initially has a wide base with steep slopes associated with the parallel ridges. The channel gains definition as catchment size increases, with alluvial fans and colluvium from the parallel ridges reducing the valley floor width further enhancing channelization.

The watercourse runs 16km east to west before reaching a gorge (informally named Broadway Gorge), where the northern and southern parallel ridges move closer together. At this point, the creek is less than 15m wide with the depth of gorge approximately 50 metres. Upstream of Broadway Gorge, there are a several other gorges (albeit shorter in length and height) present where minor tributaries of Pinarra Creek enter the strike valley through the northern parallel ridge.

Downstream of Broadway gorge, Pinarra creek turns to the south, exiting the strike valley via a second gorge cutting through the southern parallel ridge. The creek runs for to the south, for 20km before discharging into Boolgeeda Creek. There are two significant tributaries draining into the main reach approximately 5km and 7km downstream of the project disturbance limit, along this south drainage part of the reach.

Strike East Creek

Strike East Creek mirrors Pinarra Creek, but flows west to east, through the eastern half of the Eliwanna deposit (refer Figure 6). Like Pinarra Creek, the strike valley initially has a wide base with steep slopes with the channel gaining definition downstream. The creek flows west to east along a 13km section of the strike valley before turning south through the southern parallel ridge and travelling a further 8km before discharging into Boolgeeda Creek. Unlike Pinarra Creek, no gorges are present as Strike East Creek flows through the strike valley or the southern parallel ridge, with channels always associated with adjacent floodplains through these reaches.

Flying Fish 1

Flying Fish 1 is split by the northern parallel ridge, with two thirds draining hilly terrain to the north and one third associated with the strike valley (refer Figure 6). The main branch of Flying Fish 1 creek runs for 13km before forming a large gorge where it crosses through the northern parallel ridge. Runoff from the strike valley tributary flows through the proposed project area for 8km before discharging into the main branch of Flying Fish 1 immediately downstream of the gorge. The creek runs a further 5km before flowing into Strike East Creek which travels a further 3km to discharge into Boolgeeda Creek.

Flying Fish 2

Within the Flying Fish 2 catchment, the parallel ridges are aligned south-west to north-east. (refer Figure 7). Two thirds of the catchment drains to the strike valley, where the main branch of Flying Fish 2 flows for 9km before discharging to the south through the southern parallel ridge. Rio Tinto's Brockman 4 railway runs parallel to and on the south side of Flying Fish 2 creek. A minor tributary drains a third of the catchment north of the northern parallel ridge. This watercourse crosses the ridge immediately upstream of the catchment boundary shown on Figure 7.

Other Catchments

A series of small catchments that drain northwards to Duck Creek are where several process and non-process infrastructure installations are proposed. This includes the rail loop (this is part of the Eliwana Rail Project) and an operations camp. These catchments are typically steep and undulating throughout with deeply dissected drainage lines. Some of these northern draining creek lines have pools observable where there is bedrock outcropping. These catchments are shown collectively on Figure 8.

2.2 Stream Flows and Catchment Response

Pilbara creeks are typically ephemeral, and with the exception of pools and groundwater fed springs, are dry for the majority of the year. Pilbara soils typically have high initial infiltration rates for dry catchment conditions, i.e. when the antecedent moisture content of the soils is low. Significant streamflow usually occurs when antecedent moisture content of the soils is high, which is caused by significant rainfall in the days or weeks preceding a storm event. There are typically two different types of climatic events which cause flood response in the Pilbara, namely: Cyclonic activity/Tropical Low Pressure Systems and localised diurnal thunderstorms.

Cyclonic activity can result in severe and widespread flooding generally on a river catchment scale; this flooding activity can be forecast in advance (albeit with significant uncertainty). This type of flooding typically produces large peak flows and may result in damage to infrastructure due to magnitude of flows and total volume of water. However, not all cyclones will result in severe flooding.

Isolated thunderstorms have the potential to create fast and localised flooding, referred to as flash flooding. These events are much harder to predict as they can occur in the upper reaches of catchments. These events generally have a lower potential for widespread damage as the extent and magnitude of flooding is much smaller than cyclonic events.

2.2.1 Water Quality

The streamflow in the ephemeral creeks in the Duck Creek catchment (and wider Pilbara) are typically fresh, but highly turbid due to the rapid rise of creek levels in response to rainfall, when flooding occurs. The highly variable nature of rainfall and flooding across the Pilbara also results in significant variation in the physical parameters across samples within the same basin. To illustrate this variation, water samples from the Ashburton River basin from the DWER *Water Information Reporting* database have been analysed and compared against available Pilbara wide surface water quality data. Available data from the DWER dataset has been presented in Table 3 and includes the range across all Pilbara watercourses as well as the range within the Ashburton River basins. Water quality in naturally occurring pools can be highly variable, in part due to the individual characteristics of each pool, its water supply(rainfall, creek flow, alluvial groundwater or groundwater structure), the preceding climate (drought/flood history, recent groundwater recharge etc.), and interaction with livestock.

Table 3: Surface Water Quality Data

	Pilbara Wide (DWER)		**Ashburton (DWER)**	
	Minimum	Maximum	Minimum	Maximum
pH (pH units)	5.2	9.4	6.7	8.8
EC (µS/cm)	3	6090	83	6090
Turbidity (NTU)	0.1	3200	0.5	3200
Alkalinity (mg/L)	3.6	420	35	274
TDS (mg/L)	22	3932	70	2618
Nitrate as N (mg/L)	0.05	32	1	3
Hardness (mg/L)	3.6	1538	48.9	1539
Dissolved Silica (mg/L)	1	68	7.7	22

The ephemeral creeks of the Pilbara typically have high bed loads in their natural state with many instances of significant erosion on existing stream banks and notable areas of instability in the natural environment, highlighting that erosion is a naturally occurring process in Pilbara watercourses, which is reflected by the range of Turbidity values in the DWER water quality data. This range of conditions is illustrated visually in (Appendix 1) with examples at Hamersley Gorge (Southern Fortescue River) and Weeli Wolli Creek showing the variation within and between events. Sediment transport is discussed further in Section 2.3.

2.3 Geomorphology

In order to understand and characterise the geomorphology and sediment transport regime, a baseline geomorphology assessment was undertaken and is provided in Appendix 2. This assessment included inspection, with a focus on sediment sampling within catchments likely to be most affected by mining including Pinarra Creek, West Creek and Flying Fish. The subsequent desktop review included catchment and stream order analysis, comparison of channel planform and morphology, incipient motion analysis and sediment continuity analysis. The conclusions drawn should be read in context of the entire report and as such are not summarised in this impact assessment report to avoid misinterpretation.

2.4 Hydrological Analysis

The site hydrology was investigated using a variety of techniques including rainfall-runoff routing and hydraulic modelling. The focus on this investigation was to determine an appropriate methodology for application of rainfall temporal patterns and losses in order to develop conceptual hydraulic models for analysis of present hydrologic conditions and potential project impacts. This investigation is summarised in the *Eliwana Project Hydrology Study*, and results were used for modelling described in Appendix 3.

2.4.1 Regional Flow Monitoring

There are several active Department of Water and Environmental Regulation (DWER) stream gauging stations on the Ashburton River, but only one (Nanutarra -706003) located downstream of the Eliwana project area (refer Figure 1). Despite the high quality, long record available at the gauge, the contributing area is 30,000km^2, significantly larger than the catchment areas of the Eliwana project. The physiographic characteristics of the catchments within the project area are also different to the characteristics of the catchments of the DWER gauge. This results in DWER gauges not being suitability representative of the flood response of the project area and as such have not been used for model development and validation.

2.4.2 Project Monitoring

A number of creek level monitoring sites were installed in around the Pinarra Creek catchment in 2016 for monitoring of flows. The sites have been installed at locations with channel cross sections best suited to capture of streamflow data for use in hydraulic modelling, for validation of site hydrology. This resulting monitoring data has not been used for concept model development and validation due to short length of record and lack of large rainfall events, but is intended to be used to refine site hydrology when an appropriate length of record has been established. The monitoring network is likely to be expanded over time as site access is improved.

3. HYDRAULIC MODELLING – BASELINE AND IMPACT SCENARIOS

The *Eliwana Project Hydrology Study* assessed a range of modelling approaches to determine an appropriate hydrologic methodology to be applied to two-dimensional hydraulic modelling. This exercise was undertaken to ensure that modelling approach and assumptions were consistent with guidance of the recent update to Australian Rainfall and Runoff (ARR) (Ball et al. 2016).

This hydraulic modelling has been undertaken using the TUFLOW software package (Version 2016-03-AE), using direct rainfall inputs onto a grid developed from LIDAR survey, in order to estimate flood patterns for current condition (baseline) and to estimate project impacts (ultimate).

The adopted hydrological approach includes direct rainfall modelling of the entire catchment using:

- A proportional loss model, which varies with event magnitude, applied to rainfall hyetograph with rainfall excess applied across the model domains; and
- The rangelands west temporal patterns published in ARR (Ball et al. 2016).

Further details of the rationale behind this approach is provided in *Eliwana Mine Project Hydrology Study,* provided in Appendix 3.

3.1 Design Rainfall

The Intensity Frequency Duration (IFD) table, showing the design rainfall depths adopted for design events with range of annual exceedance probabilities (AEPs) are provided in Table 4. This data has been obtained from the Bureau of Meteorology website (http://www.bom.gov.au/water/designRainfalls/ifd/). These IFDs were published in 2016 and represent the revision of design rainfall estimates adopted by ARR (Ball et al. 2016). The design rainfalls were applied to hydraulic models as event totals for a range of durations and magnitudes (corresponding to different AEP events).

Table 4: 2016 BOM Design Rainfall Depths (mm) – Location: 22.479S 116.827 E

	Annual Exceedance Probability (AEP)						
	100%[3]	50%	20%	10%	5%	2%	1%
Duration	**Rainfall Depth (mm)**						
1 min	1.7	2.0	2.8	3.3	3.9	4.6	5.2
2 min	2.7	3.1	4.4	5.2	6.1	7.1	7.9
3 min	3.9	4.5	6.3	7.5	8.7	10.2	11.4
4 min	5.0	5.7	8.1	9.6	11.2	13.3	14.8
5 min	6.0	6.9	9.7	11.7	13.6	16.1	18.1
10 min	10.0	11.5	16.4	19.7	23.0	27.4	30.8
15 min	12.8	14.7	21.0	25.2	29.5	35.1	39.4
30 min	17.9	20.6	29.1	35.0	40.8	48.5	54.4
1 hour	22.9	26.4	37.3	44.8	52.1	61.9	69.4
2 hour	28.0	32.3	46.0	55.4	64.7	77.2	86.9
3 hour	31.1	36.0	51.8	62.7	73.6	88.4	99.9
6 hour	36.9	43.2	63.7	78.3	93.1	114.0	130.0
12 hour	43.7	51.7	78.6	98.3	119.0	148.0	171.0
24 hour	51.1	61.1	95.4	121.0	149.0	188.0	220.0

[3] One exceedance per year

	Annual Exceedance Probability (AEP)						
	100%[3]	50%	20%	10%	5%	2%	1%
48 hour	58.6	70.5	111.0	143.0	176.0	224.0	263.0
72 hour	63.0	75.7	120.0	153.0	189.0	239.0	280.0

3.2 Rainfall Losses and Temporal Patterns

Temporal patterns from ARR (Ball et al. 2016) extracted from the ARR data hub (http://data.arr-software.org/) were used in the hydraulic modelling. The effect of application of a number of different temporal patterns was assessed in the *Eliwana Mine Project Hydrology Report* (Appendix 3). Following this analysis, the rangelands west temporal patterns from ARR (Ball et al. 2016), specifically patterns 8, 16 and 28, were adopted for subsequent hydraulic modelling.

The adopted model approach assumed proportional rainfall loss, using loss rates recommended in Flavell (2012). This loss rate was varied with event magnitude, where higher losses were applied to more frequent rainfall events. This approach was verified through comparison with other available methods, as described in Appendix 3.

3.3 Model Domains

The adopted modelling approach described above was applied to all project catchments discussed in section 2.1.2, including the areas downstream of the project disturbance area. The model domains ended at a point of confluence with a similar or larger size watercourse/tributary that was outside from the project disturbance. A total of 6 separate model domains were developed including:

- West Creek (refer Figure 9),
- Pinarra Creek (Figure 10),
- Flying Fish (capturing Strike East Creek and Flying Fish 1) – (refer Figure 11),
- Flying Fish Downstream (from the Flying Fish domain to the Boolgeeda Creek Confluence) - (refer Figure 11),
- Flying Fish East (capturing Flying Fish 2) – (refer Figure 12),

- Infrastructure (capturing a series of small catchments around the proposed infrastructure areas) – (refer Figure 13).

3.4 Grid Size and Roughness

The models each applied the direct rainfall approach described above, with a 5m grid built from a 1m grid of LIDAR survey data as the basis topography, where available. Features such as the gorges and general floodplain features were well represented by the model. The selected grid size allowed accurate modelling of the site and creek while maintaining manageable model simulation run times. The Flying Fish Downstream model was built to cover a gap in the LiDAR coverage. This model uses a 10 metre grid based on Landgate data obtained from the Government of Western Australia. In the area covered by the 10m grid there is appropriate representation of flowpaths for comparative analysis of scenarios.

The Manning's 'n' roughness parameter affects flood velocities, flow paths, flood depths and extents. The Western Pilbara is predominantly natural rural landscape, with altered terrain typically limited to small town centres, sealed/unsealed roads, minor pastoral disturbance and number of mining operations. The lack of historic flood data for this area and the relative homogeneity of the landscape make it difficult to categorise different roughness areas with any certainty. For this reason, and from previous experience in nearby catchments, a constant manning's 'n' roughness coefficient of 0.05 was selected. Although there is potential for roughness/manning's n variation between hillslopes, channel and floodplain in some areas, the impact of the relative uncertainty of rainfall distribution and losses far exceeds that of roughness uncertainty. Consequently there is limited value in varying roughness within the domain for this comparative modelling assessment, without a suitable catalogue of monitoring data for validation of modelling results.

3.5 Model Scenarios

Hydraulic modelling was undertaken for a baseline scenario and ultimate scenarios, with sensitivity analyses conducted for selected variables. The baseline scenario reflects current conditions, where the catchments are largely undisturbed, with some minor alteration arising from pastoral uses and current exploration activities. The ultimate scenario aims to quantify the maximum possible impact to surface water flows due to project disturbance. The ultimate scenario assumes the following:

- All pits are developed to full depth with no in-pit backfill (for worst case impacts); and
- No pit diversions are in place, with runoff allowed to freely enter pit voids;

In TUFLOW, the ultimate scenario involved altering the model grid by superimposing the ultimate pit surfaces over the existing terrain.

Although some catchment modification may result from other infrastructure such as haul roads and waste dumps, this infrastructure has not been included in the modelling as it is all located upstream of pits which intercept creek lines. Consequently, modelling of the pits only is sufficient to evaluate the impact to surface water flows outside of the disturbance area.

The ultimate scenario is considered to be a conservative estimate of impacts as it is likely that pits would be developed progressively (not concurrently) and overburden/mineral waste from new pits would be dumped into adjacent pits in many cases due to a shorter haul distance and better environmental outcome. Where practicable, it would be desirable for creek diversions be put in place to limit both environmental and operational impacts, however it is likely topographic (e.g gorges) and tenure constraints may preclude creek diversion in a number of instances. The rationale for assessing this ultimate scenario in line with the above assumptions is to set an upper bound on the potential level of impact of the project on the reaches of the creek immediately downstream of the project disturbance area.

4. MODEL RESULTS

4.1 Model Output Presentation

The *Eliwana Mine Project Hydrology Report* (Appendix 3) concluded that the 6 hour storm was critical for peak flows and flood extent for a number of catchments in the project area including Pinarra Creek at the model outlet. Consequently this event duration was then used to assess changes arising from the proposed development for all model domains. While some locations in the upper reaches of the model domains have a different critical duration, the 6 hour storm was most representative over cumulative project area, and for areas downstream of the proposed disturbance those locations.

A series of figures have been prepared for each model domain for the 50%, 10% and 1% AEP events, which have been selected to represent scenarios of a frequent, rare and very rare flood events. The figures show:

1. Baseline flow depths;
2. Baseline flow velocities;
3. Ultimate flow depths and inundation extent comparison; and
4. Water level difference plots

The Flying Fish and Flying Fish Downstream domains are shown on the same figures for ease of understanding. Note that the Infrastructure domain results only contain baseline scenario figures, as no pits are proposed in this area. These figures showing model output for the various domains is provided in Appendix 4-8.

4.2 Model Output Analysis

4.2.1 Baseline Scenario

Analysis of model output across the domains provided the following observations for baseline conditions (these complement the catchment descriptions provided Section 2.1):

- Main channel alignments and morphology strongly controlled by the strike valley;
- Adjacent floodplains active in rare events;
- Significant gorge features with high depths and velocities at constrictions within the strike valley where flows cross the northern ridge with no active floodplain through these reaches;

- Channel flow dominated environment with minimal overland or sheetflow even for rare events, except where the base of the strike valley coincides with a catchment divide

4.2.2 Impact Scenario

Observations from comparison between ultimate scenario and baseline model results were as follows:

- Significant interception of flows in pits, particularly those that intercept lower order creek channels (refer Appendix 2 for stream order analysis), resulting in ponded water in pits;
- Reduction in flow downstream of pit boundaries, as shown by reduction in depth and flood extent; and
- Flood extent reductions are most severe immediately downstream of pits and progressively reduce with increasing distance downstream towards the model boundaries, as additional catchment area (outside of disturbance footprint) feeds into creek channels.

Observations specific to each model domain area discussed below.

West Creek

The West Creek model domain is shown in Figure 9 and model results are provided in Appendix 4.

The most significant change in the West Creek catchment is a large pit (approximately 1km long) intersecting the main channel upstream of the gorge. Modelling predicts that this pit will fill in rare-very rare scenarios, resuming flow to the creek which is terminated by the pit in more frequent events. The frequency of resumption of flow will be dependent on detailed pit geometry and event duration, so the specific frequency of creek flow resumption is indicative only (shown to be the 1% AEP event in Appendix 4).

In the 50% AEP event, large changes in depth (>1 m) primarily are confined to the reaches immediately downstream of the pit with the model outlet experiencing reductions typically less than 0.5 m. In the 10% AEP event, large depth reductions (>1 m) extend up to 4 km downstream of the pit, although at the outlet are less than 0.5 m in the main channel and 0.25 m on the adjacent floodplain. In the 1% AEP flood where the ultimate scenario shows resumption of creek flow at the downstream end of the pit, few depth decreases greater than 1m are predicted and at the model outlet, depth reductions are typically 0.5 m.

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Many other minor pits are located in the West Creek catchment. These are primarily located on the northern flank of the strike valley or on top of the southern ridge. These pits have no significant upstream catchment, intersect local runoff only and do not result in significant change to water levels in the main channel. There is likely to be significant other disturbance in this catchment by other features such as roads and waste rock landforms, however the impact of these features to the receiving catchment is unlikely to be larger than that created by the large pit that is intercepting the main west creek line.

Pinarra Creek

The Pinarra Creek model domain is shown in Figure 10 and model results are provided in Appendix 5.

Pinarra Creek contains more pits than any of the other local catchments and as a result, has the largest extent of change within the catchment, as predicted by modelling. Pits are located primarily on the southern flank of the strike valley or on the valley floor. Several of the smaller pits intersect minor catchments, but greatest change arises from pits which intersect the main channel of Pinarra Creek. The frequency of resumption of creek flow across these pits will be dependent on detailed pit geometry and event duration, so the specific frequency of creek flow resumption is indicative only. The modelling does not predict creek flow resumption in the 1% AEP (refer Appendix 5), for the 6 hour duration event. Consequently, the events resulting in resumption of creek flow across pits is likely to be occurring with frequency deemed *very rare* or *extreme* by ARR (Ball et al. 2016).

It should be noted that all pits were assessed as part of the ultimate scenario. The frequency of creek flow resumption is likely to increase if rare floods occur prior to development of ultimate footprint, or if there is in-pit backfill or conversely is likely to decrease if there are diversions implemented.

Flood extents predicted by the model are significantly different between the ultimate scenario and baseline scenarios. Ultimate scenario flows are typically confined to the main channel for all events whereas in the baseline scenario, the 10% and 1% AEP events spread across the width of the adjacent floodplain (apart from the gorge sections, where a staged channel/floodplain morphology is not present). The ultimate scenario flood extents are typically a third to a quarter of that in the baseline scenario. Estimated reductions in flow depth typically exceed 0.25 m along this section with larger changes (>1 m) immediately downstream of the pits and approaching Broadway gorge.

The tributary flowing into Pinarra Creek just upstream of the model outlet appears to have a limiting effect to the changes arising from the proposed disturbance. In the final 1 km reach of the creek within the model domain, flow extents are only slightly reduced from the baseline scenario. Decreases in flow depths predicted in the model range from 0.4 m in the 50% AEP event to 0.8 m in the 1% AEP event.

There is likely to be significant other disturbance in this catchment by other features such as roads and waste rock landforms, however the impact of these features to the receiving catchment is unlikely to be larger than that created by the interception in pit across the catchment.

Flying Fish

The Flying Fish and Flying Fish Downstream model domains are shown in Figure 11 and model results are provided in Appendix 6.

The Flying Fish model domain pit area includes Strike East Creek and Flying Fish 1 Creek. The Flying Fish Downstream domain captures the area around the confluence of these two watercourses. Both domains are shown in the model result figures. Several pits are proposed within the strike valley part of each catchment. This includes pits which intersect the main branch of Strike East Creek and Flying Fish 1.

The largest pit affecting Strike East Creek is approximately halfway between the western catchment boundary and the Flying Fish 1 confluence. The effect on flow depth is relatively minor, with reductions exceeding 0.5 m immediately downstream of the pit but less than 0.15 m at the model boundary in the 50% AEP event. Changes to the flood extents for the 50% AEP event are also relatively minor. The 1% AEP event is significantly altered with the baseline scenario showing flows across the width of the floodplain whereas the ultimate scenario shows flows confined to the channel.

Pits developments are confined to the one-third of the Flying Fish 1 catchment located within the strike valley. At a number of locations, pits intercept the strike valley tributary channel, meaning the strike valley section of the catchment is highly altered with greatly reduced flood extents and contributes no downstream flows in the ultimate scenario.

The two thirds of Flying Fish 1 catchment draining the area north of the strike valley is intercepted by a shallow pit located 2.5km upstream of the model outlet. The frequency of resumption of flow will be dependent on detailed pit geometry and event duration, so the specific frequency of creek flow resumption is indicative only (shown to be the 1% AEP event in Appendix 6). The indicative resumption of creek flow in the 1% AEP event results in a smaller changes between the pit and the model outlet, with a relatively minor reduction in flood extents, compared to the 50% and 10% AEP events, where flood extents are reduced to between a quarter and half that of the baseline scenario.

The combined effect of the changes in the Strike East and Flying Fish 1 catchments are illustrated in the Flying Fish Downstream model domain. This domain is entirely outside the strike valley and no pits are proposed in this area. Some "internal" boundary affects are evident where the Flying Fish domain overlaps with the Flying Fish Downstream domain. Also evident is the reduced grid resolution and vertical accuracy in the downstream domain, however the results appear to be satisfactory for a comparative scenario assessment.

The reach between the confluence of Flying Fish 1 and Strike East Creek and the model outlet (and the confluence with Boolgeeda Creek) is 3km long. In this section, the upstream pit developments result in water level depth reductions of less than 0.5 m in the 50% AEP event and less than 1 m in the 1% AEP case. These depth reductions do not translate to major flood extent reductions, with flow widths in the ultimate scenario being typically at least 75% of that of the baseline scenario. There may be some loss in definition due to coarser resolution and vertical accuracy of the topographic data, where the distinction between channel and floodplain is not as clear is in the areas where LiDAR data is available, so the main creek valley through this area may have slightly larger impacts to depth and extent than shown by modelling and this should be taken into account for assessment of indirect impacts.

There is likely to be significant other disturbance in this catchment by other features such as roads and waste rock landforms, however the impact of these features to the receiving catchment will not be larger than that created by the large pit that in intercepting the main creek lines.

Flying Fish East

The Pinarra Creek model domain is shown in Figure 12 and model results are provided in Appendix 7.

The Flying Fish East domain marks the point where the strike valley trends more to the north east than the east. The main watercourse in this modelled is referred to as Flying Fish 2 and includes a third of the catchment north of and two thirds within, the main strike valley. A prominent feature of the model is Rio Tinto's Brockman 4 railway. Waterway crossings of the railway have not been modelled for consideration of worst case scenario, resulting in over predictions of upstream ponding.

The largest changes in flood depth and extent in the Flying Fish East model domain are caused by two small pits near the southern end of the model. These pits intercept flows in the main channel, 1.3km and 3km upstream of the model outlet. The 50% AEP event is partially intercepted by the upstream pit and completely captured by the downstream pit. As a result, water levels are reduced by up to 1 m while the flood extent between the two pits is dramatically reduced. This impact extends along the main channel from the upstream pit to a point 500m from the model outlet, where flows from the western third of the catchment join the main channel. Below the confluence, changes to flood depths and extents are relatively minor, as is the case further upstream in the 10% and 1% AEP events, where creek flows are indicated to resume through the modelled scenarios (although as with above domains, the frequency of resumption of creek flow across these pits will be dependent on detailed pit geometry and event duration, so is indicative only).

As the railway culverts have not been included, this has resulted in conservatively estimating the changes the pits impose on downstream flows. If runoff from upstream of the railway, were to reach the downstream pit areas, creek flow resumption is expected to be more frequent, reducing the potential downstream shadow effect.

There is likely to be significant other disturbance in this catchment by other features such as roads and waste rock landforms, however the impact of these features to the receiving catchment will not be larger than that created by the interception of flows in the pits in this domain.

5. DISCUSSION OF POTENTIAL IMPACTS

5.1 Changes to Hydrologic Regime due to Catchment Modifications

Through modelling of baseline and ultimate scenarios, areas likely to be affected by the project have been identified in order to understand impacts to the hydrologic regime and to enable investigation of potential indirect impacts to flora and fauna survey. Areas located outside of the project disturbance footprint with significant reductions to surface water flows have been identified have been highlighted in Figure 14.

During operations, if large volumes of surface water are intercepted by pits during flood events, it will be discharged back to the watercourse after the event via pumps and pipe infrastructure in accordance with licence conditions and/or industry guidelines (such as the Water *Quality Protection Guidelines for Mining and Mineral Processing Guidelines)*. Consequently, it is likely that the majority of intercepted surface water will be discharged to watercourses and there will not be a significant change of volume in these cases, although sediment content and floodplain connectivity associated with peak discharge rates may be affected.

However, on closure, catchment changes will be permanent and reductions in flows will persist. In this case, the greatest potential for impacts created by the mining activities are likely to be related to frequent events, as these provide a more regular source of flow and inundation. The focus of the impact assessment has been on the 50% AEP event. The assessment also includes broader consideration of larger events, but the impacts shown in these scenarios should be carefully considered against the relative frequency of the event.

