Water Resource Evaluation / Projects & Development

Baby Hope Hydrology & Hydraulic Assessment

28 February 2014

Executive Summary

This report presents the results of a flood study to determine the expected annual exceedance probability (AEP) design flood quantiles for Pebble Mouse Creek at the Baby Hope ore deposit and the Hope Downs 1 South East pit. Additionally, the results of 2D hydraulic modelling have been used to determine the 1% AEP flood depths and extent under existing and post pit development conditions for the Baby Hope deposit.

A RORB rainfall-runoff routing model was calibrated to the Tarina gauging station on Weeli Wolli Creek (708014) and used to estimate design flood quantiles at Baby Hope and the HD1 SE pit. The expected 1% AEP design flows for Pebble Mouse Creek at the Baby Hope deposit and HD1 SE pit are 970 m^3/s and 890 m^3/s respectively.

The spatial variability of rainfall and streamflow exhibited in the region introduces a large degree of uncertainty in design flood estimates, as there are no streamflow gauges or rainfall gauges within the Pebble Mouse Creek catchment. To reduce uncertainty in estimates it is recommended that pressure transducers are installed in Pebble Mouse Creek to record the surface water response to rainfall events. This data can then be used to validate the design flood estimates for Baby Hope.

Looking south over the Baby Hope deposit from the northern range; one of many deeply incised creeks that drain south over the deposit and are intercepted by the pit

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1. Introduction

1.1 Terminology

Probability concepts are fundamental to design flood estimation. The terminology used in the communication of these concepts is paramount if it is to be effective for all stakeholders. The term ‘average recurrence interval’ or ‘ARI’ has generally been used within Rio Tinto and by industry professionals to describe the probability of a particular magnitude of flood occurring i.e. ‘100 yr ARI’ or ‘1 in 100 year flood’.

Average Recurrence Interval (**ARI**) - the average period between occurrences equalling or exceeding a given value.

This description of flood events has often been misinterpreted by professionals, community members impacted by floods and other stakeholders as the probability of the chosen event is not explicitly defined. To ensure effective communication of event probabilities alternative terminology has been adopted by the Bureau of Meteorology (**BoM**) and other industry bodies. Australian Rainfall and Runoff (**ARR**) has outlined the proposed terminology to be adopted (Ball 2013), and this follows;

Annual Exceedance Probability (**AEP**) - the probability of an event occurring or being exceeded within a year. For example a 1% AEP event has a 1% probability of being equalled or exceeded in any year.

The AEP expressed as a percentage, will be used to describe flood event probabilities for this study. Additionally, where appropriate, peak flows described as Q_y for the year ARI, will now be described as $Q_{n\%}$ AEP (including the percentage sign). Table 1-1 gives the AEP equivalent for ARI’s commonly in used in flood studies.

Table 1-1: ARI and equivalent AEP

ARI	AEP (1 in x)	AEP %
1.44	2	50
4.48	5	20
9.49	10	10
20	20	5.0
50	50	2.0
100	100	1.0
200	200	0.50
500	500	0.20
1000	1000	0.10

1.2 Previous reports

Surface water investigations of the local catchment area have been previously undertaken for the development of Hope Downs 1. Regional catchment hydrology has been investigated for the development of Yandicoogina. Studies relevant to the Baby Hope deposit hydrology include:

- “Hope Downs Iron Ore Project: Preliminary Investigation into Surface Water Hydrology” – unpublished technical report prepared for Hope Downs Management Services, Halpern Glick Maunsell 1999.

- “Hope Downs Project Stage 1: Report for review of hydrology” – technical report prepared for Rio Tinto Iron Ore Expansion Projects, KBR March 2006.
- “Hope Downs Project Stage 1: Surface water management plan” – technical report prepared for Rio Tinto Iron Ore Expansion Projects, KBR March 2007.
- “Weeli Wolli hydrology and hydraulics” – unpublished internal technical report 2013 RTIO-PDE-0117748.

Other relevant regional studies include:

- “Surface Hydrology of the Pilbara Region” – technical report by the Water and Rivers Commission (Ruprecht, J. & Ivanescu, S., 2000).
- “Pilbara Surface Water Management Strategy” unpublished internal report RTIO-PDE-0053914.

2. Catchment characteristics

The Baby Hope study area is located in the Pebble Mouse Creek catchment within the Weeli Wolli Creek catchment that forms part of the Fortescue River Region (BoM 2012a). Pebble Mouse Creek has a total catchment area of approximately 340 km^2 to the confluence with Weeli Wolli Creek, 258 km^2 of which is upstream of the study area (Figure 2-1). The targeted ore deposit lies on the lower northern slopes of a 2 km wide valley, approximately 10 km south west of Hope Downs 1 mine site and 78 km north west of the Newman township. A railway line and road, both containing culverts, are located south of the deposit on the opposite side of the Pebble Mouse Creek valley.

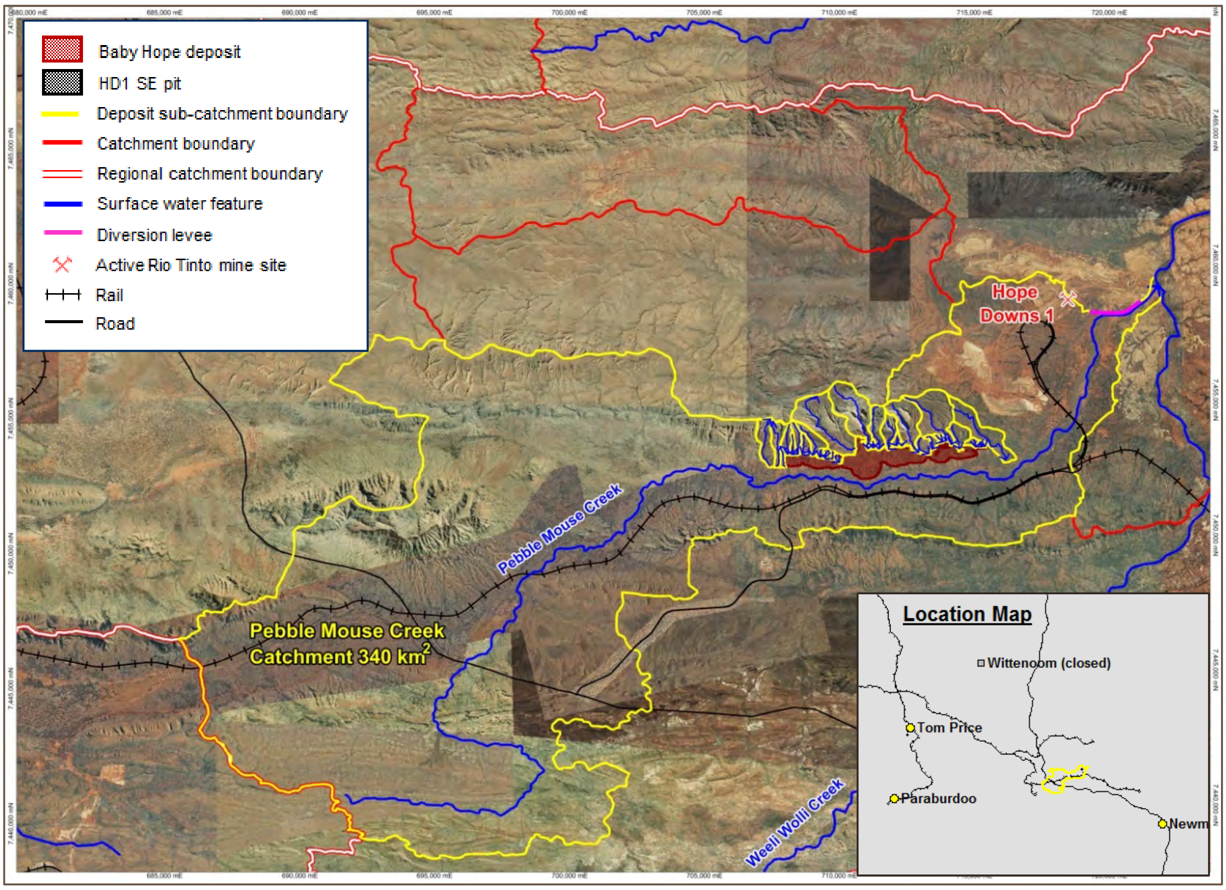

Figure 2-1: Catchments reporting to the Baby Hope ore deposit

The upper reaches of Pebble Mouse Creek tributaries are dominated by the Newman land system and lower reaches by the Boolgeeda and Platform land systems (van Vreeswyk *et al*. 2004). The Newman land system is characterised by rugged jaspilite plateaux, ridges and mountains supporting hard spinifex grasslands. The Boolgeeda and Platform land systems are characterised by stony slopes and plains below hill systems supporting hard and soft spinifex grasslands and mulga shrub lands.

Pebble Mouse Creek is generally well defined with little braiding and has an equal area slope of 3.4 m/km. The lower section of the catchment, approaching the deposit becomes confined in a 2 km wide valley that runs west to east with average low flow channel width of 10 m and depth of 1.5 m. A diversion levee was constructed to divert a section of the Pebble Mouse Creek low flow channel around Hope Downs 1 mine site as shown in Figure 2-1.

Runoff from the upper catchment produces the bulk of the flood water during large flood events with smaller sub-catchments on the north and south side slopes of the lower catchment contributing a minor proportion of run-off volume during flood events. A relatively steep range of hills directly north of the deposit area consists of many small but significant sub-catchments that have deeply incised creeks flowing south over the deposit. The deep incisions created by the creeks suggest that the range has been subjected to high water velocities and erosion.

Currently there are no stream flow or rainfall gauges within the Pebble Mouse Creek catchment. However the Tarina stream flow and rainfall gauge on Weeli Wolli Creek is located approximately 13 km downstream from the Pebble Mouse/Weeli Wolli confluence. The Wonmunna rainfall gauge is located approximately 8 km from the Pebble Mouse catchment centroid.

3. Regional and local climate

3.1 Regional climate characteristics

The Pilbara region spans across three Köppen climate zones: hot (persistently dry) grassland in the west, hot (winter drought) desert in the east and areas of hot (persistently dry) desert in the north and south (BoM 2005a). It is typically classified as an arid to semi-arid climate, but annual rainfall totals are highly variable. Rainfall occurs predominantly in summer, with major falls caused by tropical cyclones, monsoon lows and convective thunderstorms. Rainfall is typically greatest around the Hamersley Ranges and decreases with distance from the coast. Tropical cyclones are a feature of the region and typically occur between January and March, with none expected between May and November. Extended periods of low rainfall can be common occurrences.

The spatial variability of rainfall across the Pilbara is high as a result of convective/cyclonic rainfall mechanisms. Average evaporation rates greatly exceed average rainfall rates and temperature variations can be extremely large (Ruprecht and Ivanescu 2000). Mean annual evaporation rates range from 3000 to 4000 mm across the region, approximately an order of magnitude greater than the mean annual rainfall range of 200 to 500 mm.

3.2 Local climate

Based on the Köppen classification system the Baby Hope site is described as a grassland: hot (persistently dry) (BoM 2005a). The Newman Bureau of Meteorology weather station (78 km southeast of Baby Hope) shows an average annual maximum temperature of 33° Celsius and summer maximum averages of 40° Celsius.

3.2.1 Rainfall

Long term daily gridded rainfall data has recently become available for Australia from the Bureau of Meteorology (Bo M, 2012b). The gridded data has been derived from recorded daily rainfalls and is provided for areas with sides approximately 5 km by 5 km.

A comparison between the recorded rainfall at Wonmunna (507012) and the gridded data at Wonmunna (700,633 mE/7,442,611 mN) indicated a strong correlation in larger rainfall days with a tendency to overestimate lower rainfall days (Table 3-1). The average number of rainfall days at Wonmunna (507012) is 57 as opposed to 74 days from BoM gridded data, with the majority of the difference coming from days with rainfall below 3 mm.

Table 3-1: Comparison of daily rainfall at Wonmunna (507012) and BoM gridded data (700,633 mE/7,442,611 mN)

Rainfall > (mm)	Average days per year 507012	Average days per year BoM gridded
1	35	43
2	29	33
3	25	27
5	18	19
10	11	10
20	5	4
25	4	3
35	2	1
50	1	1

A comparison of monthly totals from the two data sets, Figure 3-1, revealed a strong correlation with a tendency to underestimate the larger rainfall months. Analysis of the differences in monthly recorded and gridded rainfalls showed that 90% of the gridded monthly totals were within +27 mm and -26 mm of the recorded totals.

In the absence of long term recorded rainfall data from within the catchment of interest the BoM gridded data was considered to be suitable for use as an estimate of Pebble Mouse Creek catchment rainfall. Baby Hope daily rainfall from 1906 to 2012 was obtained for the centroid of the Pebble Mouse Creek catchment, shown in Figure 3-2 (700,016 mE/7,450,612 mN), and used for analysis.

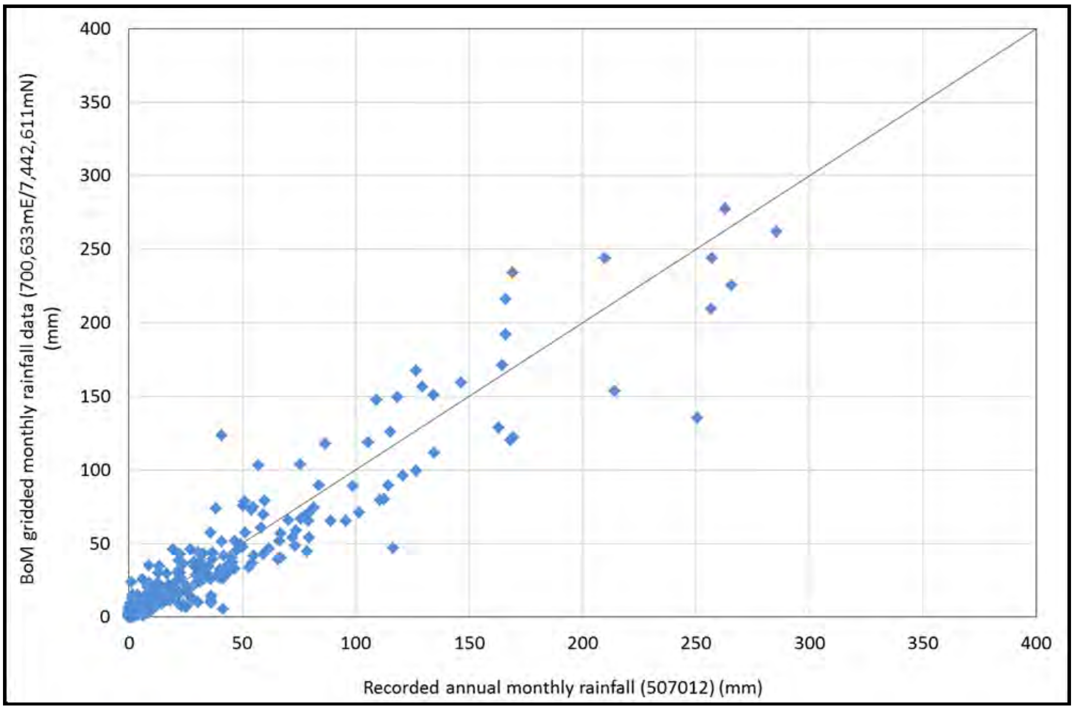

Figure 3-1: **Relationship between recorded and gridded rainfall data at Wonmunna (Station 507012)**

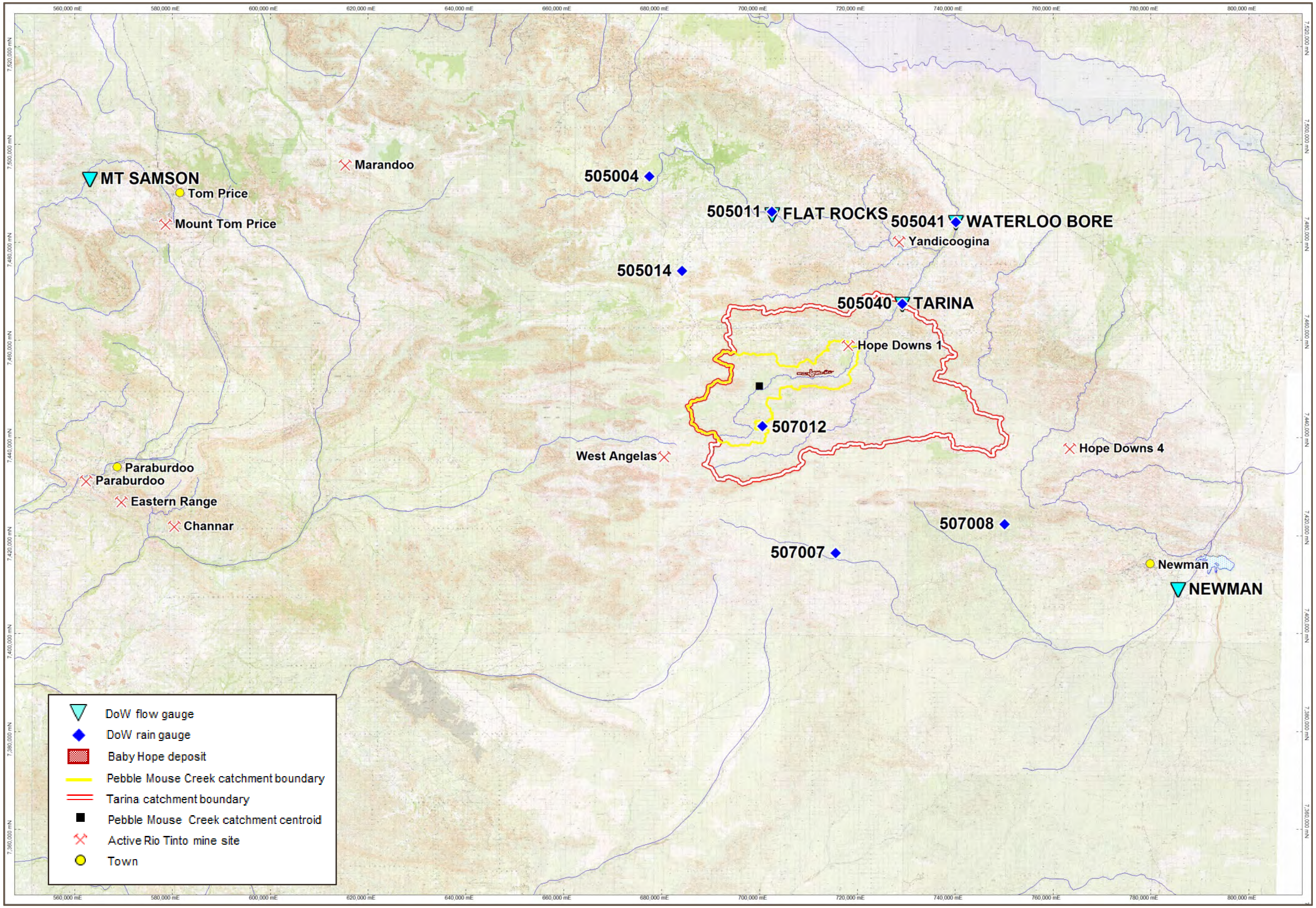

Figure 3-2: **Pebble Mouse Creek catchment within the Tarina catchment**

The monthly rainfall statistics for Baby Hope are provided in Figure 3-3. The rainfall is highly seasonal with 73% of the annual total occurring between December and April. Rainfall is typically associated with tropical low pressure systems and thunderstorm activity from the monsoonal trough that develops over northern Australia during summer. Winters are typically dry and mild though winter rain events can occur in June and July as a result of tropical cloud bands that intermittently affect the area. The high seasonality of rainfall has resulted in the adoption of a "water year" for the purpose s of hydrological analysis. The water year in the Pilbara Region is typically defined from 1 October to 30 September with the reported year stated as the year in which the water year commences. For example, the 1950 water year refers to 1 October 1950 through 30 September 1951.

