APPENDIX D-3 HYDROBIOLOGY ESTIMATES OF SAND REPLENISHMENT AT RIVERINE EXTRACTION SITES

Hydrobiology

Connors River Dam & Pipeline

Estimates of Sand Replenishment at Riverine Extraction Sites

October 2010

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EXECUTIVE SUMMARY

Sunwater commissioned Hydrobiology to estimate sediment replenishment rates for proposed sand extraction sites at Boothill Creek, Denison Creek, Funnel Creek and Isaac River. The purpose of the extraction would be to provide bedding sand for the Connors River Dam pipeline. It was assumed at about 350,000 m^3 of sand would be required.

The study incorporated two stages, namely:

- A numerical (stochastic) sediment yield/budget model; and
- A visit to site with Sunwater and DERM representatives.

To account for the spatial variability and inherent uncertainties in both sediment supply and sediment transport modelling, the sediment yield model was set in a Monte Carlo framework. This is an analytical technique for estimating the solution of a numerical mathematical problem (e.g. a model) for situations where there is uncertainty and/or variability associated with input variables, parameters, and processes, by means of random sampling. This approach provides both the likelihood of particular outcomes occurring and the statistical distribution of those outcome events, and is therefore particularly useful for environmental risk management. For the assessment of available sediment in a river reach, the combined effect of a sediment yield model incorporated in a Monte Carlo framework offers a very significant improvement on traditional deterministic methods of calculating replenishment rates.

Overall, the results showed that the annual replenishment rate of coarse sediment in Boothill Creek/Funnel Creek, Denison Creek and Isaac River would, in total, be much higher than the nominal demand of 350,000 m^3. By way of example, it was determined that:

- About 190,000 m^3 of bed material could be extracted from Boothill Creek (incorporating Funnel Creek confluence). It is expected that the extraction pit would typically be filled within two years;
- About 100,000 m^3 of bed material could be extracted from Denison Creek. It is expected that the extraction pit would typically be filled within one year and
- A total of about 200,000 m^3 of bed material could be extracted from Isaac River without affecting the current extraction entitlements downstream of the proposed extraction site. It is expected the extraction pit would typically be filled within one year following extraction.

Overall, it is considered that high rates of sand movement occur in these river systems, that there is considerable sediment storage within the beds of these rivers (much of which may have accumulated since European settlement), and that sediment replenishment of required Take would occur within a low number of years following extraction.

Site inspections and discussions with DERM were generally consistent with the model outputs.

Proposed Connors River Dam & Pipeline

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1 INTRODUCTION

Sunwater commissioned Hydrobiology to of sand sediment transport rates (supported by appropriate documentation) in relation to its Quarry Material Allocation Notice applications to the Queensland Department of Environmental and Resource Management (DERM) for extraction of pipeline bedding sand from in-river sources. Golder Associates has identified a number of sites along the pipeline route from which bedding sand may be sourced, subject to DERM approval.

1.1 Objectives

The objective of this study was to estimate the likely rate of sand replenishment at three rivers as shown in Figure 1-1 in accordance with DERM expectations.

1.2 Regulatory Requirement

We understand that DERM uses the concept of the Average Material Transport Rate (AMTR) of the river's bed material load to determine allocation limits (normally less any amount that DERM considers necessary to maintain both local and downstream morphological processes). Key considerations in this regard include:

- Maintaining the physical integrity of the watercourse, including bed and bank stability;
- Condition and ability to function naturally;
- Supply of sediment to estuarine and marine environments; and
- Available sediment in the watercourse and consideration of existing allocations.

In some cases, removal of excess sand (e.g. a 'sand slug') may be beneficial.

AMTR is a broad indicator of long-term sediment movement and the ability of a given stream to replenish the amount of quarry material taken in a single 'average' year. In reality, flow and, therefore, sand replenishment rates vary from year to year and can often be highly skewed in nature.

1.3 Risk-based approach

The calculation of AMTR can be subject to tremendous uncertainty, based on both the natural variability of field parameters, nonlinear behaviour, and poorly defined sediment transport theory, meaning that AMTR estimates can vary dramatically depending on what underlying assumptions are made.

Further, traditional methods of computing AMTR rely on the application of one or more of the semi-theoretical sediment formulae prevalent in the literature (e.g. the equations of Ackers-White, and Yang). These formulae compute the theoretical sediment transport capacity of a stream based on hydraulic parameters, regardless of the amount of sediment supplied and/or in storage. These methods then are simply hydraulic calculations and do not consider sediment availability.

Finally it is very difficult to verify theoretical sediment transport rates by fieldwork. Therefore the uncertainty and variability of the AMTR needs to be considered, and in the context of the overall catchment sediment budget.

For this study, it was considered that the sand replenishment rate be determined using a catchment sediment budget approach, whereby the movement and storage of sediment throughout the contributing catchments be considered rather than just the theoretical transport capacity of the channel. It was further considered that a 'Monte Carlo' technique should be used whereby the uncertainty, variability and random nature of sediment generation and transport could be quantified using an iterative process that would involve running model scenarios tens of thousands of times, each time using different input variables drawn at random from their pre-defined probability distribution functions. The outcome of this process would be that the probabilities of different outcomes could be quantified, and the overall risk determined.

These matters were discussed with Sunwater and representatives DERM at a meeting on 6 Jul 2010 where the aforementioned method was agreed to.

1.4 Proposed extraction sites

The proposed extraction sites are shown on Figure 1-1.

The sites are:

- Boothill Creek (two potential sites);
- Funnel Creek Junction (effectively part of the Boothill Creek system);
- Denison Creek; and
- Isaac River (between AMTD 210 and 238 (Nortje pers. comm.)

It is expected that a total of approximately 340,000 m^3 (563,000 t) of bedding sand will be required (Golder Associates 2009). This has been rounded to 350,000 m^3 for modelling purposes.

The Funnel Creek Junction was considered to be a part of Boothill Creek for modelling purposes.

1.5 Morphological Setting

The background geomorphology and geology of the study area is described in Sunwater (2008). Of relevance to this study are the following:

- The extensive sand-bed morphology of the regional streams and river as observed by early European explorers. Ludwig Leichhardt (Leichhardt 1847) visited the upper

Isaac River and, in addition to the sandy morphology, described the occurrence of instream vegetation, gullies, anabranches and off-river channels, and waterholes and ponds.

- The extensive sand deposition that has occurred on the beds of the rivers across the Bowen Basin due to a variety of catchment development activities, post European settlement. Sand slugs were noted on the Isaac River, and transient sand deposits on Denison and Funnel Creeks. DNR (1998a, p5-18) noted that, for the Isaac River, bed sands were likely still accumulating.

- Neil et al. (2002) reported that the export of sediment and the mean suspended sediment concentration from the Fitzroy River basin were the highest for all Queensland coastal catchments for both natural and disturbed conditions and that the increase factor for sediment yield for 'natural' compared to 'existing' was also highest (at approximately 4).

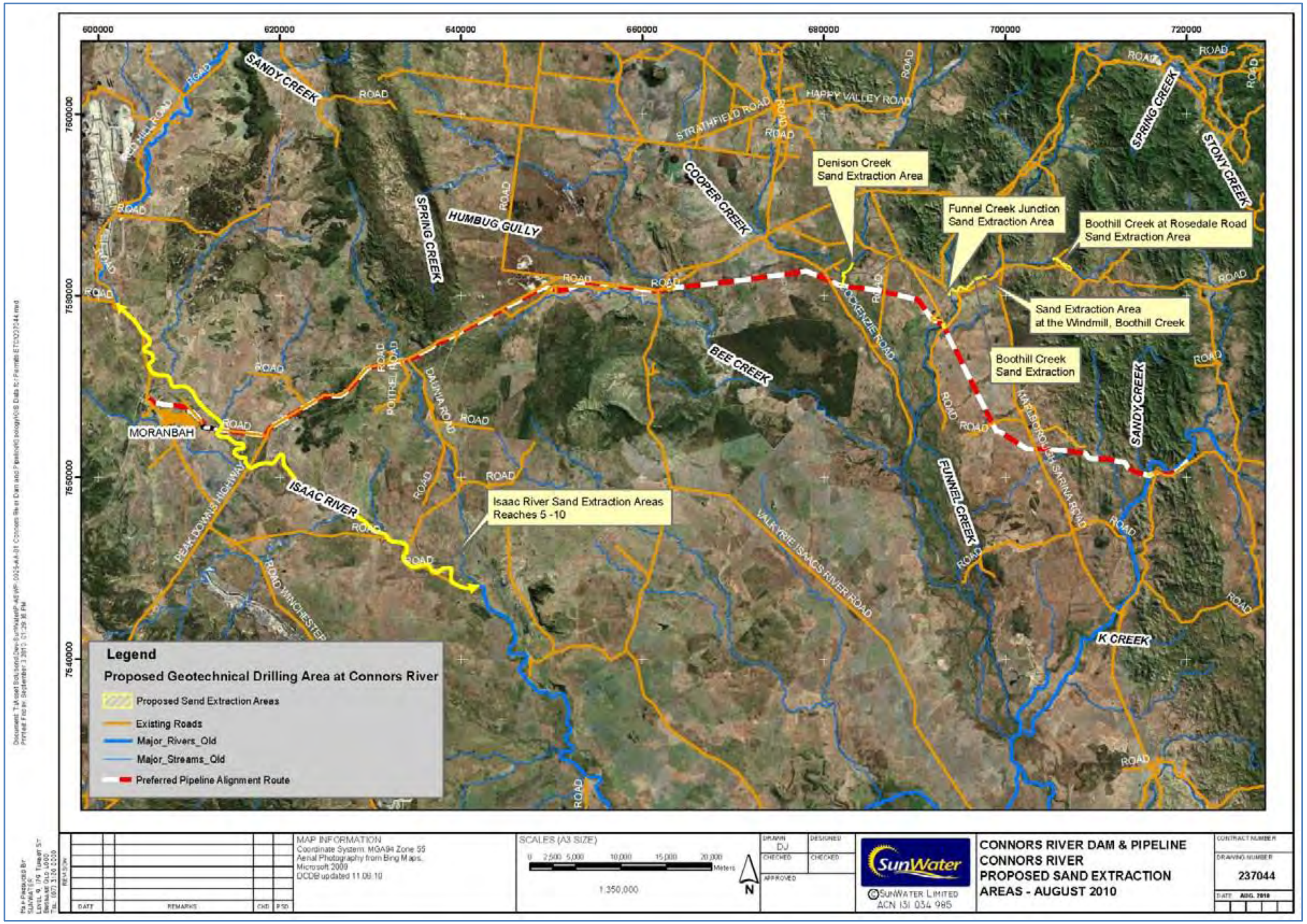

Figure 1-1 Proposed sand extraction sites

2 METHODS

There were two parts to the method, namely:

- Development of the sediment yield models; and
- A field trip with Sunwater and DERM representatives, to understand at first hand the geographical setting, and draw on the experience of those who were familiar with these river systems in order to inform the models.

2.1 Field Assessment

The field assessment took place between 23 and 26 August 2010 and involved personnel from Hydrobiology, SunWater and DERM. The field assessment served two main purposes – to stimulate discussion between the three parties about sediment quantity and quality requirements, suitable extraction locations and potential sediment replenishment rates and to allow for refinement of the sediment transport input parameters through *in situ* observations.

Each potential sediment extraction reach was visited, including reaches on Isaac River, Denison Creek, at the confluence of Funnel and Boothill creeks and the reaches of Boothill Creek upstream of this confluence. Walk-throughs were conducted with *in situ* characteristics and variability in these characteristics recorded and a photographic record acquired. Characteristics recorded included bed material, bed slope, channel bed and bankfull width, riparian and in-stream vegetation, location and size of in-stream bars (longitudinal and point), bank material, bank height and angle, the presence of benches and terraces, floodplain characteristics and flood height.

Time did not allow visits to the upper reaches of all catchments. However, small sections of the upper catchment of Boothill Creek were visited to provide some whole-of-catchment perspective. This also allowed some *in situ* observations of catchment characteristics, such as catchment slopes, catchment vegetation cover, gullying and floodplain extent.

2.2 Sediment Yield Model

2.2.1 Overall Approach

A sediment budget was constructed in order to estimate the amount of any excess coarse sediment load that may be available for extraction in Boothill Creek, Denison Creek and Isaac River by adopting a mass balance approach and a steady state system. The model was then run using a stochastic framework (Monte-Carlo method) described later.

In each river system, hypothetical extraction pits were included in the model in order to provide an estimate of the replenishment time.

The model was defined as follows:

$$Y = TCL \;\; [if\ TCL < STC] \qquad (1.1)$$

$$Y = STC \; [if \; TCL \geq STC] \quad (1.2)$$

$$y = TCL - STC \; [if \; TCL \geq STC] \quad (1.3)$$

where:

Y = Sediment yield (t/ year);

TCL = total coarse material load (t/ year);

STC = sediment transport capacity (t/ year); and

y = sediment deposition on stream bed (t/ year).

This simply states that if the sediment yield is greater than the theoretical transport capacity, then deposition occurs on the stream bed.

2.2.2 Components of the Sediment Yield Model

TCL was estimated as

$$TCL = HE + BE + BedE \quad (1.4)$$

where:

HE = coarse sediment from hillslope erosion (t/ year);

BE = coarse sediment from stream bank erosion (t/ year); and

BedE = coarse sediment from stream bed erosion (t/ year).

STC was calculated by extending Yang's (1973) equation (Prosser et al 2001) as

$$STC = K_1 \frac{12 * Q_m^{\beta} * S^{\gamma}}{W^{\beta - 1}} \quad (1.5)$$

where:

K_1 = coefficient of sediment transport capacity (dimensionless);

Q_m = Discharge (ML/ month);

S = slope of the channel bed (m/ m);

β & γ = exponents of Q_m and S respectively; and

W = channel width (m).

For the case where sediment yield was greater than theoretical transport capacity (Equation 1.2), the accumulation of excess material on the channel bed was estimated as

$$y_e = \frac{y}{1000 * W * L * BD} \quad (1.6)$$

where:

y_e = deposition of excess coarse material on channel bed (m/ year);

L = reach length (Km); and

BD = dry bulk density (t/ m^3).