It should be noted that the flood mapping shows maximum inundation. This inundation extent only occurs for a short duration at the peak of the flood, which is an important consideration given the location of the project at in the upper reaches of the local and regional catchments Upper catchment flooding is associated with a shorter duration. Furthermore, areas located downstream that are impacted by reduction in stream flows will still receive surface water runoff from direct rainfall and local catchment contribution.

5.2 Geomorphology Impacts

Geomorphology impact as discussed in the memo provided in Appendix 9.

6. CONCLUSION

This report presents the hydrologic and geomorphic characteristics of the Eliwana Project area and describes the process by which the potential impacts of the development on the hydrological regime were estimated. A hydraulic model was used to describe the local catchments around the Eliwana Project under existing conditions (the baseline scenario) and what could be considered an upper bound on potential impact arising from the development (the ultimate scenario) based on no diversion of flows around pits or backfilling of pits. The model results illustrated the impact of the project where pits intercepted catchment runoff reducing the downstream flood footprint and flow depths. In describing the impact arising from the changes to the hydrologic regime, it was concluded that:

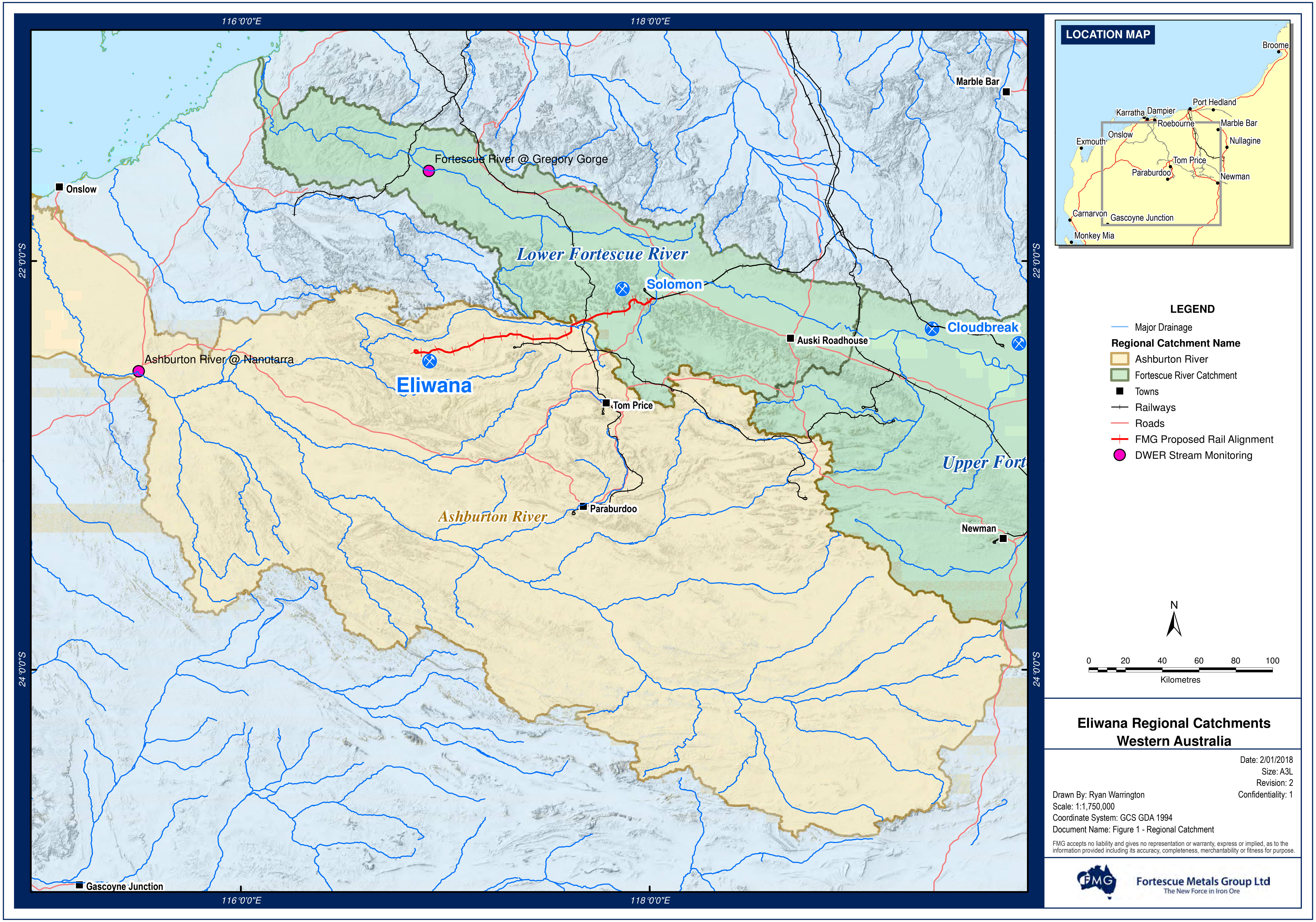
- Changes to frequent events are most significant and results from the 50% AEP event were used to describe potential impacts;
- Within the model domains, pits intercepting the main channel of the local catchments were shown to impact several areas downstream of the proposed disturbance; and
- Impacts arising from the ultimate scenario were not significant at the model boundaries and were not expected to extend beyond the model boundaries due to the confluence with a similar size or larger tributary/creek.

7. REFERENCES

Ball, J et al., 2016, *Australian Rainfall and Runoff: A Guide to Flood Estimation,* Commonwealth of Australia, Available from: http://arr.ga.gov.au/arr-guideline

Flavell, D 2012, "Design Flood Estimation in Western Australia", *Australian Journal of Water Resources*, Vol. 15, No. 1, pp. 1-20, https://dx.doi.org/10.7158/W11-865.2012.16.1.

8. FIGURES


116°0'0"E
118°0'0"E
22°0'0"S
24°0'0"S
Marble Bar
Onslow
Fortescue River @ Gregory Gorge
Lower Fortescue River
Solomon
Cloudbreak
Auski Roadhouse
Ashburton River @ Nanutarra
Eliwana
Tom Price
Upper Fort
Paraburdoo
Ashburton River
Newman
Gascoyne Junction
LOCATION MAP
Broome
Port Hedland
Karratha
Dampier
Roebourne
Marble Bar
Nullagine
Exmouth
Onslow
Tom Price
Paraburdoo
Newman
Carnarvon
Gascoyne Junction
Monkey Mia
LEGEND
Major Drainage
Regional Catchment Name
Ashburton River
Fortescue River Catchment
Towns
Railways
Roads
FMG Proposed Rail Alignment
DWER Stream Monitoring
N
0 20 40 60 80 100
Kilometres
Eliwana Regional Catchments
Western Australia
Date: 2/01/2018
Size: A3L
Revision: 2
Confidentiality: 1
Drawn By: Ryan Warrington
Scale: 1:1,750,000
Coordinate System: GCS GDA 1994
Document Name: Figure 1 - Regional Catchment
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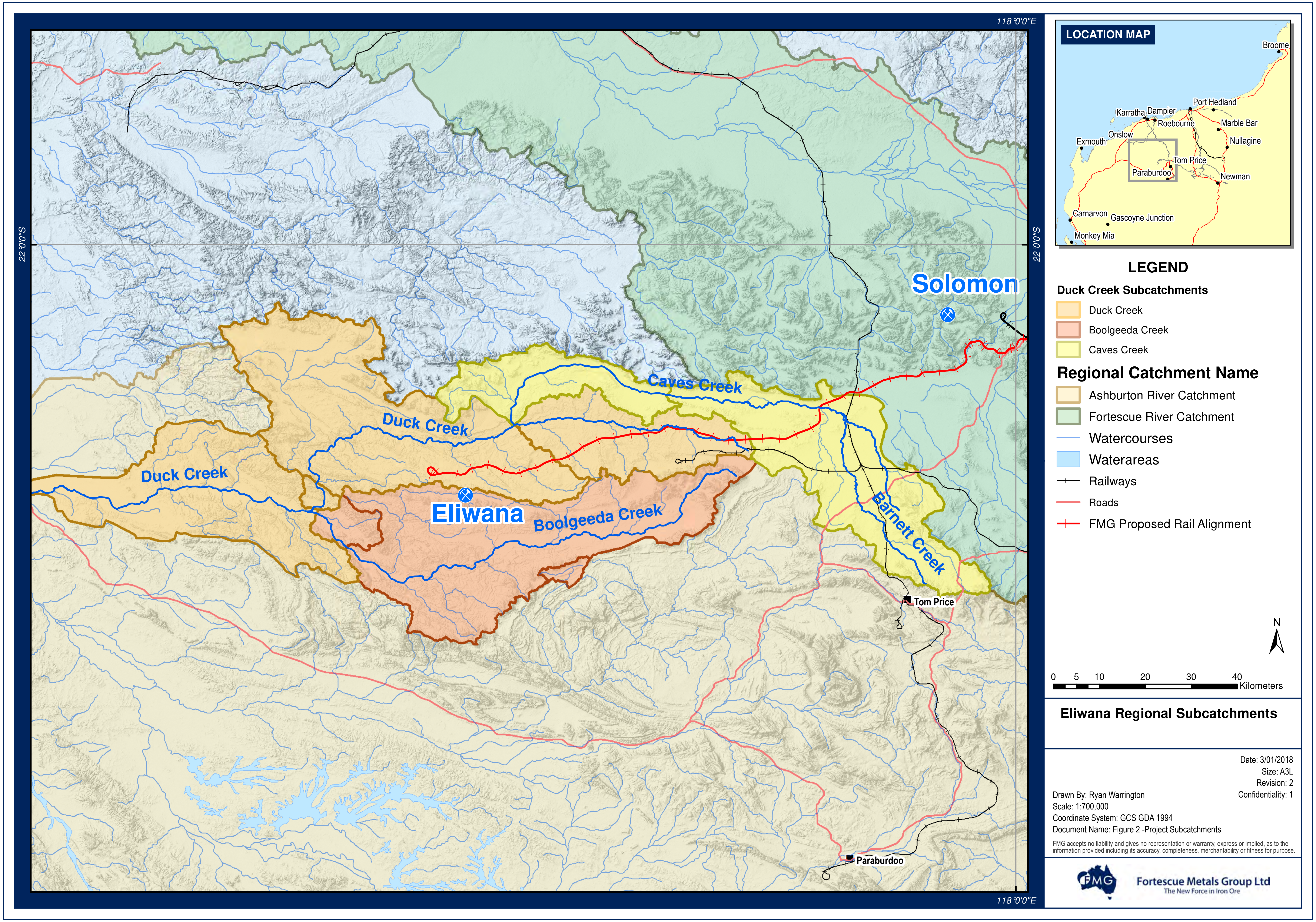
Fortescue Metals Group Ltd
The New Force in Iron Ore


118°0'0"E
22°0'0"S
LOCATION MAP
Broome
Port Hedland
Karratha
Dampier
Roebourne
Marble Bar
Onslow
Exmouth
Nullagine
Tom Price
Paraburdoo
Newman
Carnarvon
Gascoyne Junction
Monkey Mia
LEGEND
Duck Creek Subcatchments
Duck Creek
Boolgeeda Creek
Caves Creek
Regional Catchment Name
Ashburton River Catchment
Fortescue River Catchment
Watercourses
Waterareas
Railways
Roads
FMG Proposed Rail Alignment
Solomon
Caves Creek
Duck Creek
Duck Creek
Eliwana
Boolgeeda Creek
Barnett Creek
Tom Price
Paraburdoo
N
0 5 10 20 30 40
Kilometers
Eliwana Regional Subcatchments
Date: 3/01/2018
Size: A3L
Revision: 2
Confidentiality: 1
Drawn By: Ryan Warrington
Scale: 1:700,000
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FMG accepts no liability and gives no representation or warranty, express or implied, as to the information provided including its accuracy, completeness, merchantability or fitness for purpose.
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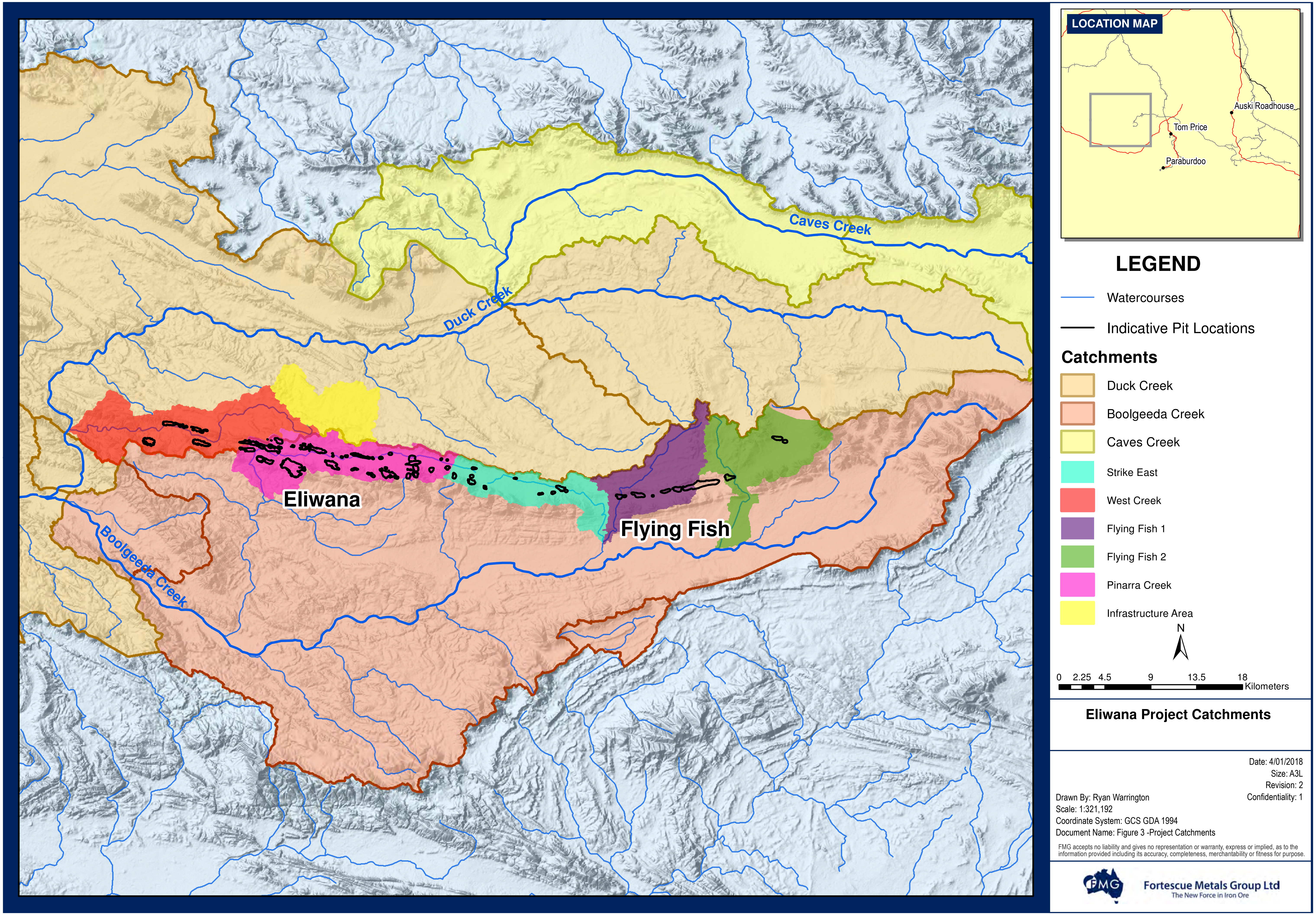

LOCATION MAP
Auski Roadhouse
Tom Price
Paraburdoo
Caves Creek
Duck Creek
Boolgeeda Creek
Eliwana
Flying Fish
LEGEND
Watercourses
Indicative Pit Locations
Catchments
Duck Creek
Boolgeeda Creek
Caves Creek
Strike East
West Creek
Flying Fish 1
Flying Fish 2
Pinarra Creek
Infrastructure Area
N
0 2.25 4.5 9 13.5 18
Kilometers
Eliwana Project Catchments
Date: 4/01/2018
Size: A3L
Revision: 2
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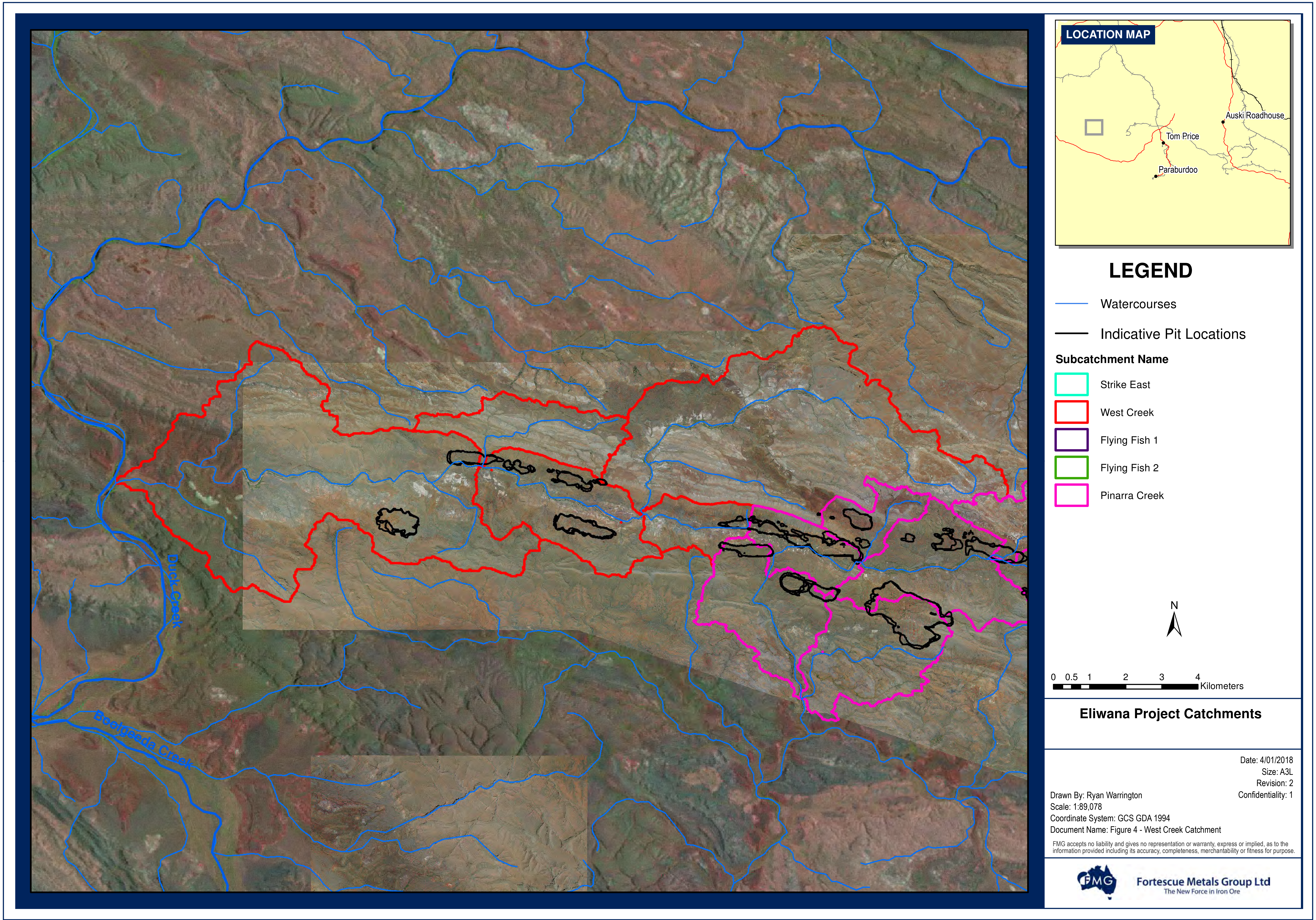

LOCATION MAP
Auski Roadhouse
Tom Price
Paraburdoo
Duck Creek
Boolgeeda Creek
LEGEND
Watercourses
Indicative Pit Locations
Subcatchment Name
Strike East
West Creek
Flying Fish 1
Flying Fish 2
Pinarra Creek
N
0 0.5 1 2 3 4
Kilometers
Eliwana Project Catchments
Date: 4/01/2018
Size: A3L
Revision: 2
Confidentiality: 1
Drawn By: Ryan Warrington
Scale: 1:89,078
Coordinate System: GCS GDA 1994
Document Name: Figure 4 - West Creek Catchment
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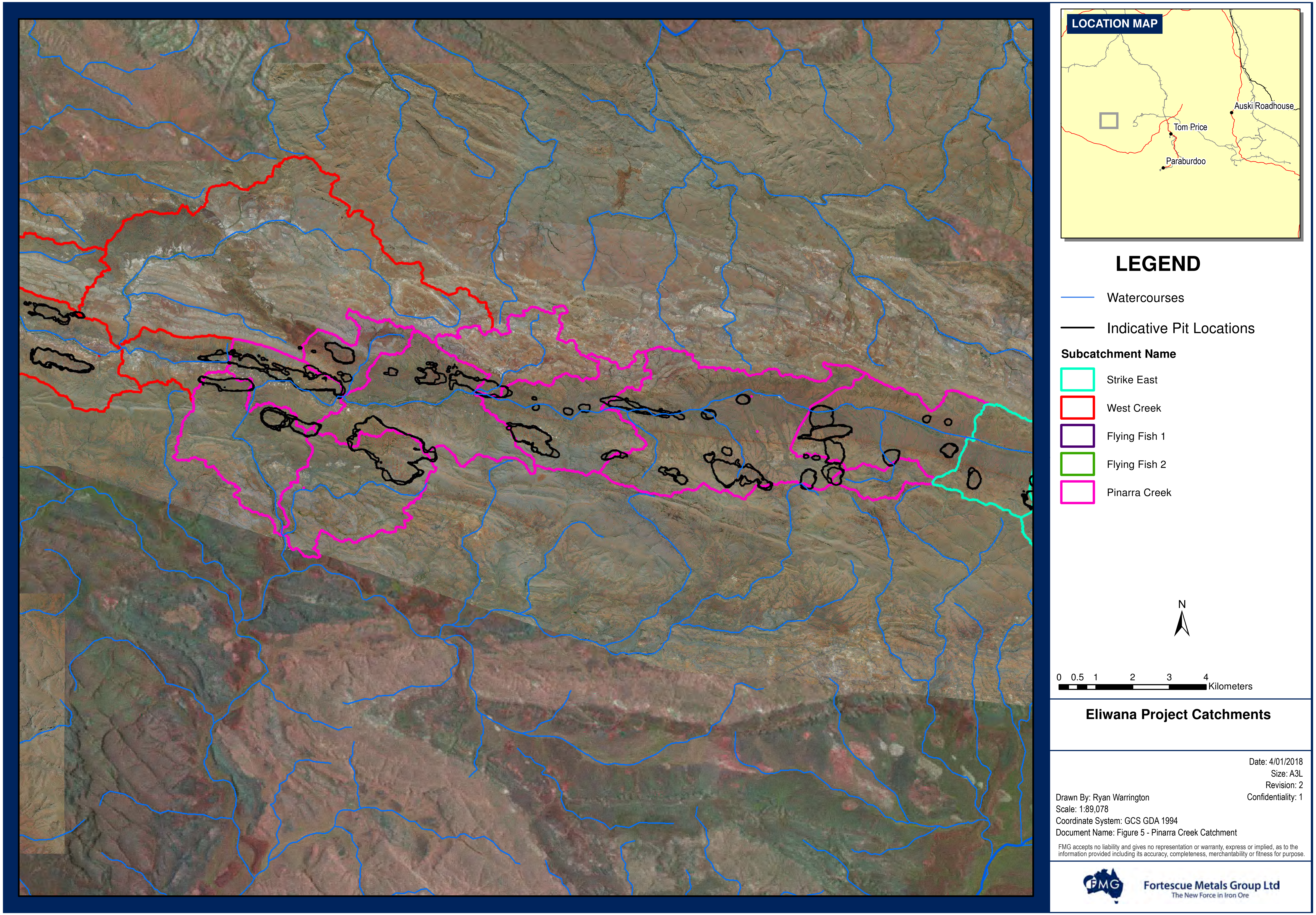

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Revision: 2
Confidentiality: 1

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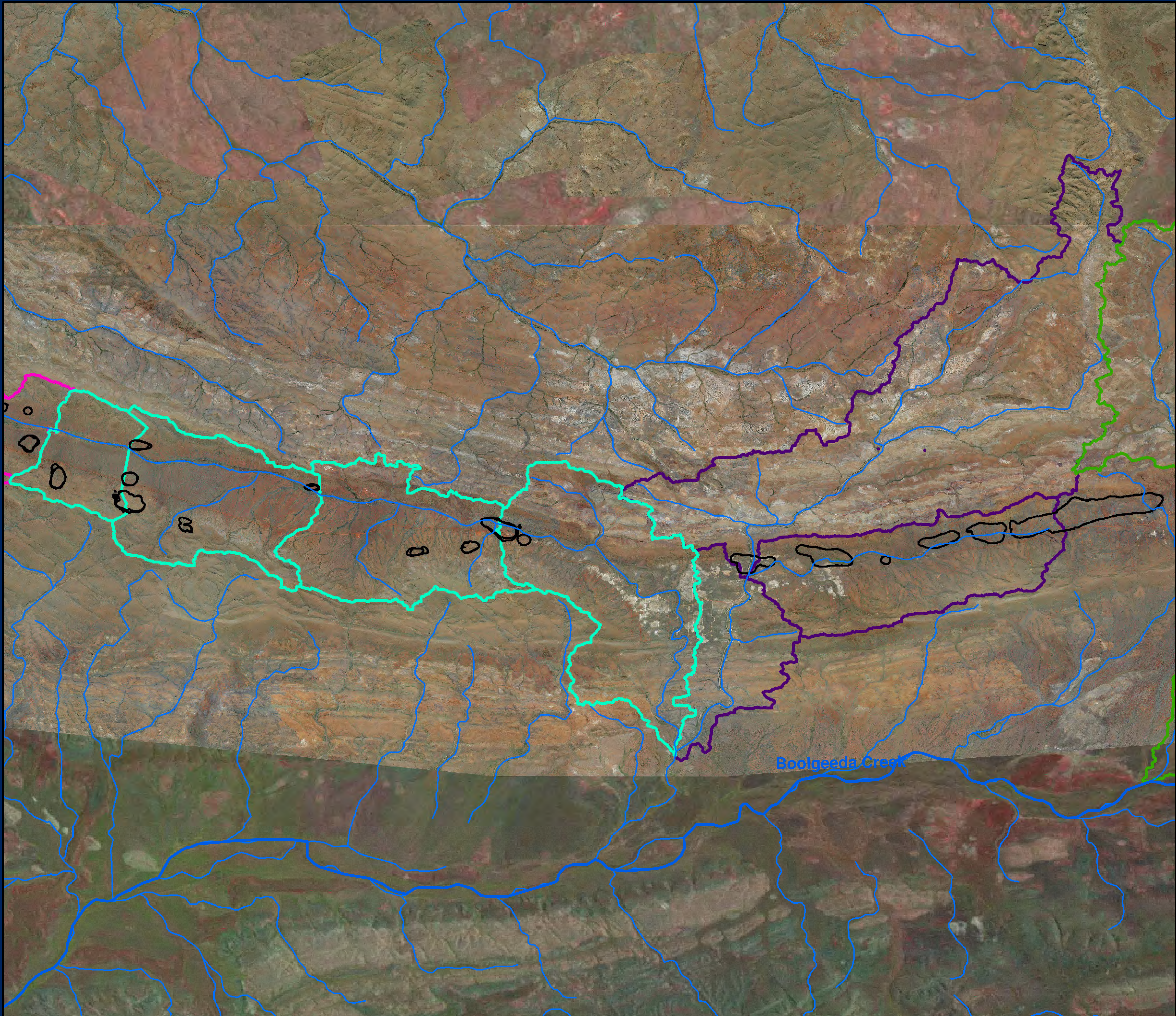
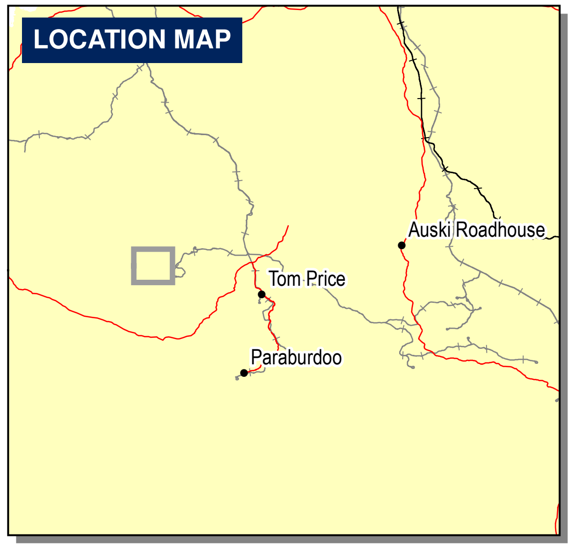
Fortescue Metals Group Ltd
The New Force in Iron Ore