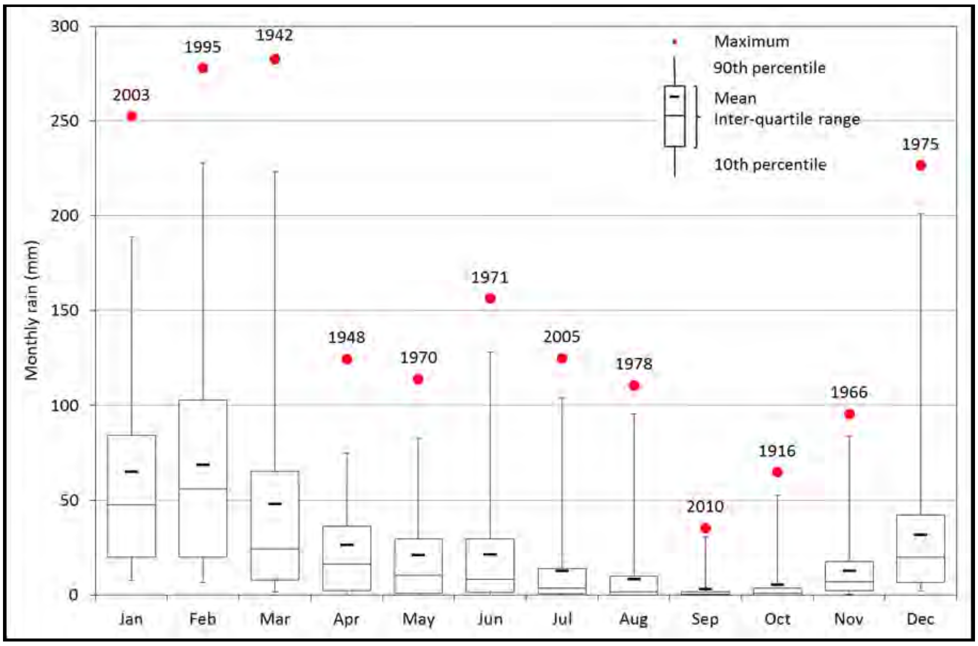

Figure 3-3: **Monthly gridded rainfall distribution for Baby Hope (700,016 mE/7,450,612 mN)**

The Coefficient of Variation (**CV**) of annual rainfall, used as a measure of inter-annual variability, is calculated as the ratio of the standard deviation to the mean annual rainfall. The CV of annual rainfall for the Baby Hope study area was calculated as 0.51, which is within the range of 0.4 to 0.7 reported for the Pilbara by Ruprecht and Ivanescu (2000).

An alternative methodology for characterising rainfall variability used by the Bureau of Meteorology calculates the rainfall *Index of Variability* (BoM 2003) as:

$$index\ of\ variability = \frac{(90p - 10p)}{50p}$$

Where:

- 90*p* is the 90th annual rainfall percentile;
- 50*p* is the 50th annual rainfall percentile, or median annual rainfall; and
- 10*p* is the 10th annual rainfall percentile.

Under this classification scheme, the Baby Hope study area was calculated to have an Index of Variability of 1.28, which falls within the BoM's "high" variability range of 1.25 -1.50.

The long term mean annual rainfall for the study area is 317 mm with a range of 65 mm to 945 mm illustrating the high inter-annual variability. A trend analysis of annual rainfall indicates a long term increasing trend of 1.4 mm/year, Figure 3-4. The trend increases substantially to 7.1 mm/year when considering only the last 20 years. A similar rising trend has been observed at multiple locations in the Pilbara region.

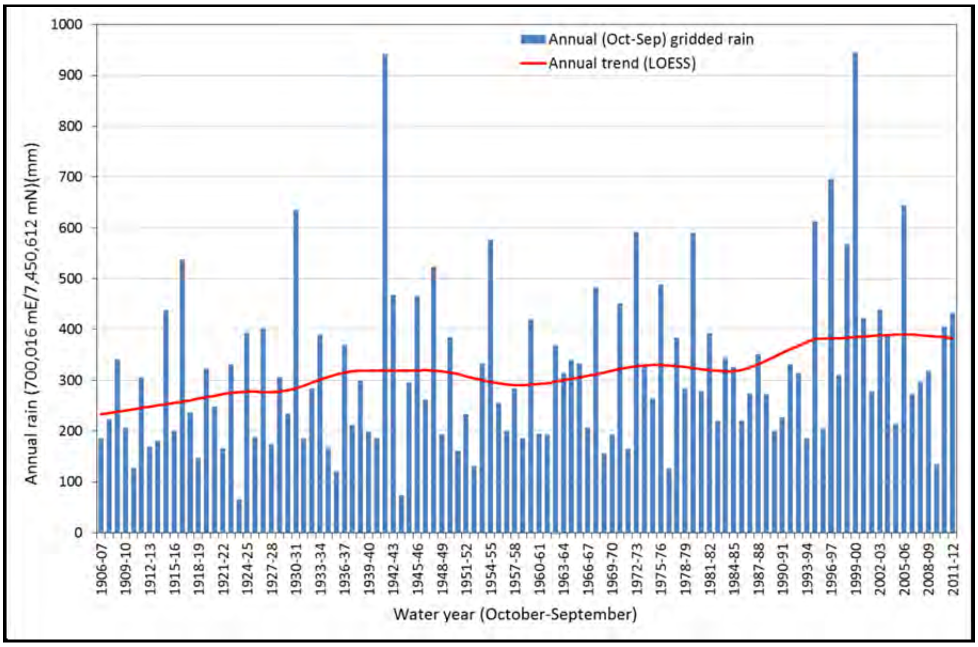

Figure 3-4: **Trend for annual (October-September) rainfall, BoM gridded data Baby Hope (700,016 mE/7,450,612 mN)**

Analysis of the daily gridded rainfall data indicates that rain events are infrequent and typically have low rainfall totals. Historically there are on average 39 rain days per year (rain greater than or equal to 1 mm) with majority of these days occurring from December to March. The daily rainfall statistics for the 107 year of record revealed; 76.4% of the daily rainfall totals are less than 5 mm; 96.4% are less than 25 mm; 98.2% are less than 35 mm; and 0.8% of daily rainfall totals are greater than 50 mm, an average of three days per year. Table 3-2 presents a summary of the gridded daily rainfall statistics for Baby Hope.

Table 3-2: **24 hour rainfall statistics BoM gridded data Baby Hope (700,016 mE / 7,450,612 mN)**

	Statistics for days when rain occurred			**Statistics for all days**		
Month	**Maximum (mm)**	**Mean (mm)**	**Standard deviation (mm)**	**Mean days of rain per year >=1 mm**	**Mean (mm) <10 mm only**	**Standard deviation (mm) <10 mm only**
January	152	5.1	11.4	7	2.1	2.4
February	116	5.8	11.3	7	2.3	2.5
March	133	5.4	11.0	5	1.9	2.3
April	96	4.6	8.4	3	2.0	2.4
May	70	4.7	7.8	3	2.3	2.5
June	110	5.1	10.0	3	2.0	2.4
July	91	4.0	8.5	2	2.0	2.4
August	46	3.7	6.4	1	2.0	2.1
September	27	2.4	4.3	1	1.6	2.0
October	35	2.6	5.0	1	1.4	1.8
November	78	2.8	5.3	2	1.8	2.2
December	156	3.7	8.6	4	1.9	2.3

3.2.2 Evaporation and Evapotranspiration

Evaporation and evapotranspiration (**ET**) measures available for the Baby Hope study area are shown in Table 3-3. The mean annual Class A pan evaporation estimated for the study area is 3,333 mm (BoM, 2006), which greatly exceeds the average annual rainfall in the area, 317 mm/year, keeping it typically dry. Sheltered monthly evaporation was estimated using a pan evaporation conversion factor of 0.63, taken from a study by Luke *et. al* (2003).

The annual mean point potential ET rate estimated for the study area is 3,030 mm/year (BoM 2005b). Point potential ET is the ET that would take place, under the conditions of unlimited water supply, from an area so small that the local ET effects do not alter local air mass properties. The BoM advises that point potential ET may be taken as an estimate of evaporation from small water bodies such as shallow water storages, which may include surface water pools within a creek system.

The annual mean areal actual ET rate for the study area is estimated to be 361 mm/year (BoM 2005b). This is the ET rate that actually takes place, under the condition of existing water supply, from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average. For example, this represents the evapotranspiration which would occur over a large area of land under existing (mean) rainfall conditions.

The annual mean areal potential ET for the study area is 1,518 mm/year (BoM 2005b). This is the ET rate that would occur under the condition of unlimited water supply, from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average. For example, this represents the evapotranspiration which would occur over a very large wetland or large irrigated area, with a never-ending water inflow. A "large" area is defined as an area greater than one square kilometre.

Table 3-3: Evaporation rates estimated for the Baby Hope study area; evaporation estimates based on at least 10 years of data1975-2005, ET data based on 30 years of data 1961-1990.

Month	Mean Class A pan evaporation (mm)	Mean sheltered evaporation (mm)	Mean point potential ET (mm)	Mean areal actual ET (mm)	Mean areal potential ET (mm)
January	394	248	392	61	202
February	304	192	311	77	164
March	310	195	289	53	146
April	244	154	205	25	102
May	175	110	132	26	67
June	129	81	91	29	48
July	144	91	110	15	57
August	188	118	155	12	77
September	260	164	229	12	111
October	357	225	334	7	160
November	393	248	377	13	181
December	435	274	405	31	203
Annual	3333	2100	3030	361	1518

4. Hydrology

4.1 Regional flow

Ruprecht and Ivanescu (2000) describe the hydrology of the Pilbara as being one of extremes, ranging from severe droughts to major floods. Pilbara streamflow is predominantly short-lived, ephemeral and in direct response to rainfall, therefore it has a similar seasonality and variability to rainfall. Surface water runoff generation in the Pilbara region typically results from infiltration excess as opposed to saturation excess. Infiltration excess occurs when the rate of rainfall exceeds the infiltration capacity of the soil and is commonly associated with high intensity rainfall and impervious catchments. Conditions satisfying saturation excess runoff generation occur during prolonged rainfall influenced by cyclones and tropical depressions. With the low rainfall in the region and general lack of groundwater contribution to surface water flow, extended periods of no flow are common.

The Pilbara region is sparsely populated and areas of interest from a streamflow perspective are often long distances from townships, making it problematic to get to many creeks while they are flowing, especially small creeks. Large flow events are difficult to measure due to safety concerns and high velocities, and invariably result in changes to the geomorphology of creeks. As a result stage-discharge relationships in the Pilbara are particularly challenging to accurately define and frequently need to be updated following large flow events. It follows that there is a distinct lack of quality streamflow data in the region, on both a temporal and spatial scale.

4.2 Local flow

There are no local streamflow gauges within the Pebble Mouse Creek catchment. The Tarina gauging station is located on Weeli Wolli Creek, approximately 13 km downstream from the Pebble Mouse/Weeli Wolli Creek confluence and is the closest stream flow gauge to the Baby Hope deposit. Streamflow gauges in catchments surrounding the Baby Hope study area are shown in Figure 3-2 and Table 4-1. Characteristics of the Pebble Mouse Creek catchment to the Baby Hope deposit and HD1 SE pit are given in Table 4-2.

Table 4-1: Local stream gauges within 150 km of Baby Hope and with greater than 20 years of data

Station number	Gauge name	Catchment area (km^2)	Slope m/km	Distance from study area (km)	Period of record	Years of data	% record complete
706207	Mt Samson	250	8	140	1/1/1967 - 21/5/2001	33	96
708001	Flat Rocks	1,370	2.9	37	15/08/1967 - present	44	98
708011	Newman	2,824	1.67	95	09/01/1980 - present	32	100
708013	Waterloo Bore	3,991	2.65	53	30/11/1984 - present	28	100
708014	Tarina	1,512	3.65	34	10/05/1985 - present	27	100

The Depart of Water (**DoW**) has developed stage-discharge relationships for the gauges listed in Table 4-1. The strength of the relationship is dependent on the quality, number, range and date of measurements. Geometry of the cross section where flow measurements have been taken may change over time resulting in an altered relationship for the location and consequently it needs to be updated or redefined depending on the level of change. The latest stage-discharge relationships available have been used in this study and are shown in Appendix B.

Table 4-2: Characteristics of the Pebble Mouse Creek catchment

Catchment	Catchment area (km^2)	Slope (m/km)
Pebble Mouse Creek at Baby Hope	258	3.5
Pebble Mouse Creek at HD1 SE pit	297	3.5

4.3 Annual flow

It is reasonable to surmise that the streamflow regime at the Baby Hope study area is similar to the downstream flows at Tarina as the Pebble Mouse Creek catchment contributes to flow at the station. A total of 47 separate flow events have been recorded at the Tarina gauge over a 27 year period of operation, which represents an average of approximately 2 flow events per year. Analysis of the Baby Hope gridded rainfall data indicates that there were on average two rainfall events 35 mm or greater over the same period, suggesting that the minimum amount rainfall required to produce flow in the catchment is 35 mm. This is supported by Charles *et. al* (2013) in their study on the Pilbara which included analysis of the Tarina catchment and found the minimum rainfall required to produce flow in the catchment is 36 mm.

The annual maximum flow time series (**AMS**) for the Tarina stream gauge is given in Figure ***4-1***. Based on the AMS large flow events are expected to occur on average once every five years. The CV of annual streamflow for Tarina is 2.08, indicating the stream flow is approximately 4 times more variable than rainfall. The AMS time series is dominated by the flow event as a result of Tropical Cyclone (**TC**) John in 1999 which is approximately 4 times greater than the next largest event. Analysis of large flows events within a catchment can provide an insight into the mechanisms that drive them.

Rainfall totals available for TC John and other large flow events at the Tarina gauge are shown in Table 4-3. The rainfall totals show that the Unnamed Tropical Low (**UTL**) in January 2003 produced a much higher rainfall than TC John particularly around the Tarina rain gauge (505040), yet resulted in much lower flows. Analysis of rainfall from the two events at the Wonmunna rainfall gauge (Appendix A) in the upper catchment reveals that rainfall from TC John at the gauge was equivalent to a 2% AEP rainfall event and rainfall from the January 2003 UTL at the gauge was equivalent to a 5% AEP rainfall event. The difference in intensity between the two rainfall events provides an explanation for the difference in flow as a result of them and highlights the spatial variability of rainfall and streamflow within the Tarina catchment.

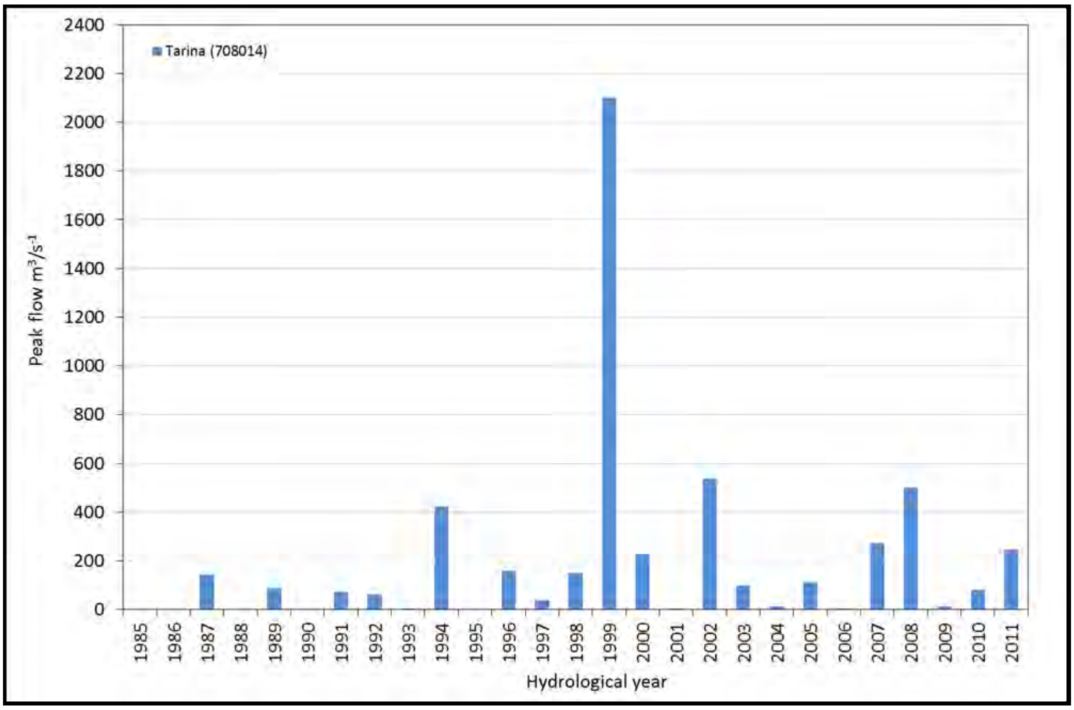

Figure 4-1: Annual maximum stream flow record for hydrological year (September to October)

Large stream flows in the Pilbara are almost always the result of tropical cyclones or tropical lows and large peak flows at Tarina correlate well with tropical cyclones or tropical lows that resulted in rainfall in the region as shown in Table 4-3.

Table 4-3: Significant rainfall events producing flows at Tarina; as a result of tropical lows and tropical cyclones

Event name	Date	Hydrological year (Sep-Oct)	Rainfall 505040 (mm)	Rainfall 507012 (mm)	BoM gridded rainfall* (mm)
TC Bobby	26/02/1995	1994	135	109	126
TC John	16/12/1999	1999	160	199	155
TC Wylva	22/02/2001	2000	140	79	72
Unnamed Tropical Low	25/01/2003	2002	317	203	246
Unnamed Tropical Low	01/03/2009	2008	116	130	93

* from centroid of Pebble Mouse catchment

Monthly streamflow analysis and flow duration curves for Tarina are shown in Figure 4-2 and Figure 4-3. The mean monthly flow at Tarina indicates the creek flows year round; this is not typical in the Pilbara and is a result of the release of surplus mine dewatering water into Weeli Wolli Creek which began in 2007. The release of the surplus water has altered the flow regime of the creek system from an ephemeral to a perennial system. The flow duration curves also indicate a change in flow regime, however there is no indication that this has significantly impacted on the AMS, with the exception of low flows.