The model for the Isaac River was more complex due to the presence of Burton Gorge Dam, and a greater number of subcatchments and existing extraction entitlements. It was assumed that all coarse sediment delivered to Burton Gorge Dam was retained in the reservoir, but that water overflow from the reservoir occurred when the dam was at full capacity. Therefore the model differed in two ways.

(a) TCL in Isaac River catchment II upstream and Isaac River catchment II downstream was calculated differently (Figure 2-1) as:

$$TCL_{catchII\ u/s} = HE + BE + BedE + Y_{catch\ I} + Y_{catch\ III} \quad (1.7)$$

$$TCL_{catchII\ d/s} = (Y_{catchII\ u/s} * SDR_c) + BE + BedE + Y_{catch\ IV} \quad (1.8)$$

where:

$TCL_{catchII\ u/s}$ = total coarse load in catchment II u/ s (t/ year);

Y_{catchI} = sediment yield from catchment I (set to zero, t/ year);

$Y_{catchIII}$ = sediment yield from catchment III (t/ year);

$TCL_{catchII\ d/s}$ = total coarse load in catchment II d/ s (t/ year);

$Y_{catchII u/s}$ = sediment yield from catchment II u/s (t/year);

SDR_c = sediment delivery ratio in channel (dimensionless); and

$Y_{catchIV}$ = sediment yield from catchment IV (t/year).

(b) water discharge (overflow) from catch I into catch II u/s was assumed to occur when Burton Gorge Dam was at full capacity (19,264 ML, SunWater 2009, Table 14-3 P. 14-8).

2.3 Extraction of bed material

The volume of material to be extracted from the bed of creeks and stream was estimated as follows:

$$V_{ex} = l * w * d \tag{1.9}$$

where:

V_{ex} = volume of bed material to be extracted (m^3);

l = length of extraction pit (m);

w = width of extraction pit (m); and

d = depth of extraction pit (m).

A minimum of 2.5 m buffer width between the pit and the banks on either side of the waterways was assumed to ensure, among others, their banks' stability. It was defined as

$$w' = (W - 5.0)[if\ W - w < 5.0, else\ w](stochastic\ generation, see\ Appendix) \tag{1.10}$$

where:

w' = adjusted width of the extraction pit (m).

2.4 Filling of the extraction pit

The model assumed that coarse material would be deposited in both the (a) supply limit scenario (Equation 1.1) and (b) the transport limit scenario (Equation 1.2). This means that if the sediment yield is greater than the theoretical transport capacity, then deposition will occur in both the extraction pit and on the bed of the channel. If the sediment yield is less than the transport capacity, there would be no deposition on the bed of the channel, but sediments would still be transported to and trapped in the hypothetical extraction pit.

Filling of the excavated pit was estimated as:

$$z = \frac{Y * (K_2 * TE)}{w' * l * BD} + y_e \tag{1.11}$$

where:

z = depth of filling (m/ year);

K_2 = blockage ratio (w'/ W); and

TE = trapping efficiency (%).

2.4.1 Trapping efficiency

Trapping efficiency (TE, %) of the extraction pit was estimated by Brune's (1953) upper trapping efficiency curve (Heinemann 1984). To allow easy calculation of TE in case of more than one extraction site in a reach, it was assumed that when the largest pit is filled then the remaining pit will also be filled in. TE was calculated as:

$$TE = 100\ [if\ \log_{10}\left(\frac{V_{ex}}{Q_a}\right) > 0.04] \tag{1.12}$$

$$TE = -15.594 * \log_{10}\left(\frac{V_{ex}}{Q_a}\right)^2 - 13.653 * \log_{10}\left(\frac{V_{ex}}{Q_a}\right) + 96.267[if\ \log_{10}\left(\frac{V_{ex}}{Q_a}\right) > 0.06] \tag{1.13}$$

$$TE = -16.986 * \log_{10}\left(\frac{V_{ex}}{Q_a}\right)^2 - 13.481 * \log_{10}\left(\frac{V_{ex}}{Q_a}\right) + 97.331[if\ \log_{10}\left(\frac{V_{ex}}{Q_a}\right) \geq 0.002] \tag{1.14}$$

$$TE = 0\ [if\ \log_{10}\left(\frac{V_{ex}}{Q_a}\right) < 0.002] \tag{1.15}$$

where:

Q_a = annual discharge (=12* Q_m, ML/ year).

2.5 Strategy Adopted to Account for Existing Entitlements

For the Isaac River, little information was available with reference to the existing entitlements upstream (catch II u/s) and downstream of the proposed extraction site (catch II d/s) except the total allocated annual volume. A conservative approach was taken to account for the current upstream entitlements (a total of 75,000 m^3/year, Golder Associates 2009, Table 2, P.3). Therefore a total of 75,000 m^3/year of coarse material was always subtracted from $TCL_{catchII\ u/s}$ first (Equation 1.7) prior to evaluation of the sediment budget. Any sediment yield or coarse material pass through the existing extraction pits was estimated by factoring $Y_{catchIIu/s}$ by SDR_c (Equation 1.8).

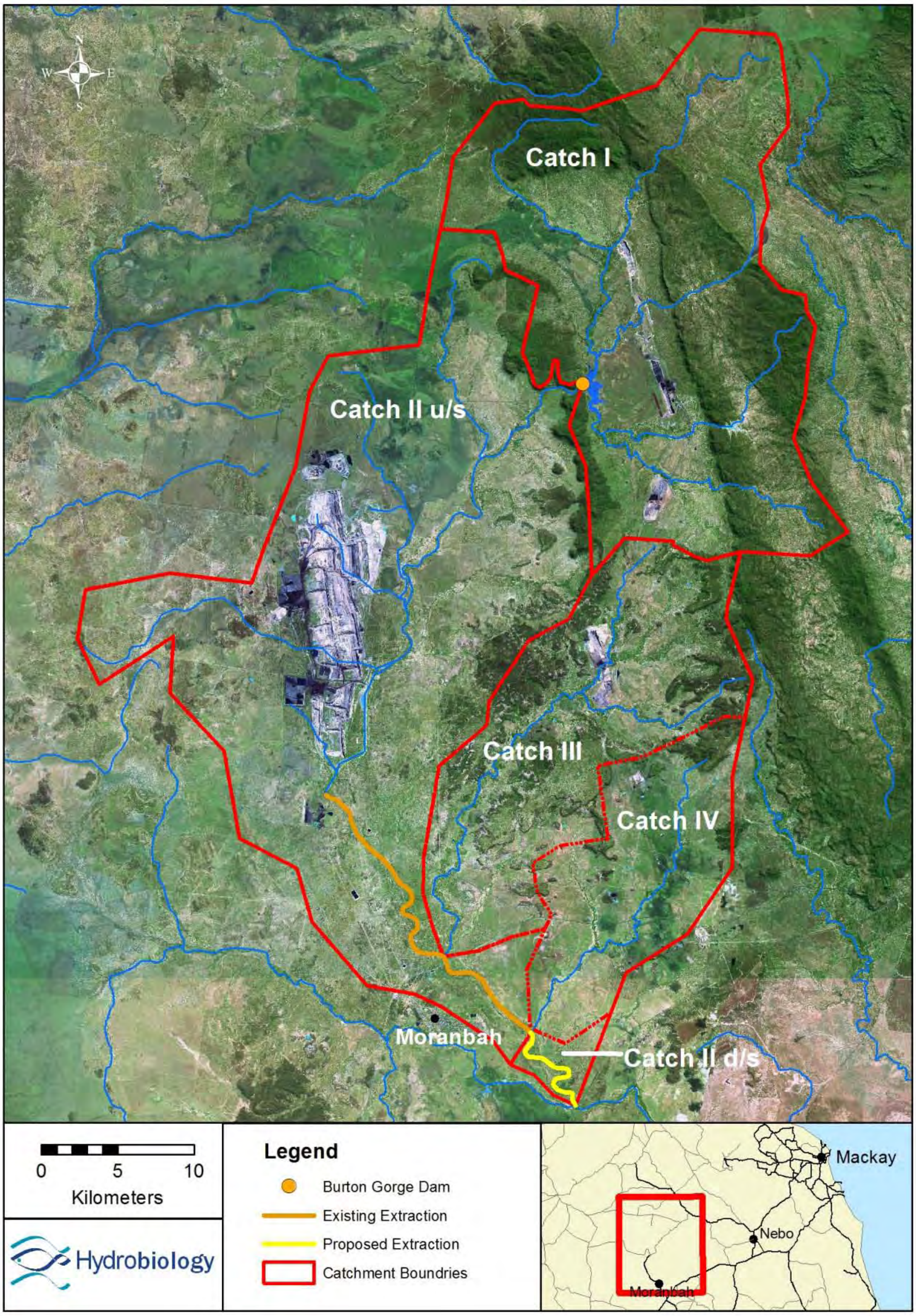

Figure 2-1 Isaac River catchment with proposed and upstream existing extraction entitlement

2.5.1 Parameterisation of the model

Variables and parameters of the sediment yield model (Equations 1.1 to 1.15) are highly variable and uncertain. Field observations, literature, geographic information system (GIS) layers, a DEM, local information and expert knowledge were utilised in defining the variables and parameters of the model. Professional judgement was utilised where no information was available. A stochastic approach (Monte Carlo framework) was adopted to parameterise the various stochastic inputs and to propagate the variability and uncertainty in the input variables and parameters into results of the model. Details about parameterising the model are described in Appendix 1.

2.5.2 Monte Carlo Simulation (MCS) Method

The MCS method is an analytical technique for estimating the solution of a numerical mathematical problem (e.g. a model) for situations where there is uncertainty and/or variability associated with input parameters and processes, by means of random sampling. It randomly draws samples from probability distribution function (PDF) of each of the uncertain input variables of a model one at a time and solves the equation(s) of a model using the selected input variables. This process is repeated many times, each time randomly selecting different values from their PDFs. The outputs or results of a model are aggregated and produced as probability distribution in order to define the likely variability of output given the uncertainty of inputs. The MCS method was applied in three steps. They were:

1. The variables and parameters of the sediment yield model (Equations 1.1-1.15) were considered stochastic variables and their PDFs were parameterised. The exceptions were that catchment area, length of reach and extraction pit length which were considered as deterministic variables;

2. The sediment yield model (Equations 1.1-1.15) was developed in Spreadsheet and it was laid in to the MCS framework. Any interdependency between and among the factors, variables and parameters of the model was maintained; and

3. A MCS of the sediment yield model (Equations 1.1-1.15) was run.

For each MCS, 65,000 sets of input variables were stochastically generated from their respective PDFs. The sediment yield model (Equations 1.1-1.15) was run for each of these sets of variables, and the sediment yield, including the filling of the excavated pit, was simulated and aggregated.

The computer program @Risk was used for the MCS.

3 RESULTS

3.1 Boothill Creek

Results of the model for Boothill Creek are shown in Figure 3-1 to Figure 3-6, and Table 3-1 and Table 3-2.

Figure 3-1 shows both the theoretical sediment transport capacity (STC)[1] and computed total coarse sediment load (TCL) (also referred to as Total Sediment Supply) in Boothill Creek were highly variable. STC was much greater than TCL (evident from both a comparison of the median values as well as the extended boxes of the box-whisker plot). Figure 3-1 also suggested that STC and TCL were highly skewed (meaning that exceptionally high rates of sediment transport occurred during a small percentage of time) and this is shown in the truncated cumulative distribution function (Figure 3-2). Table 3-1 shows the numerical results along with various other statistical characteristics of STC and TCL for Boothill Creek.

Model results also suggested that most of the coarse load of Boothill Creek comes from hillslopes, followed by the stream bed and stream bank in that order (Figure 3-3, Figure 3-4, and Table 3-2). Results also showed that for 79 % of the time, Boothill Creek was 'supply limited' and 'transport limited' for the remaining 21% of the time meaning that during exceptionally high flows, the rate of sediment transport would be equal to the transport capacity.

Despite the fact that majority of the time Boothill Creek is predicted to be supply-limited, results of the model suggest that a total of about 190,000 m^3 of coarse bed material could be extracted from Boothill Creek (Figure 3-5). This figure is based on the volume of a hypothetical pit that would replenish in a relatively short period of time.

Figure 3-5 (right plot) shows the variability of the likely volume of a hypothetical pit assuming it has a fixed length but that the width and depth were variable with reference to the variability of the existing bed material deposits. Using this volume, Figure 3-6 shows that such a pit is likely to be naturally filled typically in about two years after excavation, evident by the median line of the third box on the graph (which overlies the top of the box in this case) which reaches the ground surface (zero elevation) in year 2.

The rate at which the pit fills may reduce over time because the trap efficiency of the pit would decline as it fills. Trap efficiency would also be lower during very high flow events when residence time of coarse sediment would be short (Figure 3-5) because when discharge is very high compared to excavated pit size there is a very low capacity/ inflow ratio and thereby relatively longer filling time.

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1 STC refers to the theoretical sediment transport capacity based on hydraulics. It makes no assumptions about sediment supply. TCL is the total coarse sediment load calculated by considering the delivery of sediment from bed, bank and hillslope sources. STC is usually greater than TCL, but TCL can be > STC. For example a catastrophic event may deliver sediment to the river channel that exceeds the hydraulic capacity of the flow to transport it.