LEGEND

- Watercourses
- Indicative Pit Locations

Subcatchment Name

- Strike East
- West Creek
- Flying Fish 1
- Flying Fish 2
- Pinarra Creek

N

0 0.5 1 2 3 4 Kilometers

Eliwana Project Catchments

Date: 4/01/2018
Size: A3L
Revision: 2
Confidentiality: 1

Drawn By: Ryan Warrington
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Coordinate System: GCS GDA 1994
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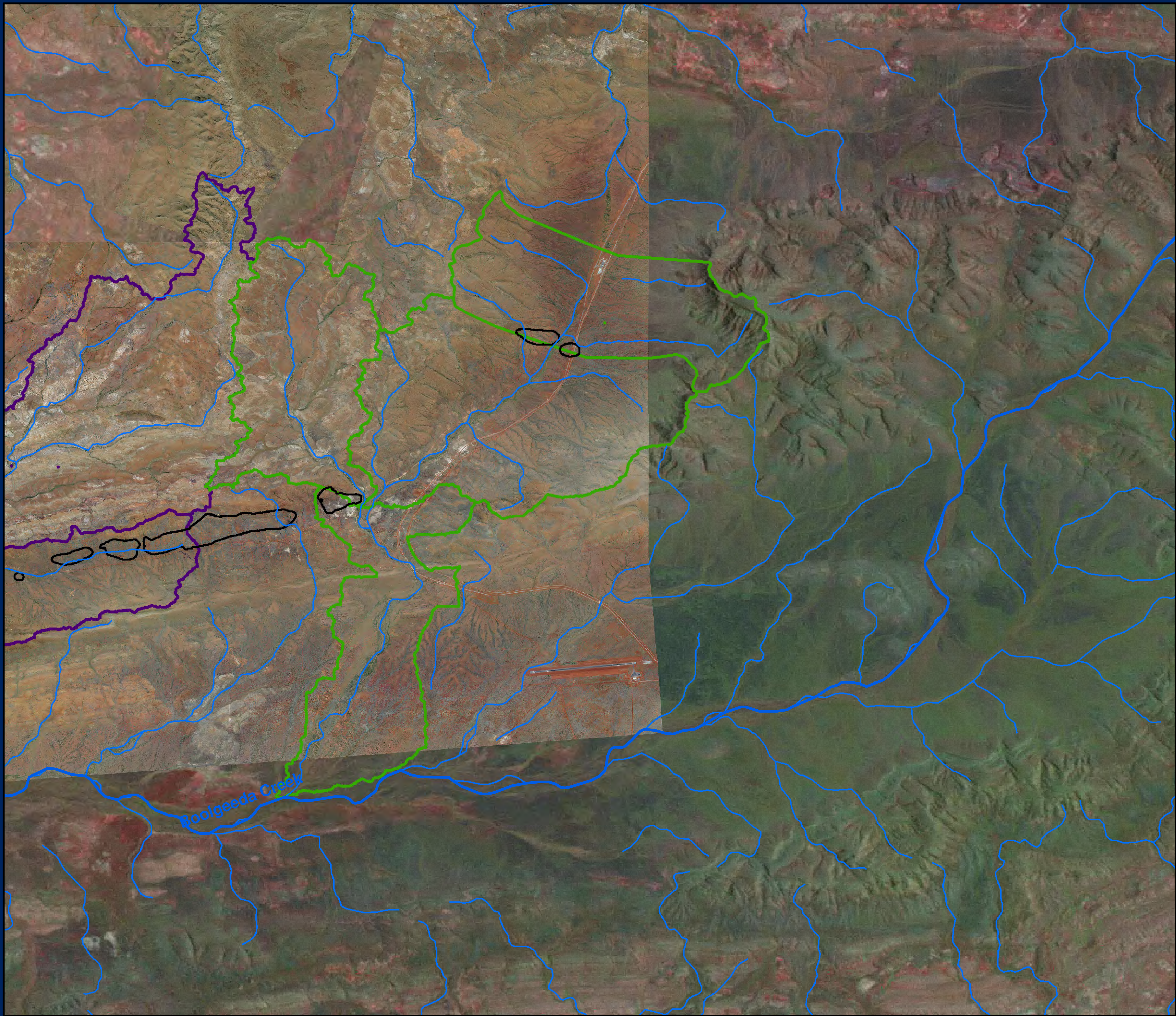
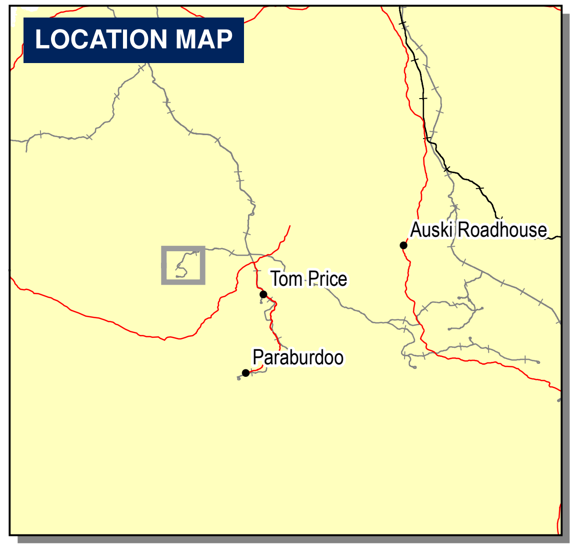
Fortescue Metals Group Ltd
The New Force in Iron Ore





LEGEND

Watercourses

Indicative Pit Locations

Subcatchment Name

- Strike East
- West Creek
- Flying Fish 1
- Flying Fish 2
- Pinarra Creek

N

0 0.5 1 2 3 4 Kilometers

Eliwana Project Catchments

Date: 4/01/2018
Size: A3L
Revision: 2
Confidentiality: 1

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Coordinate System: GCS GDA 1994
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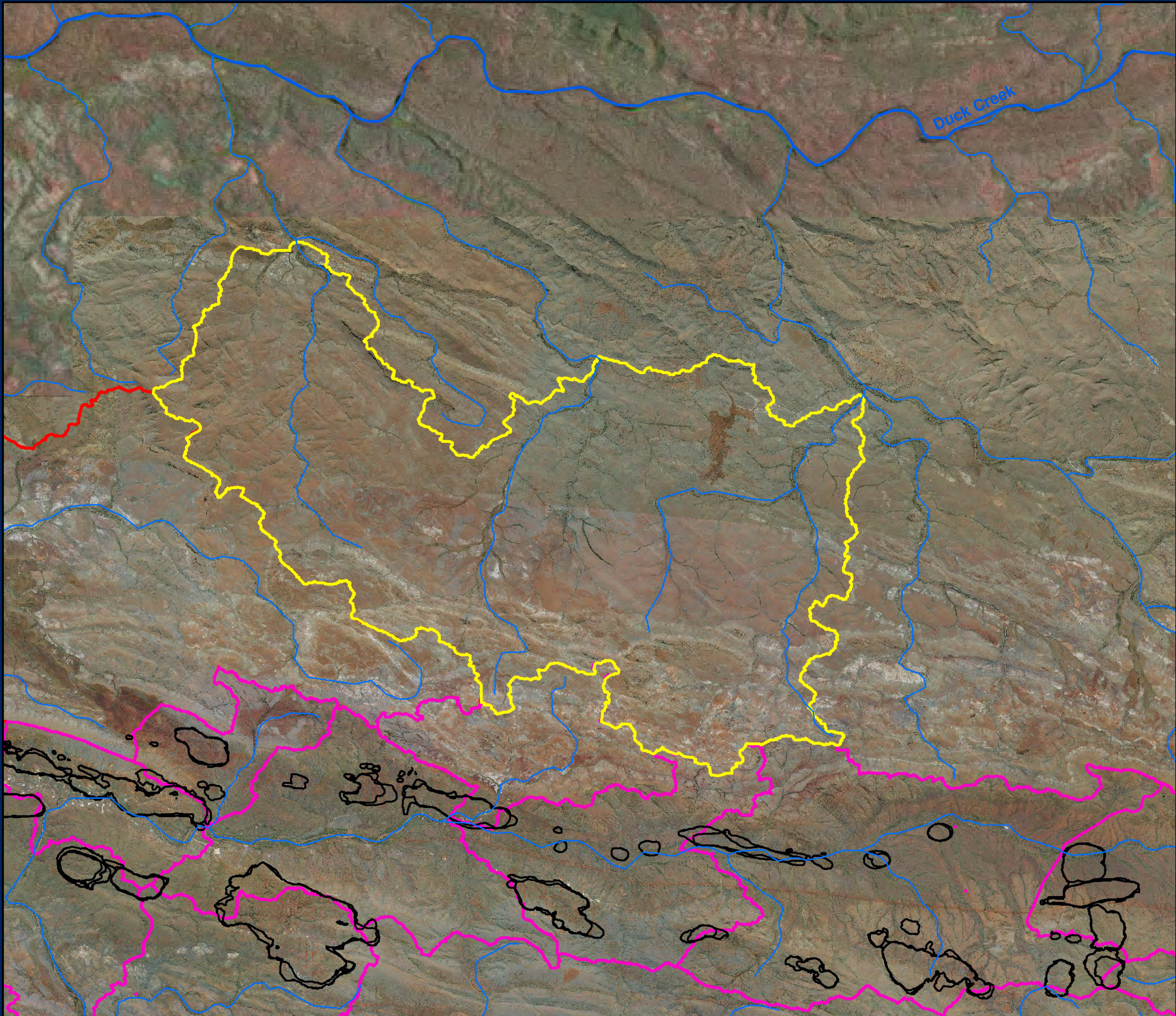

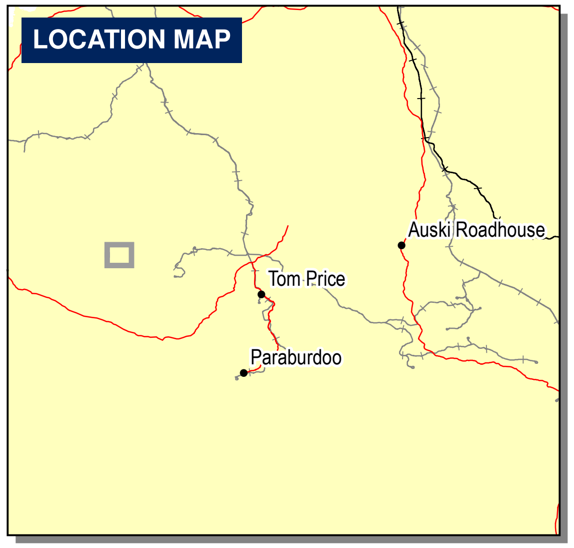

LEGEND

- Watercourses
- Indicative Pit Locations

Subcatchment Name

- Strike East
- West Creek
- Flying Fish 1
- Flying Fish 2
- Infrastructure Area
- Pinarra Creek

N

0 0.4 0.8 1.6 2.4 3.2 Kilometers

Eliwana Project Catchments

Date: 4/01/2018
Size: A3L
Revision: 2
Confidentiality: 1

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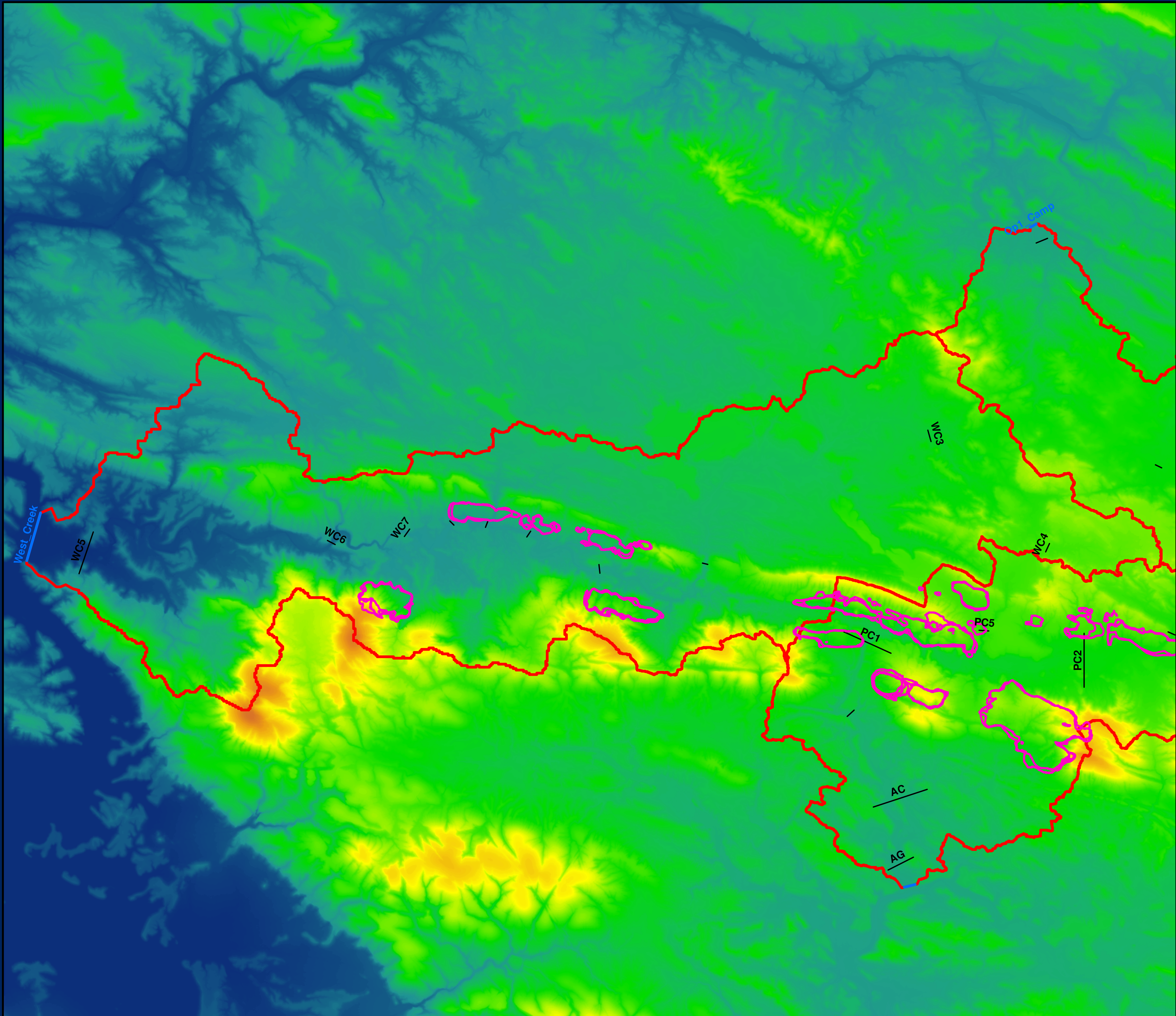
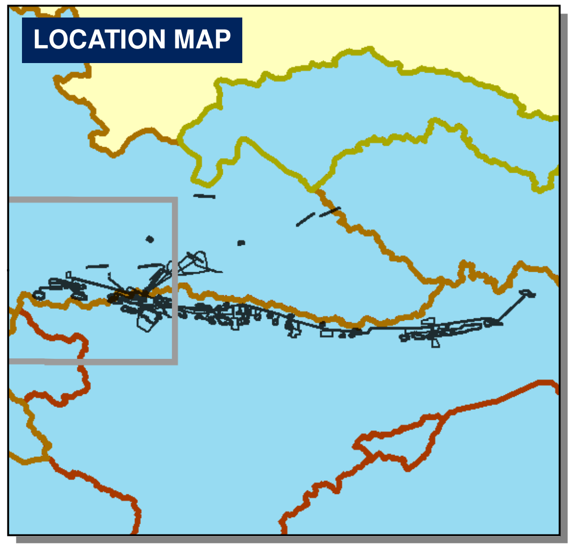
Fortescue Metals Group Ltd
The New Force in Iron Ore





LEGEND

Indicative Pit Locations

TUFLOW Inputs

- Model Boundary
- Outflow Boundaries
- Source-Area Inflows
- Reporting Hydrographs

Topography

Value

High : 800

Low : 300

N

0 0.5 1 2 3 4 Kilometers

West Creek TUFLOW Model Domain

Date: 4/01/2018
Size: A3L
Revision: 2
Confidentiality: 1

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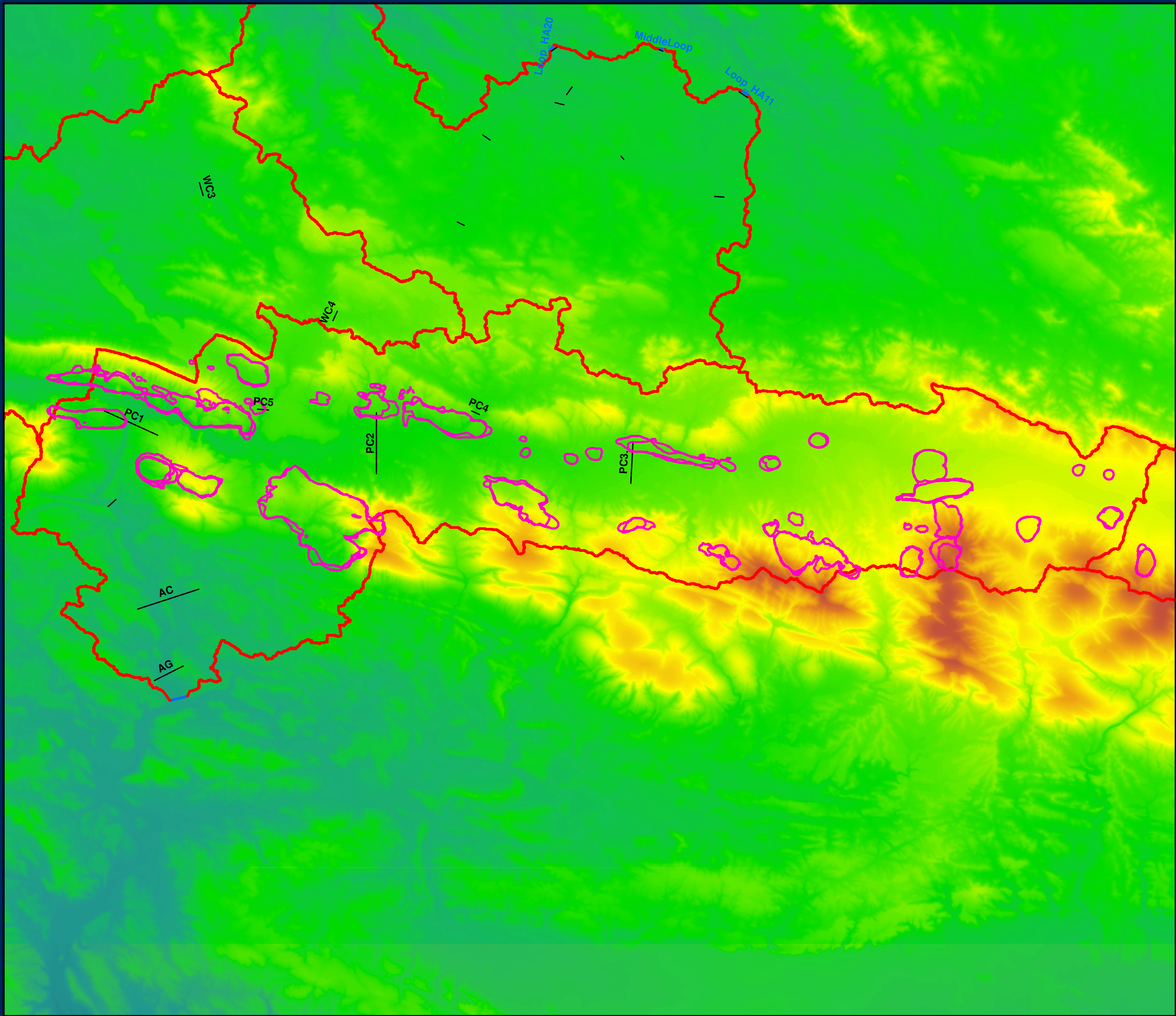
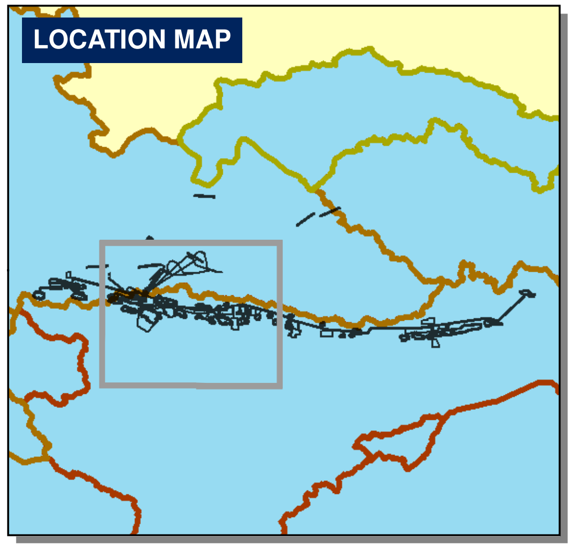
Coordinate System: MGA50
Document Name: West Creek TUFLOW Model Domain

Fortescue Metals Group Ltd
The New Force in Iron Ore





LEGEND

Indicative Pit Locations

TUFLOW Inputs

Model Boundary

Outflow Boundaries

Source-Area Inflows

Reporting Hydrographs

Topography

Value

High : 800

Low : 300

N

0 0.5 1 2 3 4 Kilometers

Pinarra Creek TUFLOW Model Domain

Date: 4/01/2018
Size: A3L
Revision: 2
Confidentiality: 1

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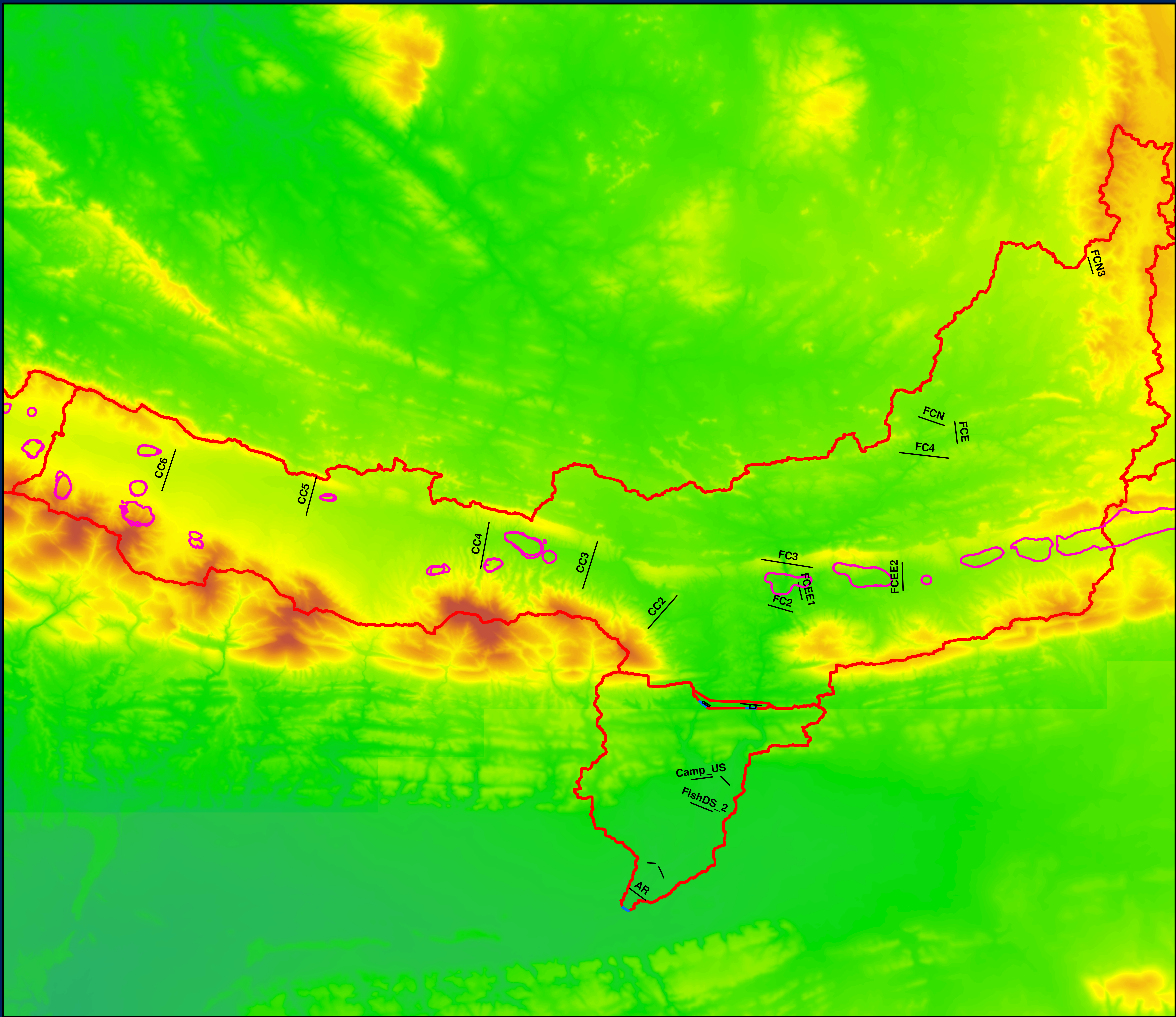
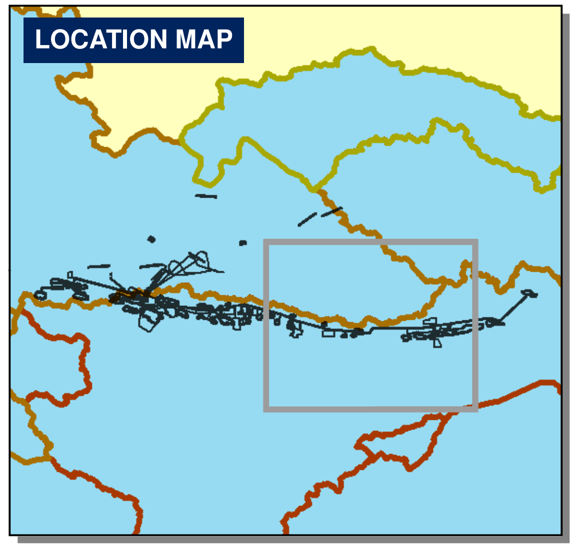
Fortescue Metals Group Ltd
The New Force in Iron Ore