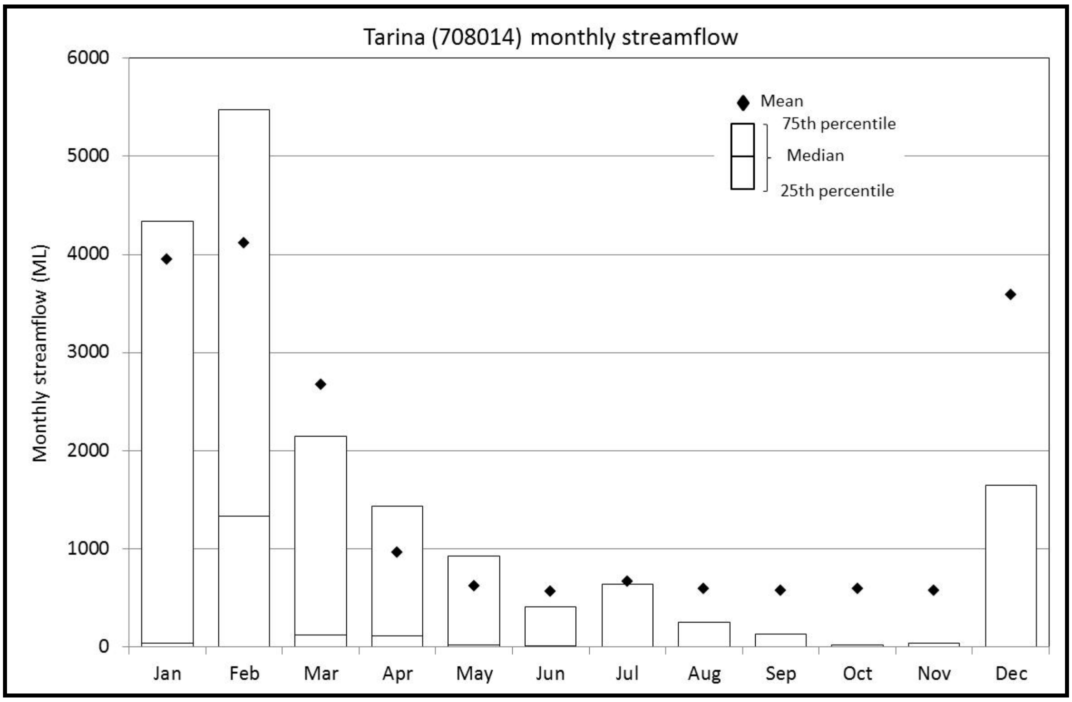

Figure 4-2: Monthly streamflow for Tarina 1985-2012

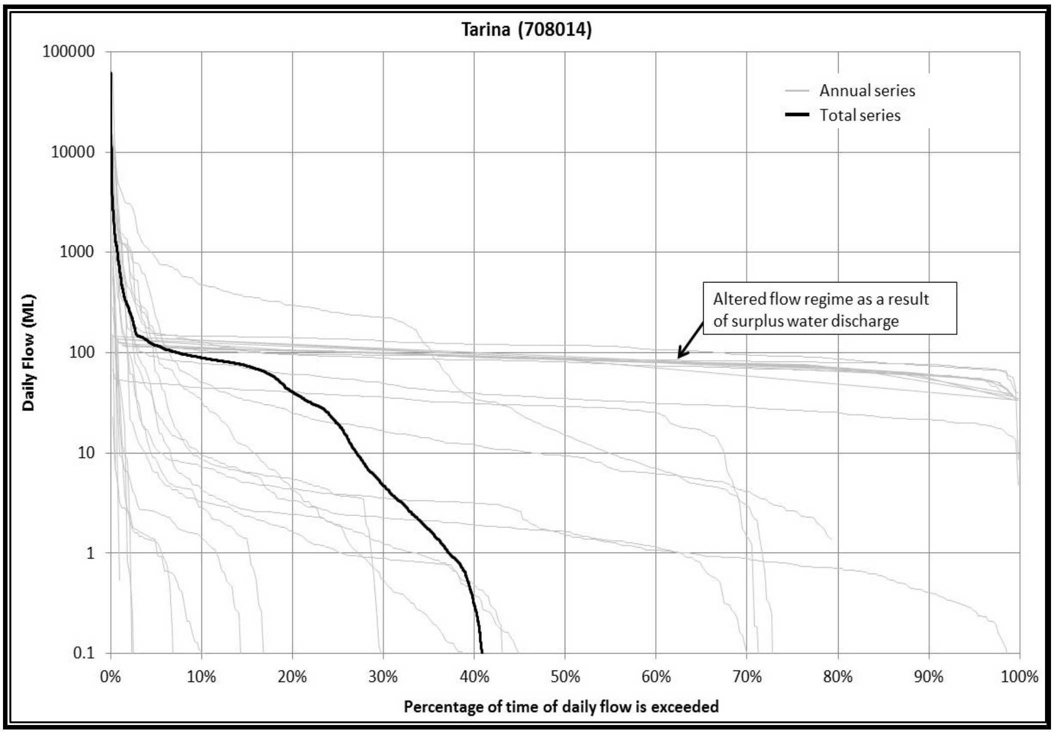

Figure 4-3: Flow duration curves at Tarina gauging station (708014) on Weeli Wolli Creek

4.4 Regional flood frequency analysis

Regional flood frequency analysis (**RFFA**) is the most commonly adopted technique to derive design flood estimates on ungauged catchments (Rahman *et.al* 2012). A RFFA method attempts to transfer flood characteristic information from a group of gauged catchments to an ungauged catchment of interest. FFAs can be undertaken on flood volumes and/or peak discharges and may be carried out graphically or analytically (Pilgrim 1998). A FFA was performed on the annual maximum series (**AMS**) of peak discharges recorded at local regional streamflow gauges with more than 20 years of data (Table 4-1). The years in which data were missing were investigated further to determine if significant rainfalls occurred during the periods for which streamflow information was lacking. For years where it was determined that the missing data would not impact on the recorded peak discharge for that year, the peak was included in the analysis.

An analytical FFA using the HEC-SSP flood frequency analysis program (USACE 2010) was undertaken. In accordance with Australian Rainfall and Runoff (**AR&R**) (Pilgrim 1998) the 3-parameter Log Pearson III distribution was adopted for this study. A conditional probability adjustment was performed in HEC-SSP to account for zero values, missing data and low outliers. Additional low outliers were excluded where the fit of the distribution was considered poor for the rarer AEP events. The observed AMS is only one representation of the AMS from the total population of annual floods. To obtain an unbiased estimate of the true AEP the average of a large number of annual series, or the expected annual exceedance probability, is required. The expected annual exceedance probability was adopted for estimates of FFA quantiles this study.

During the FFA process it was noted that the fitted distribution at Waterloo Bore was a poor fit to the observed data. Comments made by the Department of Water (**DoW**), who developed the stage-discharge relationship, suggest that there is a great deal of uncertainty in its quality. Subsequently this gauging station was removed from any analysis. The FFA distribution, rating curve and comments for Waterloo Bore can be found in Appendix A.

Table 4-4: Results of FFA for gauges surrounding the Baby Hope study area

	AEP (%) (LPIII Expected design peak m^3/s)							
Station number	**Gauge name**	**Area (km^2)**	**50**	**20**	**10**	**5**	**2**	**1**
706207	Mt Samson	250	20	90	190	310	500	640
708001	Flat Rocks	1,370	80	230	420	710	1,340	2,110
708011	Newman	2,820	230	590	1,030	1,700	3,140	4,890
708014	Tarina	1,510	80	250	500	920	1,950	3,350

Results of the FFA on gauges surrounding the Baby Hope area are given in Table 4-4 and fitted distributions are shown in Appendix A. Tarina is the closest gauge downstream of the Baby Hope study area that could be used to calibrate a rainfall-runoff routing model. The FFA for Tarina is shown in Figure 4-4. The altered flow regime at the gauge as discussed in section 4.3 was not taken into account in the FFA due to the small period of record of altered flow (5 years) and no distinct affects observed on large flow events of the AMS.

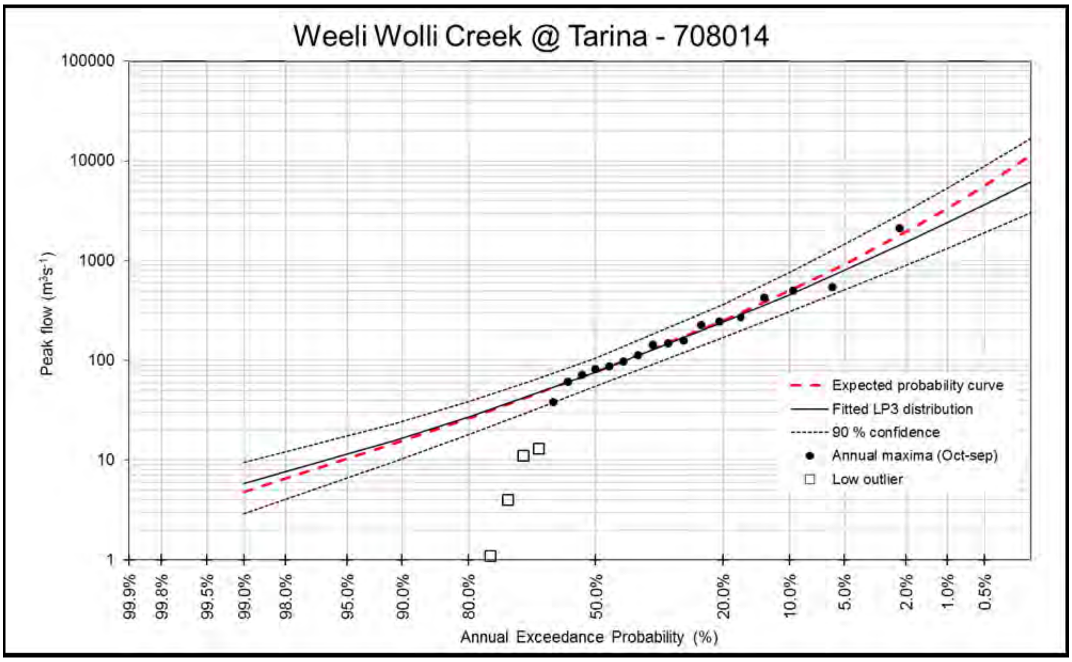

Figure 4-4: **Tarina annual maximum stream flow flood frequency analysis**

For FFA it is important to have a record which is representative of the total population, it follows that the period of record available for analysis influences the reliability of a FFA, this is highlighted by Table 4-5. The table was developed from data generated synthetically from a probability distribution, and outlines the number of years of record needed to estimate three AEP's with 95% confidence and the expected margin of error. From the table it can be seen that estimates of the 1% AEP from the 27 year record of data available for Tarina are subject to an expected error of greater than 25%. Although 27 years of data is a considerable period for a Pilbara streamflow gauge, it is important to understand the limitations of estimates made using it.

Table 4-5: **Length of record (years) required to estimates floods of various AEP with 95% confidence (Gordon et. al.2004)**

	Error	
Annual exceedance probability (AEP %)	10%	25%
10	90	18
2	110	39
1	115	48

4.5 Regional design flood estimates

Regional design flood estimates are typically based on equations developed from a RFFA. The probabilistic rational method (**PRM**) and the index flood method (**IFM**), published in ARR (Pilgrim 1987), were design peak flow estimation techniques recommended for the Pilbara region. These methods were based on the limited data available at the time and in hindsight are considered to be conservative design flood estimation techniques.

Recently there have been a number of new methods developed for the Pilbara namely; a Regional Flood Frequency Procedure (**RFFP**) by Flavell, 2000 and updated in 2006 (Flavell 2012); an updated Pilbara Index Flood method (**JDA**) (Davies and Yip 2014) and a Quantile Regression Technique (**QRT**) (Rahman *et. al* 2012). The more recent methods are based on a longer record of data and for this reason are considered to give a more reliable estimation of design flows. Estimates using the RFFP, JDA and QRT methods mentioned above were calculated for this study.

4.5.1 Regional flood frequency procedure for the Pilbara (RFFP)

A regional flood frequency procedure for the Pilbara was developed by Flavell in 2000 and updated in 2006 (Flavell 2012). The 2000 RFFP method was developed using 15 Pilbara catchments and is recommended for design events for 20 year ARI or larger, as it gives larger peak flow estimates. There are two equations for the 2000 method and again the recommended approach is to adopt the larger estimate. The two equations are as follows:

$$Q_{20} = 1.98 \times 10^{-23} (AS_e{}^{0.5})^{0.79} LAT^{-15.08} LONG^{20.91}$$

or

$$Q_{20} = Q_{10}(13.21A^{0.61})/(8.74A^{0.60})$$

Where:

Q_{20} = 20yr ARI (5% AEP) peak discharge (m^3/s);

A = catchment area (km^2)

S_e = equal area slope (m/km)

Q_{10} = $2.36 \times 10^{-34} \left(AS_e{}^{0.5}\right)^{0.81} LAT^{-15.24} LONG^{26.28} (\frac{L^2}{A})^{-0.39}$

Table 4-6: RFFP 2006 frequency factors

Frequency factor	Catchment area (km^2)						
	0.1	1.0	10	100	1,000	10,000	100,000
$\mathrm{Q}_{50}/\mathrm{Q}_{20}$	1.66	1.72	1.78	1.83	1.88	1.93	2.00
$\mathrm{Q}_{100}/\mathrm{Q}_{20}$	2.44	2.61	2.75	2.87	3.03	3.20	3.42

The Q20 is subsequently adjusted to the Q50 and the Q100 design flood estimate by applying flood frequency factors shown in Table 4-6. Equations for estimating smaller design flow events are given in the Flavell (2012) paper shown in the references. Estimates of Q100 (Q1%) using the 2000 RFFP method are given in section 4.5.5.

4.5.2 Updated Pilbara index flood method (JDA)

An updated Pilbara index flood method based on data from 57 catchments from the Pilbara, Gascoyne and Mid-west regions was developed by Davies and Yip in 2012 and updated in 2014. The method separates catchments by size with individual equations developed for; catchments less than 1,000 km^2; catchments between 1,000 km^2 and 10,000 km^2; and catchments greater than 10,000 km^2. The design equation for Baby Hope (258 km^2) using this method is as follows:

$$Q_5 = 7.32 \times 10^{-8} A^{0.651} I_{1h,2yr}{}^{5.251}$$

Where:

Q_5 = 5yr ARI (20% AEP) peak discharge (m^3/s);

A = catchment area (km^2)

$I_{1h,2yr}$ = the design intensity frequency duration (IFD) (ARR 1987) value for a 1 hour 2 year rainfall (mm/hour) at the study area centroid.

Table 4-7: JDA frequency factors

ARI (yrs)	2	5	10	20	50	100
Frequency factor	0.31	1.00	1.70	2.58	126	5.82

Q5 is subsequently adjusted to the design discharge by applying a flood frequency factor as shown in Table 4-7. Estimates of Q100 (Q1%) using the JDA method are given in section 4.5.5.

4.5.3 Quantile regression technique (QRT)

The recently completed ARR Project 5 Stage 2 study (2012) into design flood estimation has found that regression-based RFFA methods such as the QRT are preferable to PRM (Rahman *et. al* 2012). The study was conducted on 12 Pilbara catchments and resulted in the following design equation:

$$\ln(Q_{100}) = 5.87 + 0.39[\ln(area) - 4.71] + 5.34[\ln(I_{12,2}) - 1.47]$$

Where $area$ is the catchment area (km2) and $I_{12,2yr}$ is the design intensity frequency duration (**IFD**) (ARR 1987) value for a 12 hour 2 year rainfall (mm/hour) at the study area centroid. Estimates of Q100 (Q1%) using the QRT are given in section 4.5.5.

4.5.4 Scaling of flood frequency analysis

A simple form of design flood estimation for ungauged catchments is performed using area to adjust peak flow estimates from gauged catchments close to the study area of interest. The strength of this method comes from the locality of catchments used, as proximity is frequently a strong indicator of hydrologic similarity (Lowe and Nathan 2005). Estimates of $Q_{1\%}$ from the FFA on gauges in section 4.2 were scaled using the following equation from Grayson *et. al* 1996:

$$Q_u = Q_g(\frac{A_u}{A_g})^{0.7}$$

Where Q_u and Q_g are flow (m^3/s) of ungauged and gauged catchments; A_u and A_g are area (km^2) of ungauged and gauged catchments. The coefficient 0.7 accounts for the non-linear effects of catchment area on runoff. Results of the area adjusted local region FFA are shown in Table 4-8. The local area adjusted mean was calculated as the mean value of 4 scaled estimates from catchments surrounding the Baby Hope deposit. The local area adjusted mean estimate of 1% AEP peak flow for Pebble Mouse Creek to the Baby Hope deposit and to HD1 SE Pit was calculated to be 790 m^3/s and 870 m^3/s respectively.

Table 4-8: Area adjusted estimates of 1% AEP Pebble Mouse Creek at Baby Hope deposit

Station number	Catchment name	Catchment area (km^2)	FFA Log Pearson III $Q_{(1\%)}$ (m^3/s)	Pebble Mouse at Baby Hope $Q_{(1\%)}$ (m^3/s)	Pebble Mouse at HD1 SE Pit $Q_{(1\%)}$ (m^3/s)
706207	Mt Samson	250	640	650	720
708001	Flat Rocks	1,370	2,110	660	720
708011	Newman	2,820	4,890	920	1,010
708014	Tarina	1,510	3,350	910	1,010
		Local area adjusted mean		790	870

4.5.5 Regional flood frequency results

Estimates of 1% AEP for Pebble Mouse creek up to the Baby Hope deposit and HD1 SE pit, and surrounding local catchments using the preceding regional flood frequency methods are presented in Table 4-9. The results show a significant variation in estimates from the different methods for Pebble Mouse Creek ranging from 300 m^3/s to 790 m^3/s to Baby Hope deposit and from 320 m^3/s to 870 m^3/s to HD1 SE pit. Estimates of the 1% AEP using RFFP from surrounding catchments are within 20% of the FFA, with the exception of the Newman.

Table 4-9: Estimates of 1% AEP design flood using regional flood frequency analysis

Catchment	JDA (m^3/s)	RFFP (m^3/s)	QRT (m^3/s)	FFA (m^3/s)	Local area adjusted average (m^3/s)
Mt Samson	740#	760#	610*#	670	-
Flat rocks	1,560	2,400*#	1,440	2,110	-
Tarina	1,310	2,980*#	670	3,180	-
Newman	1,390	2,370*	450	4,890	-
Pebble Mouse to Baby Hope deposit	320	550	300	-	790
Pebble Mouse to HD1 SE Pit	360	610	320	-	870

**Estimation closest to the catchment FFA of methods examined*

#Estimation within 20% of the catchment FFA

4.6 Hydrologic modelling

A hydrologic model of the Weeli Wolli Creek catchment was developed using the RORB (Laurenson *et al* 2007) model in order to estimate design peak flows for Pebble Mouse Creek at the Baby Hope deposit and at HD1 SE pit. RORB is a rainfall runoff and streamflow routing model that calculates flood hydrographs from rainfall and other channel inputs. Rainfall excess, calculated by subtracting losses from rainfall, is routed through catchment storages to produce runoff hydrographs at any location; losses are processes that occur on the catchment surface before the water enters the channel network. In addition to catchment storage, RORB allows for storage reservoirs and channel inflow and outflow processes, such as base flow, to be modelled. Channel inflows and outflows can be modelled using a hydrograph, constant value or discharge relationship. The project catchment has been divided into sub-catchments bounded by drainage divides. The sub-catchments making up the model are depicted in Figure 4-5. A rainfall excess for each sub-catchment is assumed to enter the channel network at a point near the centroid of the sub-catchment, added to any existing flow in the channel and routed through a routing procedure based on continuity and a storage-discharge relationship:

$$\mathrm{S} = 3600\mathrm{kQ}^{\mathrm{m}}$$

where S is the storage (m^3), Q is the outflow discharge (m^3/s), m is a dimensionless exponent that is a measure of the catchment's non-linearity and k is a dimensionless empirical coefficient. The coefficient k is calculated as:

$$\mathrm{k} = \mathrm{k_c k_r}$$

where $\mathrm{k_c}$ is an empirical coefficient applicable to the catchment and stream network and $\mathrm{k_r}$ is a dimensionless ratio called the relative delay time applicable to an individual reach storage. Channel storages are proportional to the reach length and hydrographs are combined at channel junctions (Laurenson *et al* 2007).