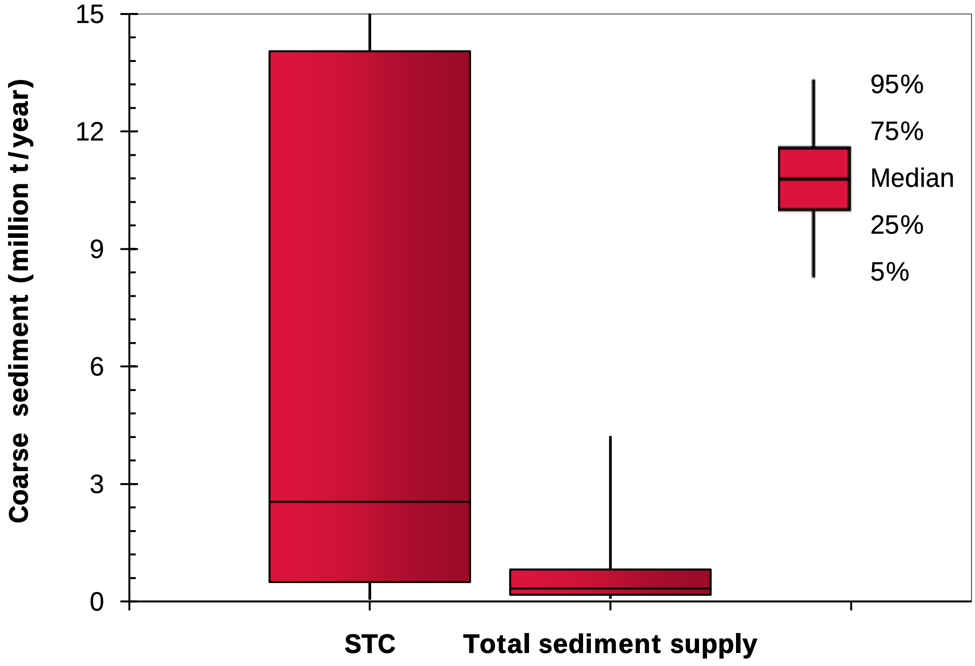

Figure 3-1 Comparison between (truncated) sediment transport capacity (STC) and total coarse sediment supply (TCL), Boothill Creek[2]

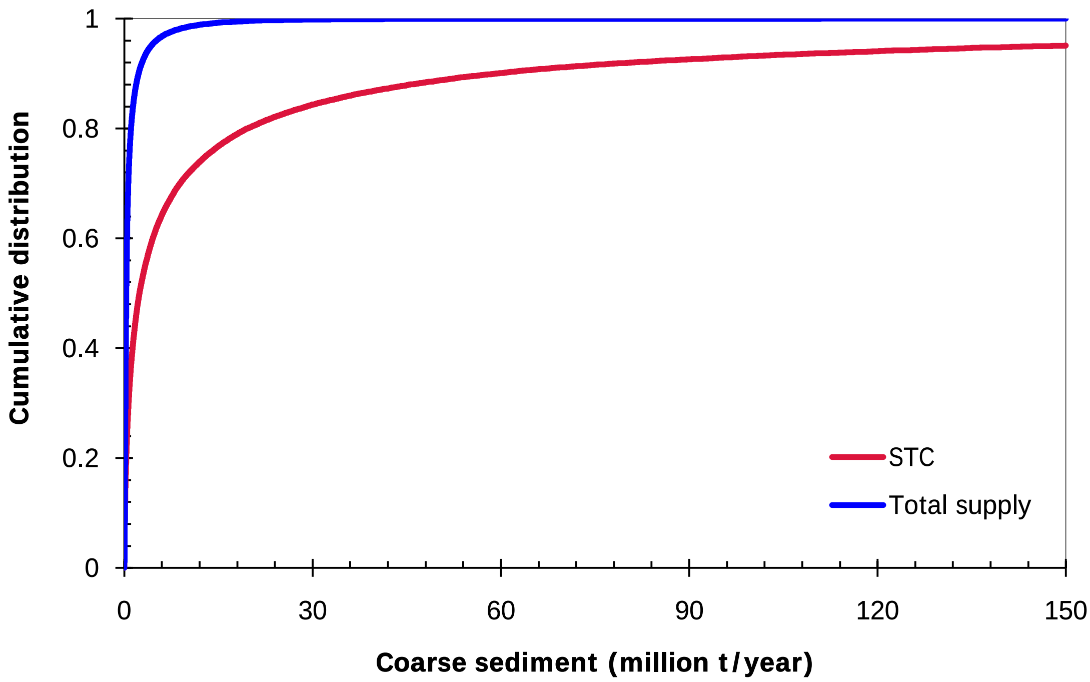

Figure 3-2 Cumulative (truncated) distribution functions of sediment transport capacity (STC) and total supply (TCL) in Boothill Creek

[2] Box and Whisker Plots. These diagrams show the median (or mean), and 5th, 25th, 75th and 95th percentiles of the results (from 65,000 model iterations). Figure 3-1 shows that the theoretical transport capacity is much higher than the actual predicted coarse load, because the former does not consider sediment availability.

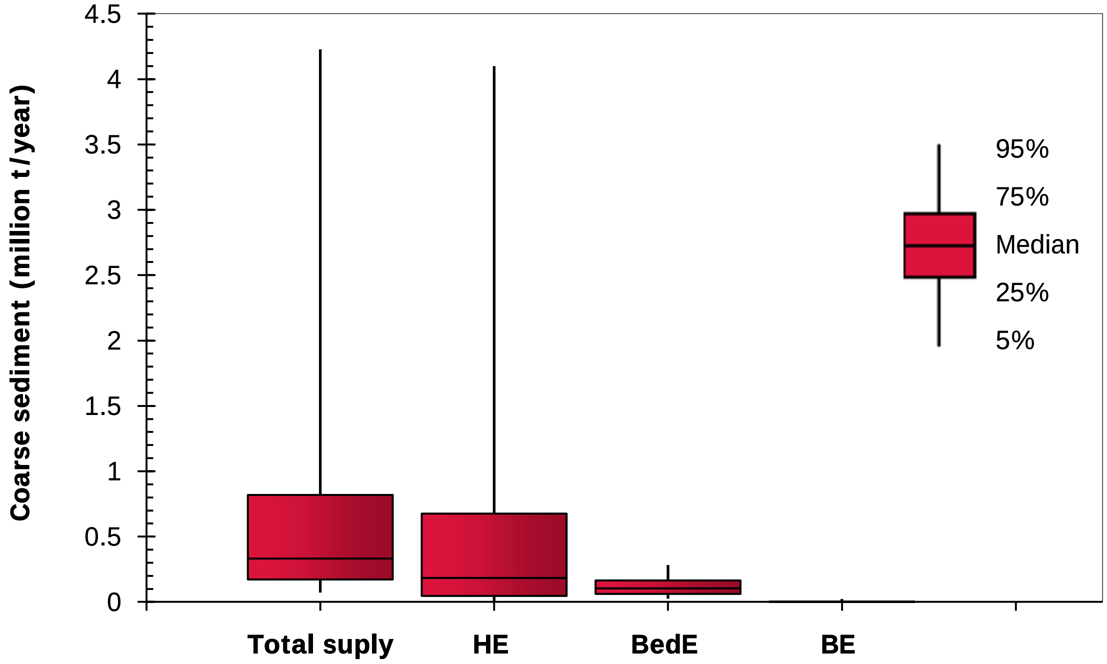

Figure 3-3 Contribution of various sources to total supply (TCL) in Boothill Creek

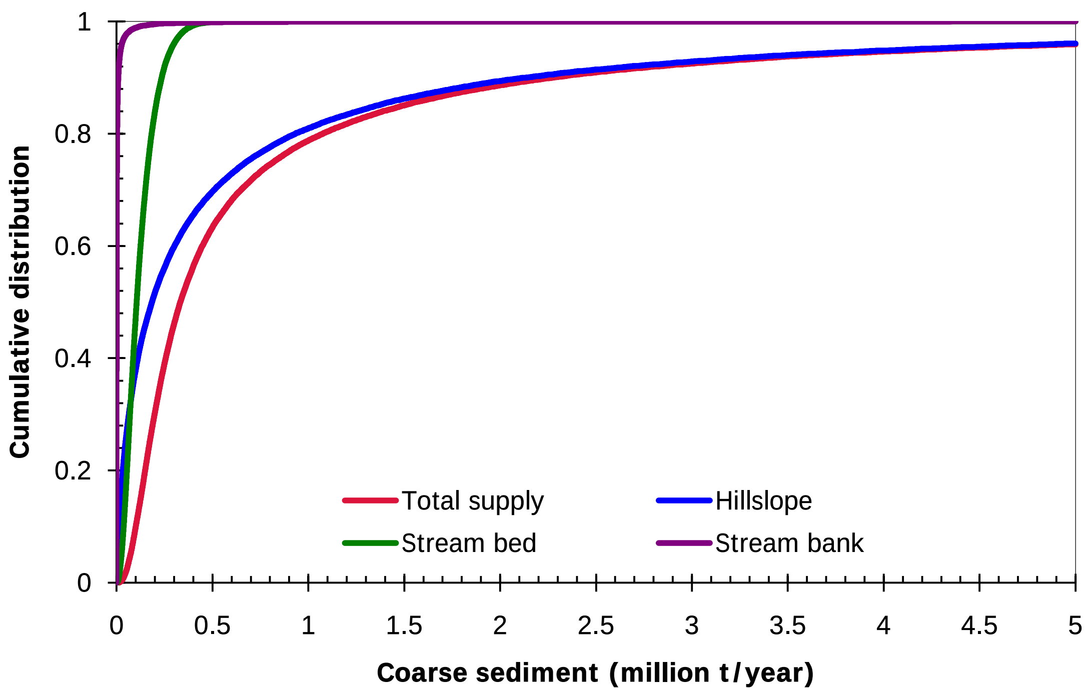

Figure 3-4 Comparison of (truncated) cumulative distribution functions of various sources of total supply (TCL) in Boothill Creek

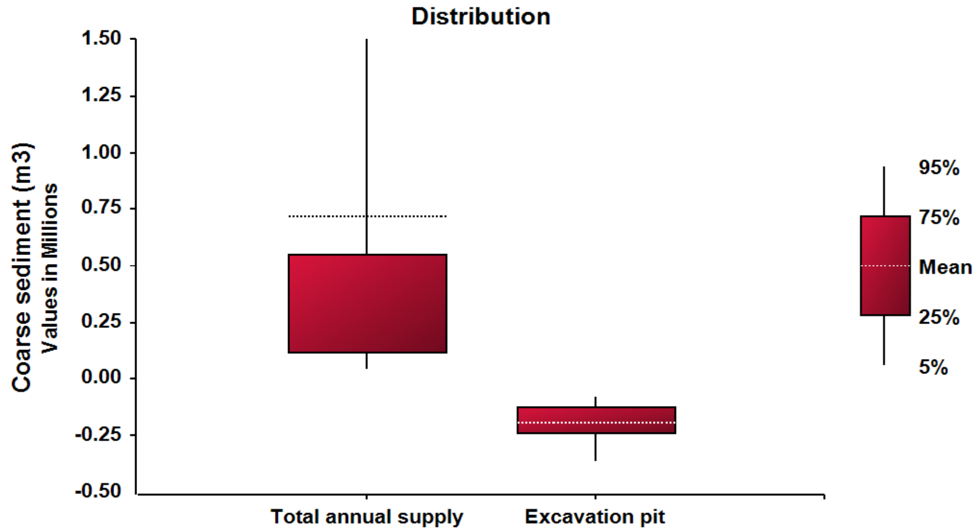

Figure 3-5 Comparison between annual coarse sediment supply (TCL) and demand (extraction amount) in Boothill Creek

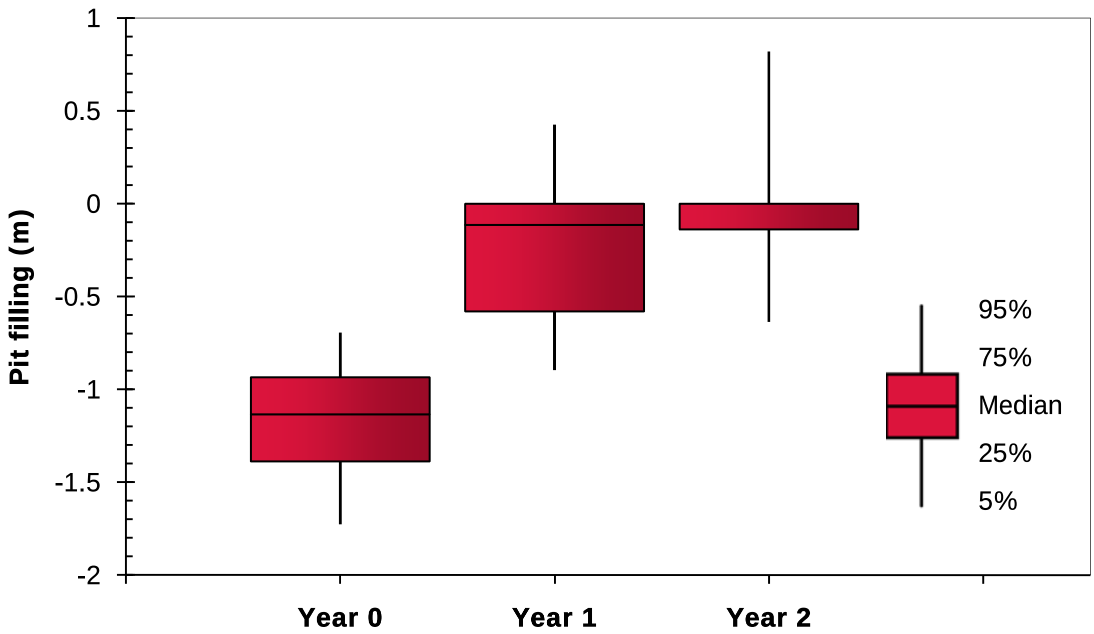

Figure 3-6 Distribution of filling of excavated pit in Boothill Creek

Table 3-1 Statistical characteristics of sediment transport capacity (STC) and total coarse sediment load (TCL) in Boothill Creek

Parameter	Statistical characteristics							
	Minimum	Mean	Maximum	Median	Standard deviation	5th percentile	95th percentile	90% confidence
Sediment transport capacity (STC) (t/year)	106	41,995,820	16,420,860,000	2,408,489	265,875,700	44,319	145,127,600	145,083,300
Total coarse sediment supply (TCL) (t/year)	3,954	1,060,670	110,926,900	332,287	2,762,713	72,016	4,225,381	4,153,365

Table 3-2 Statistical characteristics of various contributions to total coarse sediment (TCL) in Boothill Creek

Sources	Statistical characteristics							
	Minimum	Mean	Maximum	Median	Standard deviation	5th percentile	95th percentile	90% confidence
Total coarse sediment supply (TCL) (t/year)	3,954	1,060,670	110,926,900	332,287	2,762,713	72,016	4,225,381	4,153,365
Hill slope (t/year)	0.5	931,487	110,791,000	184,062	2,757,925	4,798	4,099,431	4,094,633
Stream bed (t/year)	246	122,732	624,087	104,559	81,303	25,773	283,005	257,232
Stream bank (t/year)	0.0	6,451	4,348,976	431	47,199	9	21,284	21,275

3.1.1 Field Observations

A map of the location of the assessed reaches on Boothill Creek is shown in Figure 3-7 and Figure 3-8. Photographs of particular features within the reach are also shown in this figure. A walk through of three reaches was conducted during the field assessment – one starting at the Funnel and Boothill creeks' confluence, with the other two located several kilometres upstream. No geomorphic assessments of this creek were reported in SunWater (2009); however, field observations and aerial photography analysis for this work indicated that the majority of Boothill Creek consisted of a complex multi-thread channel, with multiple benches, flood channels and vegetated islands within the greater bankfull channel. These within-channel features provided some geomorphic variability; however, this variability was often masked by large sediment deposits ('slugs' / 'waves') located all along the creek.