LEGEND

Indicative Pit Locations

TUFLOW Inputs

Model Boundary

Outflow Boundaries

Source-Area Inflows

Reporting Hydrographs

Topography

Value

High : 800

Low : 300

N

0 0.5 1 2 3 4 Kilometers

Flying Fish TUFLOW Model Domain

Date: 4/01/2018
Size: A3L
Revision: 2
Confidentiality: 1

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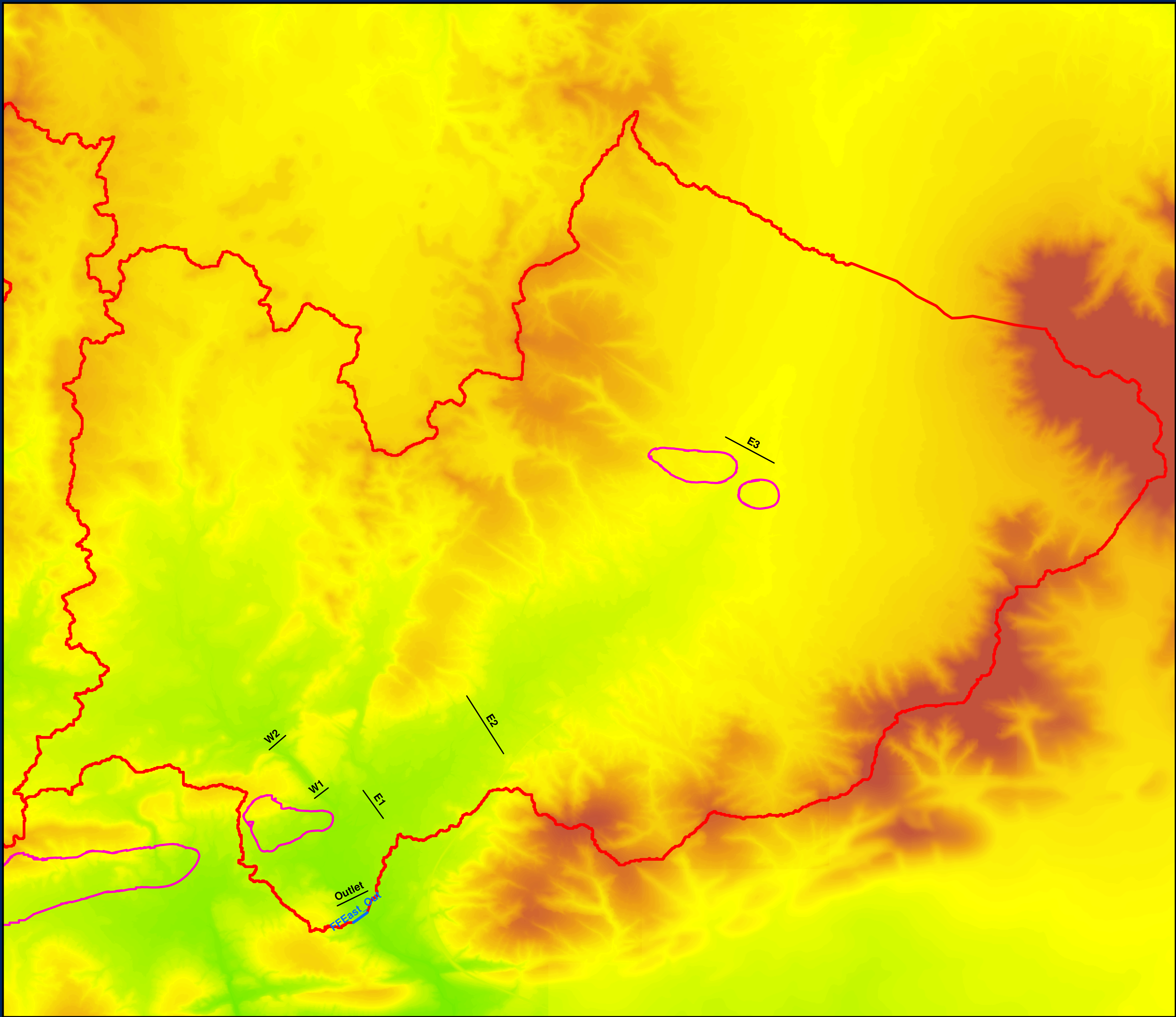
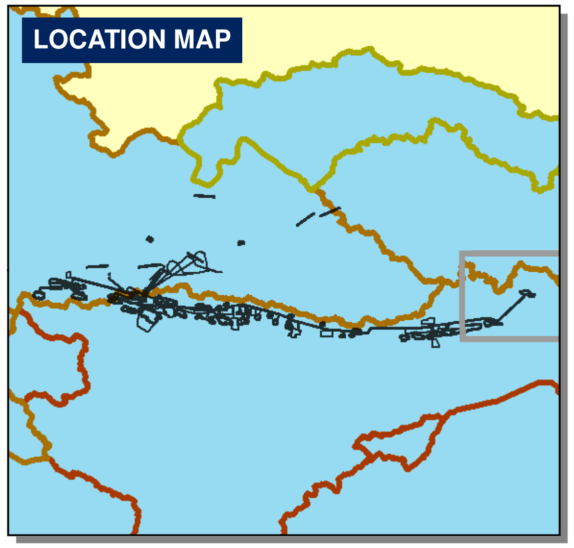
Coordinate System: MGA50
Document Name: Flying Fish TUFLOW Model Domain

Fortescue Metals Group Ltd
The New Force in Iron Ore





LEGEND

Indicative Pit Locations

TUFLOW Inputs

Model Boundary

Outflow Boundaries

Source-Area Inflows

Reporting Hydrographs

Topography

Value

High : 800

Low : 300

N

0 0.3 0.6 1.2 1.8 2.4 Kilometers

Flying Fish East TUFLOW Model

Date: 4/01/2018
Size: A3L
Revision: 2
Confidentiality: 1

Drawn By: Ryan Warrington
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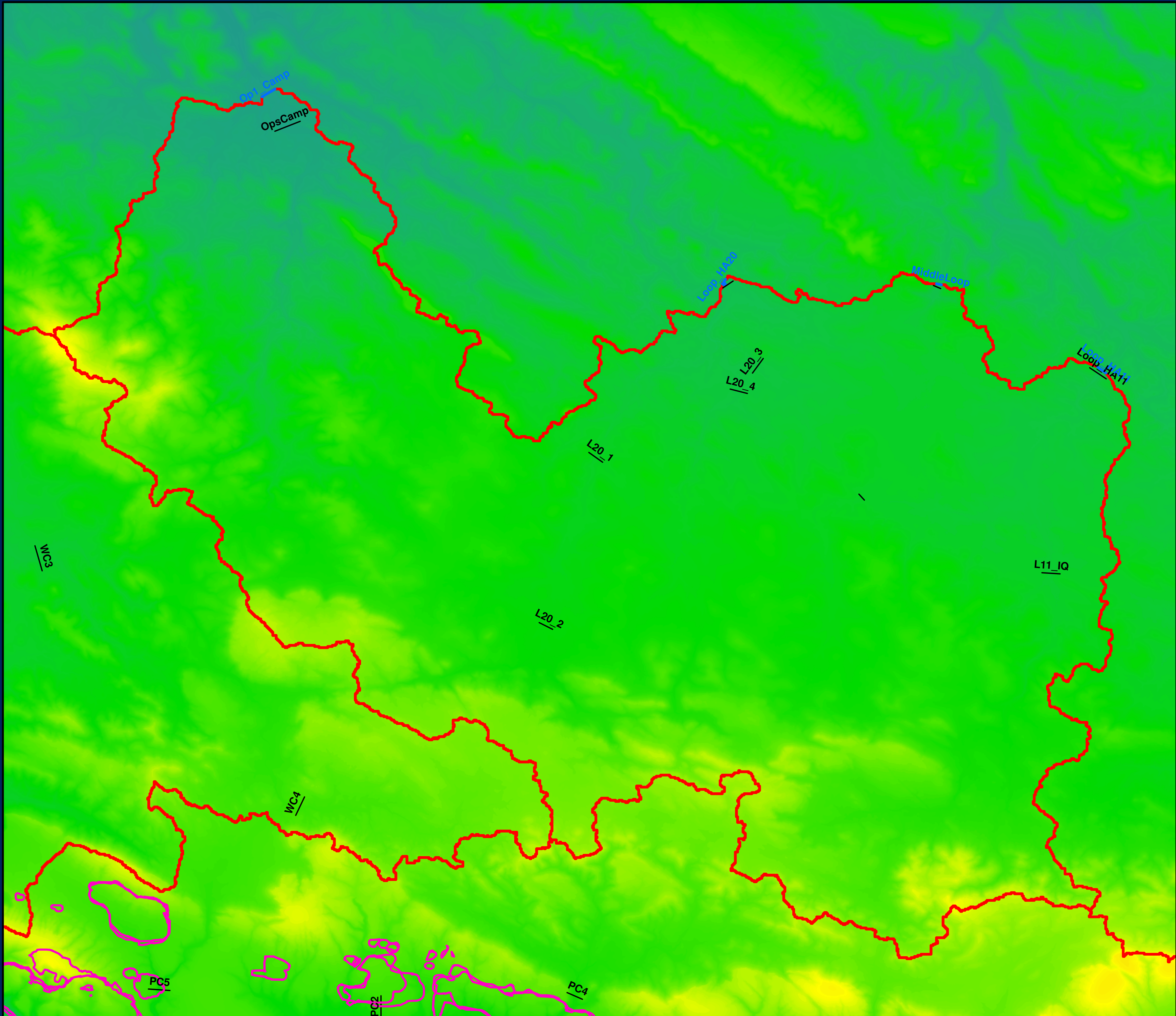
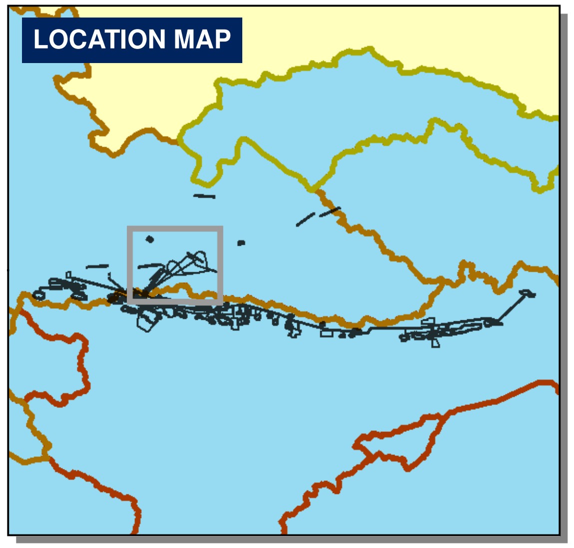
Coordinate System: MGA50
Document Name: Flying Fish East TUFLOW Model

Fortescue Metals Group Ltd
The New Force in Iron Ore





LEGEND

Indicative Pit Locations

TUFLOW Inputs

Model Boundary
Outflow Boundaries
Source-Area Inflows
Reporting Hydrographs

Topography

Value

High : 800

Low : 300

N

0 0.25 0.5 1 1.5 2 Kilometers

Infrastructure TUFLOW Model Domain

Date: 4/01/2018
Size: A3L
Revision: 2
Confidentiality: 1

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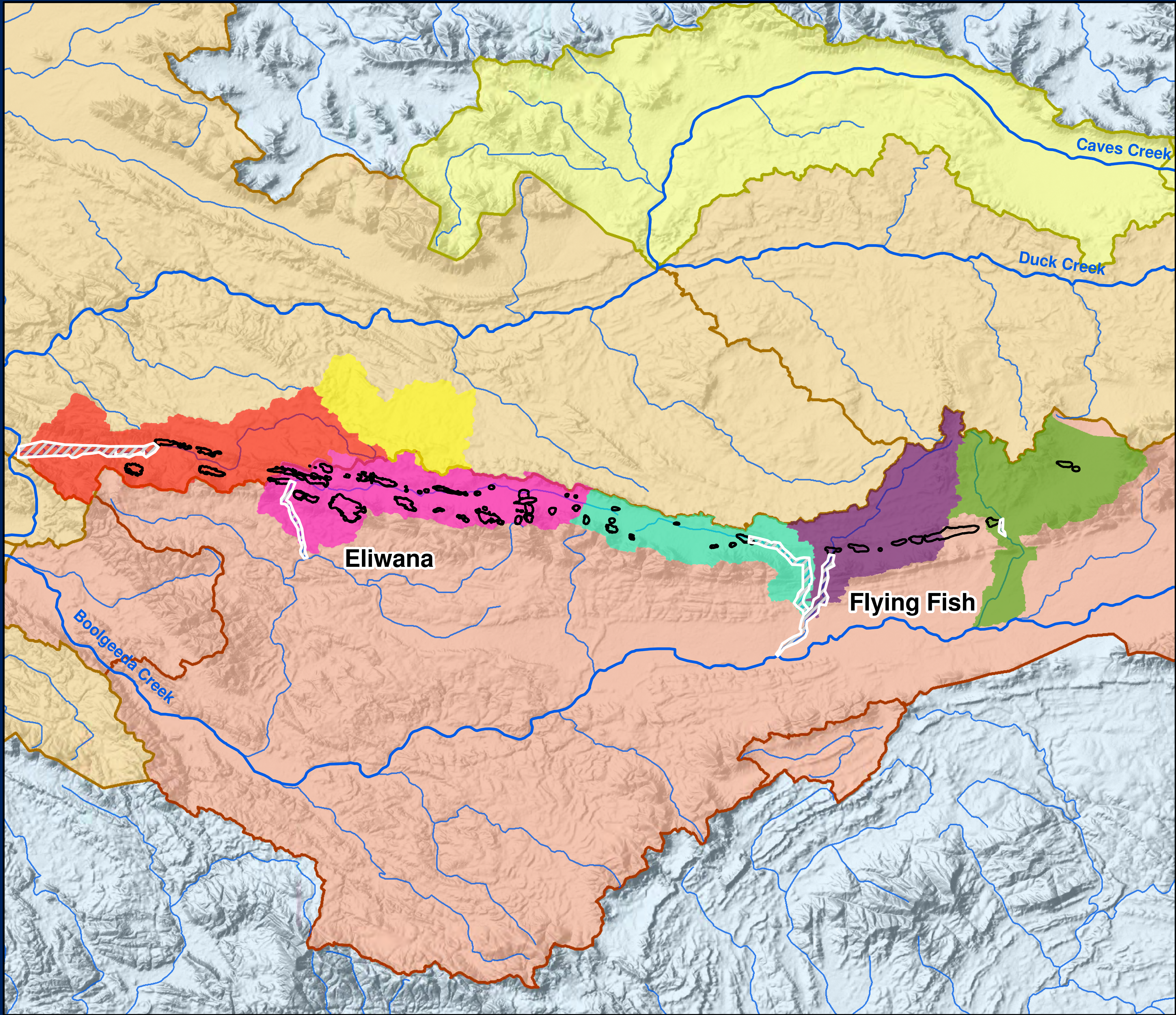
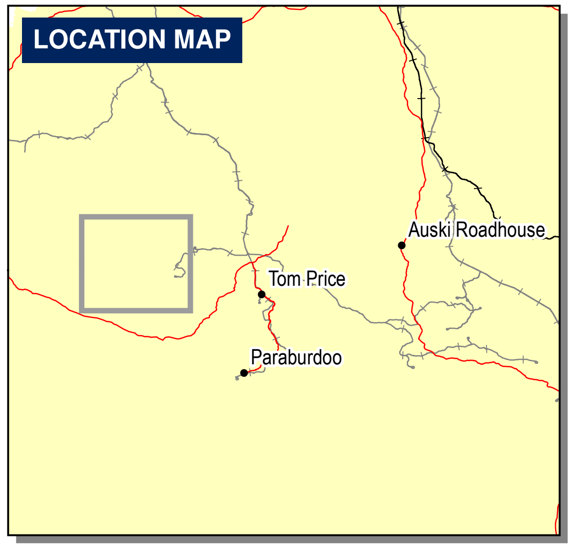
Fortescue Metals Group Ltd
The New Force in Iron Ore





LEGEND

- Potential Impact Areas
- Watercourses
- Indicative Pit Locations

Catchments

- Duck Creek
- Boolgeeda Creek
- Caves Creek
- Strike East
- West Creek
- Flying Fish 1
- Flying Fish 2
- Pinarra Creek
- Infrastructure Area

N

0 1.75 3.5 7 10.5 14 Kilometers

Potential Impact Areas

Date: 4/01/2018
Size: A3L
Revision: 2
Confidentiality: 1

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Fortescue Metals Group Ltd
The New Force in Iron Ore

Appendix 1: Pilbara Ephemeral Flow Variation

Pilbara Turbidity Examples (Top: Hamersley Gorge 31/3/10, 17/1/11, 23/3/11, 7/5/11. Bottom: Weeli Wolli Creek 13/1/12, 19/1/12)

Appendix 2: Baseline Geomorphology Assessment

Baseline Geomorphology Assessment for Eliwana and Flying Fish Deposits Fortescue Western Hub

Submitted to: **Fortescue Metals Group, Ltd.**

TETRA TECH

Submitted by: Tetra Tech Coffey

370 Murray Street

PERTH WA 6000 Australia

www.tetratech.com/australia

August, 2017

TABLE OF CONTENTS

TABLE OF FIGURES

1. INTRODUCTION

Fortescue Metals Group (FMG) is investigating the development of its Eliwana (Brockman Iron Formation) and Flying Fish (Mara Mamba Iron Formation) deposits to establish the "Western Hub" in the West Pilbara region southwest of its existing Solomon Hub (**Figure 1**). This will involve mine development both at and above the valley floor, development of mine infrastructure on the valley floor and hillsides and construction of a railway transportation corridor that crosses a number of both well and poorly-defined channels and drainages and potentially crosses over Rio Tinto's existing railway in the vicinity of Hamersley Station prior to linking into FMG's existing Hamersley railway. The mining is to be located in the sub-drainages of the Ashburton River catchment (Pinarra and Boolgeda Creeks and their tributaries and an informally named Western Channel). The approximately 140 km-long railway corridor is likely to be located in the Duck and Cave Creeks catchments that drain to the Ashburton River and in the Weelamurra and Zalamea Creek catchments that drain to the Fortescue River (**Figure 2**). In the vicinity of the Rio Tinto railway, the hydrology is extremely complex, the result of both natural and man-made (Rio Tinto railway embankment) diversions of primarily sheet floods to both Caves Creek and Weelamurra Creek.

The objective of this reconnaissance-level study was to develop a baseline geomorphic characterization of the project. The study has involved a desktop assessment based on information (pit shells, infrastructure locations, aerial photography, still and video photography) and data [topographic, overburden depths, hydrologic, hydraulic (TUFLOW output)] provided by FMG, a 3-day field based site assessment that included sampling of both surface and subsurface bed materials, and a preliminary analysis of sediment transport processes. Site hydrology is based on a preliminary assessment conducted by MWH (2011) for FMG and subsequent refinements by FMG that were used in the TUFLOW modelling and the site geology and groundwater conditions are based on an assessment conducted by Golder Associates (2017) for FMG.

2. SITE RECONNAISSANCE

A 3-day field reconnaissance of the Western Hub area was conducted between April 25 and April 27, 2017 by Dr. Mike Harvey (Tetra Tech), Mr. Ryan Warrington (FMG), Mr. Phil Bussemaker (PSM) and Mr. Gary Lazarov (FMG). During the site visit of the Western Hub, sections of Pinarra Creek, Western Channel, Boolgeeda Creek and tributaries were inspected and bed material sediment samples were collected. In addition, portions of the proposed railway corridor in the vicinity of the Caves Creek and Weelamurra Creek crossings were visited. Site visit photographs are included in **Appendix A** and referenced in the report.

2.1. Background

In general terms, the site visit confirmed that the channels within the Western Hub are similar to those in other regions of the western Pilbara where geomorphic processes tend to be driven by infrequent, high intensity and short duration hydrologic events (Lesleighter, 2012 ; Harvey et al, 2014; Fortescue, 2015b; Tetra Tech, 2016). Based on the extensive presence of high-water-mark (HWM) indicators (primarily large woody debris piles) and large imbricate boulders in the channels, it is highly likely that the channels in the area have been subjected to high flows by one or more Tropical Cyclones (TC) including the more recent ones, TC Carlos (2011), TC Heidi (2012), TC Peta (2013) and TC Christine (2014).

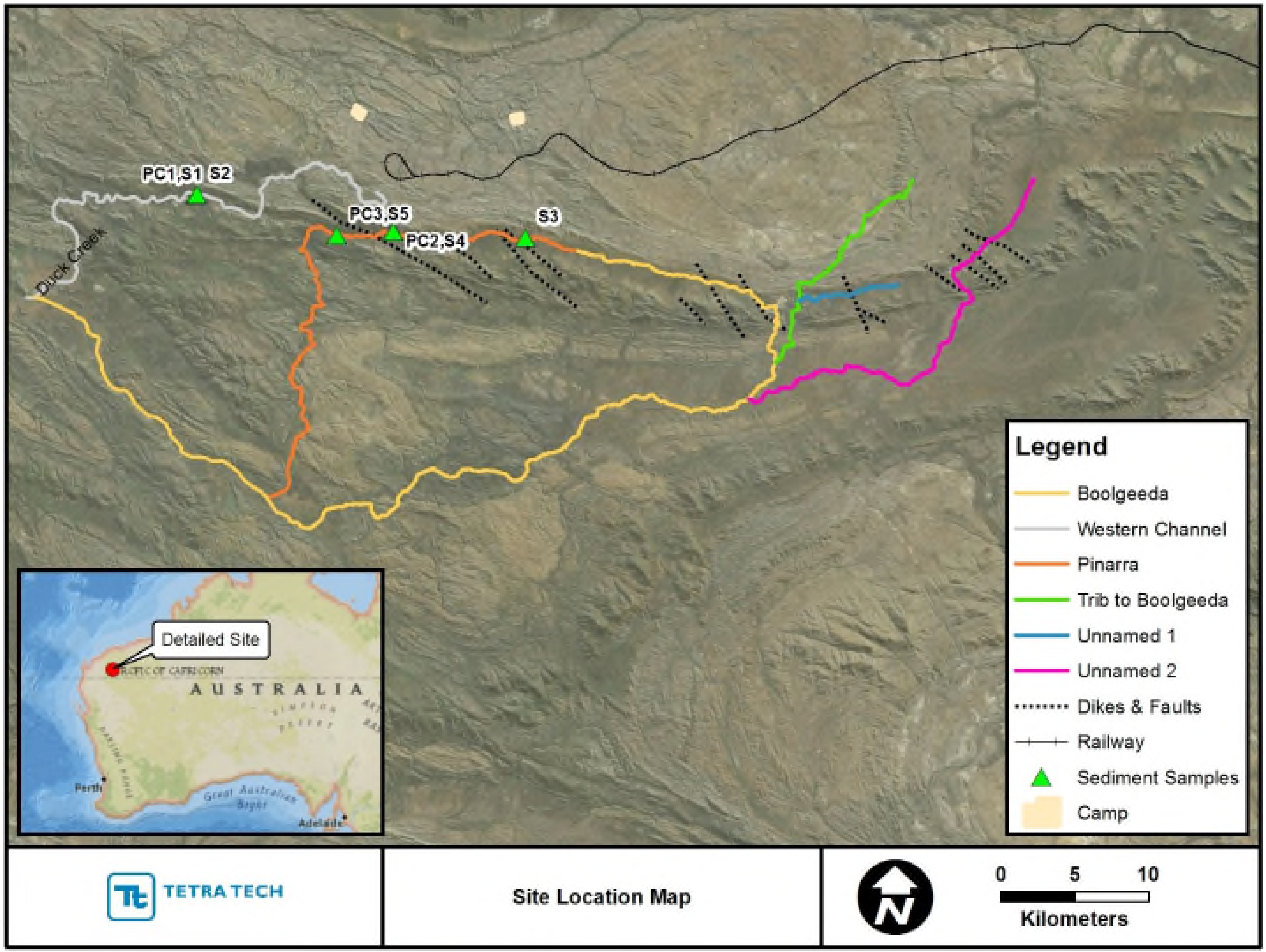

Figure 1. Site location map.