4.6.1 Tarina RORB calibration

The Tarina RORB model was calibrated using the initial/continuing loss model, where loss processes are modelled by an initial loss followed by a continuing (constant) loss rate. A value of 0.8 was adopted for the exponent m, following recommendation by RORB developers (Laurenson et.al, 2007) for ungauged catchments in the absence of more relevant information. Design values of k_c, initial loss and continuing loss for the study catchment were determined through calibration. Calibration was achieved by fitting flows produced by RORB, from the developed catchment and observed rainfall, to observed flows from Tarina gauging station. Five events were used to calibrate the RORB model to Tarina and are detailed in Table 4-10.

Table 4-10: Events used to calibrate the RORB model

Flow event peak date	Hydrological year (Oct-Sep)	Peak flows (m^3/s)	AEP (%) (from FFA)	Rainfall gauge used in calibration
28/03/1988	1992	57	50	505040
25/02/1995	1994	224	20	505040
8/01/1997	1996	108	50-20	505040
15/12/1999	1999	2,100	2	505040
25/01/2003	2002	535	10	505040

Considering the large catchment size and the use of only one rainfall gauge, the model was found to calibrate very well to observed hydrographs, as shown in Figure 4-6. The k_c parameter is the focus of calibration attempts as initial loss and continuing loss vary with antecedent conditions. The calibrated model parameters presented in Table ***4-11*** show some variation in the k_c value. Given the number of and range of calibration events an average value for the k_c parameter from the five events was adopted.

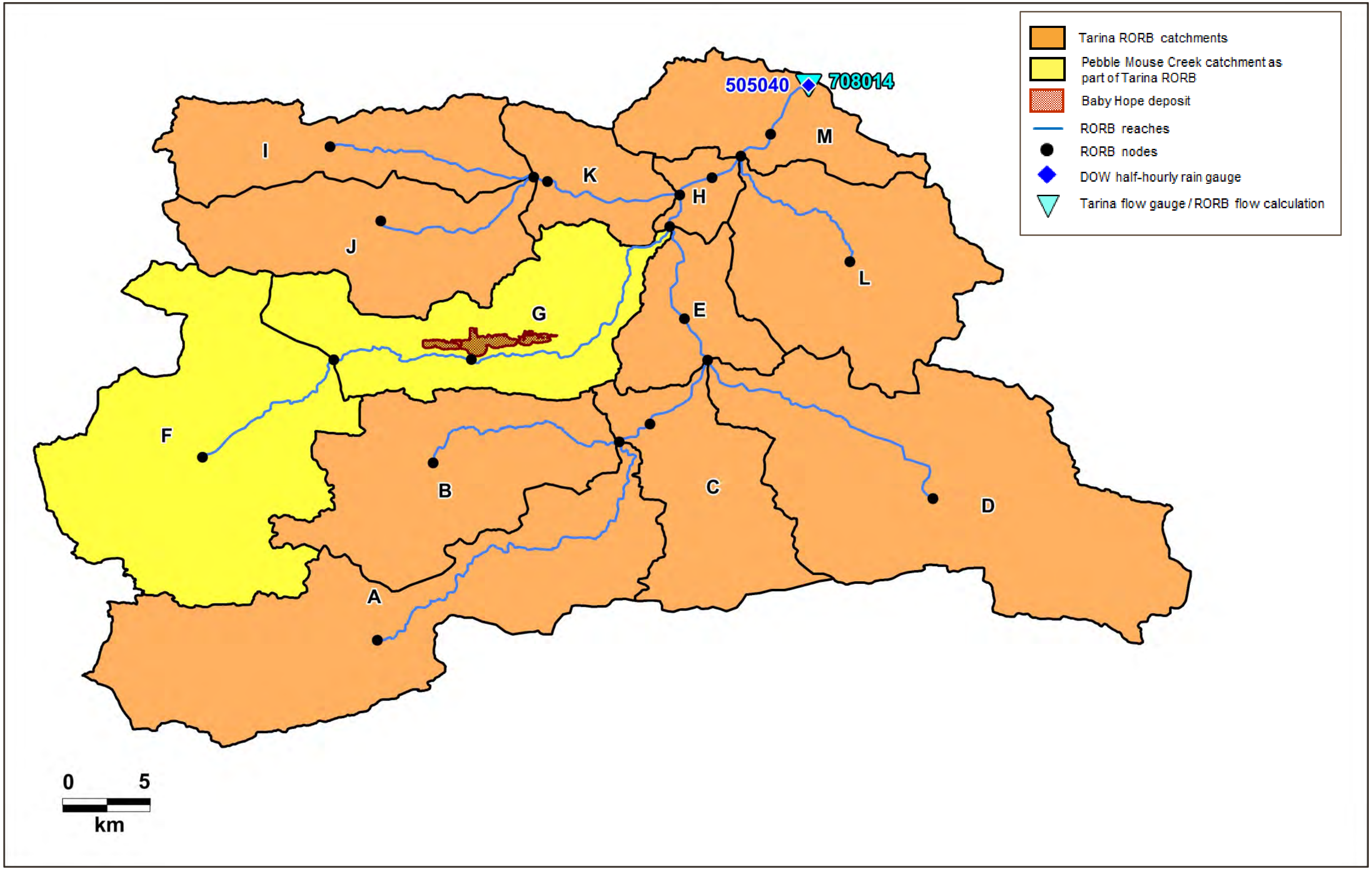

Figure 4-5: Tarina RORB model inputs; catchment sizes are listed in Appendix C

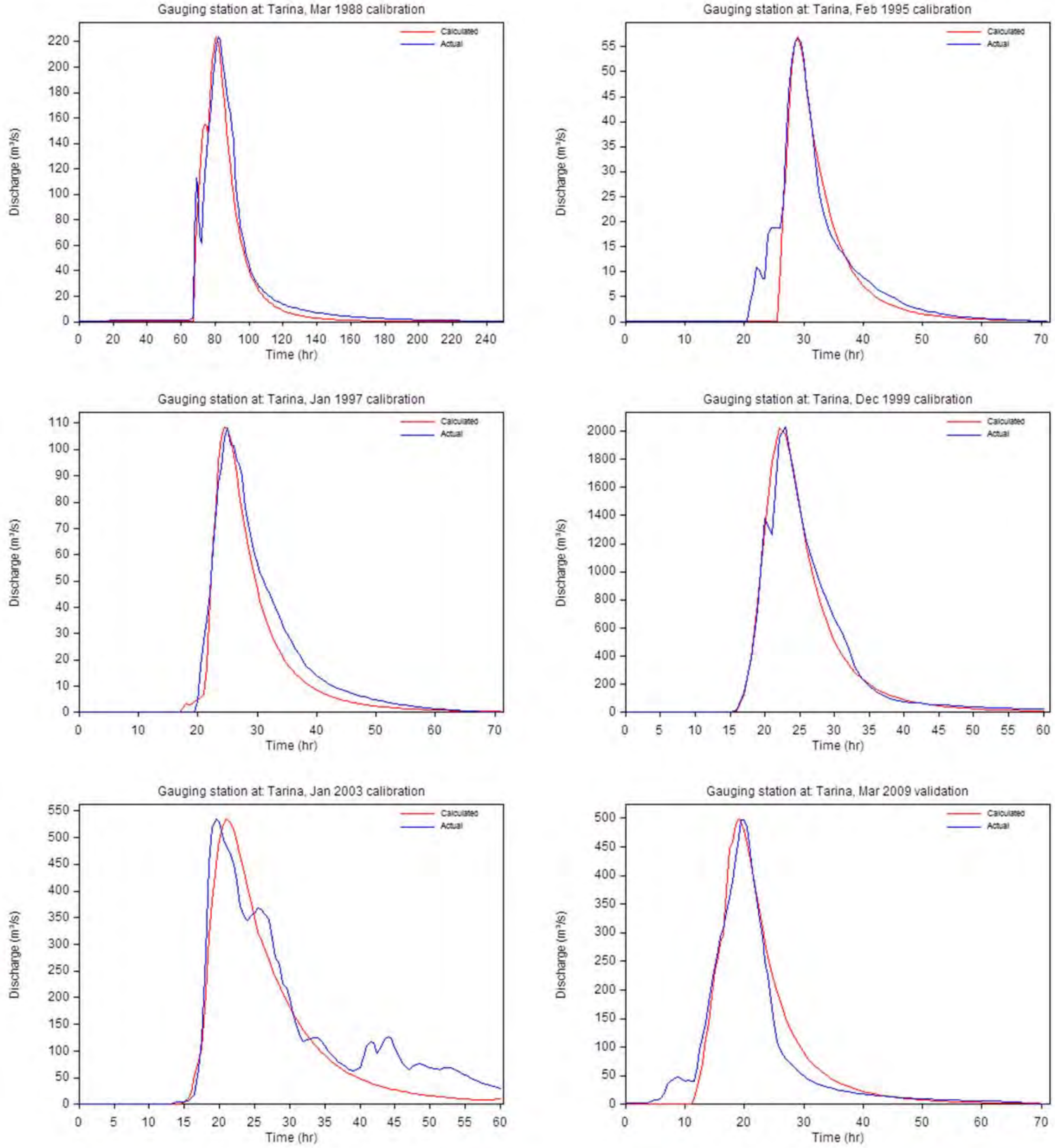

Figure 4-6: **Five calibration and one validation event at Tarina stream flow gauge**

To establish a level of confidence in the adopted k_c value a sixth event was used to validate the parameter. Validation was performed by assigning the adopted k_c value to the event and varying the losses to fit the peaks of the modelled hydrograph to observed hydrograph. Results of the validation are shown in Figure 4-6 and Table 4-11, and support the adopted k_c value.

Table 4-11: RORB parameters from calibration and validation

Flow event peak date	Peak flows(m^3/s)	Event use	k_c	d_{av}	$C_{0.8}$ value	Initial loss (mm)	Continuing loss (mm/hr)
28/03/1988	57	Calibration	9.7	30.5	0.32	80.3	1.4
25/02/1995	224	Calibration	27.8	30.5	0.91	70.0	8.7
08/01/1997	108	Calibration	12.9	30.5	0.42	57.0	8.9
15/12/1999	2,100	Calibration	21.0	30.5	0.69	45.0	11.1
25/01/2003	535	Calibration	21.4	30.5	0.70	62.2	11.0
01/03/2009	505	Validation	18.6*	30.5	0.61	46.0	10.0

*adopted K_c value, taken as the average of the five calibration events

The calibrated initial loss values are higher than the suggested 35 mm minimum required rainfall to produce flows (section 4.3). The suggested initial loss value of 35 mm is a nominal amount required to produce any flow. Actual initial loss of a given calibrated event may be influenced by antecedent conditions, where the rainfall fell in the catchment, where the rainfall was recorded, and the intensity and duration of the rainfall.

The calibrated continuing loss values of up to 11mm/hr are considerably higher than AR&R recommended continuing loss value for the Pilbara of 5mm/hr. The AR&R recommended value for the Pilbara comes from a 1982 study by Flavell *et. a.* that included six Pilbara catchments and was based the limited data that was available at the time. Continuing loss values for the Tarina calibrated events are in line with continuing loss values found in the calibration of multiple events across nineteen Pilbara catchments in a 2014 study by Pearcey *et. al*. Additionally individual catchments display individual characteristics and it is not unreasonable to surmise that the Tarina catchment has what may be considered a high continuing loss rate due to an individual characteristic, i.e. underlying geology.

The adopted k_c value of the Tarina catchment was transferred to the combined Pebble Mouse/Tarina catchment using a regional relationship developed for Pilbara catchments by Pearcey (2014). McMahon and Muller (1983) showed that k_c is directly proportional to d_{av} by the relationship:

$$C_{0.8} = \frac{k_c}{d_{av}}$$

Where d_{av} is the weighted average flow distance from all the nodes within the catchment to the catchment outlet; and where C0.8 is characteristic (when m=0.8) of the catchment that is now independent of the scale or the size of the catchment. The calculation of an average regional C0.8 value allows it to be used in ungauged catchments and gives confidence to values calculated in gauged catchments. The relationship between C0.8 and catchment area for the Pilbara is given in Figure 4-7.

The C0.8 calculated for the Tarina catchment using the adopted k_c value of 18.6 and a d_{av} of 30.50 taken from the RORB model, equates to 0.61 marginally higher than the expected

$C_{0.8}$ of 0.59 for the Pilbara. This provides confidence in the adopted value of C0.8 for the catchment.

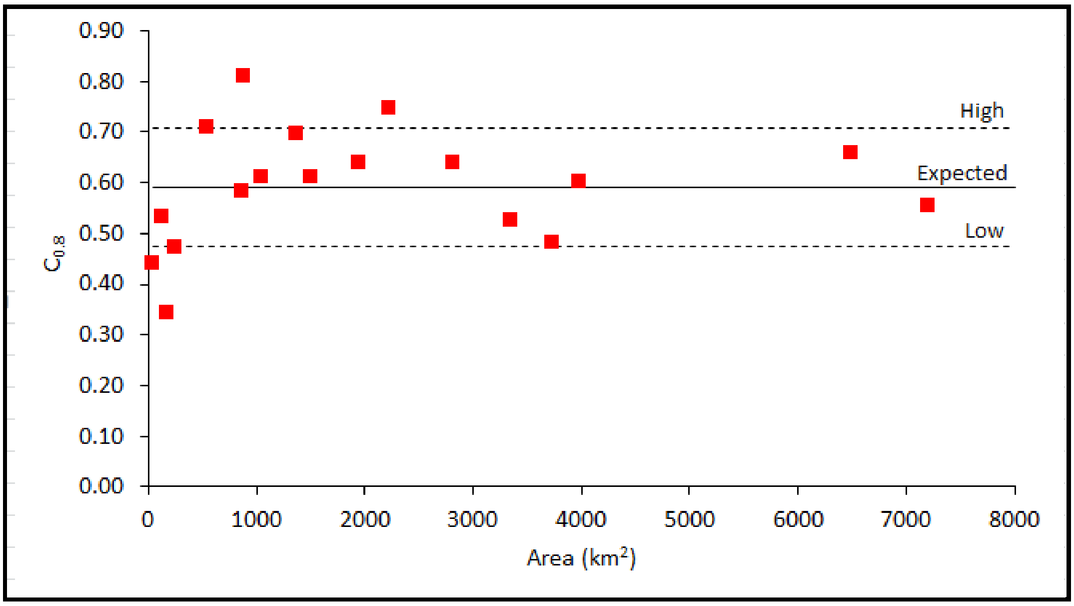

Figure 4-7: $C_{0.8}$ **relationship for the Pilbara based on 18 catchments (Pearcey *et al* 2014)**

4.6.2 Combined Pebble Mouse/Tarina RORB

The existing RORB model was refined to include a number of sub-catchments upstream from the area of interest (Pebble Mouse Creek) as recommend by Laurenson (2007) (Figure 4-8). This allowed the calibration of peak flows from design storm events at Tarina to the FFA at the gauge, whilst providing estimates of design peak flows at the Baby Hope deposit. Estimates of design peak flows approximately 9 km downstream of Baby Hope at Hope Downs 1 SE pit were also made using the same model. The calibrated $C_{0.8}$ value of 0.61 for the Tarina catchment was adopted for all events in the combined Pebble Mouse Creek/Tarina RORB model.

4.6.3 Design Event Critical Duration

The critical duration at a particular location refers to the duration of a design storm event that produces the maximum flood peak for a given annual exceedance probability. The combined RORB model was run for a range of AEP and design storm durations to determine the critical durations for Tarina. Design rainfall from the Tarina catchment centroid for events from 1% AEP to 20% AEP were applied to the model, with the C0.8 value held constant, losses were adjusted to match peak flow estimates from the model to estimates from the Tarina FFA. Once it was established that the continuing loss value for the 1% AEP event calibration was 9 mm/hr, it was held constant throughout calibration of the rest of the AEP events, with initial loss being the only parameter adjusted. The continuing loss value of 9 mm/hr was the same as the average continuing loss value obtained from the calibration of actual rainfall events over the Tarina catchment, giving added weight to the adopted continuing loss value.

An initial loss value of 0 mm/hr, used for the calibration of 1% AEP design rainfall to the FFA, enabled the continuing loss parameter to reflect the values obtained from the calibration of actual events. As initial loss varies with antecedent conditions it is considered the most appropriate parameter to vary for the calibration of design rainfall to the FFA.

Design rainfall for the 1% and 2% AEP events was taken from the CRC-Forge data for Western Australia (Durrant and Bowman, 2004). Design rainfall for 5% to 20% AEP events was taken from Intensity Frequency Duration (**IFD**) data provided by AR&R (Pilgrim 1987).

RORB applies the standard temporal patterns from AR&R (Pilgrim 1987) to the design rainfall depths. Results of the Tarina calibrations are shown in Table ***4-12***.

Table 4-12: Parameter values for calibration of the Tarina RORB to design rainfalls

AEP (%)	Peak flows at 708014 from FFA (m^3/s)	Calibrated peak flow at 708014 from design rainfall (m^3/s)	Critical duration (hrs)	$C_{0.8}$	K_c	D_{av}	IL (mm)	CL (mm/h)
1*	3,180	3,180	9	0.61	22.1	36.2	0.0	9.0
2*	1,840	1,840	12	0.61	22.1	36.2	49.8	9.0
5#	880	880	24	0.61	22.1	36.2	44.1	9.0
10#	490	490	24	0.61	22.1	36.2	64.4	9.0
20#	260	260	12	0.61	22.1	36.2	49.2	9.0

*using CRC-Forge design rainfall
#using IFD design rainfall

To obtain design peak flow estimates of peak flow for Pebble Mouse Creek at the Baby Hope deposit and at HD1 SE pit the RORB model was run with the same parameters from the Tarina calibration of design rainfall to the FFA. The design rainfall location was changed to the centroid of the Pebble Mouse Creek catchment and the areal reduction factors reduced to account for the smaller catchments upstream of the Baby Hope deposit and HD1 SE pit. Estimates of design peak flows at the Baby Hope deposit and the HD1 SE pit can be found in Table 4-13 and critical durations with areal reduction factors found in Table 4-14.