Generally speaking, gullying appeared to be more prevalent in Boothill Creek catchment than any of the other catchments visited during the field assessment. This can be largely attributed to the prevalence of clay-producing volcanics within this catchment, but also may be due to the fact that the reaches visited in Boothill Creek were located higher up in the catchment than those in the other visited catchments. Several examples of headward eroding gullies were observed to enter Boothill Creek.

The downstream reach (near the Funnel Creek confluence) consisted of a generally flat bed, with some variability provided by the presence of benches and mid-channel islands. The prevalence of these increases further upstream. Bed width was consistently between 20 and 40 metres. Banks consisted of homogeneous bank material (silty loams to silty-clay loams), were well vegetated and varied between about 8 and 10 m. Bank angle was variable and dependent on the presence of the aforementioned benches.

The middle reach consisted of similar bank characteristics to the lower reach, with slightly lower heights (6 – 8 metres). However, riparian vegetation variable, with some areas devoid of trees. Minor bank erosion was observed and linked to the sections of bank with poor riparian vegetation. Minor gullies were also observed to enter into the creek within this reach. Bed width was between 80 and 100 m. The bed consisted of variable material (coarse sand to gravel) and was complex with a variety of bed forms observed within the reach. Sections with large sandy benches with adjacent incised low flow channels were interspersed by sections with large vegetated mid-channel bars and sections with a wide, flat bed with little geomorphic variability. The presence of sand waves / slugs within the reach reduced this complexity in parts.

The upper reach consisted of banks with moderately dense riparian vegetation, although vegetation thinned in sections. Bank height varied between four and seven metres. Gully confluences were more prominent within this reach. Bank angle was variable, although more gradual sloping banks were more prevalent. Sand slugs were evident within the reach, but were interspersed by large, but infilling pools. Bed width differed considerably between the upper (30 – 40m wide) and lower (~100 m) sections of this reach. Channel form also varied considerably between the upper and lower sections, with the upper sections being more confined. A mid-channel island was observed in the upper sections. A large island / bench was also evident in the lower sections.

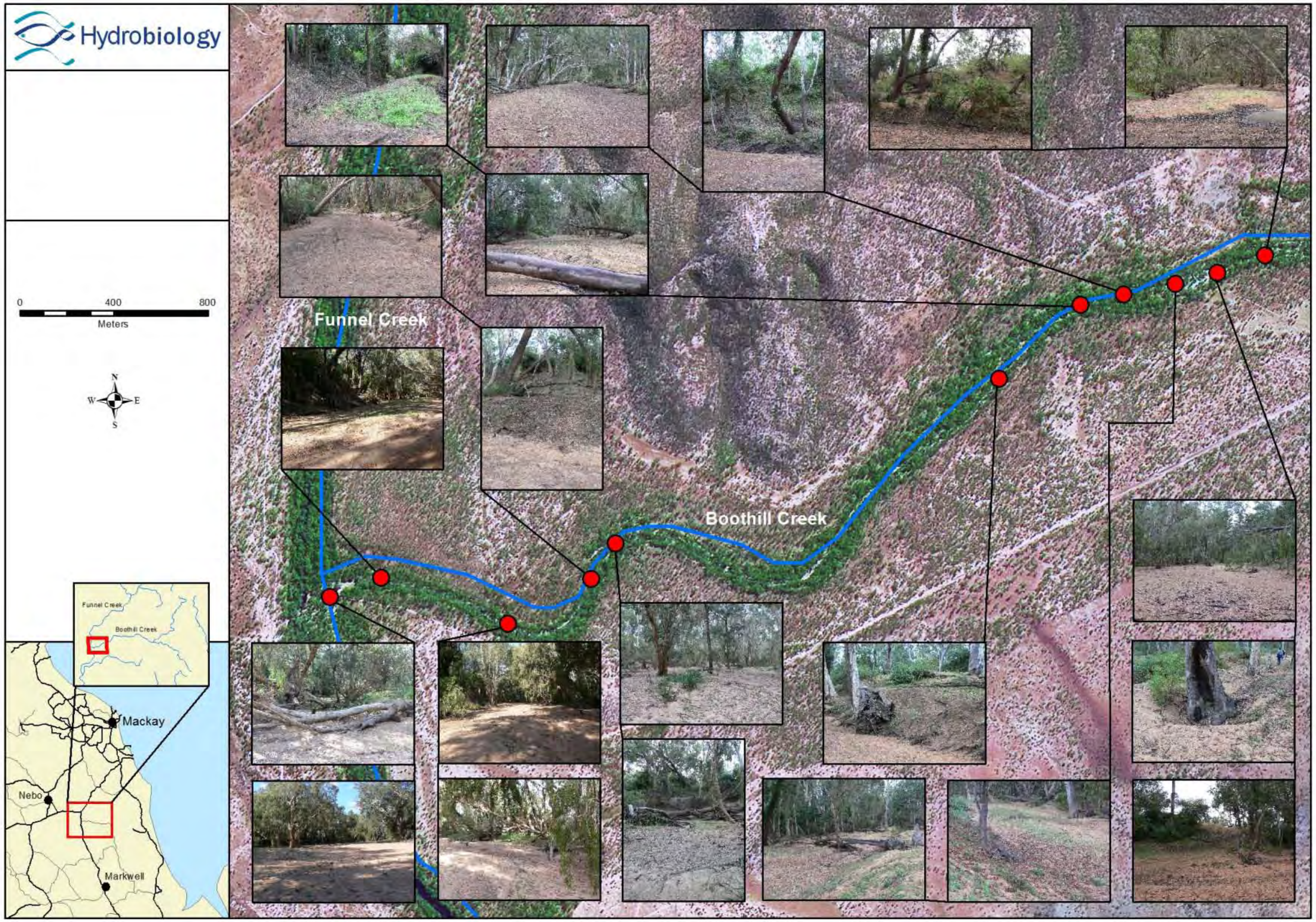

Figure 3-7 Location map and photo points, Boothill Creek/Funnel Creek

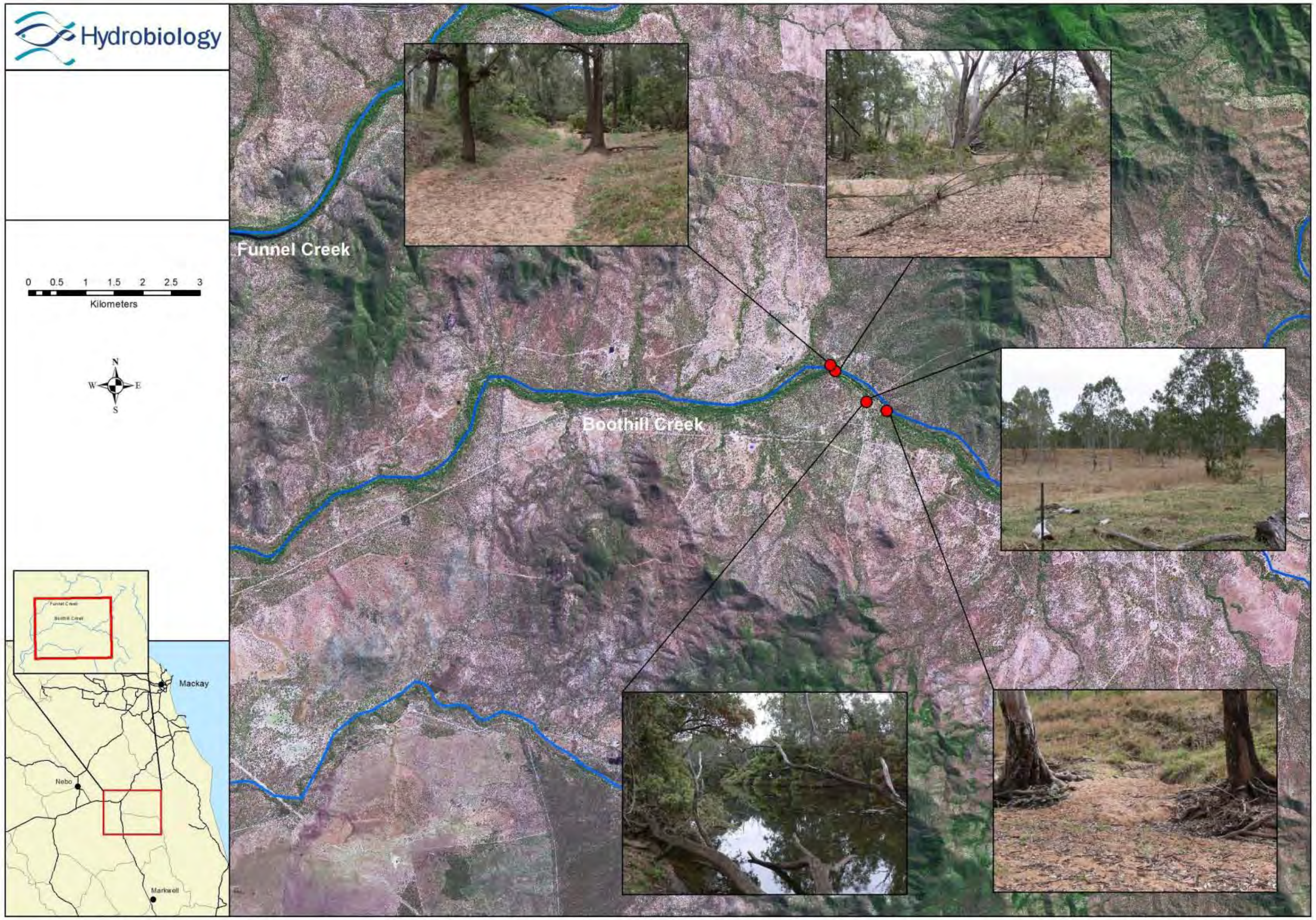

Figure 3-8 Location map and photo points, Boothill Creek at Rosedale Road

3.2 Denison Creek

3.2.1 Results

Results of the model for Denison Creek are shown in Figure 3-9 to Figure 3-14, and Table 3-3 and Table 3-4.

Similar to Boothill Creek, sediment transport capacity (STC) and total coarse sediment load (TCL) were highly variable, and characterised by very large standard deviations (Figure 3-9 and Figure 3-10, Table 3-3).

Sediment was derived mainly from hillslope sources, followed by stream bed and stream bank erosion as was the case for Boothill Creek (Figure 3-11, Figure 3-12 and Table 3-4).

Results of the Monte Carlo simulation suggested that on an average 101,000 m^3 of coarse material could be extracted from Denison Creek (Figure 3-13). Figure 3-13 (right plot) indicates the variability of extraction of coarse bed material. It is very likely that a pit of this volume would typically be completely filled in one year following excavation (Figure 3-14), which shows the median line (overlying the top of the interquartile box in this case) reaching the zero elevation line in one year.

As for Boothill Creek, the trapping efficiency of the pit would be lowest during extreme flow events and would also decline with time (as filling occurred and pit volume reduced).

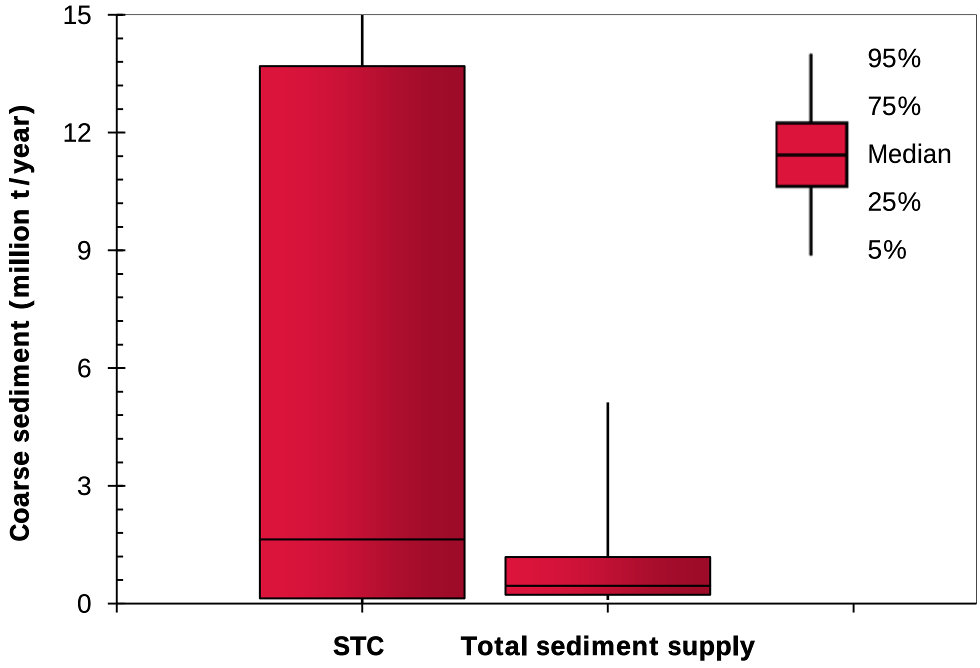

Figure 3-9 Comparison between (truncated) sediment transport capacity (STC) and total sediment supply (TCL) in Denison Creek