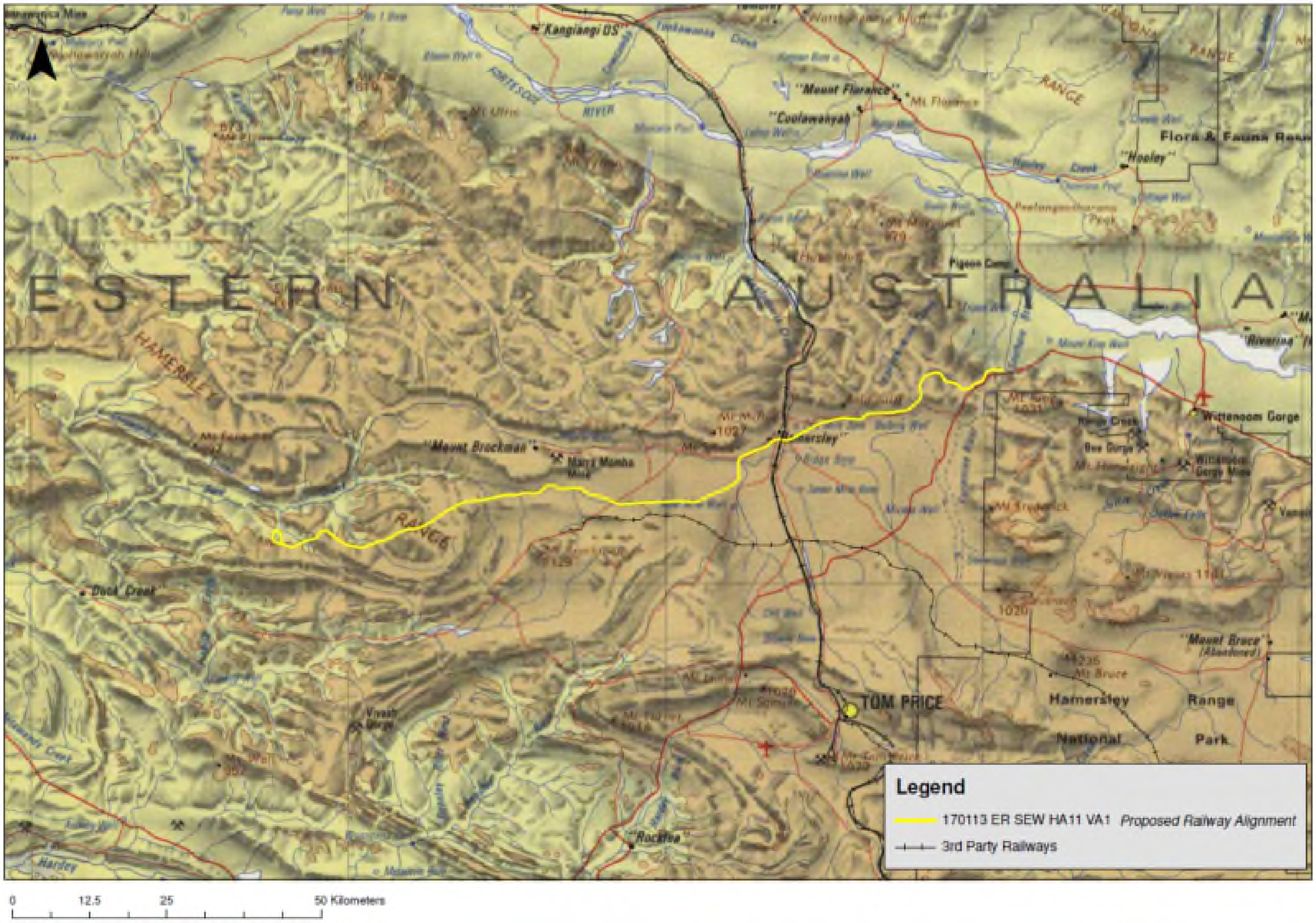

Figure 2. Proposed railway alignment.

The morphology of the alluvial sections of the ephemeral-flow creeks tends to be a relic of the last major flow event (Graf, 1988) and as a result there will always be a wide range of channel conditions distributed over both time and space (Tooth and Nanson, 2004).

Given the geologic setting of the Western Hub, which is located on the northern flank of the steeply dipping (to the south) Brockman Syncline, the creeks tend to be located within east-west running strike valleys underlain by the less erosion resistant, shale-dominated, Members (West Angelas, Paraburdoo, Bee Gorge) of the Wittenoom Formation that are flanked by the Marra Mamba Iron Formation that forms the northern ridge and the Brockman Iron Formation that forms the southern ridge (Golder Associates, 2017). Numerous, generally NW-SE trending dolerite dikes and strike-slip faults cross the E-W trending strike valleys and are probably responsible for the extensive presence of valley floor-spanning bedrock outcrops that provide local grade control in some of the creeks as well as being a local source of coarse (cobble and boulder) sediments within the channels. Hydrogeological interpretation (Golder Associates, 2017) indicates that the faults and dikes are responsible for a highly compartmentalized groundwater system. It is possible that cemented calcretes and silcretes are present in what has been identified as overburden (Golder Associates, 2017) and these also could be creating shallow perched alluvial aquifers (Harvey et al, 2014). Based on the available boring logs (Golder Associates, 2017) and field observations, the overburden underlying the creeks in the Western Hub includes modern alluvial and colluvial deposits, clayey detritals, cemented detritals, hardcap detritals as well as silcrete and calcrete layers.

In the Pilbara, groundwater-dependent riparian vegetation (GDE) associations (Eucalyptus camaldulensis, Melaleuca argentea) tend to indicate where the depth to groundwater is less than about 10m (Department of Water, 2010; McLean, 2014). However, neither species is located in the Western Hub area. In the more eastern Flying Fish area (Boolgeeda Creek), potential GDE association includes Eucalyptus xerothermica, Corymbia hamerslayana and Acacia aptaneura woodlands while in the more western Eliwana area (Pinarra Creek and Western Channel), the potential GDE association includes Eucalyptus victrix and Eucalyptus xerothermica woodlands (FMG, 2017 cited in Golder Associates, 2017). These potential GDE associations may be dependent on ephemeral recharge of perched alluvial aquifers under the creek beds. The location and impact to the potential GDE's will be discussed further in a Hydrogeological Impacts Assessment that will be completed in late 2017 (FMG personal communication).

Depending on the strength of the rocks, the gorges that are located where the creeks flow down-dip out of the strike valleys are, either very narrow and contain extensive bedrock outcrop and large colluvial boulders or are wider and contain finer alluvium. The former situation creates significant local base level controls for the upstream channels (**Figure 3**). In common with many of the catchments within the Hamersley Range, the contribution of sediment from the hillslopes underlain by the harder, ridge forming lithologies, under undisturbed conditions is very low, the result of the presence of extensive bedrock outcrop and gravel-armored hillslopes. Under these circumstances the majority of the bed material sediments being transported during the infrequent flow events are derived from reworking of in-channel storage and remobilization of sediments from the extensive alluvial fans that flank the channels (Harvey et al., 2014; Tetra Tech, 2016). However, the extensive presence of less erosion resistant lithologies (Jeerinah Fm.), primarily in the area to the north of the Eliwana and Flying Fish deposits, may indicate that the sediment yields to the higher order channels from the south-flowing tributaries may be higher.

2.2. Field Observations

Observations made during the field inspection of the Western Hub area as well as review of aerial imagery, data and reports made available by FMG were used as a basis for this section of the report.

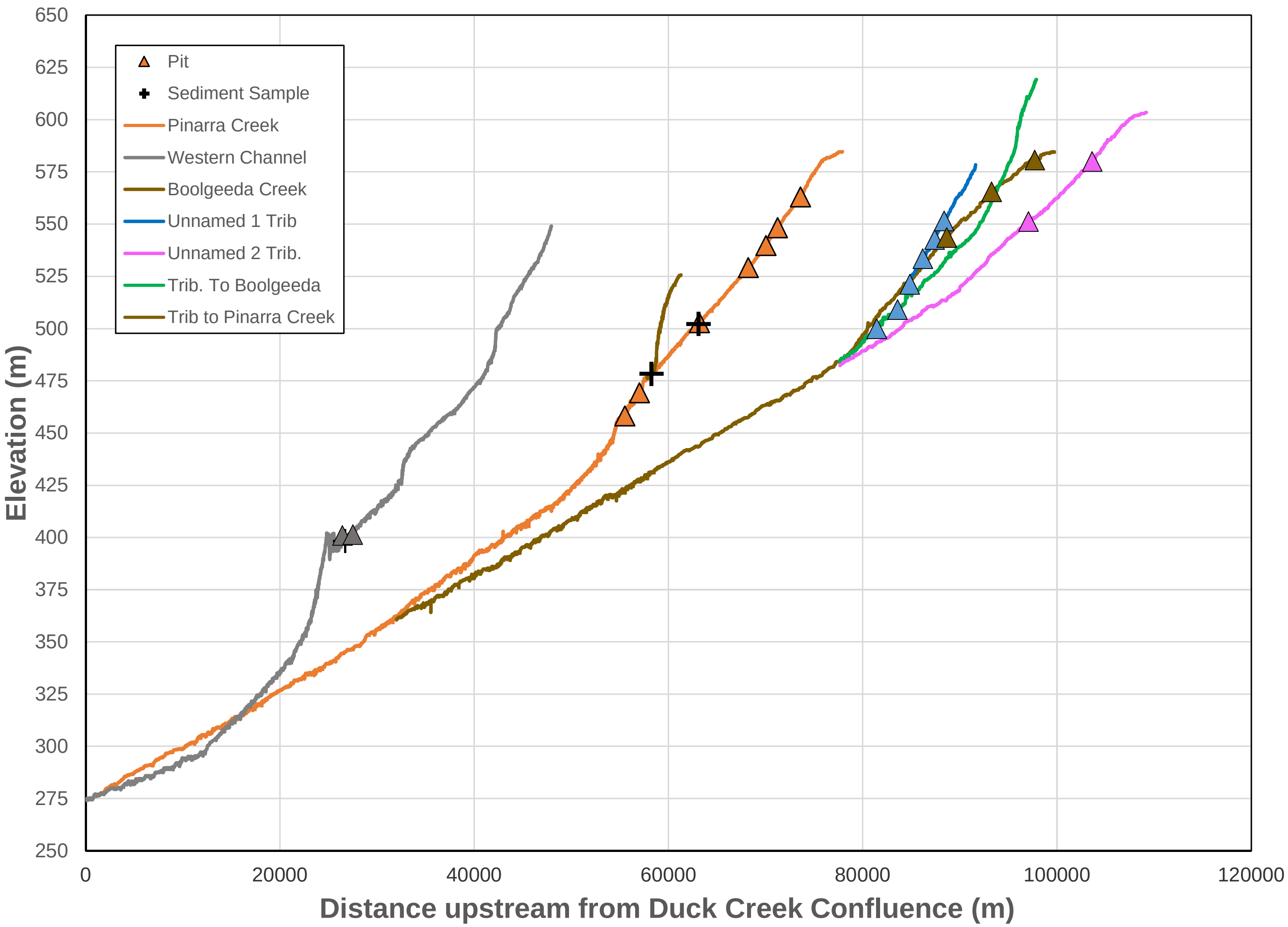

Figure 3. Longitudinal channel profiles (the origin is the confluence of Boolgeeda and Duck Creeks).

2.2.1. Pinarra Creek

Pinarra Creek is a 43-km long, west-flowing stream that has its confluence with Boolgeeda Creek (a tributary to Duck Creek) about 21km downstream of the Broadway Gorge. The approximately 22-km long reach that extends from the downstream end of the Broadway Gorge to the headwaters (Upper Pinarra Creek) and occupies the strike valley was subdivided into 6 subreaches (P1 is the upstream subreach) based on the existing channel morphology (single channel, braided, poorly defined) and the width of the valley floor as determined by bedrock outcrop, pediments or marginal alluvial fans (**Figure 4**). Valley floor-spanning cross sections derived from TUFLOW model output (flow depths) for each of the subreaches are provided in **Figures 5a** (P1, P2, P3) and **5b** (P4, P5, P6). The locations of the selected cross sections are highlighted on Figure 4. The cross sections were all reduced to a common scale in order to show the relative sizes (bankfull depths and widths) and morphologies of the Pinarra Creek channel in each of the subreaches. **Figure 6** provides a longitudinal profile of Upper Pinarra Creek. Included on the profile are the subreach boundaries, the locations of sediment samples, the locations of the pits that directly intersect the channel, the locations of the major tributaries, the locations of the generally NW-SE trending faults and dikes and the depths of the overburden. Surface and sub-surface bed material gradations determined from pebble counts and laboratory sieving, respectively are provided in **Figure 7** and **Figure 8**.

Pinarra Creek in Subreach (SR) P1 is about 3.3 km long and is laterally confined on both sides by alluvial fans and as such the channel tends to be single thread, relatively narrow (about 15m) and shallow (bankfull depth <1m) and is bounded by vegetation (Figure 6a). Overburden depths on the order of 10m in the lower portion of the subreach (Figure 7) appear to be correlated with relatively dense riparian tree stands, which may indicate the presence of shallow groundwater in a perched alluvial aquifer (FMG mapping of potential GDE as reported in Golder Associates, 2017) in the reach located immediately upstream of the mapped fault in SR P2. In contrast, overburden depths in excess of 40m in the upstream, flatter gradient portion of the SR (Figure 7), may actually represent the thickness of the bounding alluvial fans that have prograded out onto the valley floor and do not appear to support potential GDE riparian vegetation.

Pinarra Creek in SR P2 is about 4.8 km long and is less confined by the flanking alluvial fans and as a result the channel tends to be multi-thread and braided, probably the result of historic sediment deposition from the more confined upstream reach. A number of channels occupy the valley floor at different elevations and at some locations are indistinct among the woodland vegetation (**Figure A.1**) but the primary channel (**Figure A.2**) has similar dimensions to that in SR P1 (Figure 6a). The bed material recently in transport in the main channel (**Figure A.3**) tends to be finer than that observed in the less well developed channels (**Figure A.4**). Based on Sample S3 that was collected in the main channel, the median (D_{50}) size of the recently transported material is on the order of 12 mm (Figure 8). Based on pebble counts of the surface sediments in other reaches of Pinarra Creek, the D_{50} of the bed material is on the order of 35mm (Figure 7). In the upper portion of the subreach, overburden depths between the 2 mapped faults exceed 60m and may represent alluvial fill within a graben structure (Figure 6). The general paucity of riparian tree species along this portion of the creek would tend to suggest that there is no shallow perched alluvial aquifer in this part of the subreach In contrast, in the lower portion of the subreach, the overburden depths are generally very shallow, possibly the result of faulting, and the presence of potential GDE riparian tree species tends to suggest the presence of a perched alluvial aquifer.

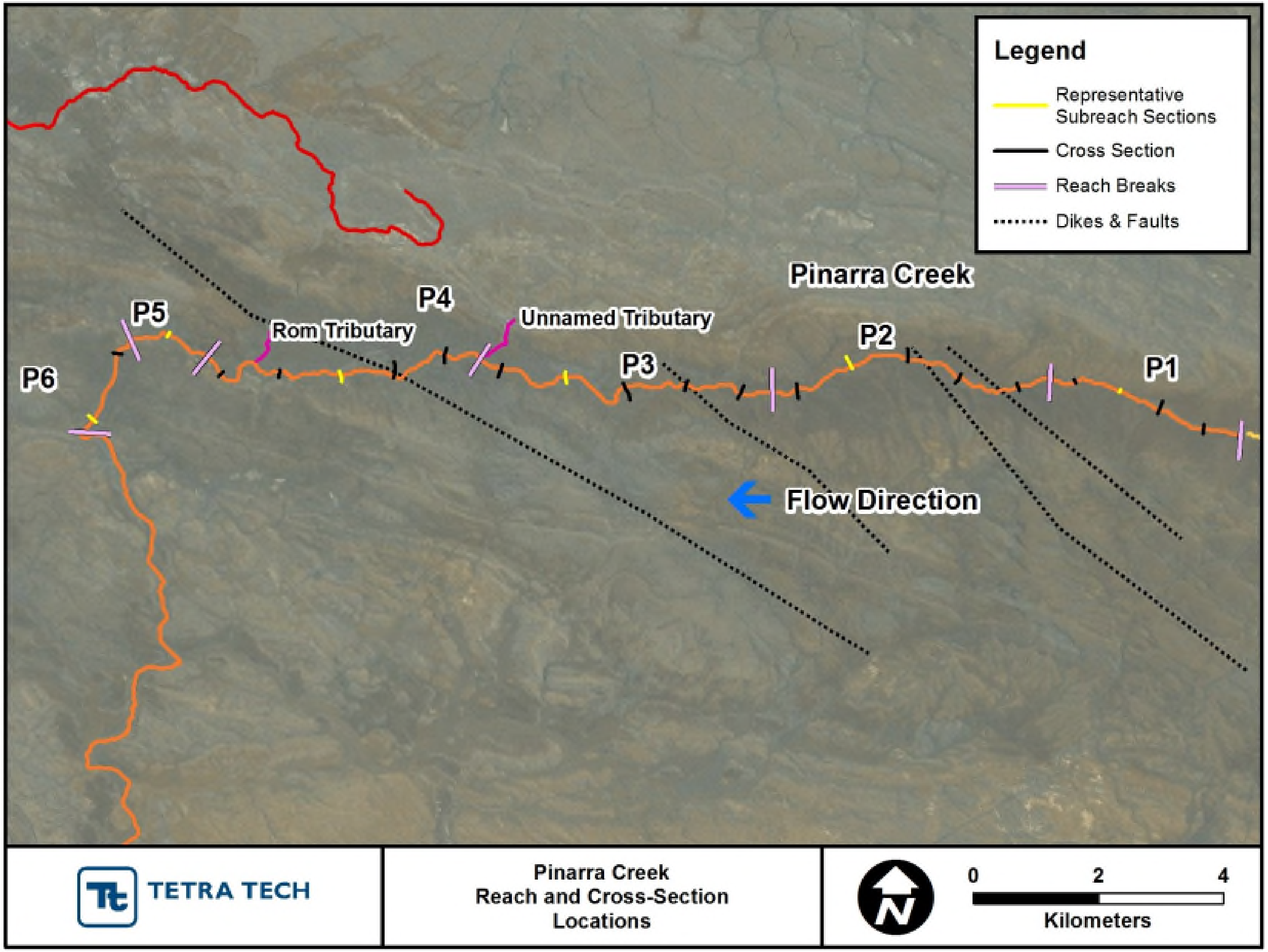

Figure 4. Pinarra Creek subreach and cross-section locations.

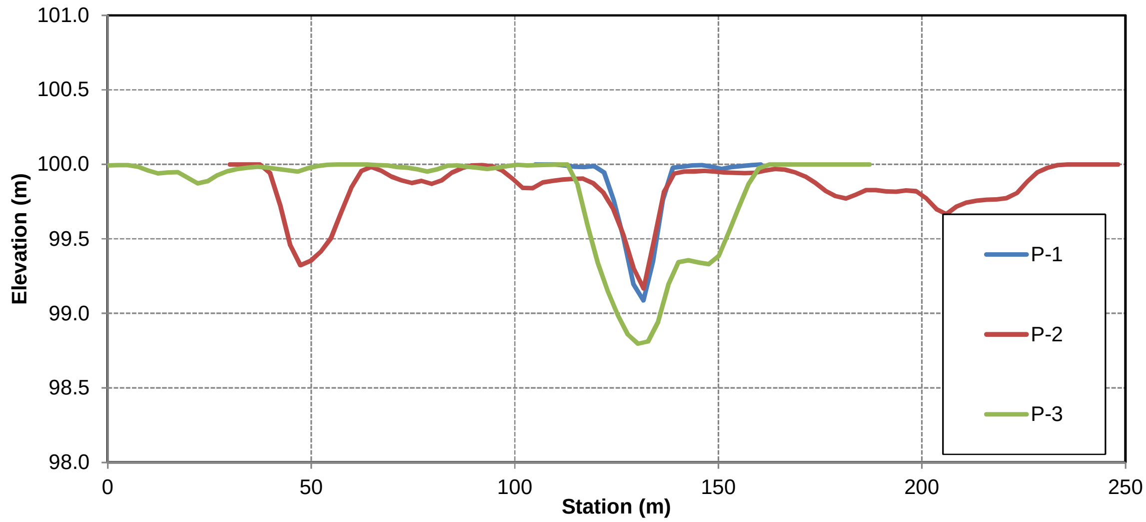

Figure 5a. Representative cross-sections for the sub-reaches P-1, P-2 and P-3 along Pinarra Creek.

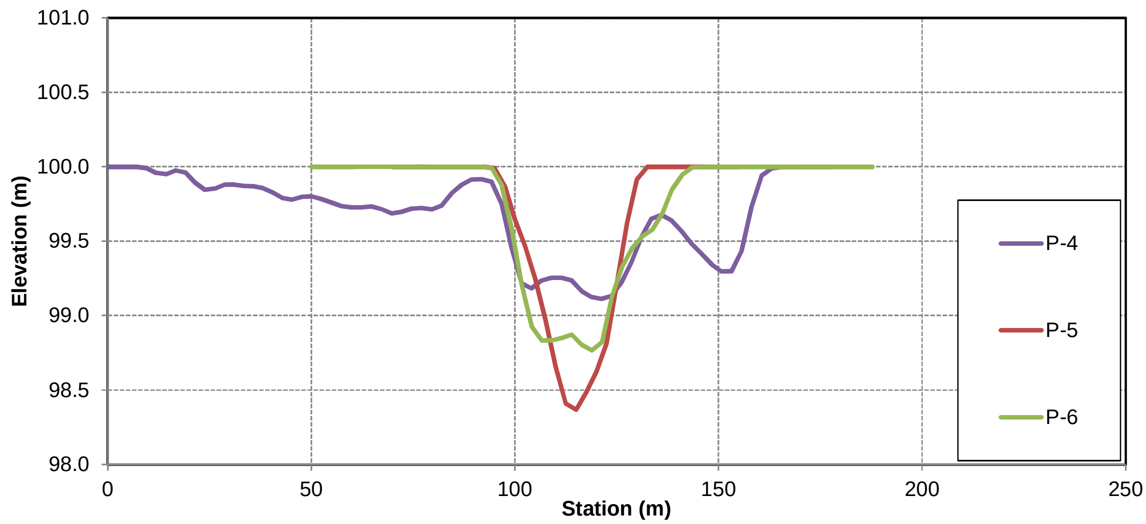

Figure 5b. Representative cross-sections for the sub-reaches P-4, P-5 and P-6 along Pinarra Creek.

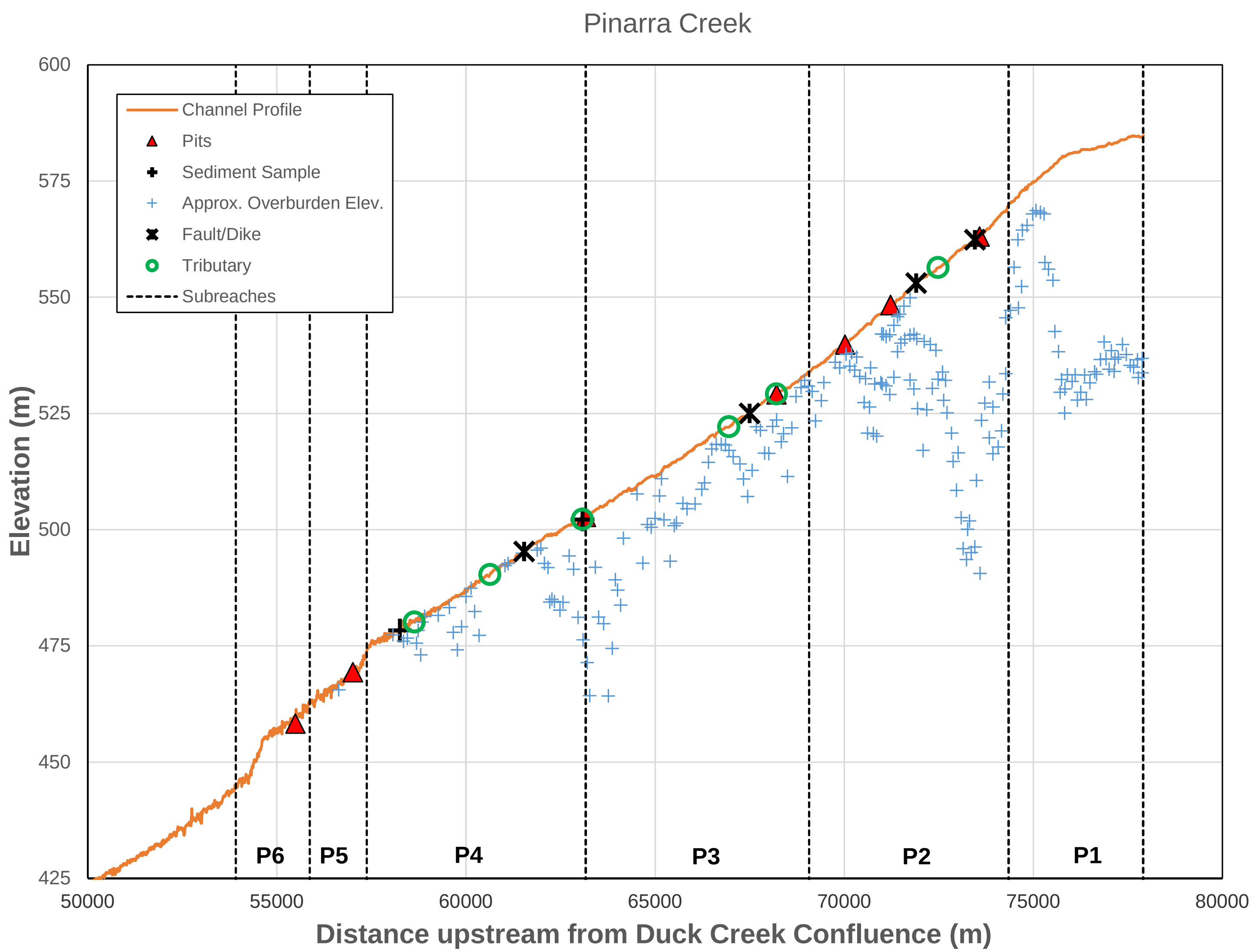

Figure 6. Pinarra Creek channel and overburden profiles.