Table 4-13: Peak flow and critical duration estimates of AEP events for Pebble Mouse Creek at the Baby Hope deposit and HD1 SE Pits

AEP (%)	Peak flow at Baby Hope deposit (m^3/s)	Critical duration (hrs)	Peak flow HD1 SE pit (m^3/s)	Critical duration (hrs)	$C_{0.8}$	K_c	D_{av}	IL (mm)	CL (mm/h)
1*	970	6	890	6	0.61	22.1	36.2	0.0	9.0
2*	510	9	480	12	0.61	22.1	36.2	49.8	9.0
5#	280	24	240	24	0.61	22.1	36.2	44.1	9.0
10#	160	24	140	24	0.61	22.1	36.2	64.4	9.0
20#	80	24	70	24	0.61	22.1	36.2	49.2	9.0

*using CRC-Forge design rainfall
#using IFD design rainfall

Table 4-14: Critical durations and areal reduction factors for the three flow calculation locations

	Tarina (1529 km^2)		Pebble Mouse at Baby Hope (258 km^2)		Pebble Mouse at HD1 SE pit (297 km^2)	
AEP (%)	Critical duration (hrs)	ARF	Critical duration (hrs)	ARF	Critical duration (hrs)	ARF
1*	9	0.80	6	0.84	6	0.83
2*	12	0.83	9	0.87	12	0.89
5#	24	0.92	24	0.95	24	0.95
10#	24	0.92	24	0.95	24	0.95
20#	12	0.89	24	0.95	24	0.95

*using CRC-Forge design rainfall
#using IFD design rainfall

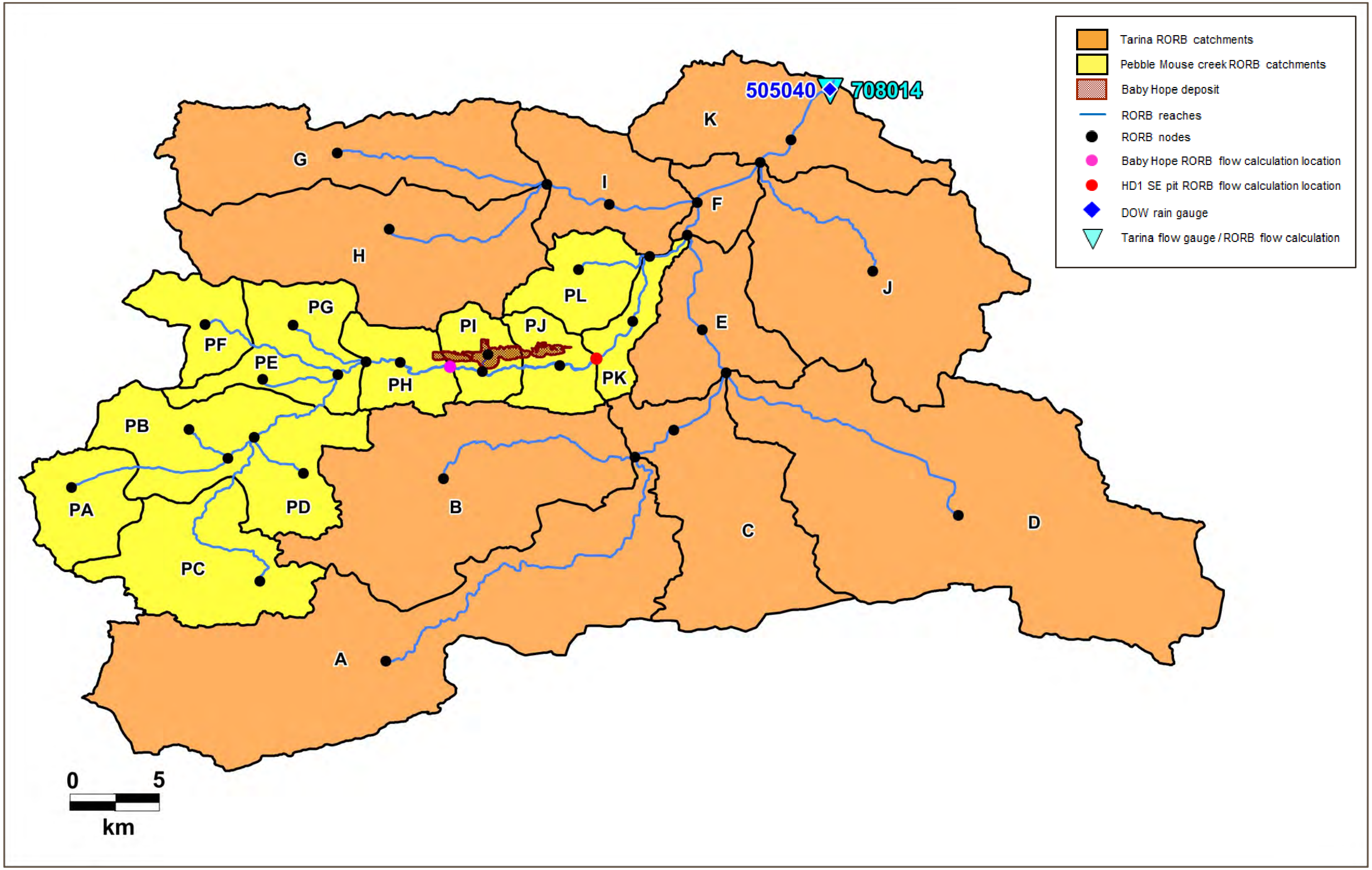

Figure 4-8: Pebble Mouse/Tarina RORB model inputs; catchment sizes are listed in Appendix C

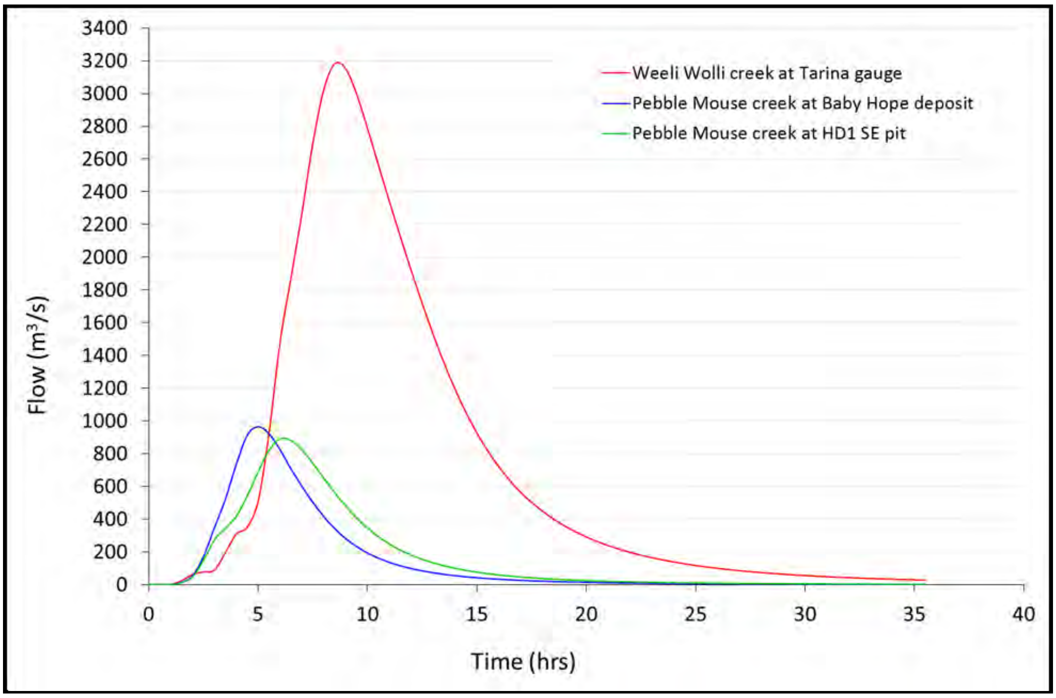

Figure 4-9: Hydrographs of estimated 1% AEP peak flows for Tarina gauging station and two locations on Pebble Mouse Creek

4.7 Recommended design flood estimation

Due to the lack of streamflow data within the Pebble Mouse Creek catchment results from the RORB model calibrated to Tarina were taken as the best estimate of design peak flows for Pebble Mouse Creek. Estimates of 1% AEP peak flows for Pebble Mouse Creek using this method were 970 m^3/s at the Baby Hope deposit and 890 m^3/s at HD1 SE pit.

5. Hydraulic modelling

5.1 2D hydraulic modelling

The TUFLOW/SMS two dimensional (**2D**) hydraulic software package was used to model existing flood conditions at the Baby Hope deposit. A 2D hydraulic model was considered to be the most effective way to model the Pebble Mouse Creek system, due to the ability to efficiently delineated detailed flood plains using high resolution topographic data.

5.2 Model Inputs

5.2.1 Digital terrain model

LiDAR topographic data is available for the Baby Hope area. The reported accuracy of the dataset is 0.3 m in the vertical direction and 0.4 m in the horizontal direction. A digital terrain model (**DTM**) of the LiDAR point cloud was built using the Global Energy Mapper software and a 5 m x 5 m grid of elevations was derived from the DTM to filter the large number of data points. The 5 m x 5 m elevation grid was used to build the DTM for the TUFLOW model. The extent of the DTM can be seen in Figure 5-1.

5.2.2 Boundary conditions

The location of boundary inputs is shown in Figure 5-1. The hydrograph calculated at the Baby Hope deposit from the combined Pebble Mouse and Tarina RORB model was used for Pebble Mouse Creek.

Table 5-1: Estimated 1% AEP flows.

Location	Critical duration	Estimated peak flow 1% AEP (m^3/s)
Pebble mouse creek at Baby Hope deposit	12 hour	970

Pebble Mouse Creek

The hydrograph was calculated at the edge of Baby Hope orebody, with boundary input location approximately 2 km upstream (SMS boundary description – Flow vs Time (QT)).

Downstream slope boundary

The downstream boundary was input as a slope (SMS boundary description - WSE vs Flow (HQ)) and calculated to be 0.0035 m/m.

Pebble Mouse Creek Tributaries

Design peak flows for the tributaries of Pebble Mouse Creek at Baby Hope were calculated using the regional flood frequency method developed by Flavell (2012) given in section 4.5.1. The time of concentration for these peak flows was calculated using the Bransby-Williams formula for ungauged catchments as recommended by ARR (1987):

$$t_c = \frac{58\,L}{A^{0.1}S_e^{0.2}}$$

Where:

t_c = time of concentration (mins)

L = mainstream length measured to the catchment divide (km)

A = catchment area (km^2)

S_e = equal area slope of the mainstream projected to the catchment divide.

Hydrographs were derived using a simple triangular relationship that has been calibrated against runoff volumes from RORB models in the Pilbara region. The hydrographs were added to the boundary locations along the northern and southern sides of the Pebble Mouse Creek valley, as shown in Figure 5-1. The hydrograph, peak flows and times of concentration for all tributary creeks are given in Appendix C.

All northern catchments were delineated into sub-catchments up to the pit outline in an effort to provide an estimate of pre-development flow velocities at all locations where surface water may enter the pit. The boundary locations of the northern catchments were placed before the edge of the proposed pit.

The southern catchments were not divided into smaller sub-catchments as it was determined that this was not a primary area of interest for the purposes of this study. Southern catchment areas were delineated to Pebble Mouse Creek and flows input upstream of this location.

Road

The road on the southern side of Pebble Mouse Creek valley was input as an added Z point line boundary, as it was built after the LiDAR data had been gathered and was not included in the DTM. The line coverage added 2.5 m to all elevation points along its alignment. It is understood that this does not accurately reflect the actual elevation of the road; however it was determined to give sufficient representation in line with the level of interest in the area.

Culverts

One dimensional (**1D**) culverts where placed in the rail and road on the southern side of Pebble Mouse Creek valley for larger creeks of the southern valley catchments. The location and size of rail culverts was determined according to Pilbara Region Imagery photograph and through visual inspection during a site visit on 12/11/2013. The location and size of road culverts was determined by inspection of Pilbara Regional Imagery photograph. The low level of detail was considered acceptable given the magnitude of flows generated from the southern catchments and the expected low influence of flood flows from this area on the area of interest.

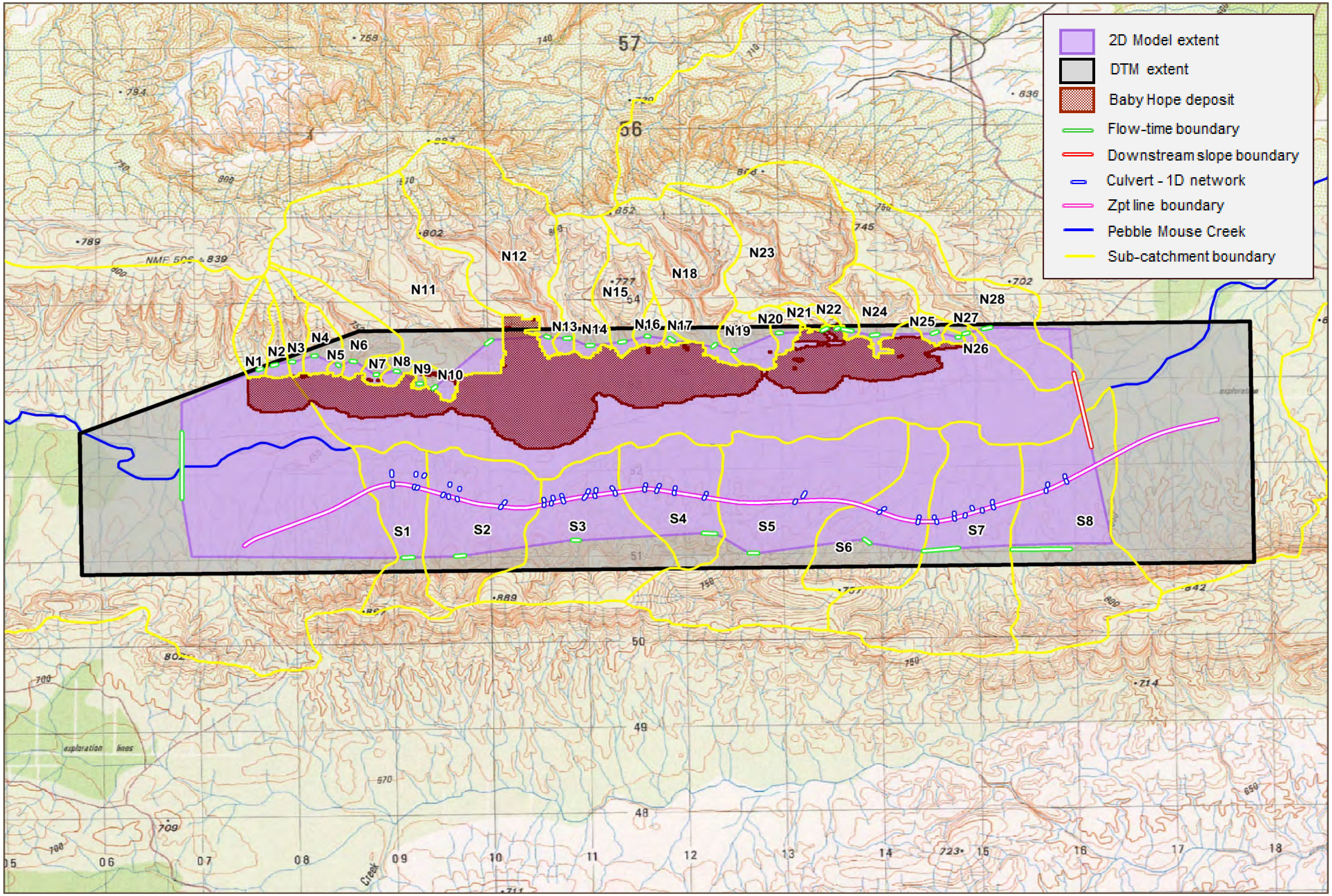

Figure 5-1: Baby Hope hydraulic model DTM extent and boundary locations

5.2.3 Bed resistance

Each cell in the 2D model was assigned a bed resistance value. The Land Unit Classification dataset (Van Vreeswyk *et al* 2004) was used as a basis for bed resistance classification. Alterations to land unit areas were delineated through detailed examination of aerial photographs and raster maps. Areas were assigned a Manning's n value ranging from 0.035 (representing the road) to 0.055 (representing vegetated creek flood plain) to describe its bed resistance as shown in Figure 5-2.

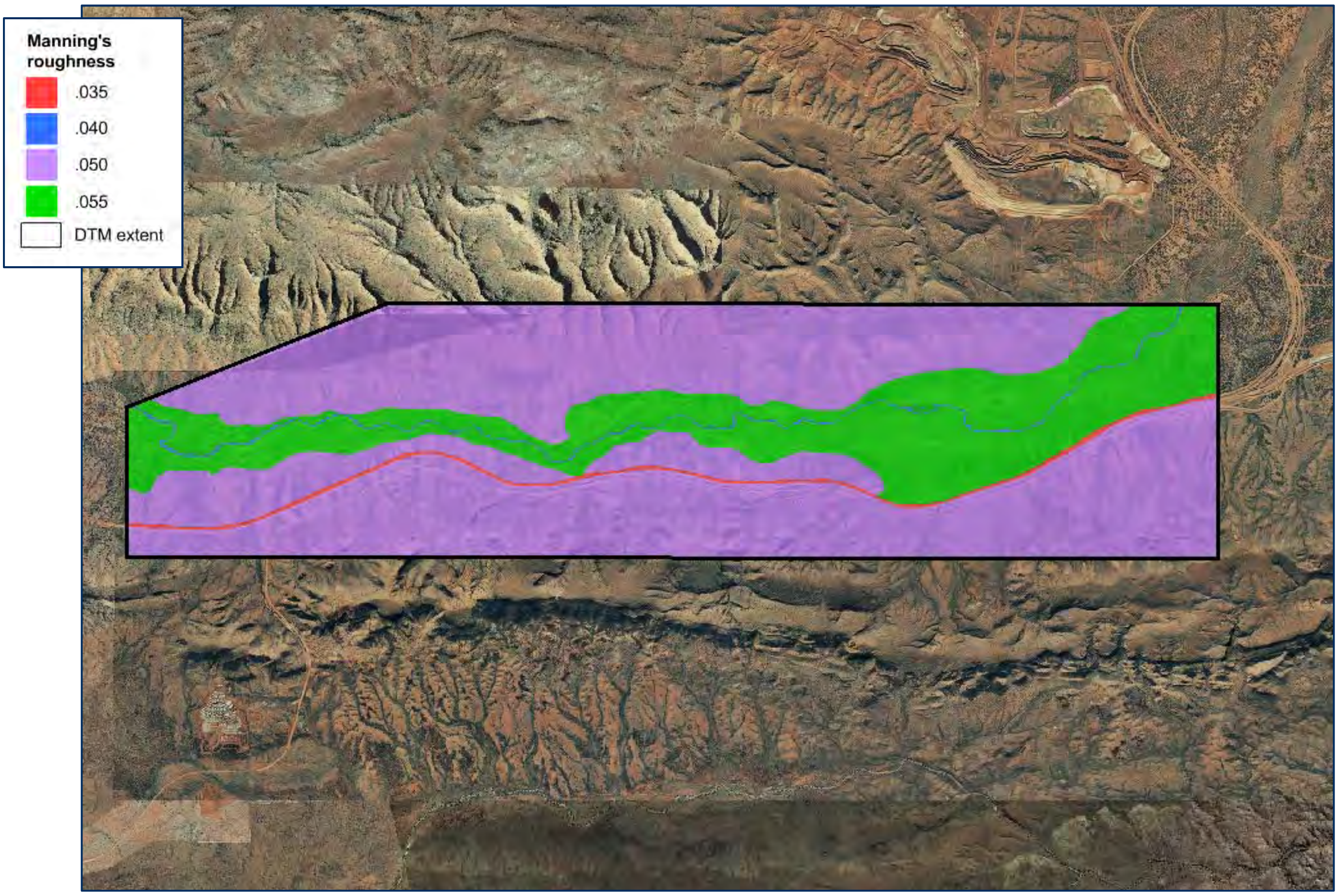

Figure 5-2: Bed resistance values used in the Baby Hope 2D model.

5.2.4 Cell size and time step

A cell size of 5 m by 5 m was used for all design events. A time step of 1.5 and 2 seconds was used for the 2D domain and 1D domain (culverts) respectively.

5.3 Modelled scenarios

The 1% AEP event was modelled for existing conditions and post pit development. There was no hydrology infrastructure development options considered in this study as the deposit is proposed to be developed without any major hydrology infrastructure. All pits are to remain outside of the 1% AEP flood plain. Maximum flood depths for existing conditions and post pit development are shown in Figure 5-3 and Figure 5-4 respectively. Maximum velocities for existing conditions are given in Figure 5-5. Throughout the modelling process it was observed that the northern and southern catchments had little to no effect on the flood extent of main flood plain of Pebble Mouse Creek.