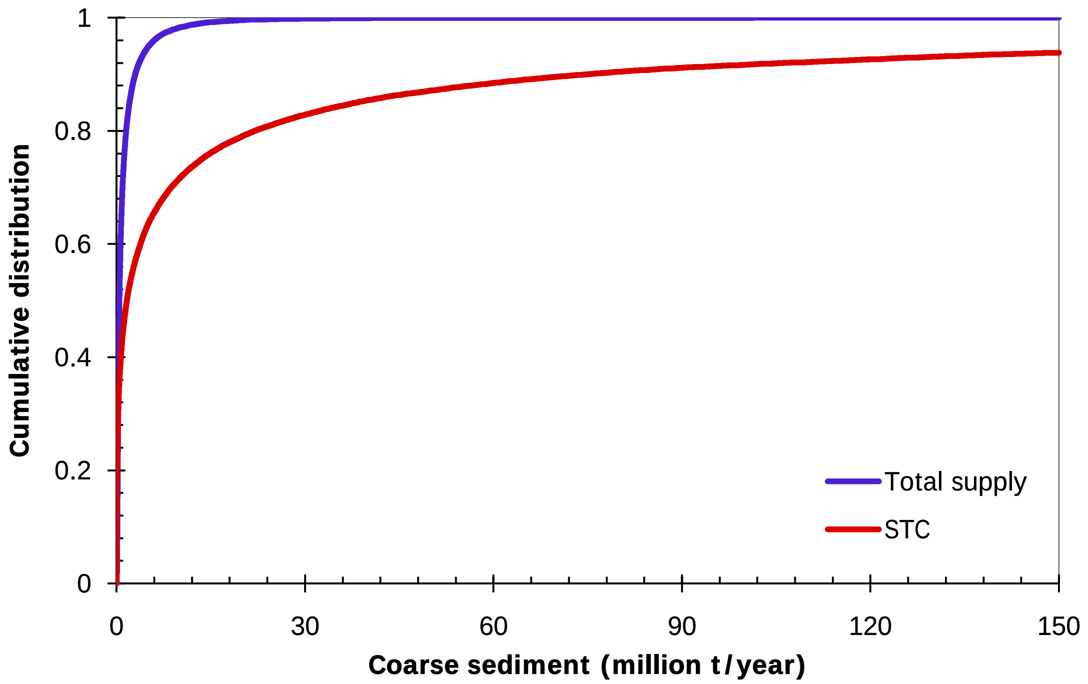

Figure 3-10 Cumulative (truncated) distribution functions sediment transport capacity (STC) and total supply (TCL) in Denison Creek

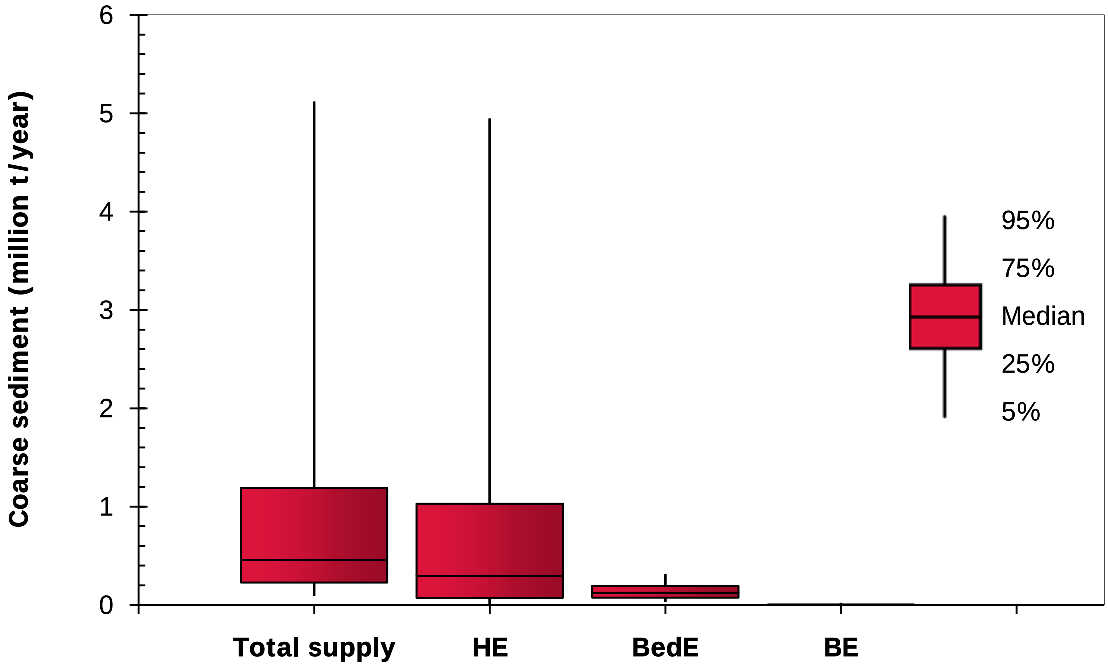

Figure 3-11 Contribution of various sources to total supply (TCL) in Denison Creek

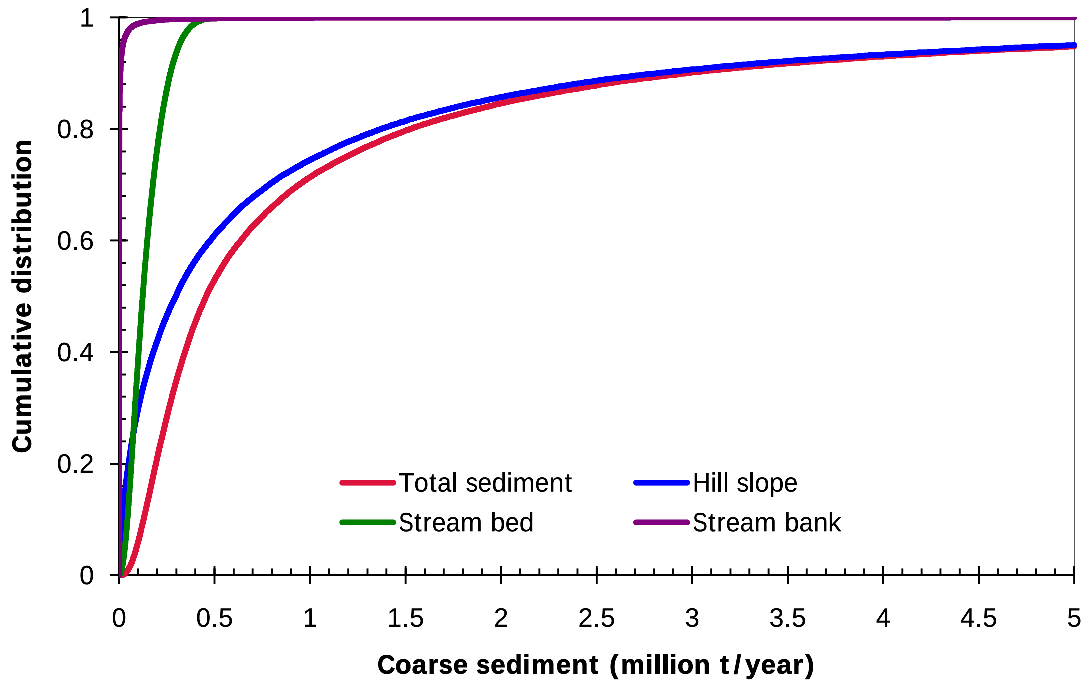

Figure 3-12 Comparison of (truncated) cumulative distribution functions of various sources of total sediment (TCL) in Denison Creek

Figure 3-13 Comparison between total coarse material supply (TCL) and proposed extraction in Denison Creek

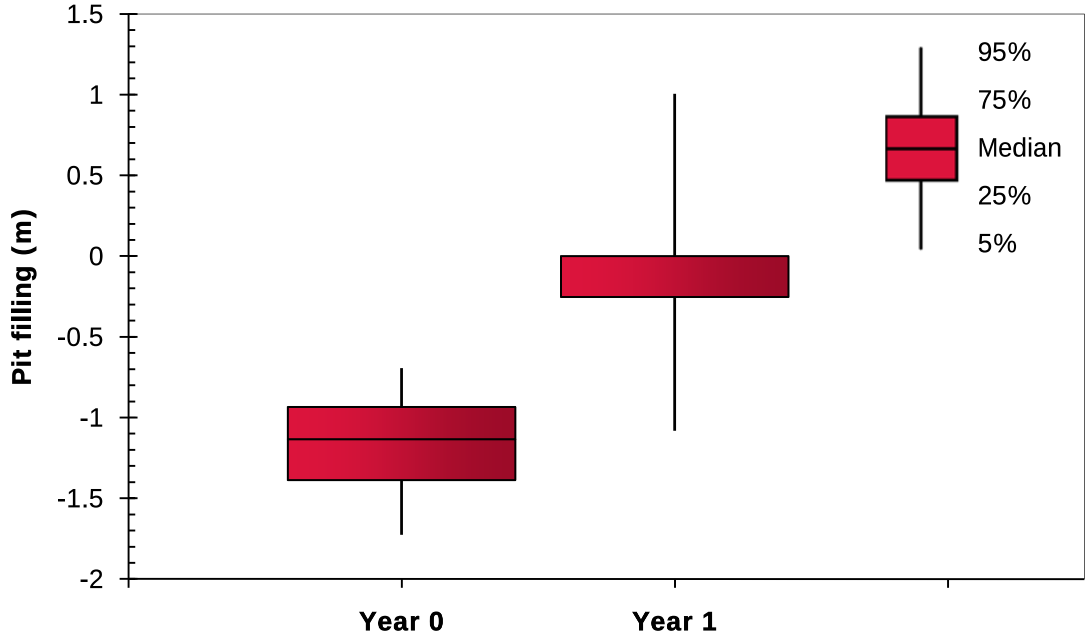

Figure 3-14 Distribution of filling of excavated pit in Denison Creek

Table 3-3 Statistical characteristics of sediment transport capacity (STC) and total coarse sediment load (TCL) in Denison Creek

Parameter	Statistical characteristics							
	Minimum	Mean	Maximum	Median	Standard deviation	5th percentile	95th percentile	90% confidence
Sediment transport capacity (t/year)	0.0	6.E+07	8.E+10	1,642,549	661,178,000	910	2.E+08	2.E+08
Total coarse sediment supply (t/year)	4,005	1,298,658	1.E+08	456,247	2,820,900	92,088	5,117,723	5,025,634

Table 3-4 Statistical characteristics of various sources to total coarse sediment load (TCL) in Denison Creek

Sources	Statistical characteristics							
	Minimum	Mean	Maximum	Median	Standard deviation	5th percentile	95th percentile	90% confidence
Total coarse sediment supply (t/year)	4,005	1,298,658	101,312,800	456,247	2,820,900	92,088	5,117,723	5,025,634
Hill slope (t/year)	1.4	1,149,739	101,097,800	296,316	2,815,091	6,404	4,947,102	4,940,698
Stream bed (t/year)	310	142,197	606,849	123,835	88,638	30,588	313,624	283,036
Stream bank (t/year)	0.0	6,723	7,854,742	193	60,104	1.0	20,398	20,397

3.2.2 Field Observations

A map of the location of the assessed reaches on Dennison Creek is shown in Figure 3-15. Photographs of particular features within the reach are also shown in this figure.

Dennison Creek was identified by SunWater (2009) as a large complex stream consisting of either single-thread or multiple-thread channels with a variety of in-stream and near-stream geomorphic features, including flood runners / channels, benches, terraces and off-river channels. The inspection of the creek during the field assessment supported the observations of SunWater (2009). The creek was seen to have more within-channel variability than Boothill Creek, with a noticeable low flow channel throughout much of the reaches that were inspected. The bed was largely composed of sands and gravels and consisted of large point bars and sacrificial benches (i.e. those consisting of sandy deposits that are 'sacrificed' during high flows). Sand slugs reduced bed variability in sections, but these were interspersed by deep (though probably infilling) waterholes and the aforementioned low flow channel.

Within the inspected reaches, Dennison Creek was narrower all of the other inspected systems. Bed width varied between about 20 – 40 metres. Bank height varied between 4-14 m but mostly exceeded eight metres. Bank material was mostly silty clays to silty loams. Raised benches / terraces were evident throughout the inspected reaches. Bank angle varied greatly and was dictated by the presence of these benches. However, most banks consisted of a steeper lower bank. Riparian vegetation was moderately dense. Very limited gullying was observed.

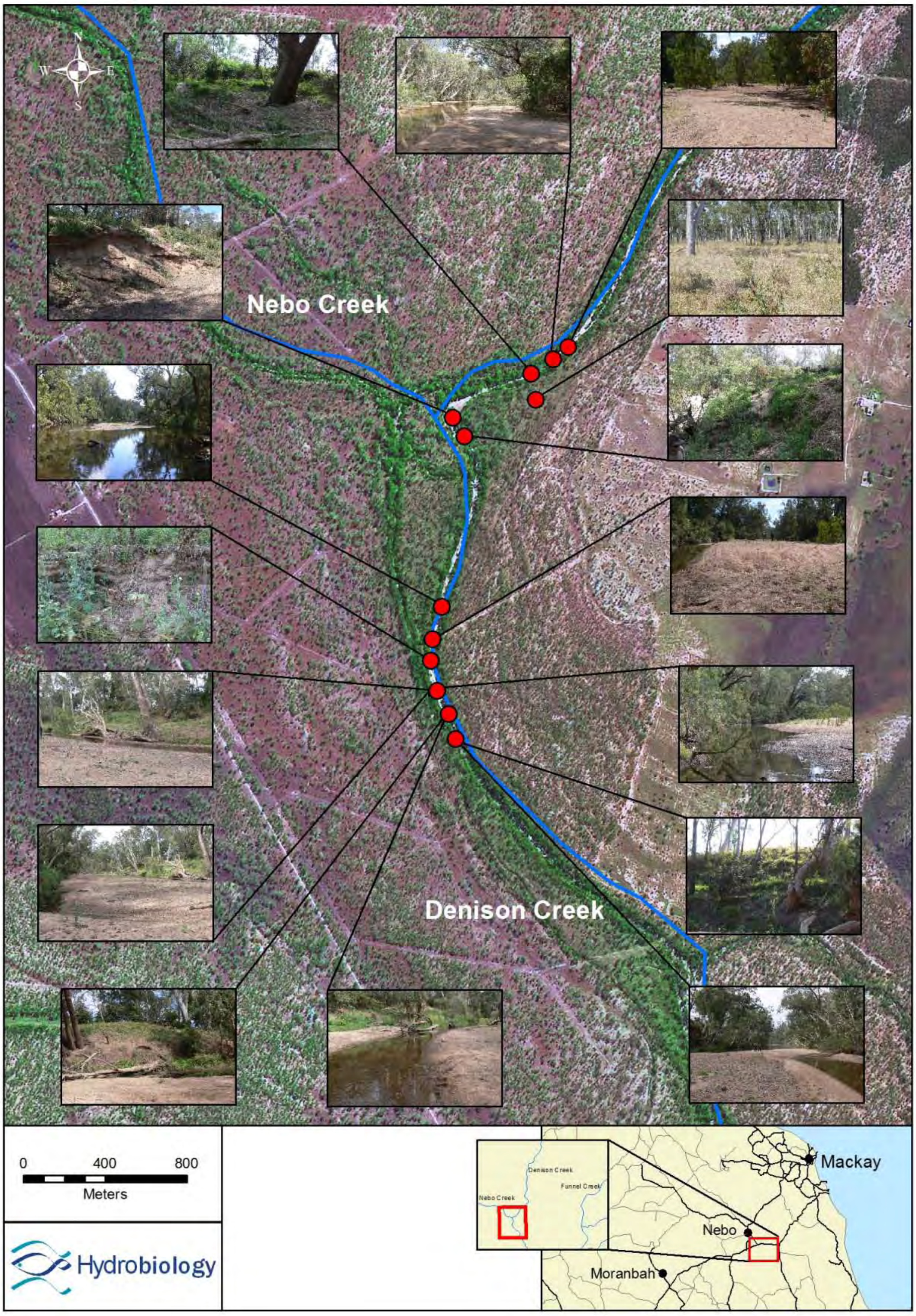

Figure 3-15 Location map and photo points, Denison Creek

3.3 Funnel Creek

Based on field observations, sand deposition at the Funnel Creek confluence was thought to be largely derived from Boothill Creek. As such, no model of Funnel Creek was constructed.