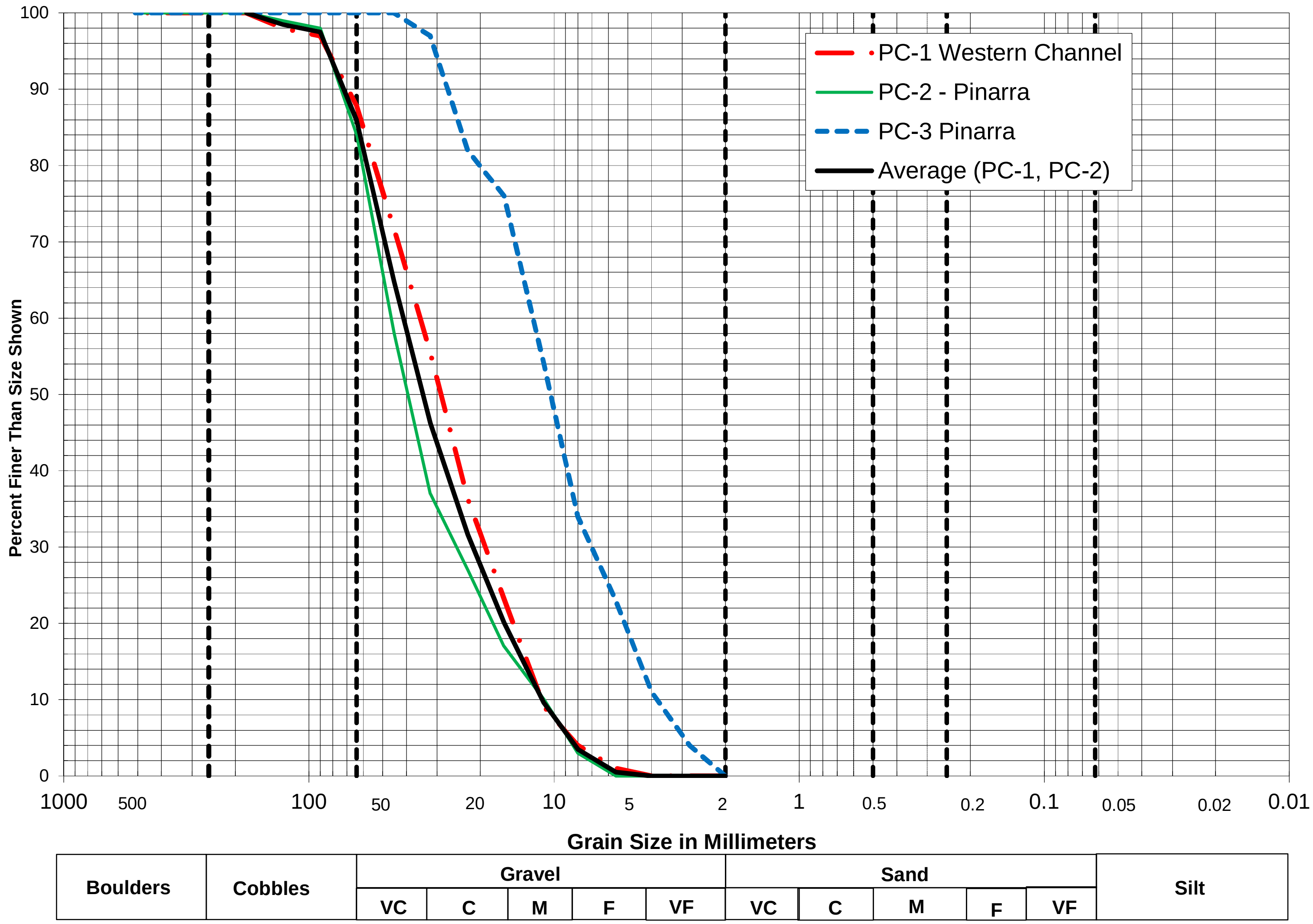

Figure 7. Sediment gradation curves from Pebble Counts.

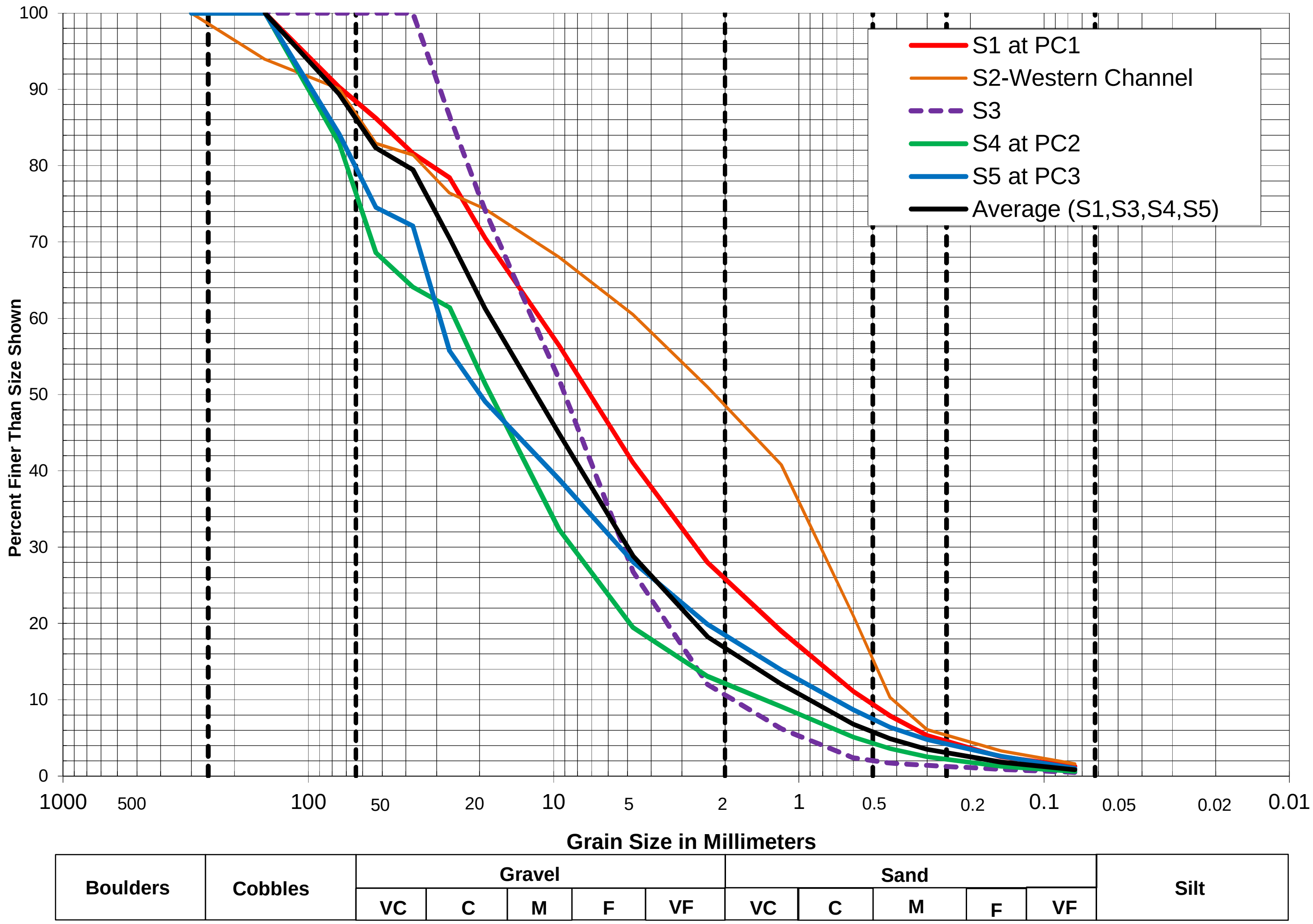

Figure 8. Sediment gradation curves from bulk sediment samples.

Pinarra Creek in SR P3 is about 5.2km long and contains both single thread and multi-thread channel segments. The single thread channel segments (**Figure A.5**) tend to be located where the valley width is more constrained by marginal alluvial fans and the multi-channel segments are located in the less laterally constrained reaches (**Figure A.6**). Single channel width is on the order of 50m and the depth is about 1.5m (Figure 5a). For most of the subreach the depth of the overburden is relatively shallow on the order of about 10m which correlates quite well with the presence of potential GDE riparian vegetation (Figure 6). Closer to the downstream boundary of the subreach overburden depths increase to over 25m which may be tied to the presence of a relatively large tributary on the north side of the valley. Based on the pebble count of the surface sediments (PC2) and associated bulk sample of the subsurface sediments (S4) the D_{50}'s are 40 mm (Figure 7) and 18 mm (Figure 8), respectively.

The unnamed, south flowing tributary just upstream of the P3/P4 subreach boundary (Figure 4) conveys a reasonable amount of both gravel (**Figure A.7**) and sand-sized (**Figure A.8**) sediment, the bulk of which has a low iron content because of the extensive presence of shales and sandstones of the Jeerinah Fm. (Golder Associates, 2017) in the contributing watershed. The relatively weak rocks that form the northern ridge through which the tributary drains do not significantly constrict the channel but the shallow depth to bedrock beneath the creek bed appears to be supporting potential GDE riparian tree species (**Figure A.9**).

Pinarra Creek in SR P4 is about 5km long and is primarily a single thread channel (**Figure A.10**) that is flanked on the north side by bedrock outcrop (**Figure A.11**) and on the south side by gently sloping gravel-capped pediments that have been cut into softer bedrock (**Figure A.12**). Depending on local aggradation or degradation in the channel, the bankfull depths range from about 0.5m to in excess of 1.5 m (**Figure A.13**) (Figure 5b). Except for the short reach immediately downstream of the P3/P4 boundary, the overburden depths are generally very shallow in this subreach (Figure 6) and as a result the depth to any perched groundwater is likely to be shallow which supports the potential GDE riparian trees (**Figure A.14**). Approximately 1000m upstream of the downstream boundary of subreach P4, a south flowing tributary (ROM tributary) enters Pinarra Creek (Figure 4). The tributary traverses a very narrow bedrock gorge formed in the erosion resistant Marra Mamba Iron Formation (**Figure A.15**). During low to moderate flows relatively fine sands and gravels are conveyed down into Pinarra Creek (**Figure A.16**). However, during larger flood events (**Figure A.17**) boulder sized sediments are transported in the very steep and confined channel (**Figure A.18**) and as a result cobble to boulder size sediments have formed a lag deposit in Pinarra Creek at and downstream of the confluence that creates a local grade control in the channel (**Figure A.19**). Surface and subsurface bed material gradations were determined for the lower portion of the subreach. Because of backwater from a very sharp bend downstream during high flow events the D_{50} of the surface gradation of the bed material (PC3) is about 12mm (Figure 7), whereas the D_{50} of the subsurface (S5) gradation is 20 mm (Figure 8).

Subreach P5 includes the about 1.4km long Broadway Gorge section of Pinarra Creek that is controlled both vertically (**Figure A.20**) and laterally by bedrock outcrop (**Figure A.21**). The bedrock controlled gorge is the base level control for Upper Pinarra Creek (Figure 6). The single thread channel is about 30m wide and infinitely deep (Figure 5b). The bed material is a mixture of gravel-cobble fluvially transported sediments and colluvially derived boulders (**Figure A.22**). Overburden depths through the gorge are very shallow (Figure 6) and it is likely that the groundwater is also shallow and supports the potential GDE riparian vegetation. High water marks in the upstream part of the gorge are over 2m above the bed (**Figure A.23**).

Subreach P6 is about 1.8 km long and includes the section of Pinarra Creek that flows south and down-dip across the Brockman ridge. The single-thread, gravel bed channel is wider than in the upstream gorge section (50m) and the bankfull depth is about 1.3m (Figure 6b). The wider valley bottom that includes a floodplain (**Figure A.24**) is likely due to the presence of less erosion resistant rocks in the valley walls (**Figure A.25**). The presence of potential GDE riparian vegetation on the channel margins indicates that perched groundwater is likely located at a shallow depth above bedrock (**Figure A.26**) which is consistent with the steepening of the channel gradient in the subreach (Figure 6).

2.2.2. Western Channel

The informally named Western Channel is an approximately 47 km long, west—south-west flowing stream that has its confluence with Duck Creek about 9km upstream of the Duck Creek-Boolgeeda Creek confluence. Its headwaters are underlain by the Jeerinah Fm., and as such are unlikely to be affected by any mining. However, for the purposes of this investigation the upper approximately 25 km of the channel have been included and has been subdivided into 5 subreaches (W1 is the upstream subreach) (**Figure 9**). At the downstream end of subreach W5 the channel enters into a bedrock gorge that appears to contain what may be perennial pools. Overburden depths were not available for the Western Channel. The locations of the representative cross sections are shown on Figure 9.

Subreaches W1, W2 and W3 are all underlain by the shale and sandstone units that comprise the Jeerinah Fm. Steeper portions of the channel in W2 probably reflect the presence of more erosion resistant rock units (**Figure 10**). The dimensions of the channel increase in the expected manner in the downstream direction with the channel width increasing from about 25 m in subreach W1 to about 50m in subreach W3 and the bankfull depth increasing from about 0.8m to nearly 2m in the same two subreaches (**Figure 11a**). Review of 2006 (18/6/2006) aerial imagery (Google Earth) indicates that that the channel is single thread through most of the subreaches which tends to suggest that the sediment delivery to the channels is quite low or possibly very fine grained. Of potential interest is the presence of numerous pools within the channel in subreach W3 (Google Earth imagery dated June 18, 2006) which might be the result of faulting. A NW-SE trending fault has been mapped across Pinarra Creek (Golder Associates, 2017) that presumably extends into W3 near the upstream end of the subreach and it is more than likely that subreach W4, where the channel flows south through a gorge bounded by the Marra Mamba Iron Fm. is also fault controlled based on topography immediately to the south and the presence of dense potential GDE vegetation species (including Melaleuca sp.) where the inferred fault crosses the small west-flowing Access Road tributary along the access road to Broadway Gorge (Figure 9). Through the gorge, the channel is about 60 m wide and about 2m deep at bankfull stage (**Figure 11b**) and is bounded by potential GDE riparian vegetation.

Subreach W5 flows west within the strike valley that is bounded to the north and south by the Marra Mamba and Brockman ridges, respectively (Figure 9). In general, the channel is single thread with a width of about 25m bounded by a floodplain and a bankfull depth of about 1.5m (Figure 11b) (**Figure A.27**). However, locally along the channel bedrock crops out and forms a local base level control and coarsens the bed material (**Figure A.28**). Approximately 30cm high sand/gravel bars were observed in the well-defined reaches of the channel and indicate that during high flow events there is significant bed material transport in the channel (**Figure A.29**). Where the channel is more constricted by bedrock outcrop the bed material tends to be coarser, the result of local supply of coarser sediments and locally higher energy due to increased flow depths (**Figure A.30**).

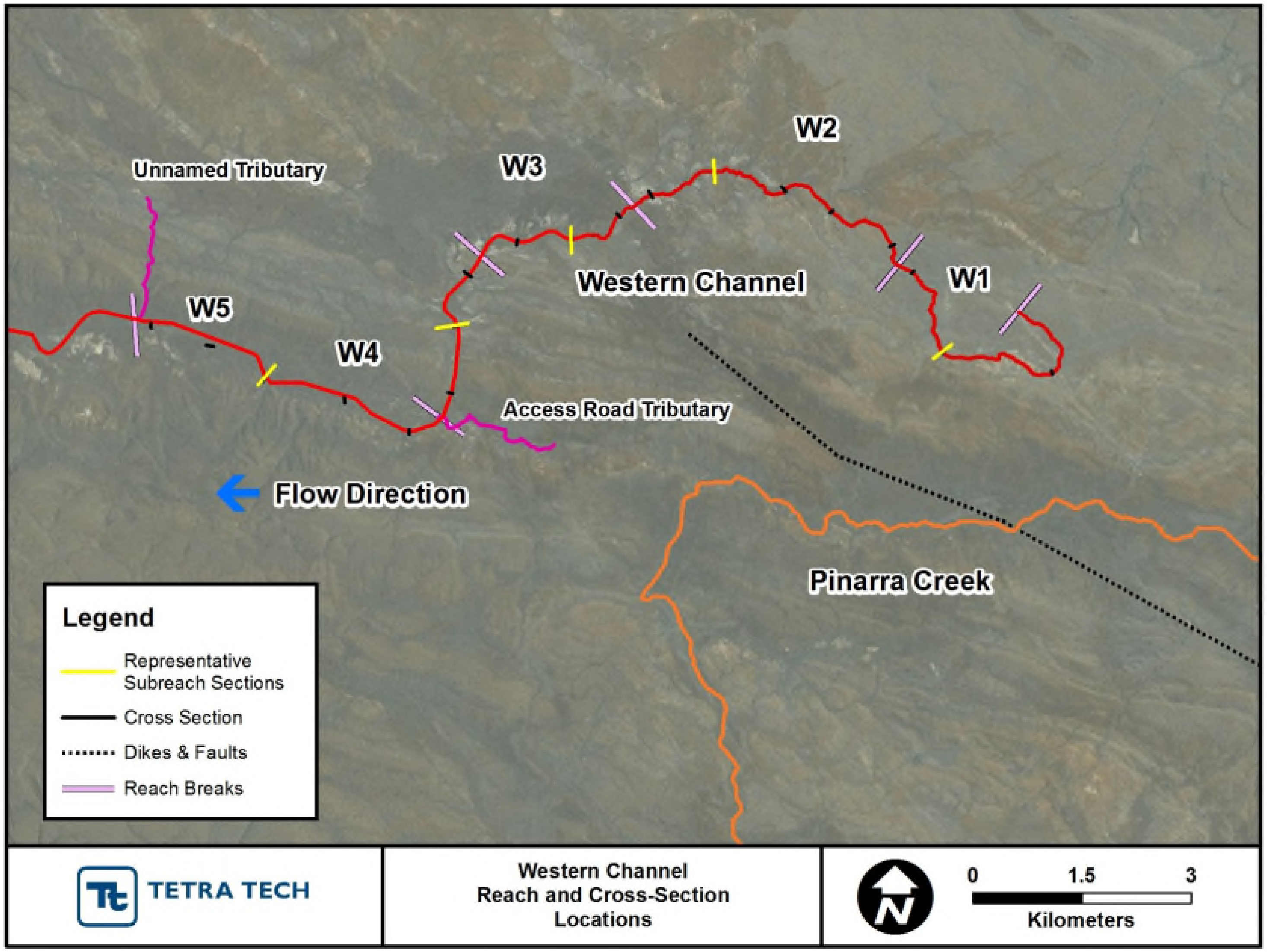

Figure 9. Western Channel subreach and cross-section locations.

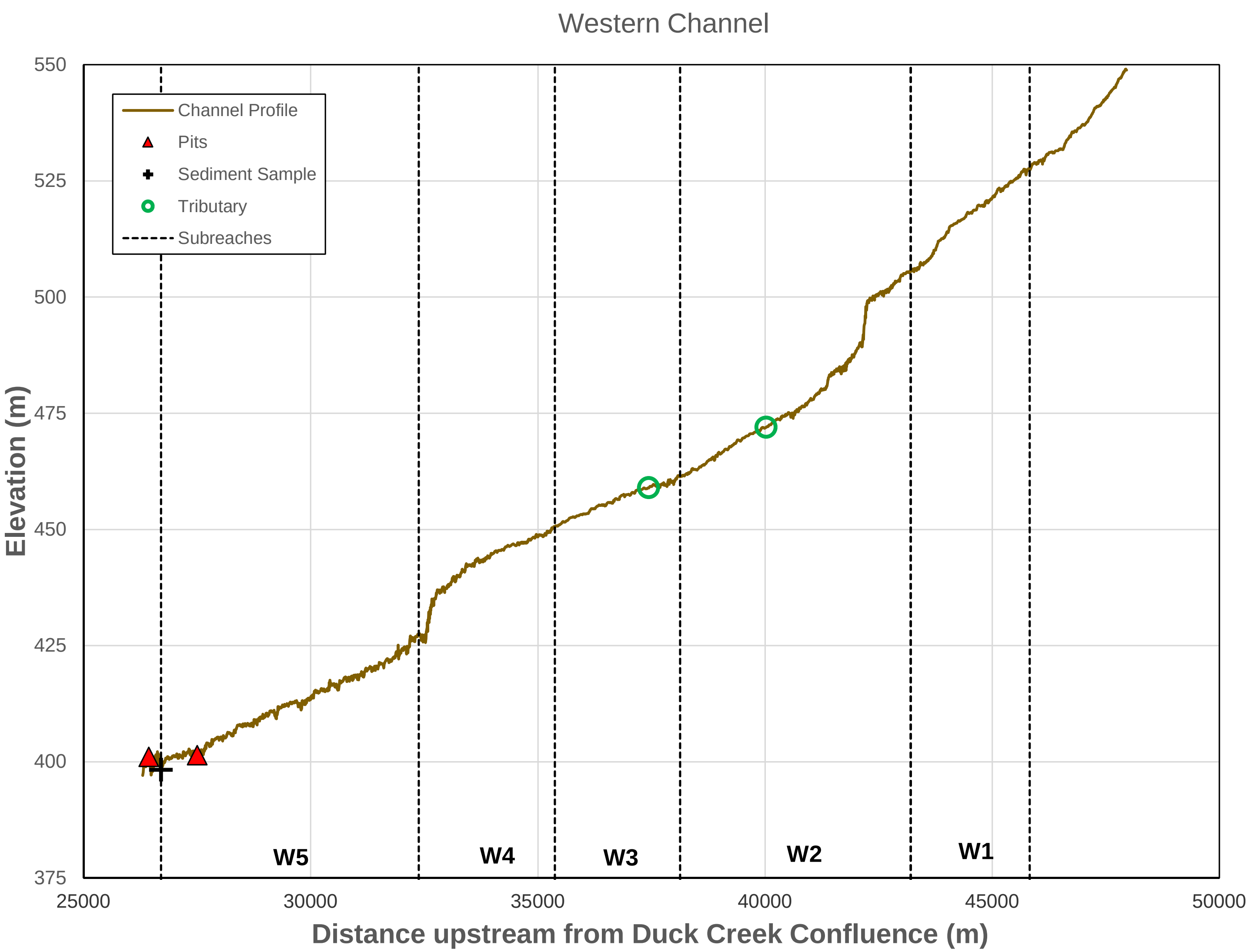

Figure 10. Western Channel longitudinal profile. (Stationing is distance upstream of the Duck Creek-Boolgeeda Creek confluence which is about 9000m downstream of the actual Confluence of Western Channel and Duck Creek)

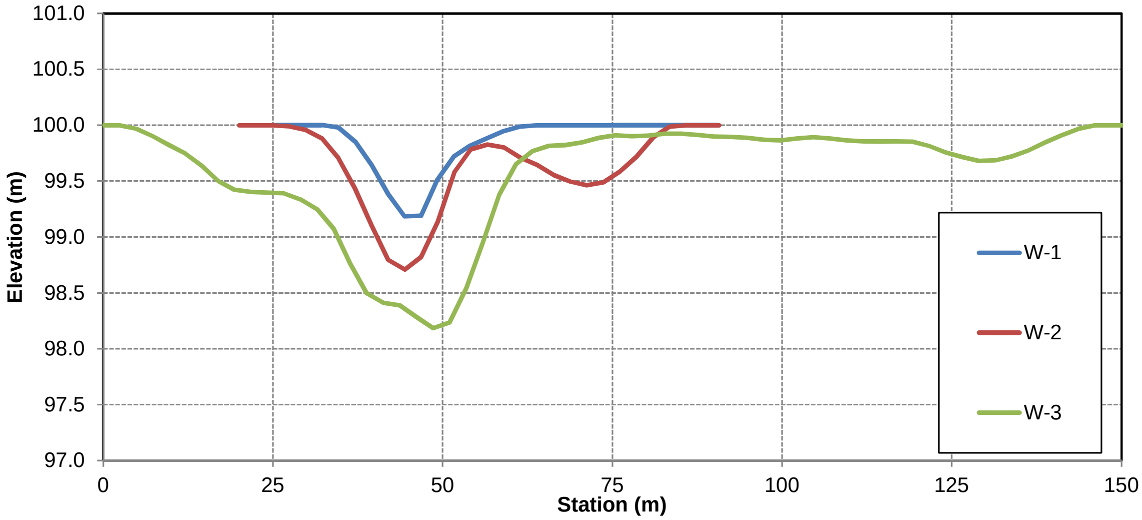

Figure 11a. Representative cross-sections for the sub-reaches W-1, W-2 and W-3 along the Western Channel.

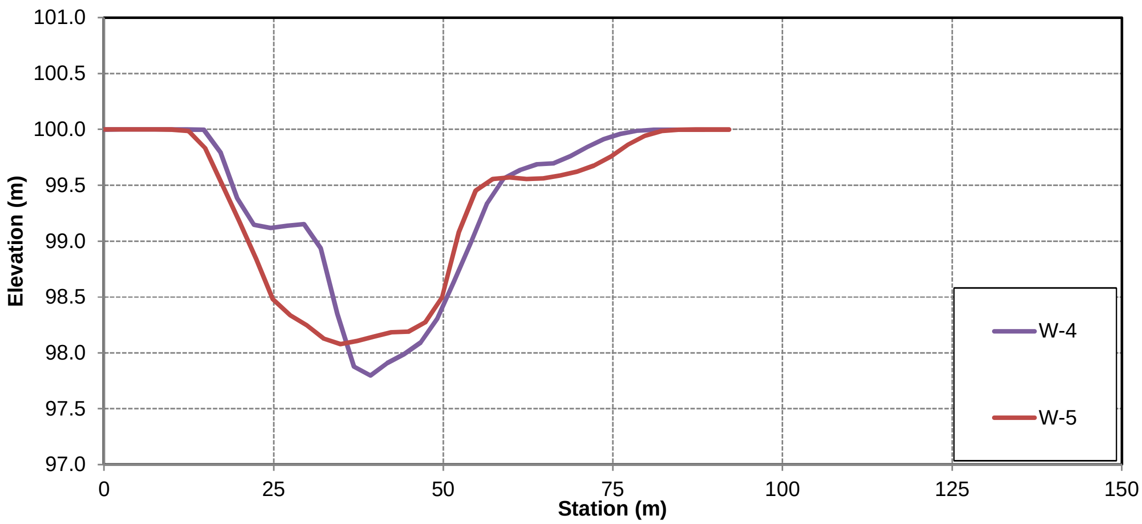

Figure 11b. Representative cross-sections for the sub-reaches W-4 and W-5 along the Western Channel.

High-water marks up to 2m above the bed of the channel were observed in the more constricted reaches (Figure A.30). The presence of potential GDE riparian vegetation species along the channel margins (Figure A.27) suggests that there may be shallow groundwater available to the plants at various times of the year. Surficial (PC1) (Figure 7) and subsurface (S1) (Figure 8) bed material samples indicated that the D_{50}'s are 30 mm and 8 mm, respectively.

A south-flowing, unnamed tributary (Figure 9), delivers flow and sediment to the Western Channel about 2km upstream of the downstream boundary of subreach W5. The tributary delivers both coarse (**Figure A.31**) and fine (**Figure A.32**) sediment to the mainstem. Bedrock outcrop and large colluvially-derived boulders provide grade control within the fairly narrow gorge (**Figure A.33**). Accumulations of coarse bed material that is infrequently fluvially transported also provides a stable substrate for potential GDE riparian trees species that are able to access any shallow groundwater and spread across the entire channel (**Figure A.34**) in contrast to where the bed material is more frequently mobilized in the mainstem Western Channel and the trees are restricted to the channel margins (Figure A.27).

2.2.3. Boolgeeda Creek and Tributaries

The upstream reaches of Boolgeeda Creek and 3 tributaries form the Flying Fish component of the Western Hub where the Marra Mamba Iron Fm. is proposed to be mined from a current total of 18 pits.

The upstream 20km long reach of Boolgeeda Creek is an east flowing stream that occupies a relatively narrow strike valley before flowing south through the Brockman Ridge (**Figure 12**). The reach was subdivided into 6 subreaches (B1-B6). The locations of the representative cross sections are shown on Figure 12 and Figure 15. In general, the channel is indistinct in the upper subreaches but single thread over most of the lower subreaches and as expected the dimensions of the channel increase in the downstream direction. In subreaches B1 and B2 the channel is poorly defined within the limits of the available mapping and sheet flooding across the valley floor is most likely to occur during flow events (**Figure 13a**). In subreach B3 the channel is multi-threaded with the main channel having a width of about 10m and a bankfull depth of about 0.5m. In subreaches B4, B5 and B6 the channel is single thread and flanked by a floodplain and much better defined with widths of about 30m and bankfull depths on the order of 2m (**Figure 13b**). In SR B1 the overburden depth exceeds 35m (**Figure 14**) but potential GDE riparian species are located on the valley floor which suggests that groundwater might be perched at shallower depths. In the remainder of the subreaches the overburden depths are in general less than 10m which could be due to the presence of mapped dolerite dikes and this appears to correlate with the extensive presence of potential GDE riparian species along the channel (Figure 14).