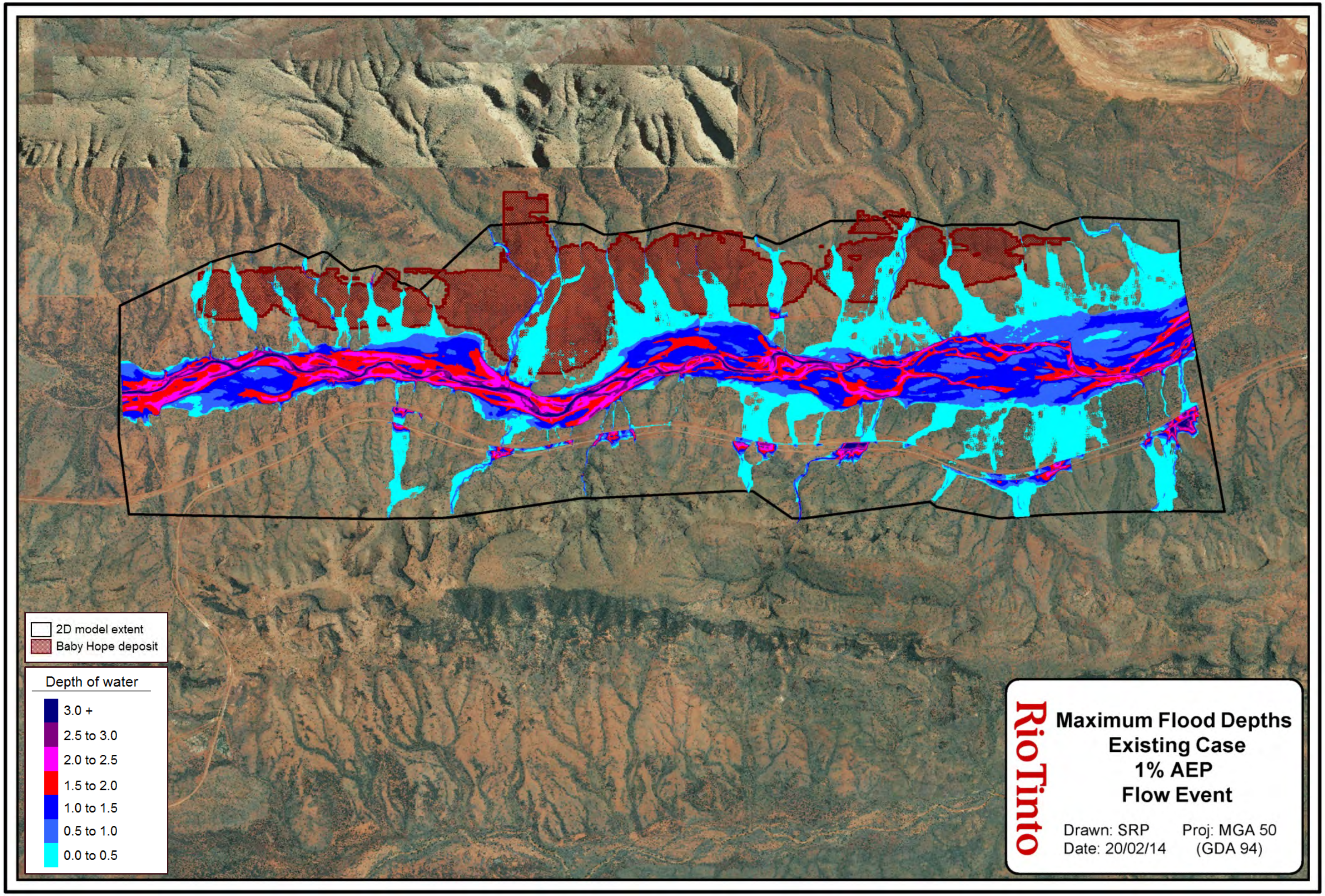

Figure 5-3: **Estimated flood extent and depths for a 1% AEP event for existing conditions at the Baby Hope deposit**

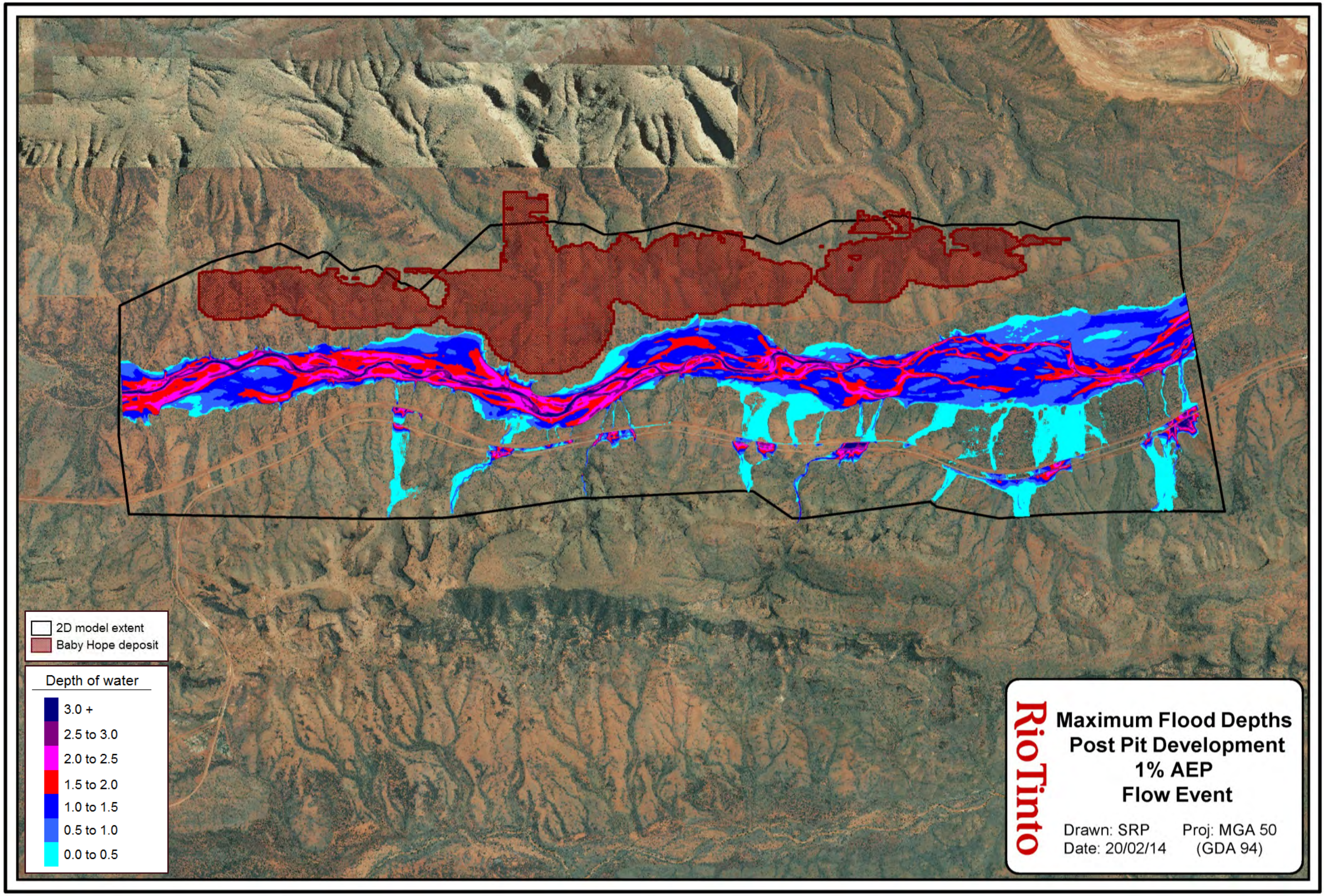

Figure 5-4: Estimated flood extent and depths for 1% AEP event at Baby Hope post pit development

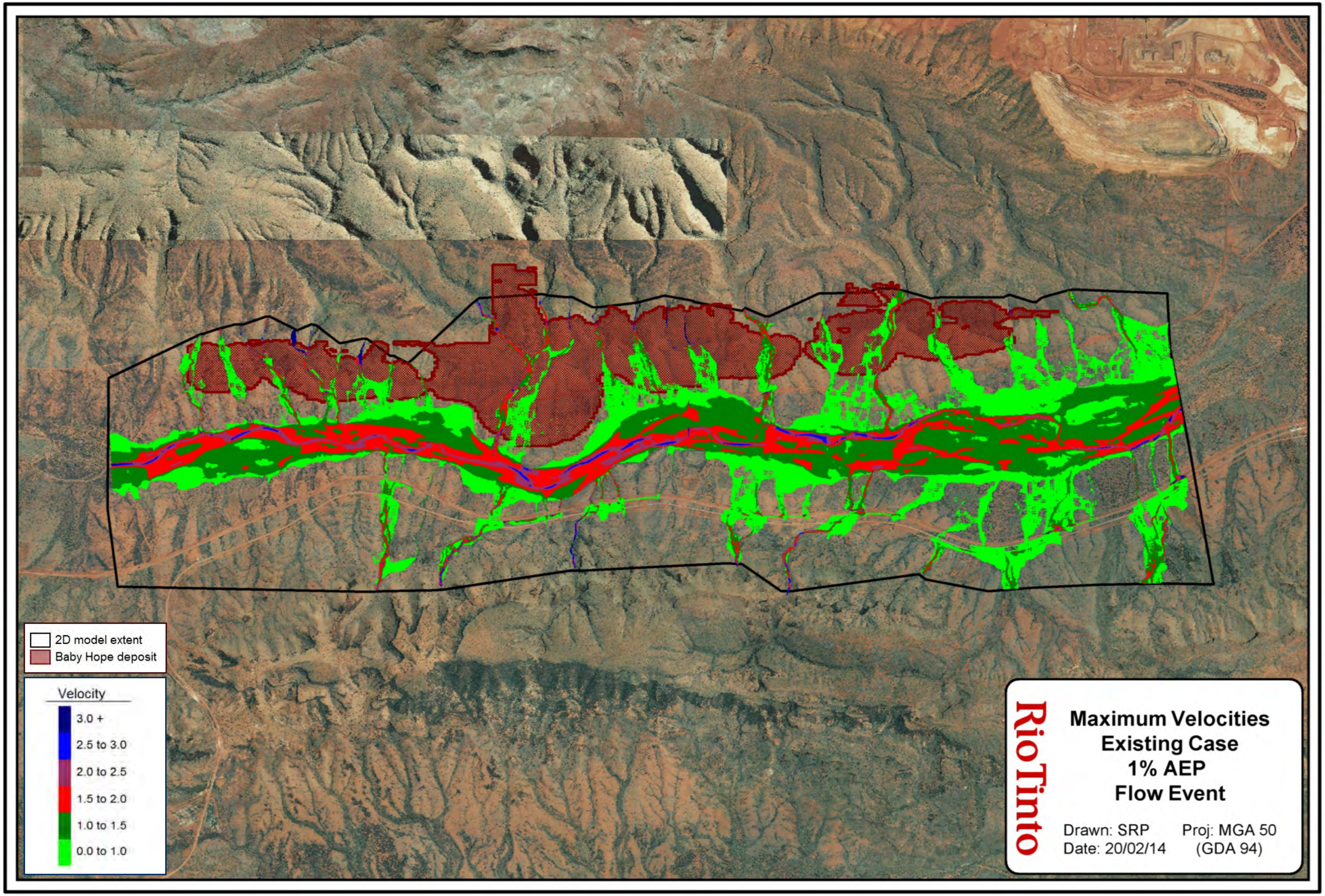

Figure 5-5: Estimated velocities for a 1% AEP event for existing conditions at the Baby Hope deposit

5.4 Model uncertainties

5.4.1 Peak flow estimates

Estimates of 1% AEP peak flow are calibrated to Tarina flow gauge FFA, 23 km downstream of the Baby Hope deposit. The Tarina FFA is based on 27 years of annual maxima and the 90% confidence interval of the distribution for the 1% AEP event is 1160 m^3/s to 7170 m^3/s. The lack of at-site streamflow and rainfall data also introduces a large degree of uncertainty in the estimates due to the high degree of spatial variability in rainfall exhibited in the Pilbara.

5.4.2 Sensitivity

A full sensitivity analysis was not performed on bed resistance values or flow inputs adopted in the model. However the 2D model was run with a 1% AEP design peak flow 20% lower and 20% higher, than the adopted value giving an insight to the sensitivity of the flood extent to peak flows. Results of the sensitivity analysis (Table 5-2) show that reducing the peak flow by 20% reduced the flood extent area by 2% and increasing the peak flow by 20% increased the flood by 3%, indicating that the model is relatively insensitive to changes in flow input. Changes in the flood extent are given in Appendix F***:*** ***Sensitivity analysis***.

Table 5-2: Results of peak flow sensitivity

Peak flow (m^3/s)	Difference (%)	Flood extent by area (km^2)	Difference (%)
780	-20	6.1	-2
970	0	6.2	0
1160	20	6.4	3

6. Conclusion

An assessment of the baseline surface water hydrology of Pebble Mouse Creek up to the Baby Hope deposit, 23 km upstream of the Tarina streamflow gauging station on Weeli Wolli Creek (708014) has been undertaken through the application of annual, monthly and daily analysis of rainfall and annual analysis of streamflow at Tarina. Furthermore, a regional flood frequency analysis has been carried out on four local streamflow gauges within a 150 km radius of the catchment centroid.

The Pilbara Surface Water Management Strategy recommends flood protection to a minimum 1% AEP if construction is to take place in the 1% AEP floodplain. Development of the Baby Hope deposit is proposed to be undertaken without major flood protection infrastructure and therefore the pit outline is to be developed outside of the 1% AEP flood plain.

The 1% AEP peak flow event for the Pebble Mouse Creek at the Baby Hope deposit was estimated using the combined RORB model of Pebble Mouse and Weeli Wolli Creeks that was calibrated to the Tarina flow gauge. The hydrograph of the estimated 1% AEP event produced by the RORB model was used as a boundary condition in the Tuflow 2D hydraulic model and this enabled the 1% AEP event floodplain to be delineated. From this study it can be concluded that:

- The expected 1% AEP event peak flows for Pebble Mouse Creek at the Baby Hope deposit from the combined Pebble Mouse/ Weeli Wolli RORB model calibrated to Tarina is 970 m^3/s.
- Annual rainfall at the Baby Hope study area has ‘high’ temporal variability. Annual streamflow at Tarina (downstream from the Baby Hope study area) is 4 to 5 times more variable than Baby Hope rainfall.
- Large flow events that are integral to the estimation of large to extreme design flood events are predominately estimated using theoretical stage-discharge relationships.
- The Tarina FFA is based on 27 years of annual maxima and the 90% confidence interval of the distribution for the 1% AEP event is 1160 m^3/s to 7170 m^3/s
- Spatial variability exhibited in the area introduces a large degree of uncertainty in design flow estimates, as there are no at-site streamflow or rain gauges.
- Based on flow data from Tarina gauging station, it is expected that an average of two flow events will occur per year in Pebble Mouse Creek. The annual rainfall assessment in Section 3.2.1 suggests that the recent period is wetter than long term average and larger flow events, with a peak greater than 400 m^3/s at Tarina, are to be expected once every five years on average.
- There are many small but not insignificant creeks that flow from the northern range in a southerly direction over the deposit. The majority of the creeks will be intercepted by the pit and have deeply incised channels, indicating these areas are subject to high velocities and erosion.
- The tributaries of Pebble Mouse Creek in the area of the Baby Hope deposit have little or no influence on the flood extent of Pebble Mouse Creek. Additionally the floodplain of Pebble Mouse Creek is not highly sensitive to changes in flow input.

7. Recommendations

The following recommendations can be made as a result of this study:

- Due to the lack of data from within the Pebble Mouse Creek catchment, the RORB model calibrated to Tarina should be adopted for the estimation of design flood quantiles for the catchment.
- Pressure transducers should be installed within Pebble Mouse Creek, upstream and downstream from the Baby Hope deposit to estimate flows for calibration/validation of the RORB model and the 2D hydraulic model.
- The Bureau of Meteorology is currently undertaking work to revise the design rainfall temporal patterns. These design rainfall patterns have a large impact on design flows. It is expected that when published the revised temporal patterns will closer resemble those used in estimating the probable maximum precipitation (**PMP**). The impact of using the PMP temporal patterns on design flood estimates should be investigated.

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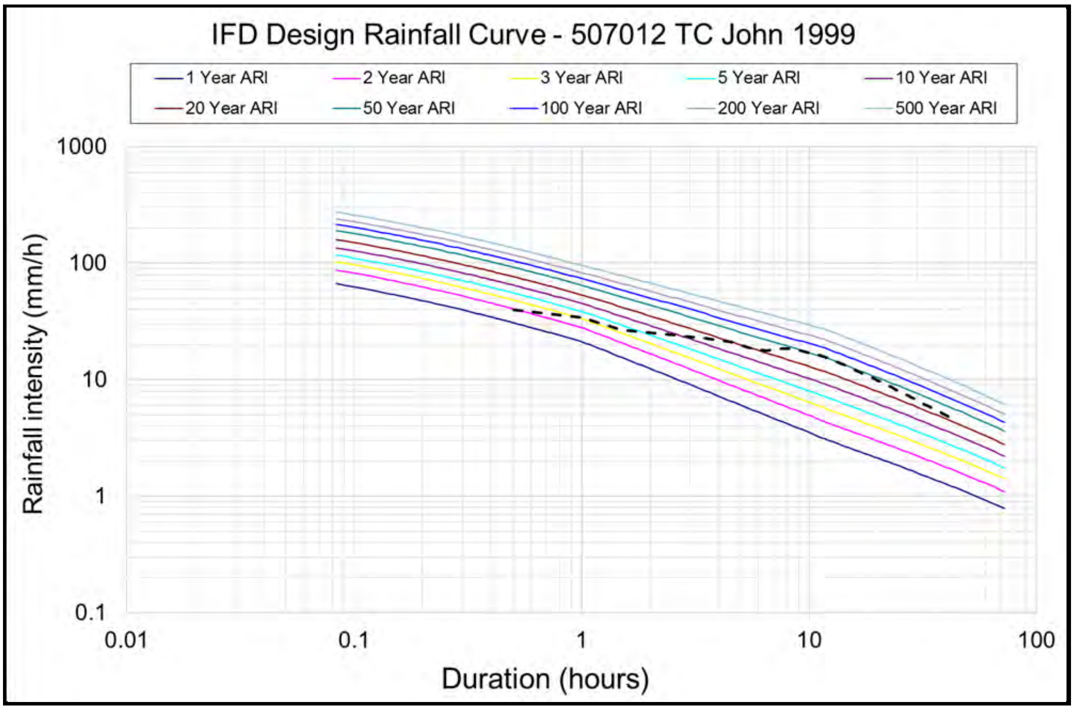
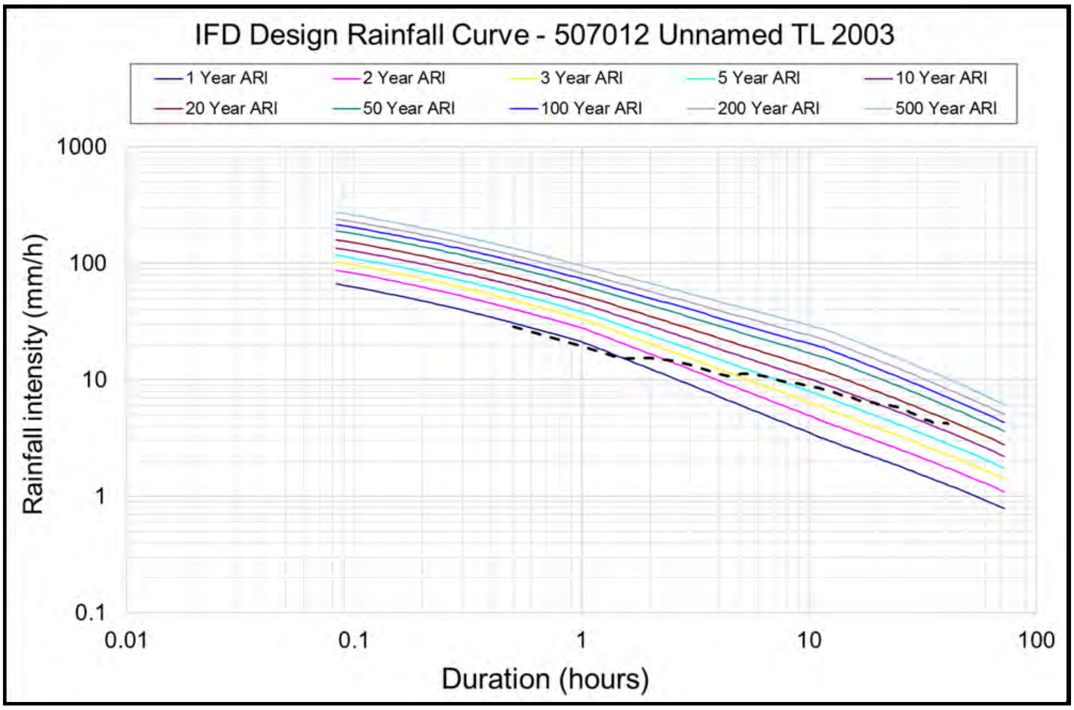
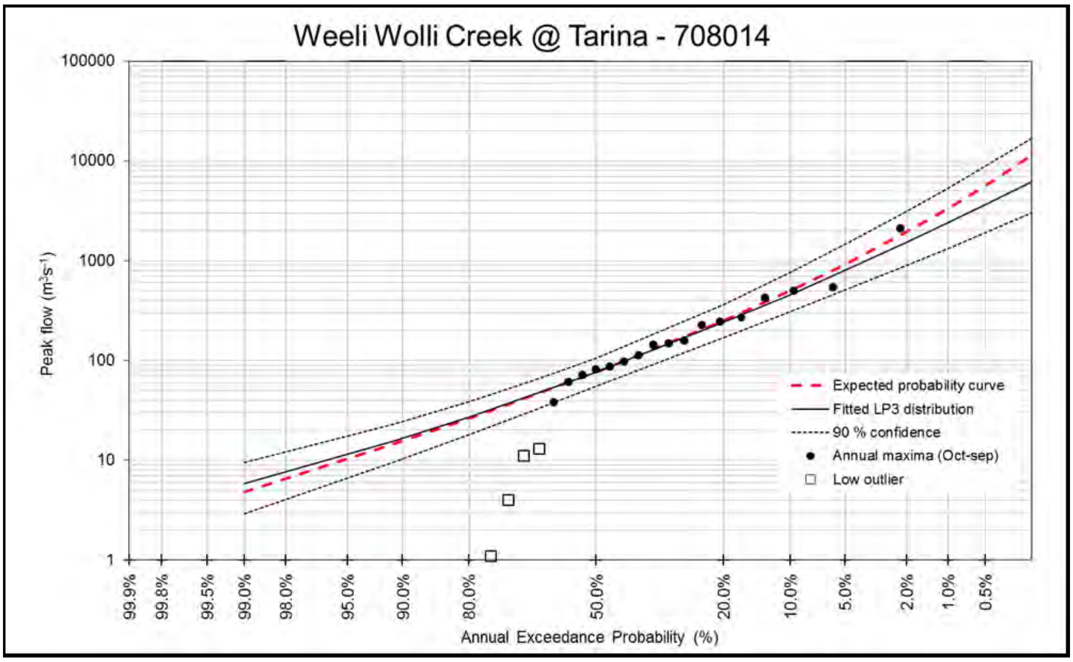
9. Appendix