3.3.1 Field Observations

A map of the location of the assessed reaches on Funnel Creek is shown in Figure 3-7). Photographs of particular features within the reach are also shown in this figure. Only two locations were visited on Funnel Creek – at its confluence with Boothill Creek and at the proposed CRD to Moranbah pipeline crossing. However, its condition at the Malborough – Sarina Road crossing was also noted. Funnel Creek was also identified by SunWater (2009) as being a large complex stream.

Field observations confirmed the SunWater (2009) description, with up to four separate channels at the proposed pipeline crossing, a single thread channel with multiple flood runners and benches downstream of the confluence, a single thread channel upstream of the confluence and upstream of the bridge crossing and a multi-thread channel downstream of the bridge crossing. This complexity led to some variability in within-channel geomorphology, although general channel features were relatively consistent.

Bank height was consistently between about six and eight metres, with banks generally moderately well vegetated. Bank angle varied, with multi-thread channel reaches consisting of steep, high banks and complex single thread channels generally consisting of an assortment of benches, terraces, bars and within-channel flood runners ensuring high variability in bank angle. Bank material was dominated by silty-clayey sands to silty loams, except where sacrificial sandy benches abutted the banks.

Bed width varied between 10 m within the separate channels at the proposed pipeline crossing and 200 m at the Boothill Creek confluence. Bed material was dominated by sands and gravels; however, coarse material deposits were not present in the same quantity as the other creeks. Bed variability was far more evident with the presence of the features discussed previously.

3.4 Isaac River

3.4.1 Results

Figure 3-16 shows that the theoretical sediment transport capacity (STC) is much larger than the calculated total coarse sediment load (TCL). Compared to Boothill Creek and Denison Creek, the Isaac River is 'supply limited' for a relatively shorter period and thus transports sediment at the theoretical maximum rate for a greater proportion of the time. Sediment transport is highly positively skewed for the Isaac River (Figure 3-17).

Results also showed that much of the coarse sediment delivered to the proposed extraction reach came from the upper Isaac River catchment (catch II u/s, Figure 2-1) despite the current upstream extraction entitlements.

Figure 3-18 and Figure 3-19 show the relative importance of sediment sources to the proposed extraction area, namely (in order):

- Total sediment yield from catch II u/s (despite existing allocations);
- Stream bed (from the proposed extraction reach);
- Total sediment yield from catch IV; and
- Stream banks from the proposed extraction reach (minor component).

Table 3-6 provides additional detail.

Within catch II u/s model results suggest that the majority of the coarse sediment is potentially coming from the stream bed, hillslope erosion and total sediment yield from catch III. (Figure 3-20).

Model results suggested that, approximately 198,000 m^3 of bed material could be extracted from within the proposed extraction reach without affecting the current extraction entitlements downstream of the proposed extraction reach (catch II d/s)(Figure 3-21). Figure 3-21 (right plot) shows the variability of the extraction amount based on the dimensions of a hypothetical pit. It is likely that such a pit would typically be filled within one year of extraction (Figure 3-22). Figure 3-23 shows the amount of 'surplus' sediment (over and above the 198,000 m3) that would pass downstream to supply the existing downstream entitlements (91,500 m^3, Golder Associates 2009, Table 2, P 3).

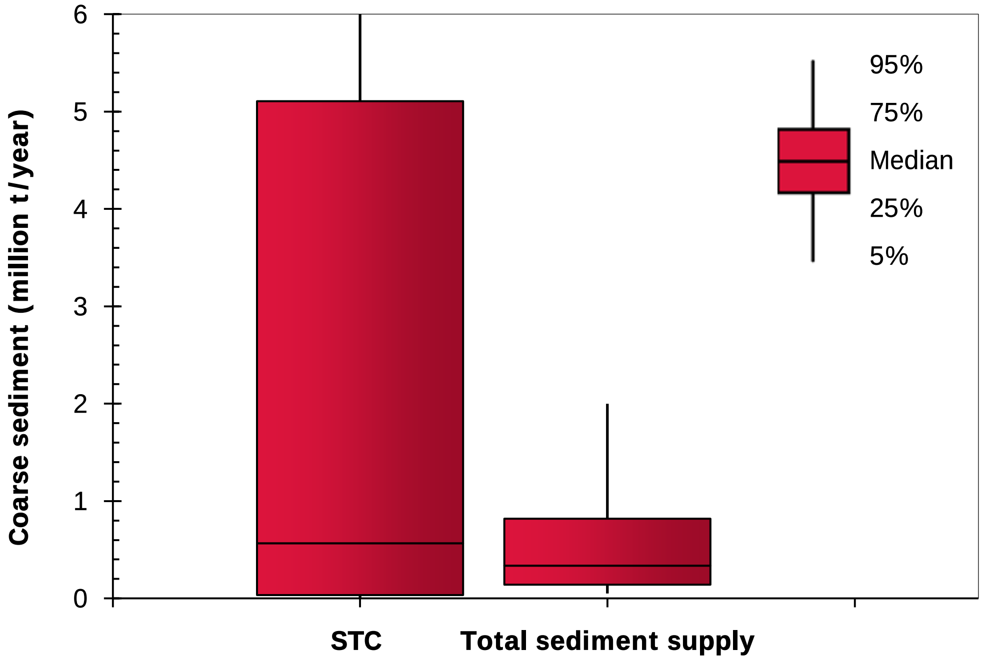

Figure 3-16 Comparison between (truncated) sediment transport capacity (STC) and total sediment supply (TCL) in Isaac River

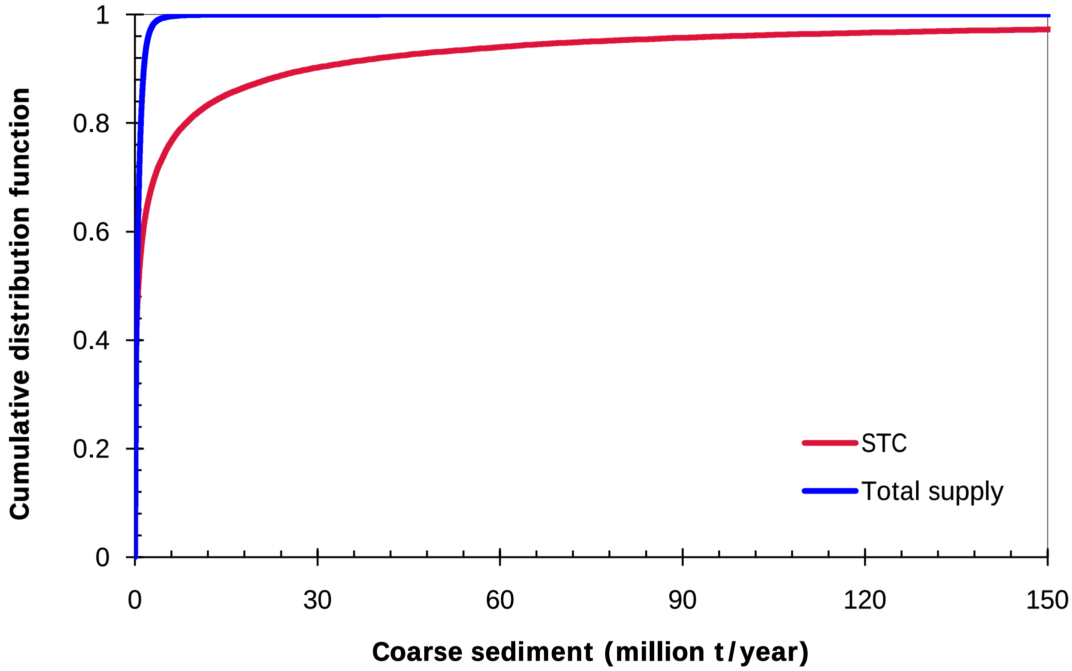

Figure 3-17 Cumulative (truncated) distribution functions of sediment transport capacity (STC) and total supply (TCL) in Isaac River

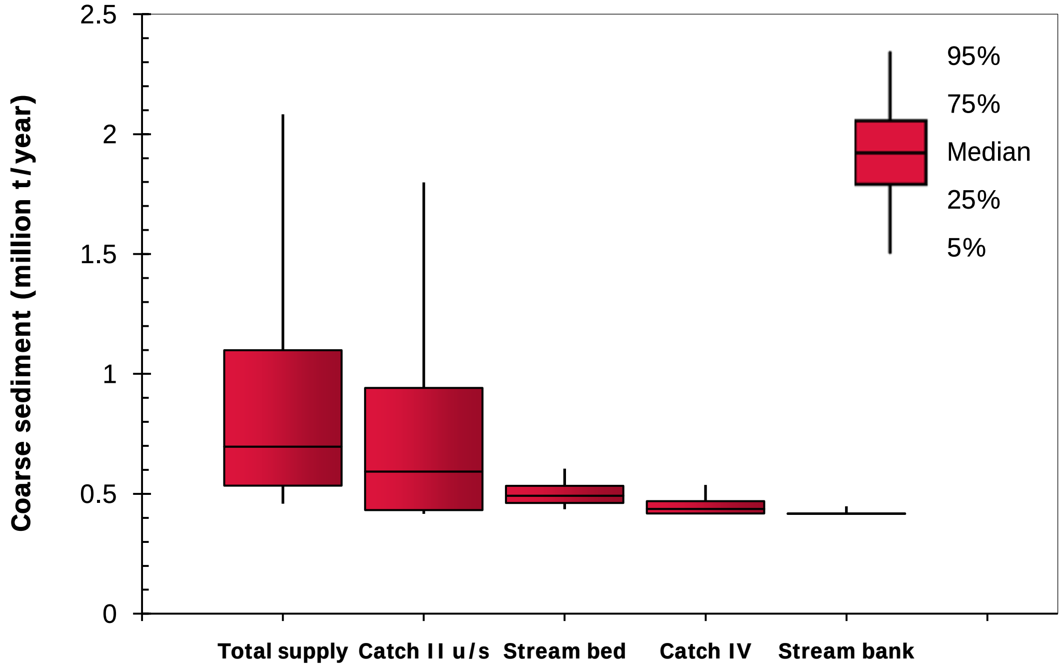

Figure 3-18 Contribution o f v arious s ources of total s upply (TCL) delivered t o proposed extraction reach in Isaac River

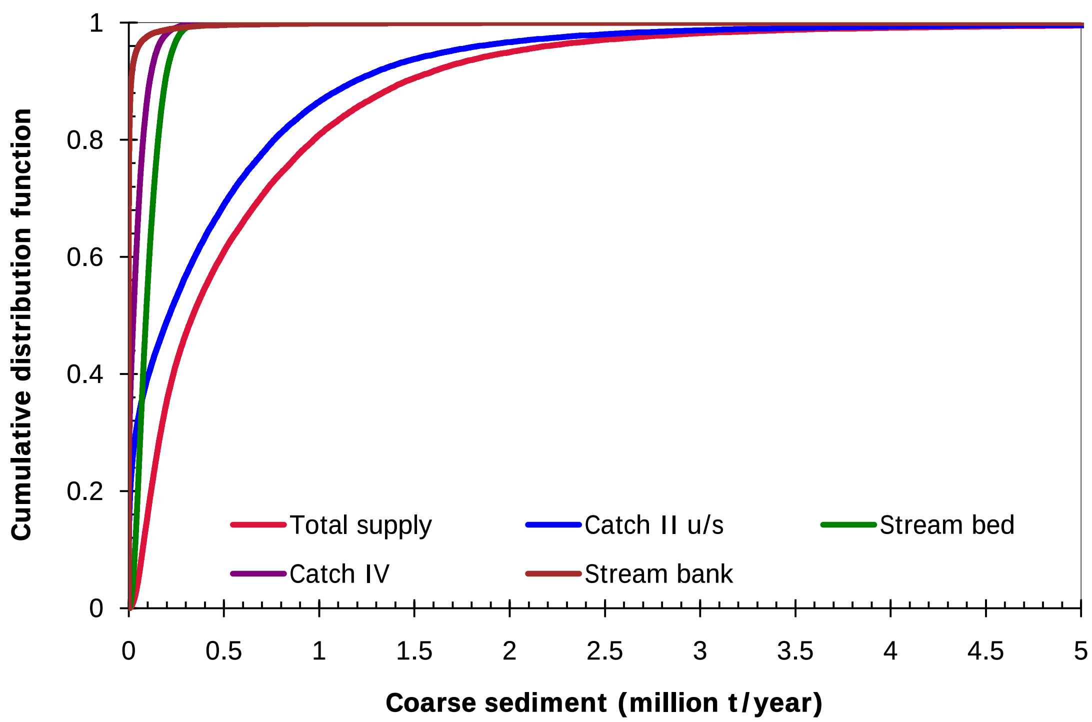

Figure 3-19 Comparison of (truncated) cumulative distribution functions of various sources of total supply (TCL) delivered to proposed extraction reach in Isaac River