2.2.3.1.1 Boolgeeda Creek Tributary

Only a single pit is proposed in the vicinity of an unnamed south-flowing tributary to Boolgeeda Creek (**Figure 15**). However, this relatively large drainage does provide important information on the highly variable characteristics and dynamics of the channels in the non-strike valley portions of the Flying Fish area. The channel geometry in the vicinity of the proposed pit is included as a subreach (U1-4) on **Figure 16**. At the confluence with Unnamed 1 Tributary, the single channel is about 20m wide and about 3m deep at bankfull stage (Figure 19) with a low width-depth ratio of about 6.5 (**Figure A.35**), the result of fine-grained and root-reinforced banks.

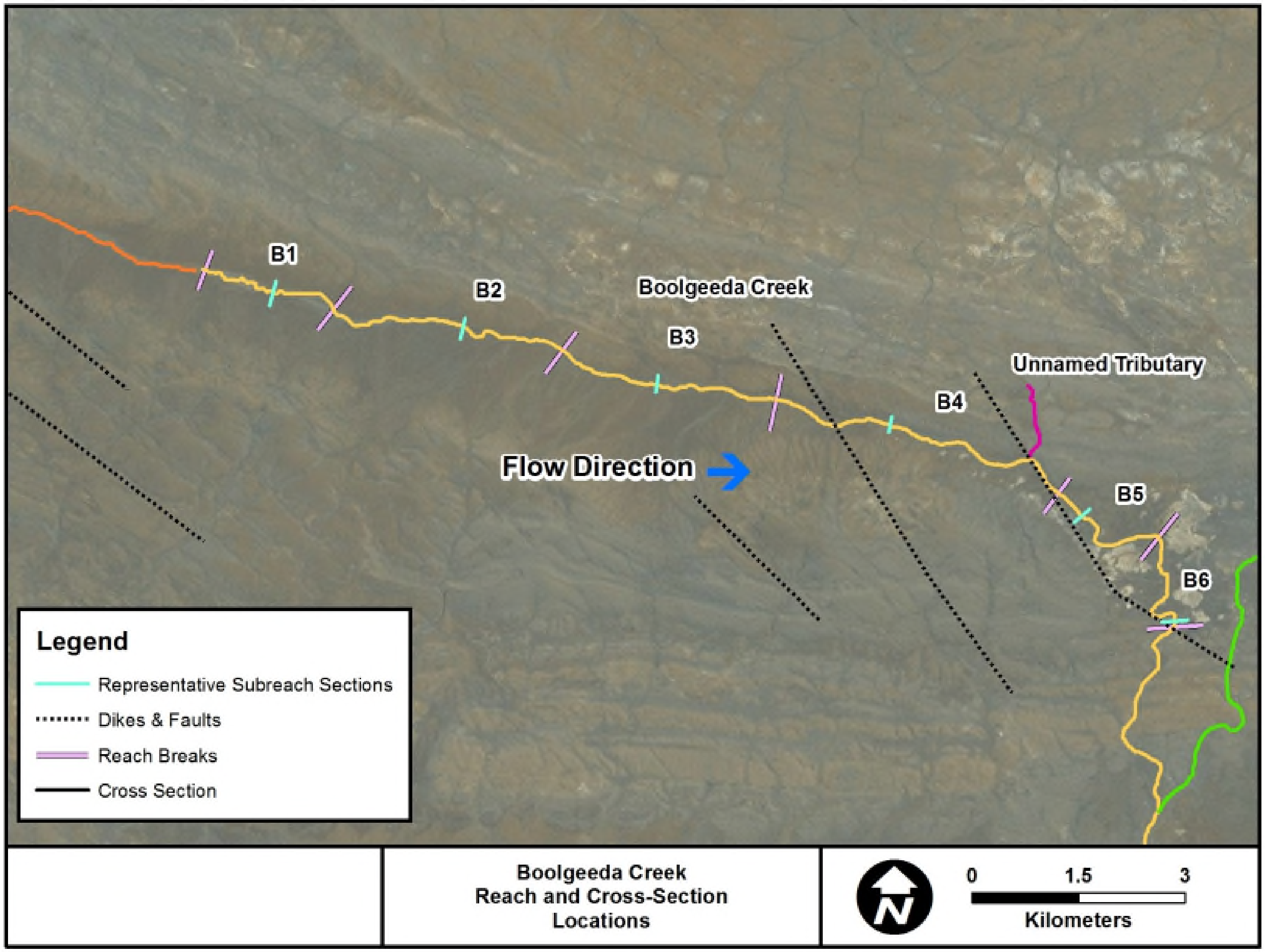

Figure 12. Boolgeeda Creek subreach and cross-section locations.

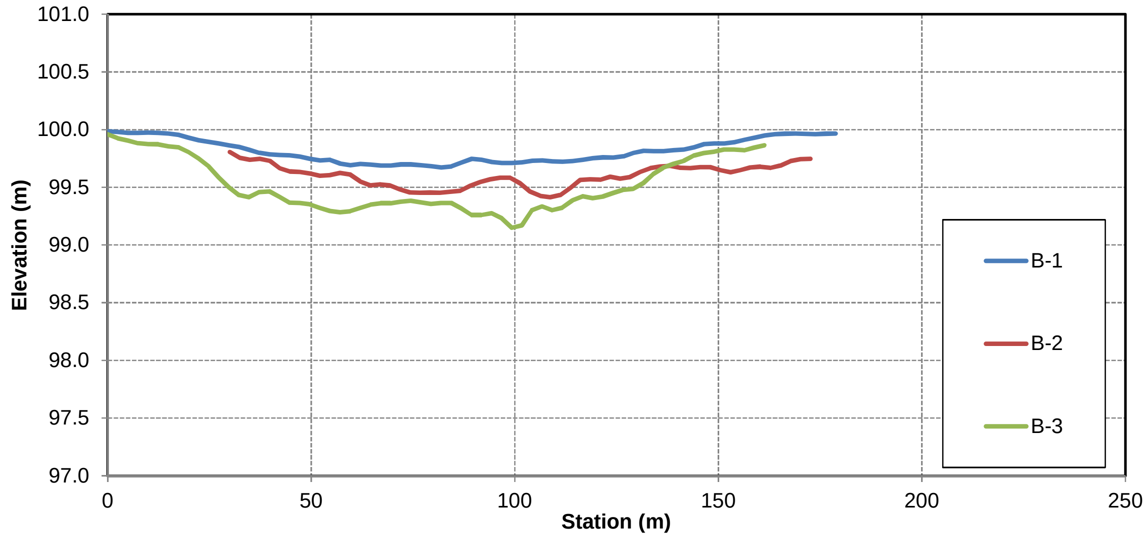

Figure 13a. Representative cross-sections for the sub-reaches B-1, B-2 and B3 along Boolgeeda Creek.

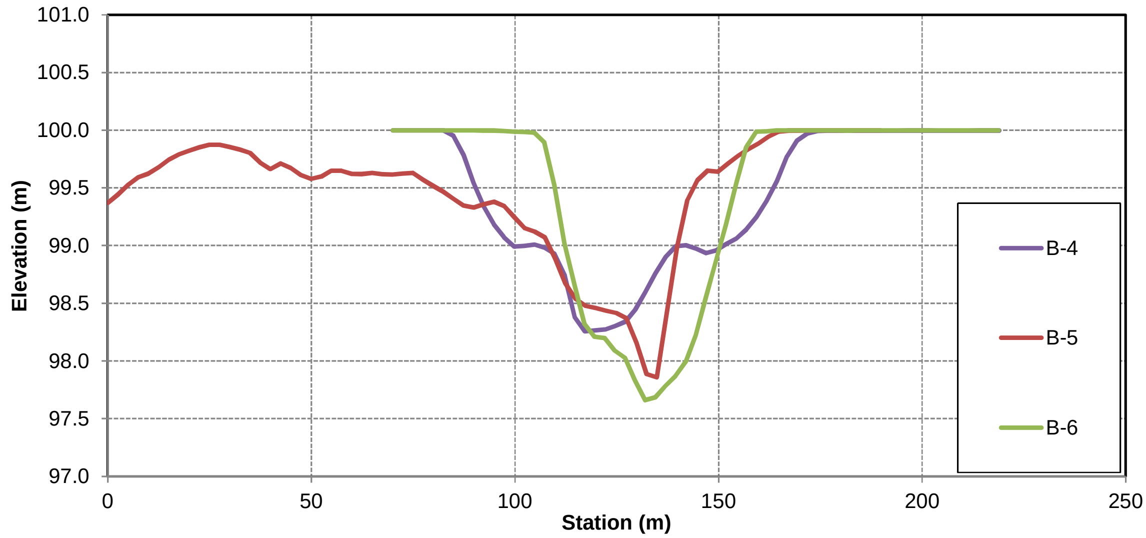

Figure 13b. Representative cross-sections for the sub-reaches B-4, B-5 and B-6 along Boolgeeda Creek.

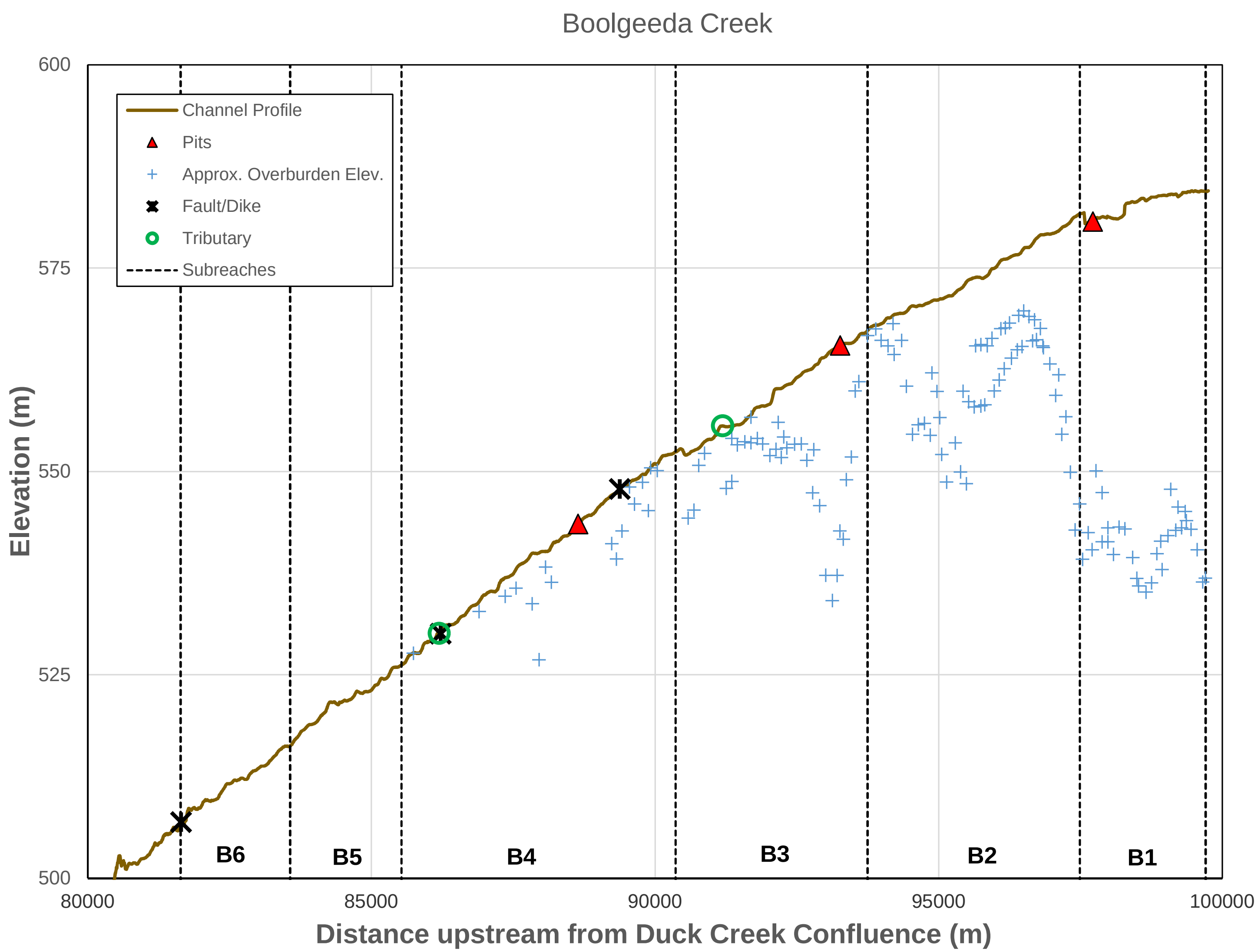

Figure 14. Boolgeeda Creek channel and overburden profiles.

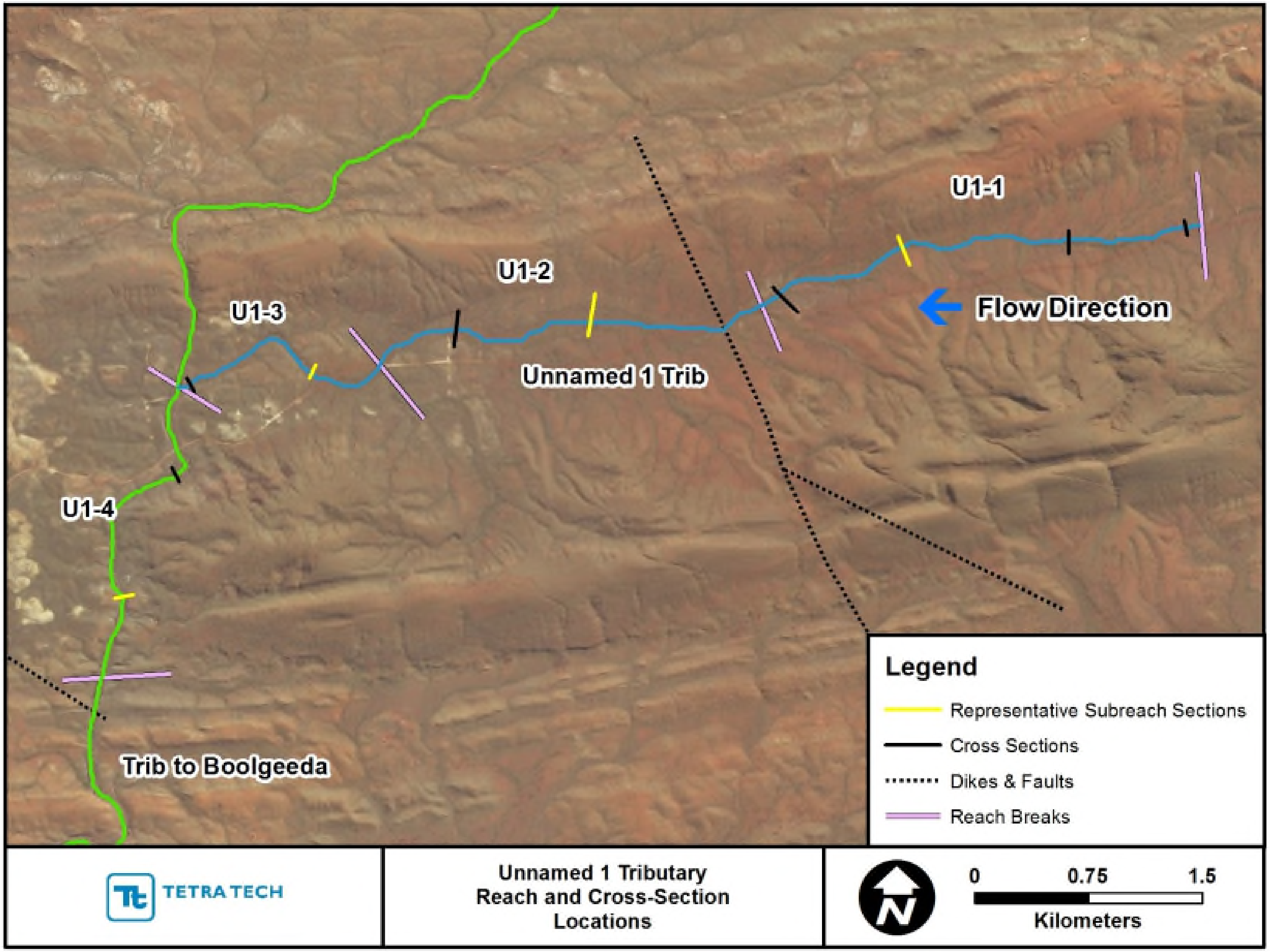

Figure 15. Unnamed 1 Tributary subreach and cross-section locations.

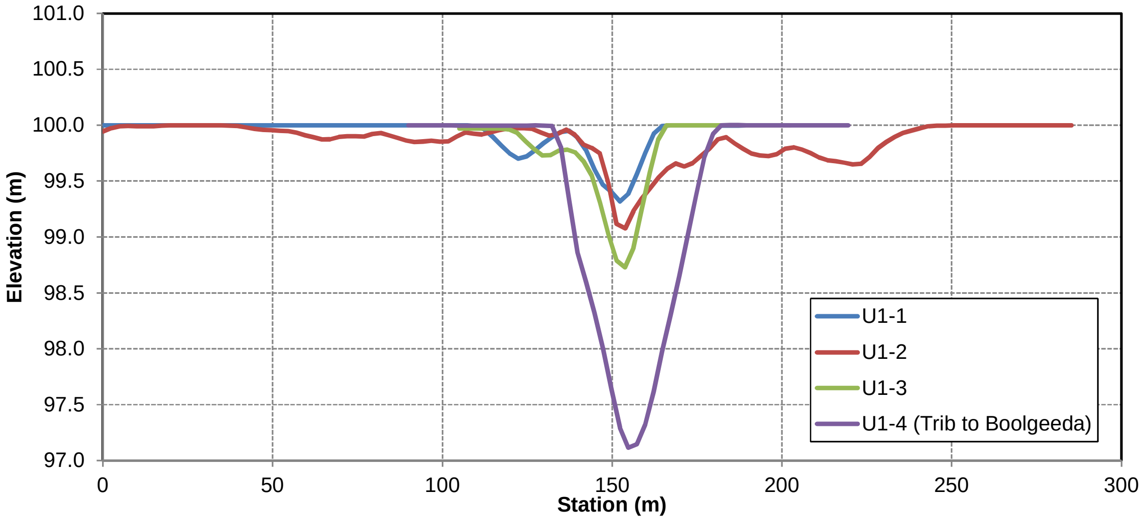

Figure 16. Representative cross-sections for the sub-reaches along the Unnamed 1 Tributary.

Approximately 100m upstream, the channel bifurcates around a vegetated island, most likely initiated by a large flood event (**Figure A.36**). Upstream of the split flow reach the channel is again deep (~2m) and narrow (~8m) and the bed material is much coarser and the cobble-size sediments exhibit imbrication indicating fluvial transport (**Figure A.37**). Approximately 50 m upstream of the narrow reach, the channel widens considerably (~20m) but has well defined banks that are about 1m high (with-depth ratio 20) with much finer bed material (**Figure A.38**). About 150m downstream of the gorge the channel becomes very poorly defined with multiple small channels incised into very coarse (cobble-boulder) bed material on a heavily vegetated valley floor fan (Fischer and Harvey, 1990) that has formed where the flood flows expanded downstream of the gorge and deposited the coarse material (**Figure A.39**). The fan tends to self-reinforce since flow depths tend to be low during flood flows and the hydraulic roughness is high due to the extensive presence of woody vegetation and this leads to a stepped-channel profile. Within the confines of the gorge, the channel tends to be well-defined and is capable of transporting a wide range of sediment sizes (**Figure A.40**). Within the gorge, impact scars on riparian trees indicate that a fairly recent flow was on the order of 1.5m deep but older scars at higher elevations indicate flow depths in excess of 2m during historic events (**Figure A.41**).

2.2.3.1.2 Unnamed 1 Tributary

Unnamed 1 Tributary is about 8km long and flows west in a strike valley to its confluence with the south-flowing Tributary to Boolgeeda Creek (Figure 14). The reach was subdivided into 3 subreaches (SR U1-1, U1-2, U1-3) and a section of the tributary channel was added as the fourth subreach (U1-4). In SR U1-1 the channel is multi-thread and poorly defined. In SR U1-2 the channel is also multi-thread but the main channel is better defined and about 1 m deep (Figure 16) in a wider section of valley. In SR U1-3 the channel is primarily single-thread, about 20m wide and about 1m deep (**Figure A.42**), and is confined by pediments in a narrower valley (Figure 16). At the downstream end of SR U1-3, the channel is incised and headcutting upstream (**Figure A.43**) due to a fairly recent avulsion of the channel and discharge of overbank flows into the deep channel of Boolgeeda Tributary (Figure 16). In SR U1-1 the depth of the overburden is highly variable and ranges from 2-3m to over 30m which probably correlates with the general absence of potential GDE vegetation in the subreach (**Figure 17**).

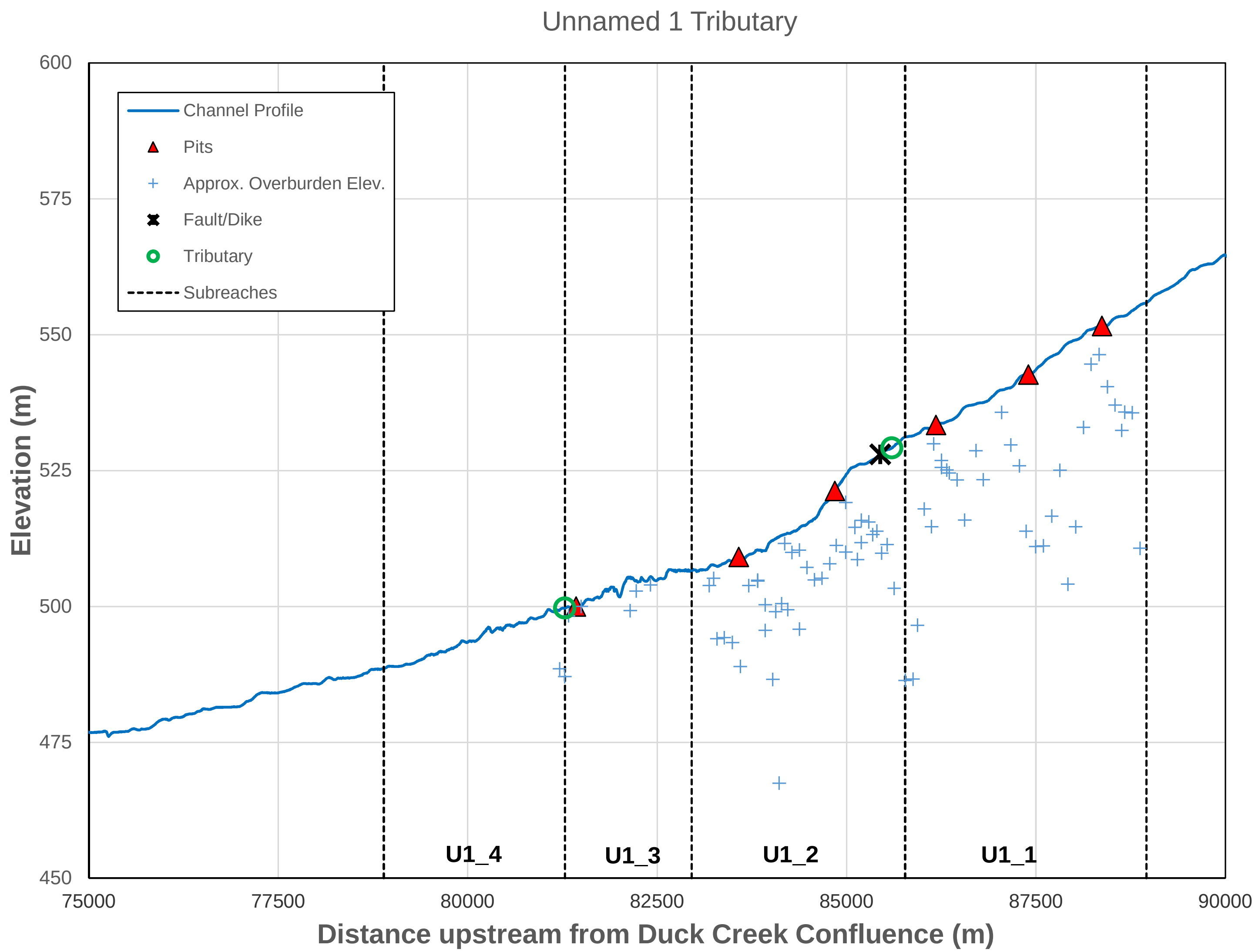

Figure 17. Unnamed 1 Tributary to Boolgeeda Creek channel and overburden profiles.

In SR U1-2 the overburden depths are less variable and along most of the subreach the depth is in the range of 10m or less, which also appears to correlate with the presence of potential GDE riparian vegetation along the channel. Shallow overburden depths in SR U1-3 correlate well with the presence of potential GDE riparian vegetation along the channel (Figure 17).

2.2.3.1.3 Unnamed 2 Tributary

Unnamed 2 Tributary flows about 11 km in a southwest direction though a linear strike valley before cutting south through the Brockman Ridge (Figure 14). Currently, there is no hydraulic modeling of this tributary and consequently the reach was not subdivided. However, review of 8/9/2005 Google Earth Imagery indicates that at the upstream end of the catchment the channel is very poorly defined in a narrow valley bottom flanked by pediments. Farther downstream the channel is also poorly defined but in a much wider valley bottom. Based on the apparent morphology of the channel and valley floor it is likely that fairly shallow sheet flooding occurs during flood events. Upstream of where the mapped dolerite dikes cross the channel the overburden depths exceed 20m (**Figure 18**) and there does not appear to be much riparian vegetation along the channel. In the reach where the 3 mapped dikes cross the creek, the overburden depths are generally less than 10m (Figure 18) and there is evidence of potential GDE riparian vegetation along the creek. Similarly, relatively shallow overburden depths are present above the gorge and there is ample evidence of potential GDE riparian vegetation (Figure 18).