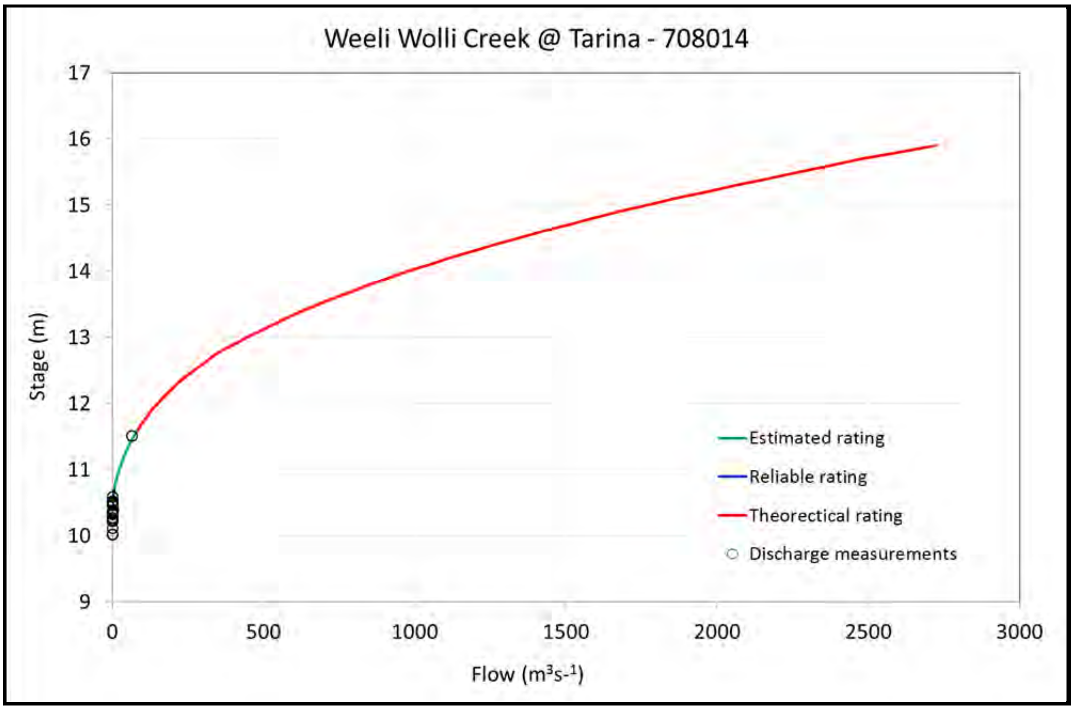
Appendix A: AEP Event design rainfall curves

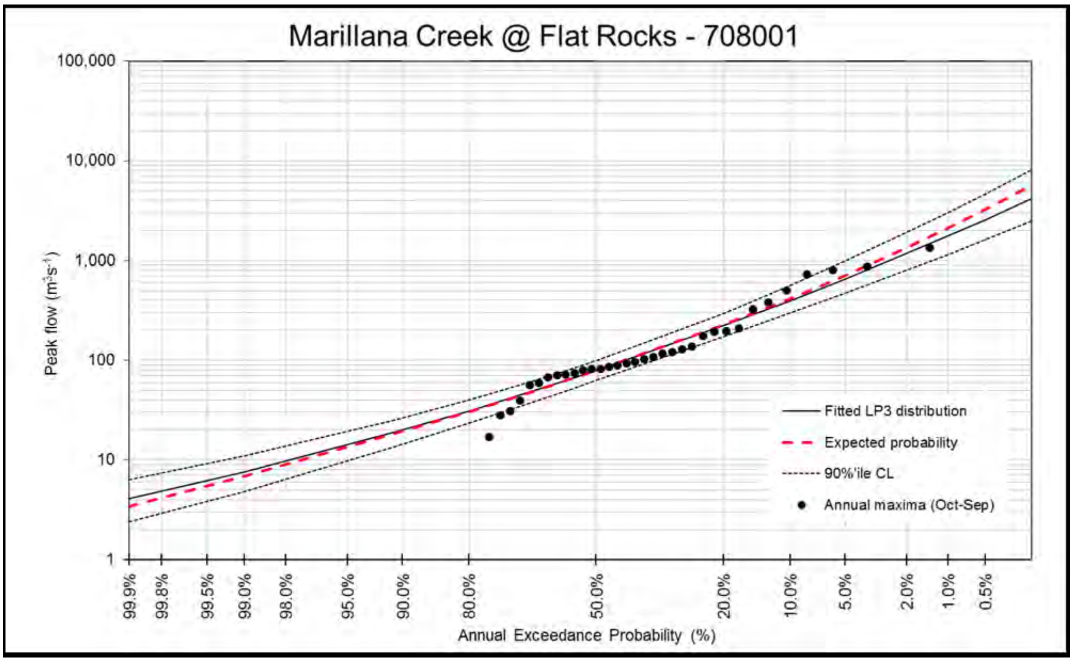


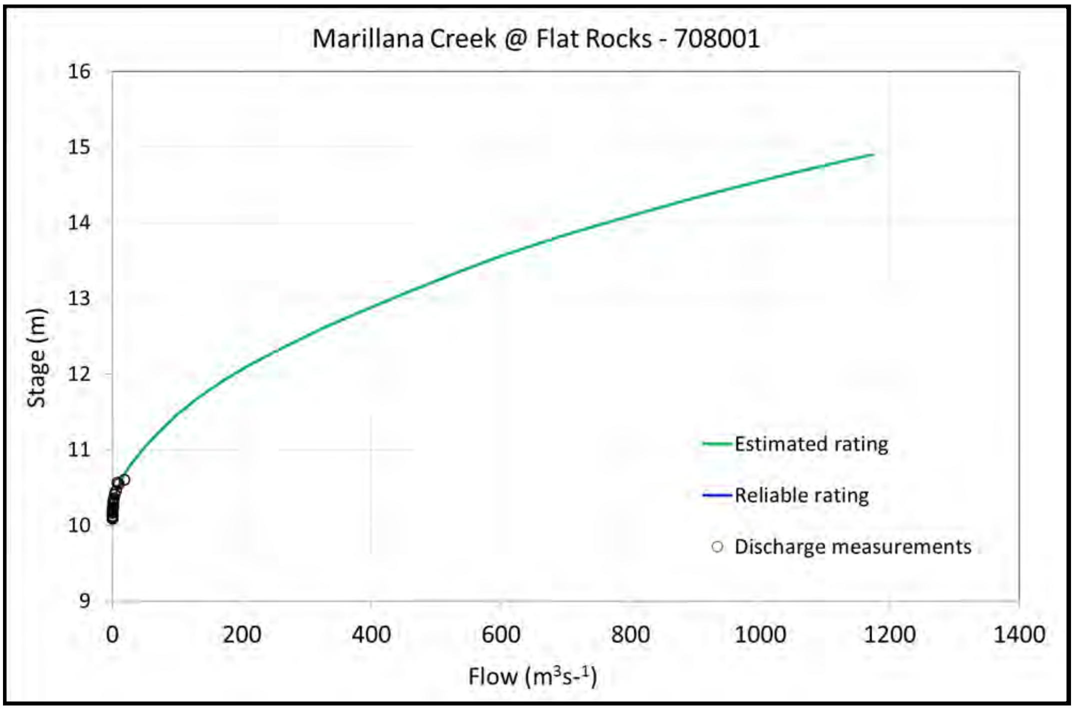


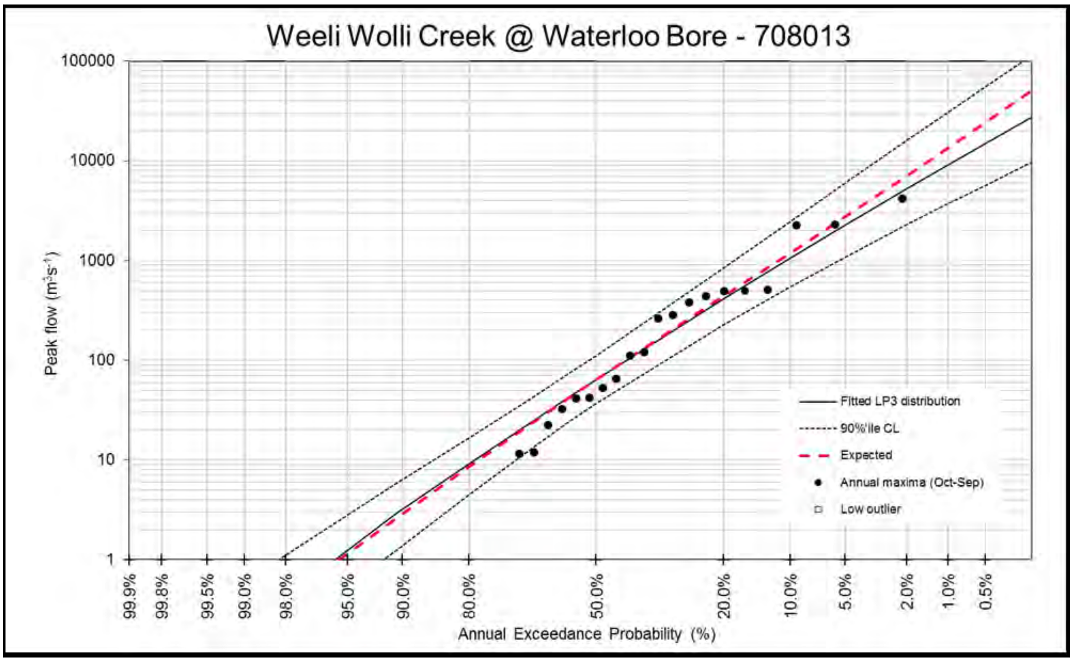
Appendix B: Flood frequency analysis and associated stage-discharge rating curves

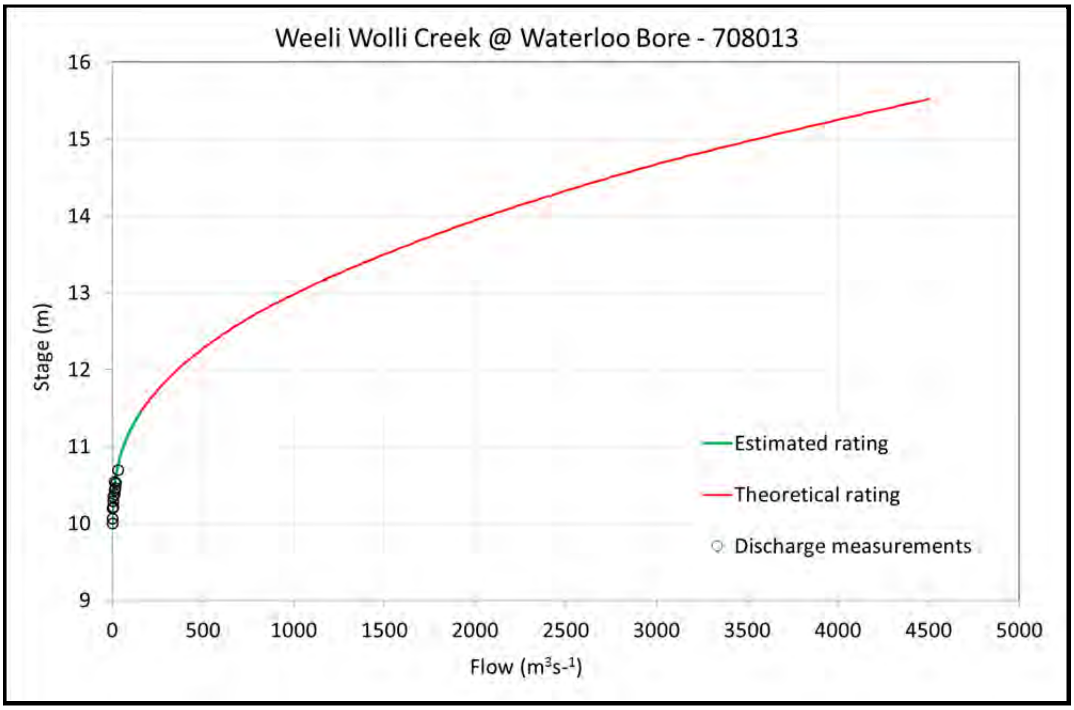





Marillana Creek @ Flat Rocks - 708001
100,000
10,000
1,000
100
10
1
Peak flow (m^3s^{-1})
99.9%
99.8%
99.5%
99.0%
98.0%
95.0%
90.0%
80.0%
50.0%
20.0%
10.0%
5.0%
2.0%
1.0%
0.5%
Annual Exceedance Probability (%)
Fitted LP3 distribution
Expected probability
90%'ile CL
Annual maxima (Oct-Sep)

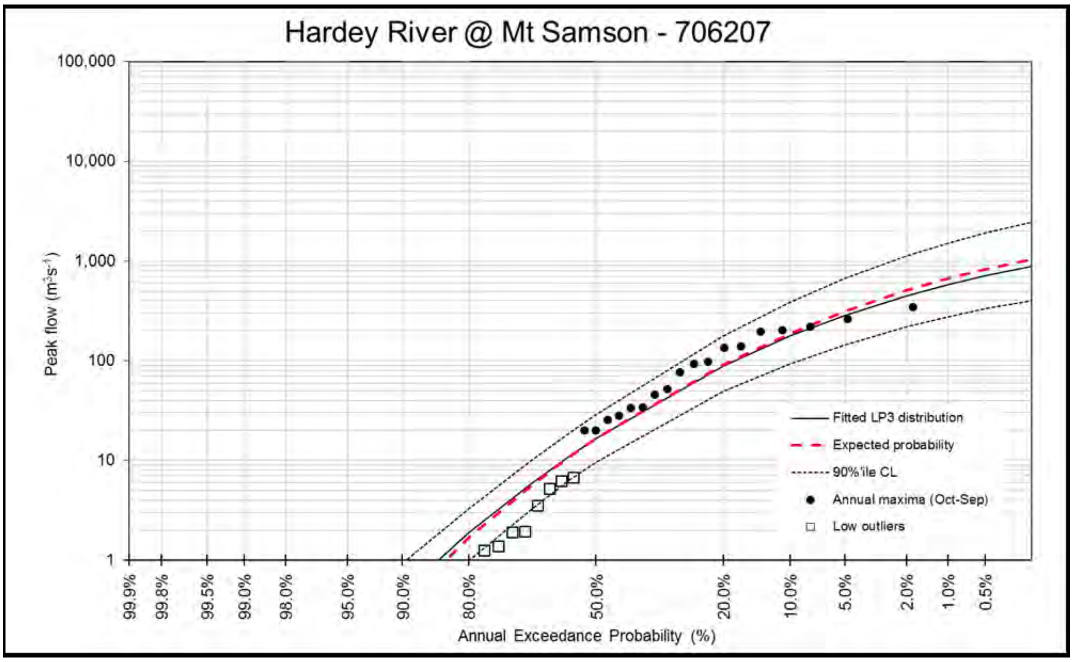

Marillana Creek @ Flat Rocks - 708001
16
15
14
13
12
11
10
9
Stage (m)
0
200
400
600
800
1000
1200
1400
Flow (m^3s^{-1})
Estimated rating
Reliable rating
Discharge measurements