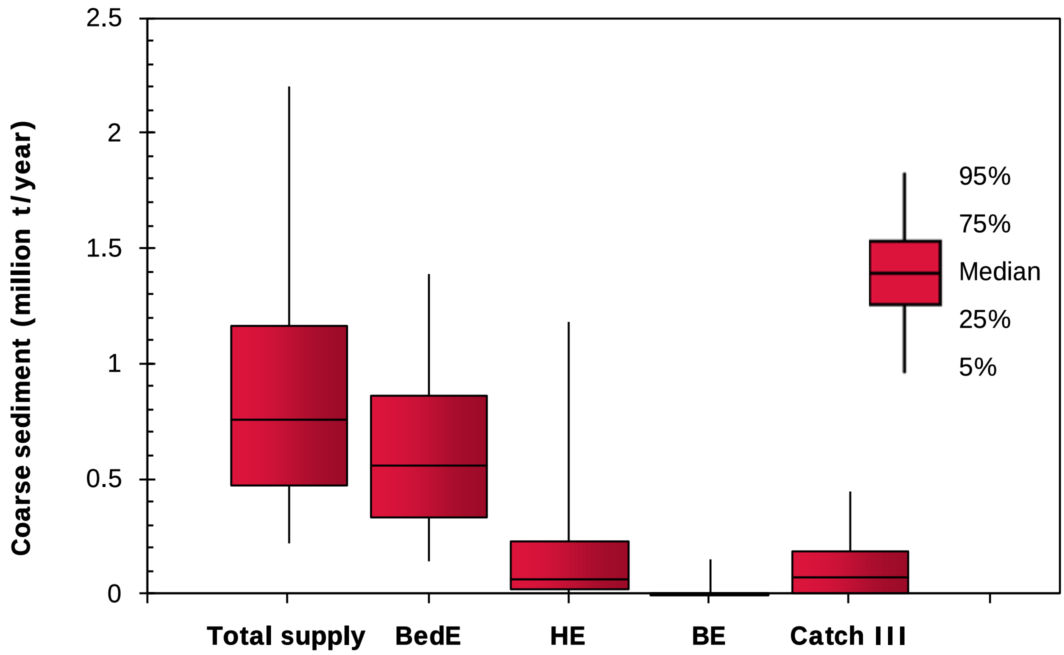

Figure 3-20 Sources of total supply (TCL) in catch II u/s, Isaac River

Figure 3-21 Comparison between total annual supply (TCL) and proposed extraction in Isaac River

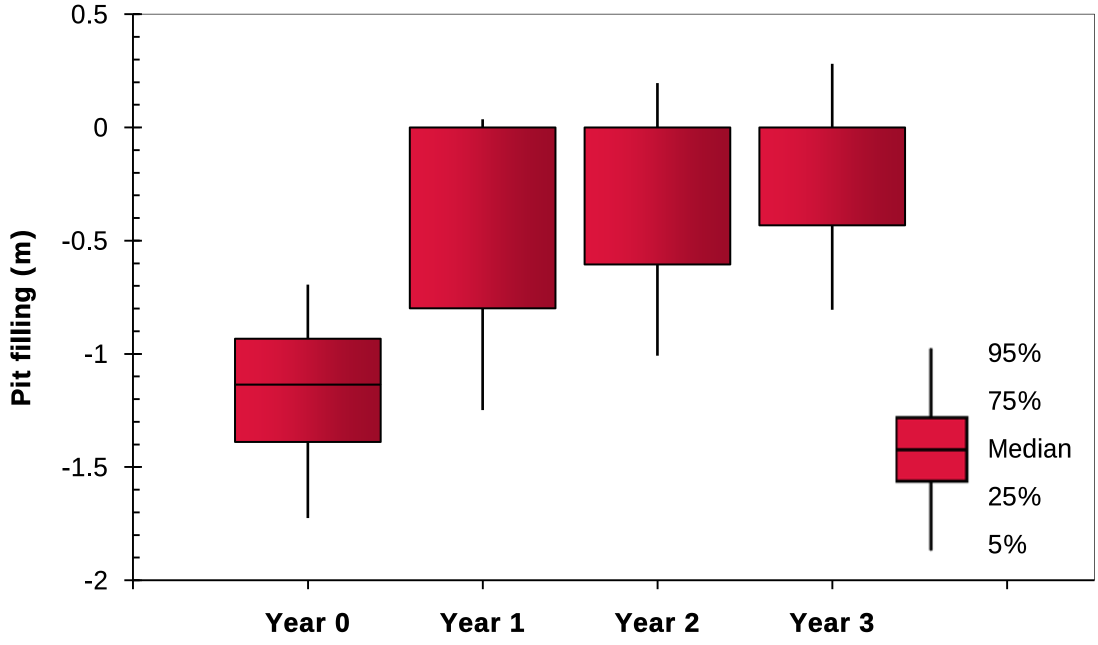

Figure 3-22 Expected rate (distribution) of filling of excavated pit in Isaac River

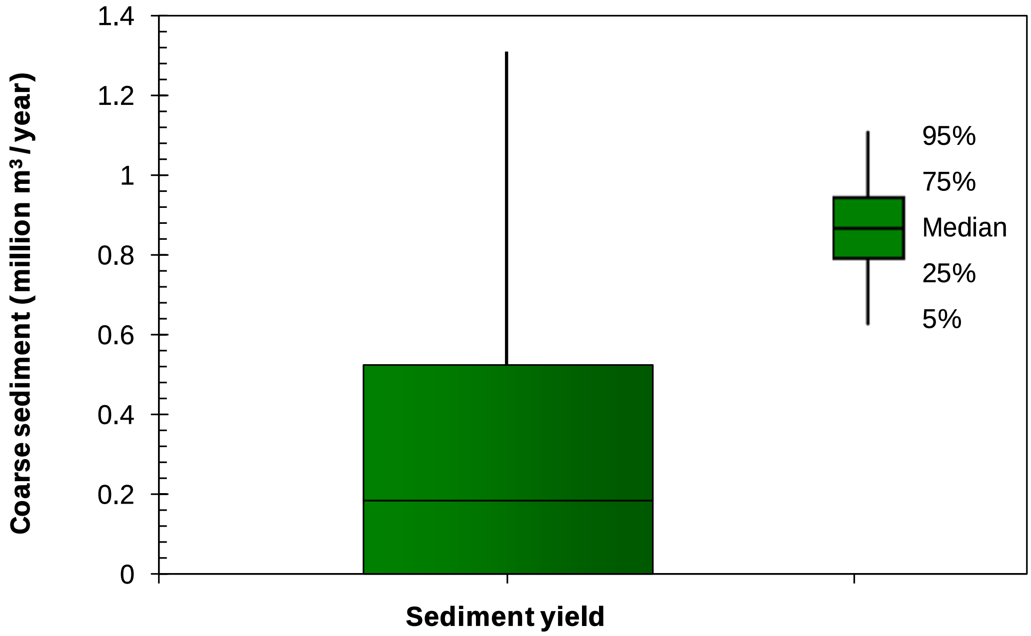

Figure 3-23 Distribution of excess sediment (TCL) passing the proposed extraction pit in Isaac River

Table 3-5 Statistical characteristics of sediment transport capacity (STC) and total coarse sediment load (TCL) along proposed extraction reach in Isaac River

Parameter	Statistical characteristics							
	Minimum	Mean	Maximum	Median	Standard deviation	5th percentile	95th percentile	90% confidence
Sediment transport capacity (catch II d/s) (t/year)	0.0	21,310,750	15,325,960,000	566,618	151,652,900	86	73,685,870	73,685,780
Total coarse sediment supply (catch II d/s)(t/year)	1,257	621,207	40,190,400	336,412	852,645	50,855	1,999,473	1,948,618

Table 3-6 Statistical characteristics of various sources to total coarse sediment load (TCL) along proposed extraction reach in Isaac River

Sources	Statistical characteristics							
	Minimum	Mean	Maximum	Median	Standard deviation	5th percentile	95th percentile	90% confidence
Total coarse sediment supply (catch II d/s) (t/year)	1,257	621,207	40,190,400	336,412	852,645	50,855	1,999,473	1,948,618
Stream bed (t/year)	752	103,456	466,484	90,816	63,787	23,283	226,187	202,904
Stream bank (t/year)	0.0	12,280	6,976,211	229	100,258	0.7	37,895	37,894
Catchment II yield (u/s)((t/year)	0.0	463,065	34,950,490	211,822	772,908	42	1,658,662	1,658,620
Catchment IV yield (t/year)	0.0	42,406	783,760	24,673	53,026	4.9	144,821	144,816

Table 3-7 Statistical characteristics of various sources to total coarse sediment load (TCL) in catch II u/s in Isaac River

Sources	Statistical characteristics							
	Minimum	Mean	Maximum	Median	Standard deviation	5th percentile	95th percentile	90% confidence
Total coarse sediment supply (t/year)(catch II u/s)	10,691	954,465	35,046,040	765,668	884,295	221,442	2,193,566	1,972,124
Stream bed (t/year)	4,840	635,714	2,760,388	557,000	393,223	142,880	1,395,628	1,252,748
Hillslope (t/year)	2.8	269,954	17,927,020	70,109	658,079	2,798	1,174,465	1,171,667
Catchment III yield (t/year)	0.0	131,043	2,821,904	77,579	169,444	19	444,675	444,656
Stream bank (t/year)	0.0	48,797	31,058,580	915	386,364	2.9	146,256	146,254

3.4.2 Field Observations

A map of the location of the assessed reaches on Isaac River is shown in Figure 3-24 and Figure 3-25. Photographs of particular features within the reach are also shown in this figure.

SunWater (2009) described Isaac River as a large historically incised meandering river that has, in more recent times, undergone considerable bed sediment deposition. Field observations for this project confirmed this description, with no obvious thalweg observed at any visited locations within the Isaac River and a relatively uniform bed across the channel at all locations. Bed slope was very low. Sediment slugs were evident at several locations within the reaches visited, further reducing the bed variability. Some bed rock outcropping was evident in locations, indicating historic incision. Vegetated and non-vegetated longitudinal bars were a common feature that introduced some variability to the bed. Bed width varied between 40 and 70 m, while bankfull width generally exceeded 100 m.

Banks were generally high (4-10m) within the reaches visited, with the majority of banks being between seven and ten metres high. Banks were composed of silty loams and silty-clay loams, although some dispersive / slacking clay outcropping and sandy banks were evident in isolated locations. Bank angle generally reflected the erodibility of bank material, with banks consisting of dispersive clays and sands consisting of a steeper scarp than those consisting of the more common loam-like material. Regardless, most banks consisted of a steeper lower bank and variable upper bank. Sacrificial benches and terracing was evident throughout the river. Riparian vegetation was present in low to medium densities providing some additional stabilisation. Only limited erosion was observed.

The surrounding catchment at the sites visited was flat to mildly undulating. Gullying was not widespread within these reaches, attributable to the floodplain / bank material and the low slope of the surrounds. Gullying did, however, increase further upstream due to increasing valley slope.

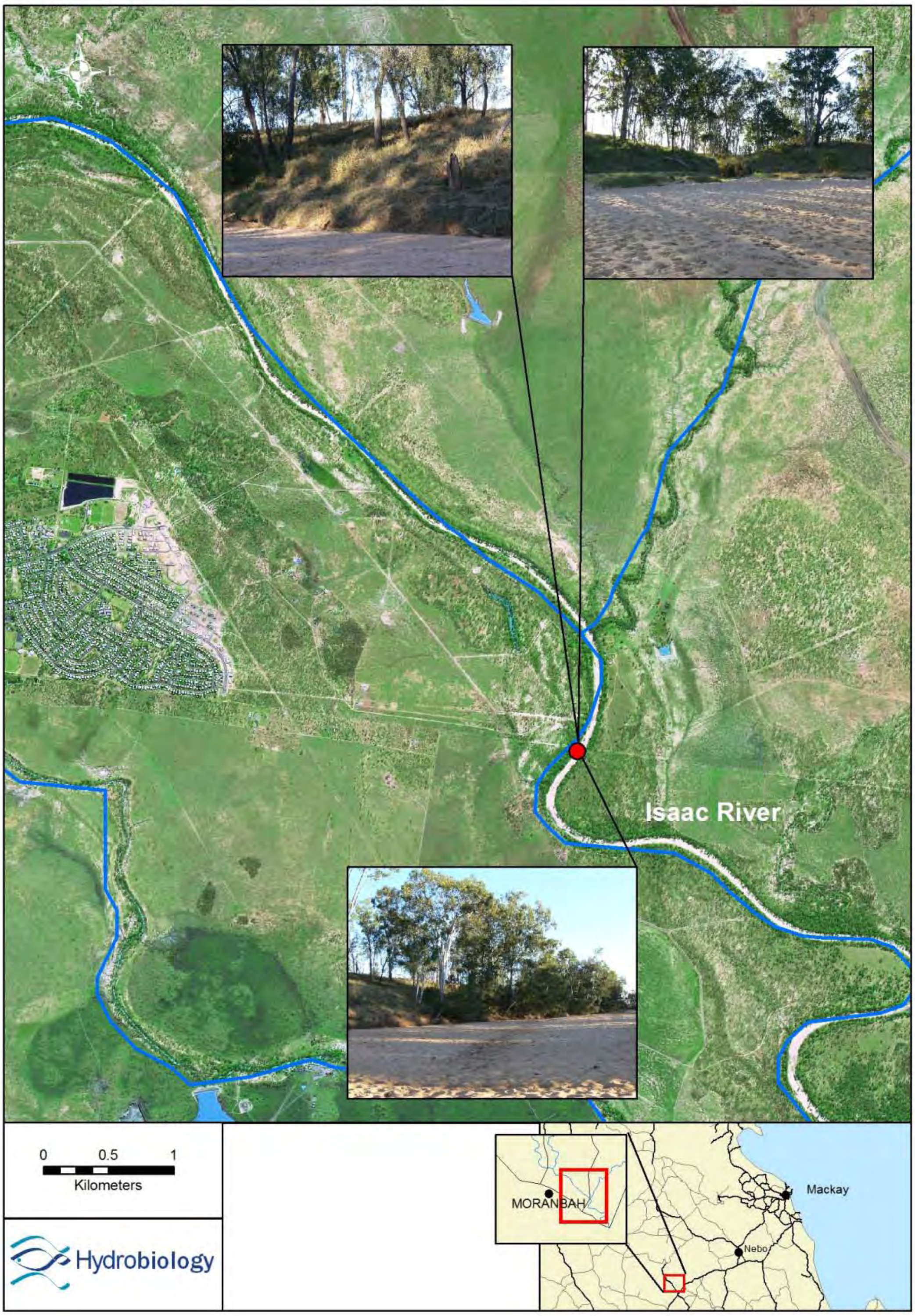

Figure 3-24 Location map and photo points, Isaac River (upstream sites)