2.2.4. Railway Transportation Corridor

The railway transportation corridor crosses a number of small tributaries in the headwaters of Duck Creek north of the Flying Fish area as well as the upper reaches of Caves Creek west of the existing Rio Tinto railway line. At the Caves Creek crossing, the channel is well defined with a width of about 15m and a bankfull depth of 1.5m and is flanked by potential GDE riparian trees (**Figure A.44).** Local erosion and deposition in the channel is controlled by woody debris and riparian trees (**Figure A.45)**. Higher elevation terraces are subject to erosion by the creek (**Figure A.46**). The bed material with an estimated D_{50} of about 25mm is mobilized by 20% to 50% AEP flows farther downstream in the Silvergrass area (Harvey et al., 2014). Just upstream of the proposed crossing of Caves Creek by the FMG railway is the confluence with a west flowing upper basin tributary that is crossed by the Rio Tinto railway line and access road that traverses the cracking clay Themeda grasslands (**Figure A.47**). The tributary flows are conveyed under the railway and road by 15 1500mm culverts set in concrete (**Figure A.48**). Installation of the culverts exposed calcrete in or under the bed of the creek and review of aerial photography indicates that the discrete channels that traverse the grasslands are very shallow and have very even width which suggests they are flowing in very similar materials. This suggests that the cracking clay grasslands are underlain by calcrete at shallow depth and are formed and maintained by sheet flooding (Harvey et al, 2014). Regional geologic mapping indicates the extensive presence of the Oakover Fm. (calcrete) in the area (FMG, 2015b). Clearly, the presence of the Rio Tinto railway line and access road has affected the distribution of sheet flooding upstream of the embankment. Downstream of the embankment where the same tributary discharges to the lower elevation woodlands it is clear that the channel is formed in alluvium and that the channel morphology is highly irregular (**Figures A.49, A.50, A.51**).

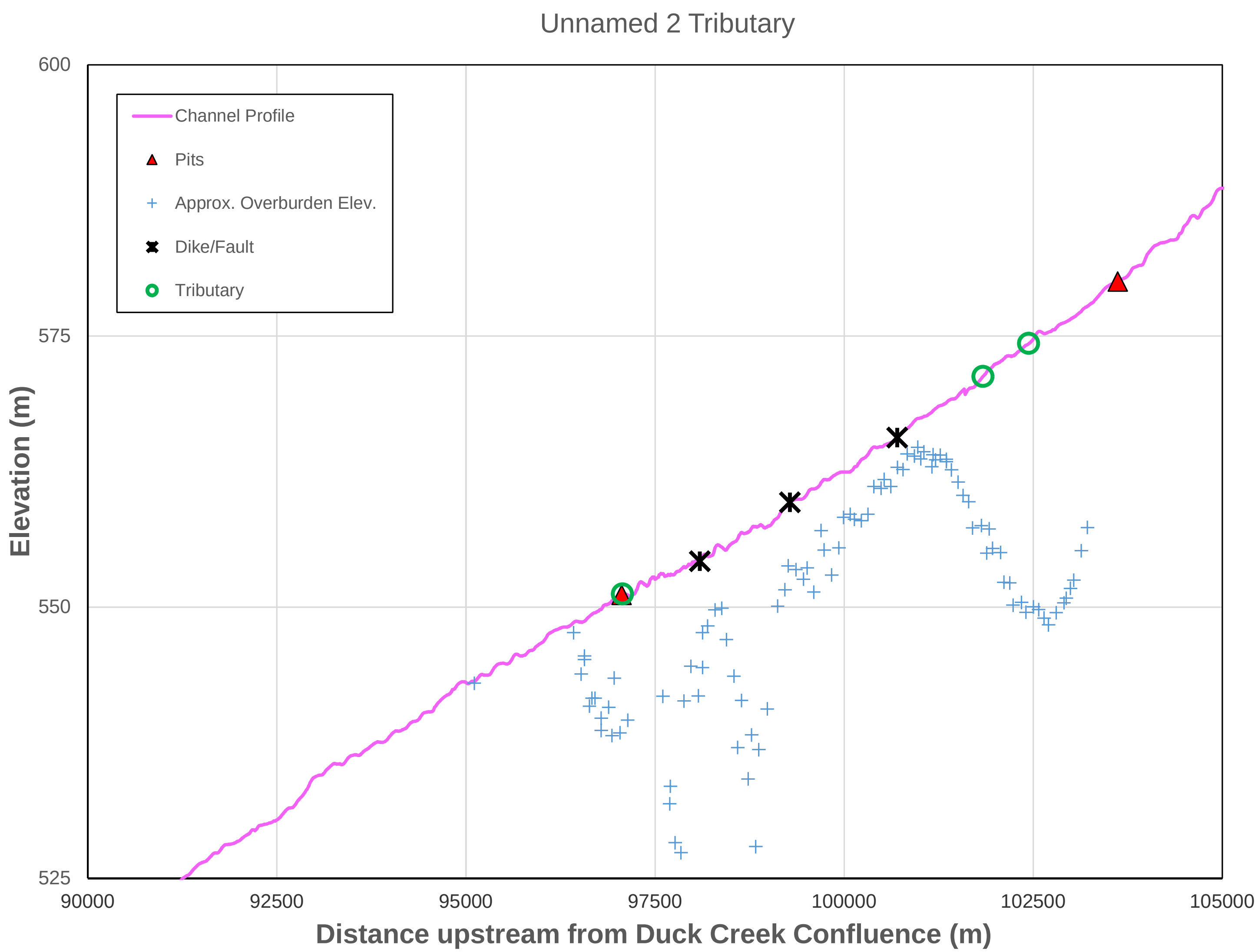

Figure 18. Unnamed 2 Tributary to Boolgeeda Creek channel and overburden profiles.

Farther downstream of the proposed FMG railway crossing, the channel of Caves Creek has been shown to be inset into calcrete and silcrete with a thin (<10m) layer of alluvium and a perched alluvial groundwater table (Harvey et al., 2014).

As proposed, the FMG railway corridor will have to cross over Rio Tinto's existing railway in the vicinity of Hamersley Station prior to linking into FMG's existing Hamersley railway (Figure 2). To the east of the Rio Tinto railway, the FMG railway corridor will have to cross over Weelamurra Creek that currently receives more flow than it did historically because of diversion of flow by the Rio Tinto railway embankment. Potentially the FMG embankment will further modify the flow splits between Caves Creek and Weelamurra Creek. However, Weelamurra Creek is inset into calcrete (**Figure A.52**) that is more than likely to prevent any channel adjustment in response to increased flows and any increase in the flows is likely to be beneficial for the permanent pools (FMG, 2015b) located about 20km downstream in Weelamurra Creek. The primary hydrological issue is the potential for third party impacts on the existing Rio Tinto railway. The magnitude of the potential impacts will depend to a large extent on refining the hydrology of the area since it is currently unclear as to how much flow may be diverted naturally from what appears to be a common floodplain with the South Fortescue River on the eastern side of the basin.

3. STREAM ORDER EVALUATION

The Strahler stream order numbers (Horton, 1945; Strahler, 1952; Strahler, 1957) are used to define stream size based on a hierarchy of tributaries. In the application of the Strahler stream order to hydrology, each segment of a stream or river within a river network is treated as a node in a tree, with the next segment downstream as its parent. When two first-order streams come together, they form a second-order stream. When two second-order streams come together, they form a third-order stream. Streams of lower order joining a higher order stream do not change the order of the higher stream. Thus, if a first-order stream joins a second-order stream, it remains a second-order stream. It is not until a second-order stream combines with another second-order stream that it becomes a third-order stream.

The available topography within the Western Hub (10m Landgate DEM) was used in conjunction with ESRI ArcMap 10.2 (ESRI, 2012) and the Spatial Analyst add-on software to define the stream orders. The stream-ordering process involved development of a series of raster files, including flow direction and flow accumulation rasters, that were conditionally formatted for the Strahler Method as applied by the Spatial Analyst Hydrology tool. Once developed, the stream ordering was screened to eliminate disconnected or intermittent rill channels. It is important to note that the evaluation is limited by the extents of the available topography (10m DEM), so the actual magnitude of the stream orders may be somewhat different than reported; however, the relative stream orders nevertheless provide insight to the drainage characteristics of the primary channels. It is also important to note that the Strahler stream order is typically applied to perennial streams, and not to ephemeral channels such as those within the Western Hub area, where defining stream channels is more difficult.

3.1. Pinarra Creek

The stream ordering evaluation of the Pinarra Creek catchment is shown in **Figure 19**. Pinarra Creek in SR P1 is mainly a 4th order stream, in SR P2 and P3 it is a 5th order stream and in SR P4, P5 and P6 it is a 6th order stream. The major south-flowing tributaries to Pinarra Creek range from 3rd order to 5th order streams. The north flowing tributaries are generally 2nd and 3rd order streams.

3.2. Western Channel

The stream ordering evaluation of the Western Channel catchment is shown in **Figure 20.** The creek in SR W1 is primarily a 3rd order stream, in SR W2 it is a 4th order stream and in SR W3, W4 and W5 it is a 5th order stream.

3.3. Boolgeeda Creek

The stream ordering evaluation of the upper Boolgeeda Creek catchment is shown in **Figure 21**. The creek in SR B1 is a 3rd order stream, in SR B2, SR B3 and SR B4 it is a 4th order stream and in SR B5 and B6 it is a 5th order stream.

3.4. Boolgeeda Creek Tributary and Unnamed 1 and 2 Tributaries

The stream ordering evaluation of the Boolgeeda Creek Tributary, Unnamed 1 Tributary and Unnamed 2 Tributary catchments are shown in **Figure 22**. The creek in the Boolgeeda Creek Tributary is a 5th order segment. The Unnamed 1 Tributary is a 3rd order stream in SR U1-1 and a 4th order stream in SR U1-2 and SR U1-3 (Figure 25). The lower reaches of the Unnamed 2 Tributary is located in a 5th order stream segment.

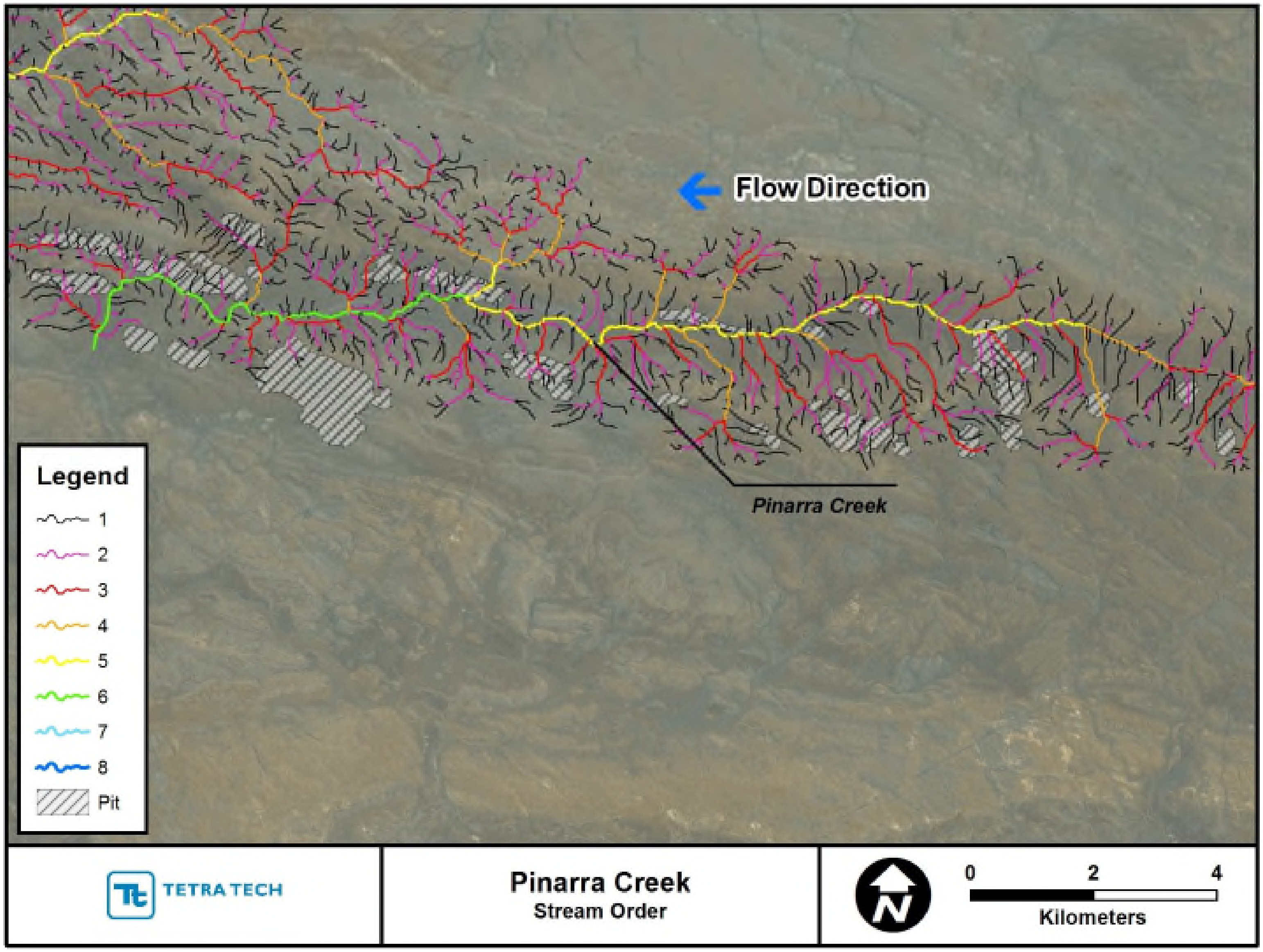

Figure 19. Stream ordering of the Pinarra Creek Catchment.

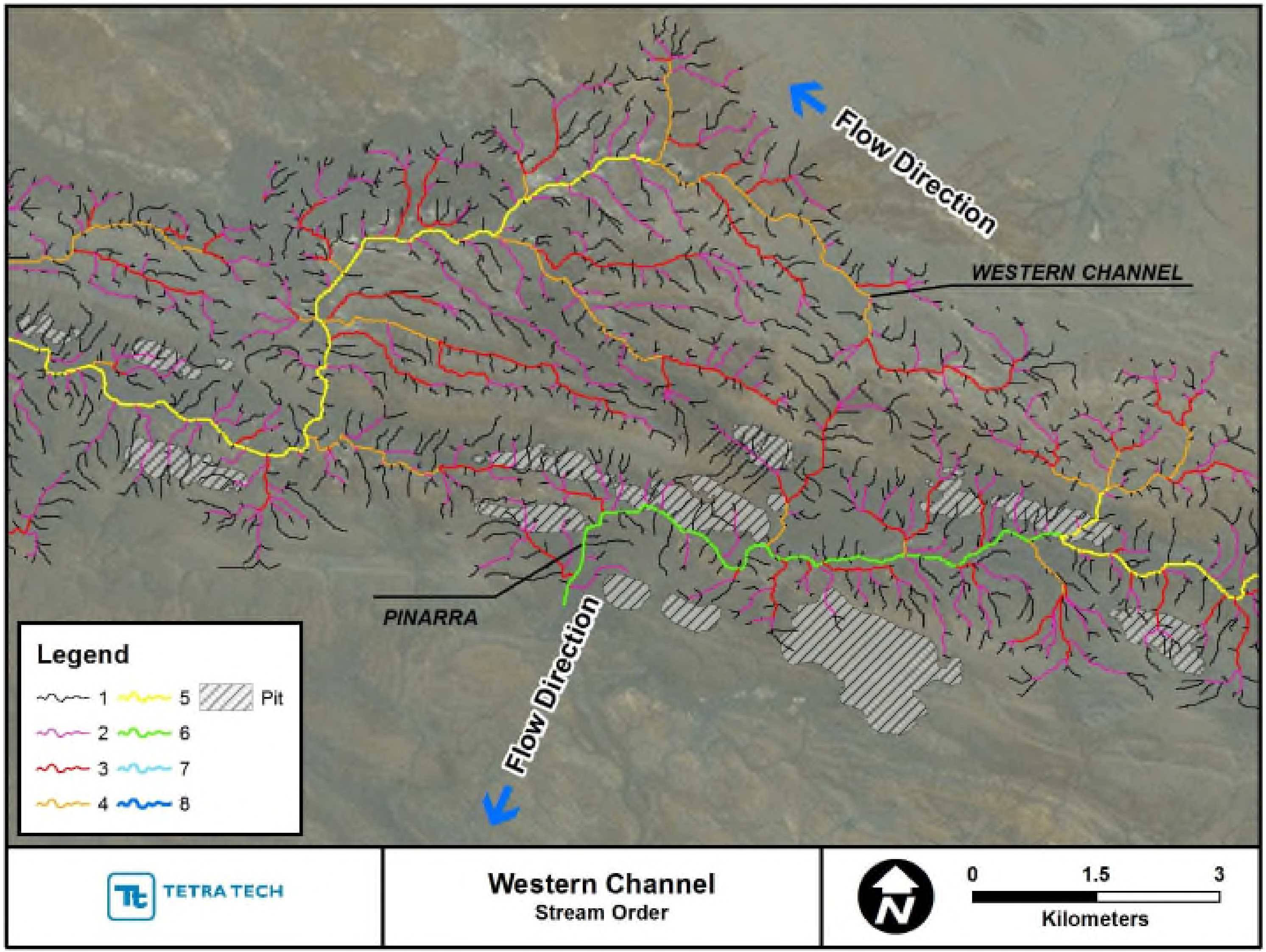

Figure 20. Stream ordering of the Western Channel Catchment.

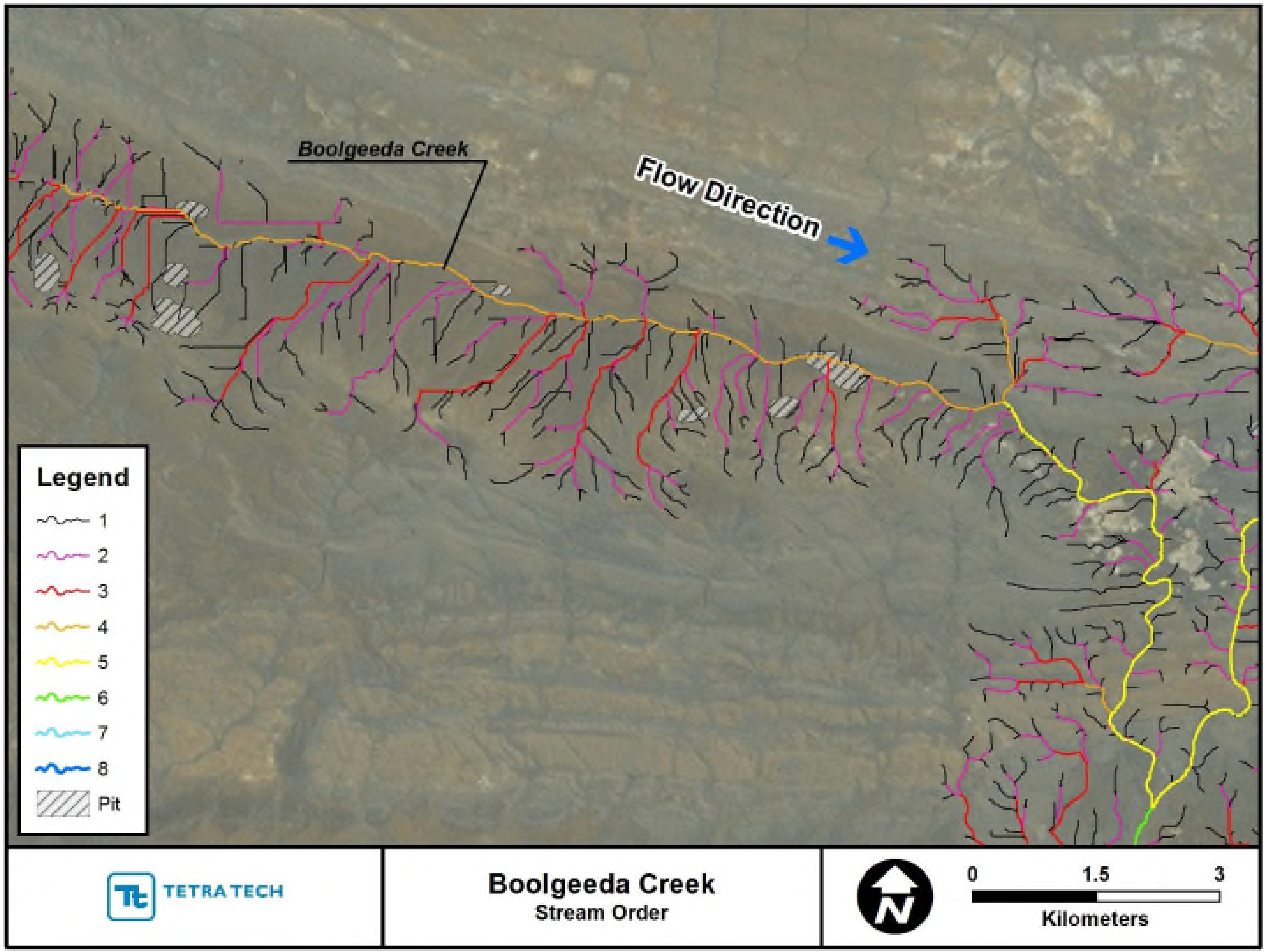

Figure 21. Stream ordering of the Boolgeeda Creek Tributary Catchments.

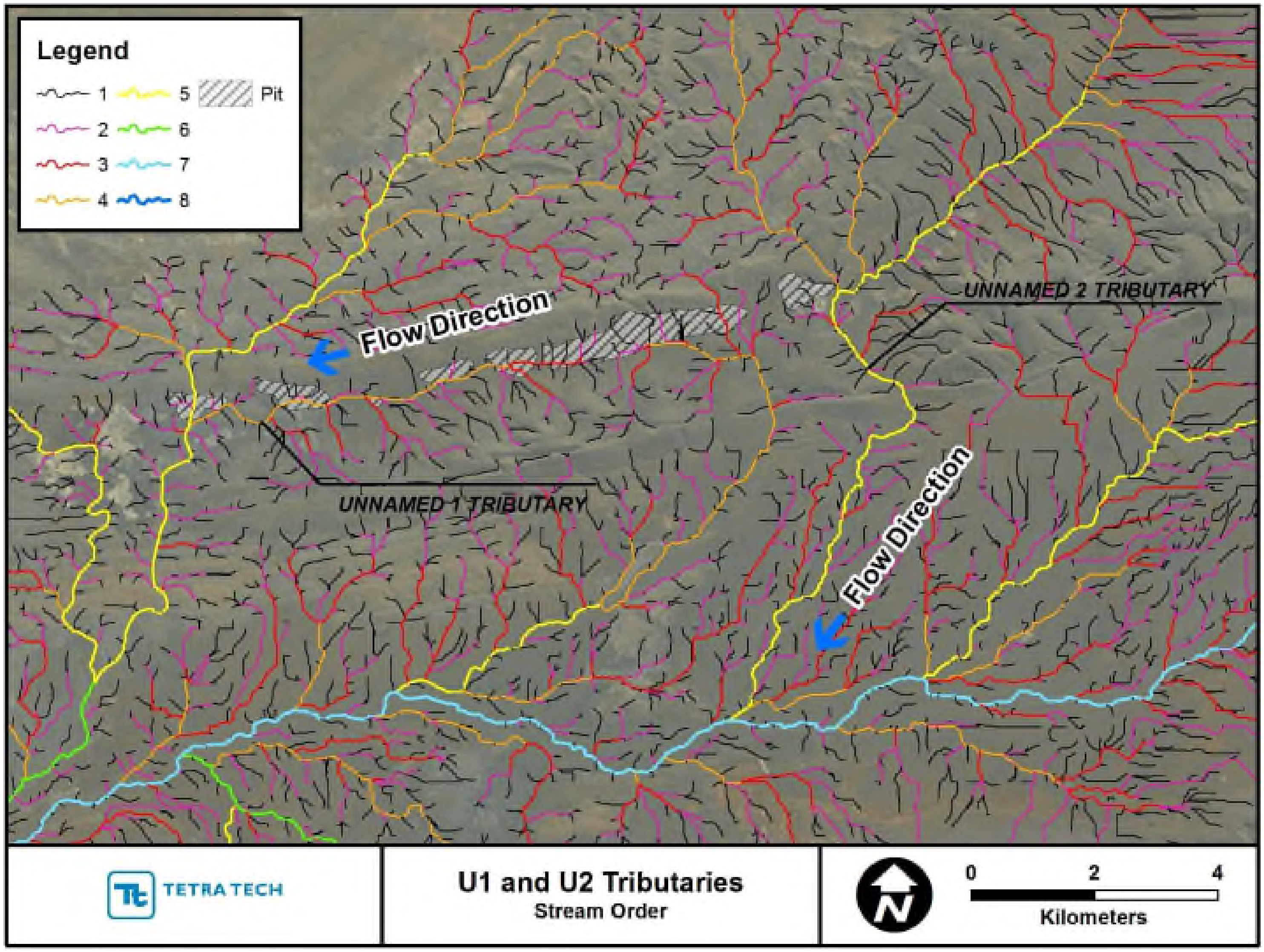

Figure 22. Stream ordering of the Boolgeeda Creek Tributary Catchments.

4. INCIPIENT MOTION ANALYSIS

An incipient-motion analysis (i.e., an evaluation of flows required to mobilize the bed material) was performed for each of the channels that were included in the TUFLOW modeling (conducted by Fortescue) by evaluating the effective shear stress on the channel bed in relation to the amount of shear stress that is required to move the surface particles on the beds of the channels. Because of the general similarity of the surface bed materials an average gradation was developed from PC-1 and PC-2 for use in the reconnaissance level incipient motion analysis of the Western Hub channels (Figure 7). The D_{50} of the average gradation is 35 mm and the D_{84} is 60 mm.

4.1. Basic Theory

The shear stress required for bed mobilization was estimated from the standard Shields (1936) relation, given by:

$$\tau_c = \tau_{*c} (\gamma_s - \gamma) D_{50} \qquad (1)$$

where τ_c = critical shear stress for particle motion,

τ_{*c} = dimensionless critical shear stress (often referred to as the Shields parameter),

γ_s = unit weight of sediment (~2,650 kg/m^3),

γ = unit weight of water (1,000 kg/m^3), and

D_{50} = median particle size of the bed material.

In gravel-bed streams, when the critical shear stress for the median (D_{50}) particle size is exceeded, the bed is mobilized and all sizes up to about 4.5 times the median size can be transported by the flow (Parker et al., 1982; Andrews, 1984).

Reported values for the Shields parameter range from 0.03 (Neill, 1968; Andrews, 1984) to 0.06 (Shields, 1936). A value of 0.047 is commonly used in engineering practice, based on the point at which the Meyer-Peter, Müller (MPM) bed-load equation indicates no transport (MPM, 1948). Detailed evaluation of the MPM data and other data (Parker et al., 1982; Andrews, 1984) indicate that true incipient motion occurs at a value of about 0.03 in gravel- and cobble-bed streams. Neil (1968) concluded that the dimensionless shear value of 0.03 corresponds to true incipient motion of the bed-material matrix while 0.047 corresponds to a low, but measurable transport rate. A value of 0.03 was used in this analysis.

In performing an incipient-motion analysis, the bed shear stress due to grain resistance (τ') is used rather than the total shear stress, because τ' is a better descriptor of the near-bed hydraulic conditions that are responsible for sediment movement. The grain shear stress is computed from the following relation:

$$\tau' = \gamma Y' S \qquad (2)$$

where Y' = the portion of the total hydraulic stress associated with grain resistance (Einstein, 1950), and

S = the energy slope at the cross section.