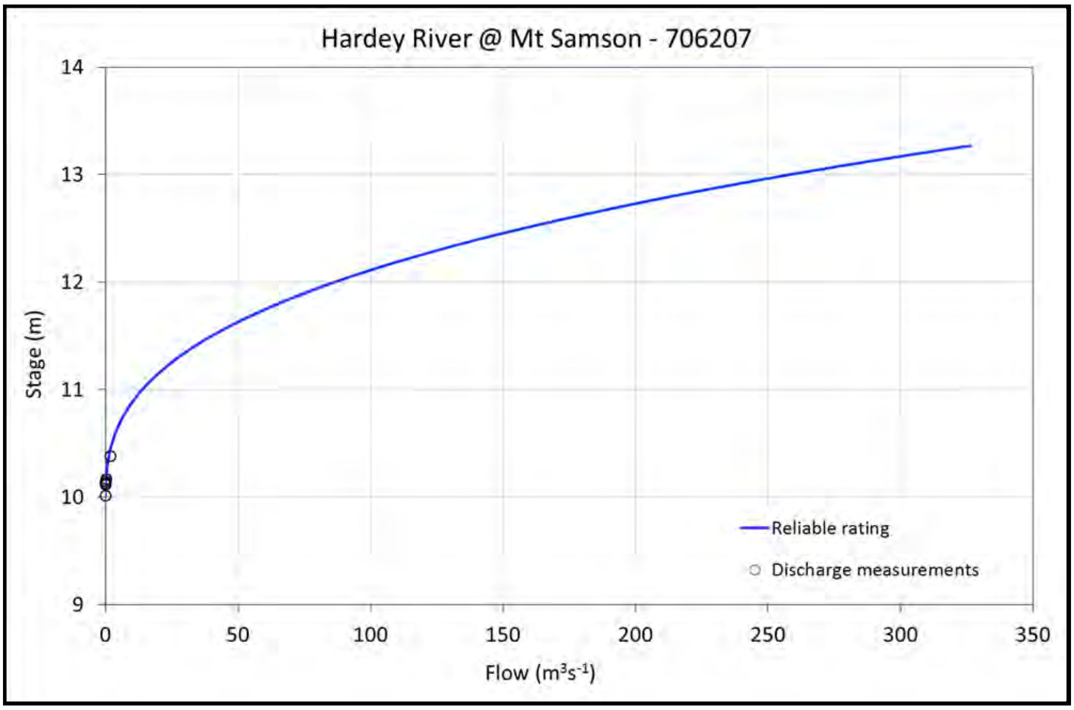


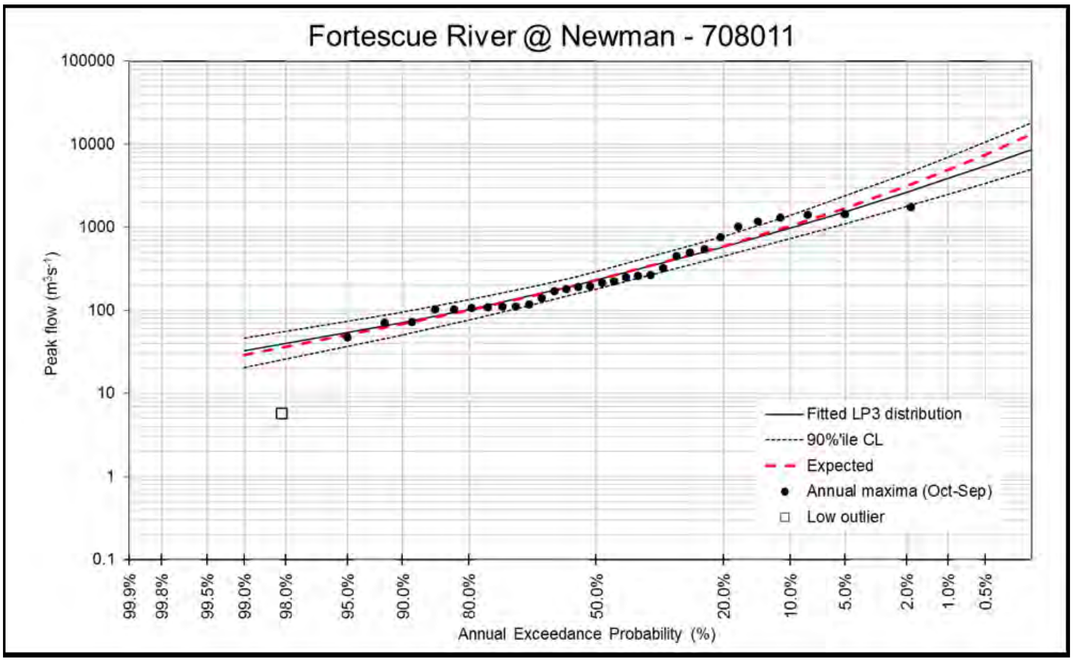


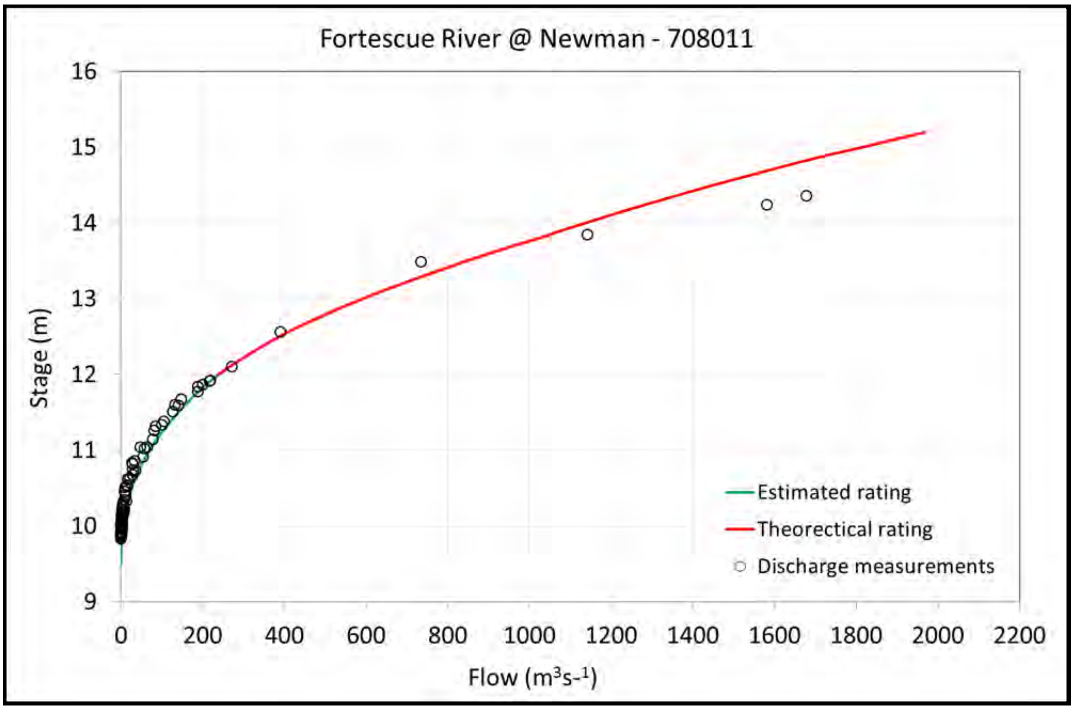
Waterloo Bore rating curve comments provided by Mr Ross Doherty from DOW -

> ‘Poor gauging station site – braided channel, unstable bed, in-channel vegetation etc. Has been modelled with HEC-RAS but unconfirmed by gauging. Estimated uncertainty – greater than +/-25%’


Hardey River @ Mt Samson - 706207
Peak flow (m^3s^{-1})
100,000
10,000
1,000
100
10
1
99.9%
99.8%
99.5%
99.0%
98.0%
95.0%
90.0%
80.0%
50.0%
20.0%
10.0%
5.0%
2.0%
1.0%
0.5%
Annual Exceedance Probability (%)
Fitted LP3 distribution
Expected probability
90%'ile CL
Annual maxima (Oct-Sep)
Low outliers


Hardey River @ Mt Samson - 706207
Stage (m)
14
13
12
11
10
9
0
50
100
150
200
250
300
350
Flow (m^3s^{-1})
Reliable rating
Discharge measurements


Fortescue River @ Newman - 708011
Peak flow (m^3s^{-1})
100000
10000
1000
100
10
1
0.1
99.9%
99.8%
99.5%
99.0%
98.0%
95.0%
90.0%
80.0%
50.0%
20.0%
10.0%
5.0%
2.0%
1.0%
0.5%
Annual Exceedance Probability (%)
Fitted LP3 distribution
90%'ile CL
Expected
Annual maxima (Oct-Sep)
Low outlier


Fortescue River @ Newman - 708011
Stage (m)
16
15
14
13
12
11
10
9
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
Flow (m^3s^{-1})
Estimated rating
Theorectical rating
Discharge measurements

Appendix C: RORB model catchment sizes

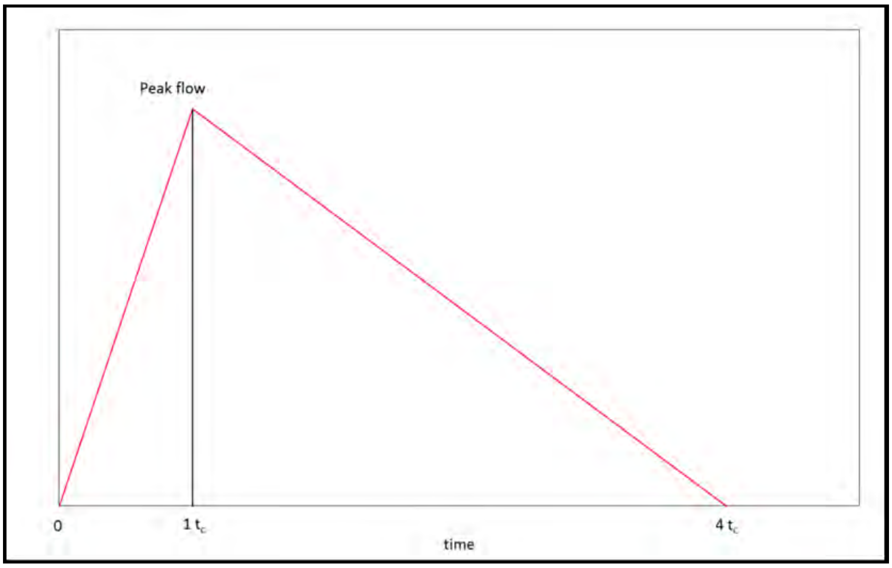
Tarina RORB catchment sizes

Catchment	Area (km^2)
A	212
B	129
C	91
D	243
E	51
F	216
G	124
H	18
I	87
J	110
K	47
L	131
M	71
Total	**1526**

Pebble Mouse/Tarina RORB catchment sizes

Catchment	Area (km^2)
PA	61
PB	30
PC	45
PD	33
PE	19
PF	24
PG	23
PH	23
PI	18
PJ	20
PK	15
PL	25
A	212
B	129
C	91
D	243
E	51
F	18
G	87
H	110
I	47
J	131
K	71
Total	**1526**

Appendix D: Side catchment boundary conditions



Relationship used to produce hydrographs for southern catchments; based on volumes from RORB models of Pilbara catchments

Parameters of side boundary catchment estimated peak inflows; boundary locations given in Figure 5-1

Catchment	Area (km^2)	L (km)	S_e (m/km)	1% AEP Peak Q (m^3/s) (RFFP)	Tc hours
S1	1	2.2	51.1	17	1.0
S2	2	2.2	46.1	33	0.9
S3	2	2.4	73.7	37	0.9
S4	1	1.5	44.2	19	0.7
S5	4	3.6	27.1	43	1.6
S6	1	2.0	28.8	14	1.0
S7	3	3.2	24.2	31	1.4
S8	3	3.4	46.6	41	1.4
N1	0.31	1.1	101.6	8	0.5
N2	0.13	0.8	101.7	4	0.4
N3	0.28	1.3	86.5	8	0.6
N4	0.22	0.7	103.4	7	0.3
N5	0.03	0.2	211.3	2	0.1
N6	0.54	1.4	79.3	12	0.6
N7	0.07	0.4	184.4	3	0.2
N8	0.08	0.4	198.0	4	0.2
N9	0.04	0.2	287.9	4	0.1
N10	0.09	0.3	67.4	4	0.2
N11	2.93	3.5	42.7	38	1.5
N12	2.21	3.2	29.7	26	1.4
N13	0.06	0.3	127.6	3	0.1
N14	0.72	1.9	58.3	14	0.8
N15	0.56	1.3	60.7	12	0.6
N16	0.12	0.4	105.7	5	0.2
N17	0.03	0.2	101.6	2	0.1

N18	1.54	2.3	51.6	24	0.9
N19	0.29	0.9	51.8	6	0.4
N20	0.14	0.7	113.5	5	0.3
N21	0.07	0.4	74.8	2	0.2
N22	0.04	0.2	115.0	2	0.1
N23	2.08	3.0	42.6	29	1.3
N24	0.51	1.0	43.3	11	0.5
N25	0.09	0.3	124.3	5	0.1
N26	0.03	0.2	115.0	2	0.1
N27	0.04	0.3	67.3	1	0.2
N28	1.76	3.4	20.0	19	1.7

Total runoff volumes potentially reporting to the deposits, using basic runoff coefficients as described in the Pilbara Surface Water Management Strategy

		Likelihood	**Almost Certain (1 yr ARI)**	**Likely (2 yr ARI)**	**Possible (10 yr ARI)**	**Unlikely (50 yr ARI)**	**Rare (500 yr ARI)**	**100 yr ARI 24 hours**
		Rainfall (mm)	**60**	**80**	**150**	**230**	**375**	**261**
Catchment	Area (km^2)		Vol Captured (m^3)	Vol Captured (m^3)	Vol Captured (m^3)	Vol Captured (m^3)	Vol Captured (m^3)	Vol Captured (m^3)
N1	0.31		7,000	11,000	25,000	45,000	74,000	55,000
N2	0.13		3,000	5,000	11,000	19,000	32,000	23,000
N3	0.28		7,000	10,000	23,000	41,000	67,000	49,000
N4	0.22		5,000	8,000	18,000	32,000	53,000	39,000
N5	0.03		1,000	1,000	2,000	4,000	6,000	5,000
N6	0.54		13,000	19,000	44,000	79,000	129,000	96,000
N7	0.07		2,000	2,000	6,000	10,000	16,000	12,000
N8	0.08		2,000	3,000	7,000	12,000	19,000	14,000
N9	0.04		1,000	1,000	3,000	6,000	10,000	7,000
N10	0.09		2,000	3,000	8,000	14,000	22,000	16,000
N11	2.93		35,000	57,000	149,000	293,000	477,000	332,000
N12	2.21		27,000	43,000	112,000	221,000	361,000	251,000
N13	0.06		1,000	2,000	5,000	8,000	13,000	10,000
N14	0.72		17,000	25,000	58,000	105,000	171,000	126,000
N15	0.56		13,000	20,000	45,000	82,000	133,000	98,000
N16	0.12		3,000	4,000	10,000	18,000	29,000	22,000
N17	0.03		1,000	1,000	3,000	5,000	8,000	6,000
N18	1.54		19,000	30,000	78,000	154,000	251,000	175,000
N19	0.29		7,000	10,000	24,000	43,000	70,000	52,000
N20	0.14		3,000	5,000	12,000	21,000	34,000	26,000
N21	0.07		2,000	2,000	6,000	10,000	17,000	12,000
N22	0.04		1,000	1,000	3,000	5,000	9,000	6,000
N23	2.08		25,000	40,000	105,000	208,000	339,000	236,000
N24	0.51		12,000	18,000	41,000	74,000	121,000	90,000
N26	0.03		2,000	3,000	7,000	14,000	22,000	16,000

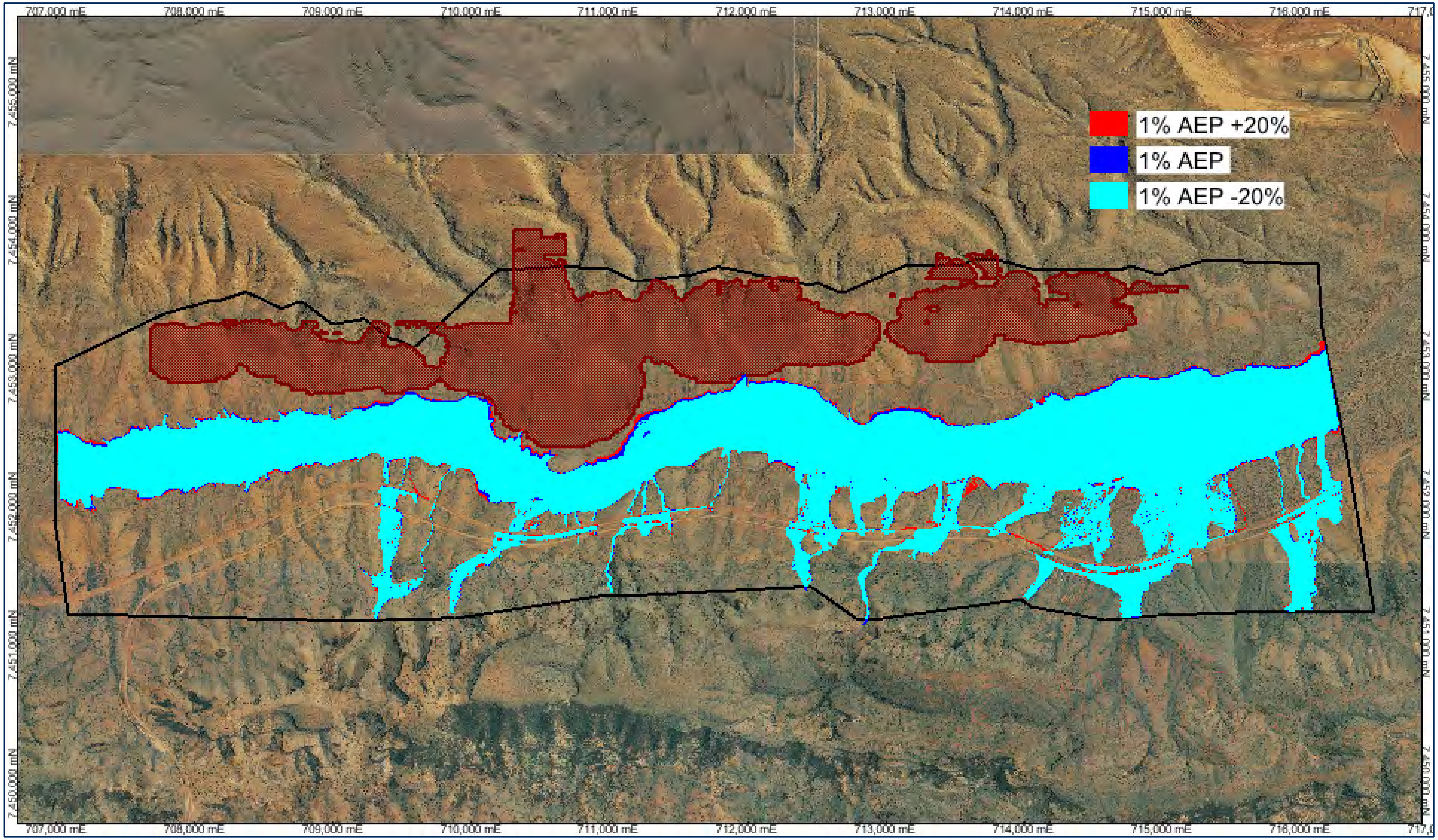
		Likelihood	Almost Certain (1 yr ARI)	Likely (2 yr ARI)	Possible (10 yr ARI)	Unlikely (50 yr ARI)	Rare (500 yr ARI)	100 yr ARI 24 hours
		Rainfall (mm)	60	80	150	230	375	261
Catchment	Area (km^2)		Vol Captured (m^3)	Vol Captured (m^3)	Vol Captured (m^3)	Vol Captured (m^3)	Vol Captured (m^3)	Vol Captured (m^3)
N27	0.04		1,000	1,000	2,000	4,000	7,000	5,000
N28	1.76		1,000	1,000	3,000	5,000	8,000	6,000

Appendix E: Photos of the Baby Hope study area

Pebble Mouse Creek main channel approximately 707,160 mE/7,452,260 mN.

The northern range looking south over the Baby Hope deposit and across the range highlighting the slope

Appendix F: Sensitivity analysis



Flood extents as a result of peak flow sensitivity analysis