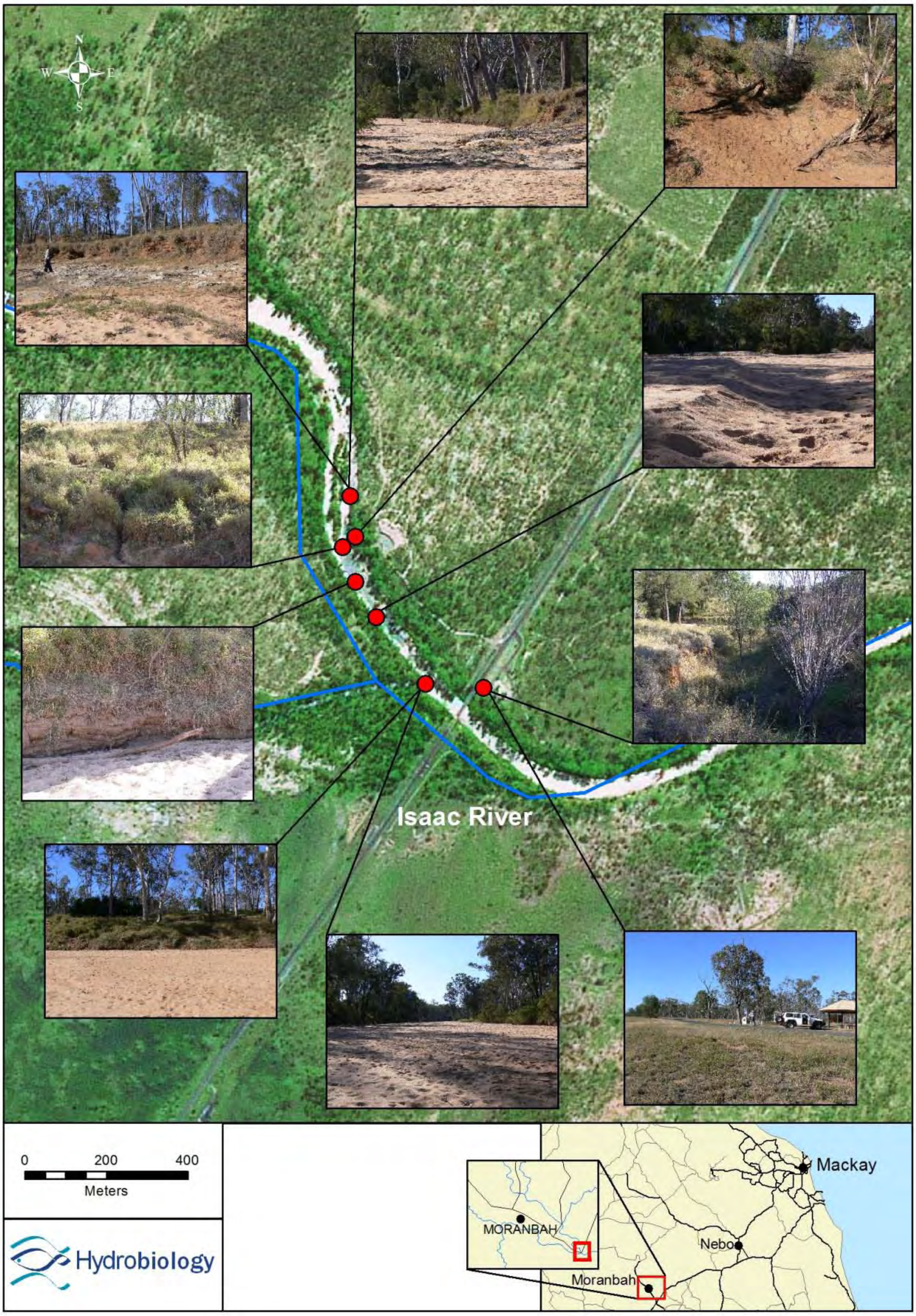

Figure 3-25 Location map and photo points, Isaac River (downstream sites)

3.5 Discussion

Sediment transport capacity (STC) and total coarse load (TCL) were highly variable in Boothill Creek, Denison Creek and Isaac River. Sediment transport distributions were also highly positively skewed meaning that exceptionally high pulses of sediment replenishment would occur during higher flows. Calculations showed that the theoretical STC was much larger that the total sediment load calculated using the sediment budget and steady state approach, suggesting that the rivers were mostly supply-limited. Overall, however, calculations strongly suggested that the required Take of approximately 350,000 m^3 could be extracted across these sites with a high probability that this amount would typically be replenished within a low number of years.

By way of examples, sediment yield modelling showed that:

- About 190,000 m^3 of bed material could be extracted from Boothill Creek (incorporating Funnel Creek confluence). It is expected that the extraction pit would typically be filled within two years;
- About 100,000 m^3 of bed material could be extracted from Denison Creek. It is expected that the extraction pit would typically be filled within one year and
- A total of about 200,000 m^3 of bed material could be extracted from Isaac River without affecting the current extraction entitlements downstream of the proposed extraction site. It is expected the extraction pit would typically be filled within one year following extraction.

There are no data available to test the model, and therefore, the results should not be considered as absolute values, rather indicative. However, morphological observations of each site made during the site visit, in addition to DERM observations on processes of sediment transport within these rivers were consistent with the results of the model. Overall, it is considered that high rates of sand movement occur in these river systems, that there is considerable sediment storage within the beds of these rivers (much of which may have accumulated since European settlement), and that sediment replenishment of required Take would occur within a low number of years following extraction.

With better information validating the assumptions (e.g. confirming the behaviour of the inputs) and higher resolution datasets, confidence in the model would be increased. In particular, there was considerable uncertainty regarding sediment inputs from the beds of creeks (Type II error).

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Appendix 1 Model Variables and Parameters

A1 Hillslope Erosion (HE)

Coarse sediment yield from the hillslopes was estimated by using modified plot-scale Universal Soil Loss Equation (USLE, Wischmeier and Smith 1978) model (Equation A.1). It was then scaled up to catchment scale by utilising hill sediment delivery ratio (Equation A.4) and the Monte Carlo simulation (MCS) method (section 2.5.2). The plot scale USLE model is defined by:

$$A = RKL_1S_1CP \quad \text{(A.1)}$$

where:

A = average annual soil loss (t/ ha);

R = rainfall/ runoff erosivity factor (MJ-mm/ ha-hour-year);

K = soil erodibility factor, a measure of the resistance of the soil to erosion (t-ha-hour/ MJ-mm-ha);

L_1 = hillslope length factor (dimensionless);

S_1 = hillslope gradient factor (dimensionless);

C = cover and management factor (dimensionless); and

P = support practice factor (dimensionless).

P was set to one to reflect the assumption that there were limited soil conservation measures adopted in catchments of Boothill Creek, Denison Creek and Isaac River. Consequently Equation A.1 was reduced to:

$$A' = RKL_1S_1C \quad \text{(A.2)}$$

Total soil loss from each catchment was estimated as:

$$A_{total} = C_a * A' \quad \text{(A.3)}$$

where:

A_{total} = total soil loss (t/ year); and

C_a = catchment area (ha).

The delivery of eroded coarse material (sediment yield) from the hillslopes into channels and streams within each catchment was estimated as:

$$HE = A_{total} * SDR_h * \delta \quad \text{(A.4)}$$

where:

HE = coarse sediment yield from hillslope (t/ year);

SDR_h = sediment delivery ratio from hill, reflecting the proportion of eroded sediment transported into the concentrated channels and streams from hillslopes (dimensionless); and

δ = proportion of coarse material in the delivered sediment (dimensionless).

A1.1 Rainfall erosivity factor (R)

The rainfall erosivity factor (R, MJ-mm/ ha-hour-year) reflects the ability of rainfall and resulting surface runoff (overland flow) to cause soil erosion at a particular location. R is the average annual sum of the Erosion Index (EI), where E is the total storm kinetic energy and I is the maximum 30 minute intensity for an individual storm during a rainfall record of extended duration (at least 22 years) to accommodate apparent cyclical rainfall patterns (Wischmeier and Smith 1978). A rainfall event is defined as a period of rain of at least 12.5 mm or a 15 minute intensity of 25 mm / hour and it is separated by a period of no rainfall that lasts for at least six hours (Wischmeier and Smith 1978).

Value of R was obtained for catchments of Boothill Creek, Denison Creek and Isaac River from R map (Rosewell 1993, Figure, P.80). Variability and uncertainty in R within each catchment was stochastically simulated by assuming a triangular distribution of R and by utilising Monte Carlo Simulation. Appendix Table 1 and Appendix Table 2 show the probability distribution of R (and other stochastic variables and parameters) of the model.

A1.2 Erodibility factor (K)

The soil erodibility factor (K, t-ha-hour/ Mj-mm-ha) reflects the inherent properties of soil and, for a particular soil, it is defined as the rate of soil loss per erosion index unit measured on a unit plot of 21.1 m length with a uniform 9 % slope maintained under continuous bare fallow, tilled up and down the slope over an extended period of at least 10 years (Toy and Foster 1998). K measures:

- The susceptibility of soil or surface material to erosion;
- The transportability of the sediment; and
- The amount and rate of runoff on a unit plot.

The value of K is always > 0 and normally < 1.0 (Rosewell 1993). A K value less than 0.02 indicates low erodibility, a K value between 0.02 and 0.04 indicates moderate erodibility and a K value greater than 0.04 indicates highly erodible soils (Rosewell 1993).

Catchments of Boothill Creek, Denison Creek and Isaac River were considered to be moderately eroding. In the absence of good knowledge of the K values in non-arable land, the values of K were considered synonymous with tilled and disturbed agricultural soils. Spatial variability and uncertainty in K was simulated stochastically as in R (Appendix Table 2). Likely correlation of K with rainfall and other factors, based on limited information, professional judgement and consistency, was maintained during the simulation (Appendix Table 3a).

Appendix Table 1 Distributions of stochastic variables in Boothill Creek, Denison Creek and Isaac River catchments

Catchment	Probability distribution function		Remarks
	Variables & parameters	Distribution	
Boot hill creek (301 km2)	w	T(20,25,95)	1truncated at (0,809) 2truncated at (0.0018,0.5) 3truncated at (100,1500) 4truncated at (0.5,22.5)
	d	T(0.5,1,2)	
	i	IG1(64.8237,18.437)	
	W	T(25,35,100)	
	S	E2(0.16073)	
	MN	D({0.025,0.03,0.035,0.04},{0.1,0.1,0.2,0.6})	
	R	T(2000,3000,5000)	
	I1	Er3(4,743.41)	
	θ	LL4(0.23522,3.0589,1.8134)	
	wFP	T(50,400,1500)	
	H	T(2,4,12)	
	L	U(18,19)	
	D	TG(0.25,0.5,2,5,95)	
Denison creek (862 km2)	w	T(15,40,75)	5truncated at (0,1350) 6truncated at (0.0019,0.48) 7truncated at (10,1500) 8truncated at (0.2,14)
	d	T(0.5,1,2)	
	i	BG5(0.43156,38.777,0,6483.5)	
	W	T(20,60,80)	
	S	Pt26(0.04831,1.6824)	
	MN	D({0.025,0.03,0.035,0.04},{0.1,0.6,0.2,0.1})	
	R	T(2000,3000,5000)	
	I1	Lg7(3317.65,938.94)	
	θ	P58(4.4373,17.819, Shift(-1.6665))	
	wFP	T(50,500,1000)	
	H	T(1,4,12)	
	L	U(19,20)	
	D	TG(0.25,0.5,2,5,95)	
Isaac River (catch I) (582 Km2)	i	BG9(0.33369,4.0056,0,752.41)	9truncated at (0,600)
Isaac River (catch II u/s) (*806 Km2)	i	BG10(0.34357,3.6712,0,540.76)	*coal seam area(100Km2) excluded as sink source 10truncated at (0,500) 11truncated at (0.0025,0.06) 12truncated at (100,1500) 13truncated at (0.335,6.7) 14truncated at (0.05,1)
	W	T(35,50,100)	
	S	LN11(0.02127,0.047663)	
	MN	D({0.025,0.03,0.035,0.04},{0.6,0.2,0.1,0.1})	
	R	T(2000,2500,3000)	
	I1	N12(4361.5,2390.5)	
	θ	LN13(1.9476,4.1315)	
	wFP	T(200,500,1500)	
	H	T(2,4,10)	
	L	U(38,38.5)	
	D	TG(0.5,1,4,5,95)	
	SDRc	Lg14(0.90962,0.16905)	

Appendix Table 1 contd… Distributions of stochastic variables in Boothill Creek, Denison Creek and Isaac River catchments

Catchment	Probability distribution function		Remarks
	Variables & parameters	Distribution	
Isaac River (catch III) (407 km^2)	i	BG[15](0.34357,3.6712,0,540.76)	[15]truncated at (0,500) [16]truncated at (0.0034,0.23) [17]truncated at (100,1500) [18]truncated at (0.0001,2.62)
	W	T(10,20,90)	
	S	P_t[16](0.74699,0.0034032)	
	MN	D({0.025,0.03,0.035,0.04},{60,20,10,10})	
	R	T(2000,2500,3000)	
	l_1	IG[17](2850.3,10713.7)	
	θ	Lg[18](1.14886,0.56344)	
	w_{FP}	T(20,400,600)	
	H	T(1,2,6)	
	L	U(26,27)	
	D	TG(0.25,0.5,1.5,5,95)	
Isaac River (catch IV) (212 km^2)	i	BG[19](0.34357,3.6712,0,540.76)	[19]truncated at (0,500) [20]truncated at (0.00076,0.04) [21]truncated at (100,1500)
	W	T(10,40,90)	
	S	E[20](0.0104)	
	MN	D({0.025,0.03,0.035,0.04},{0.1,0.1,0.6,0.2})	
	R	T(2000,2500,3000)	
	l_1	Lg[21](3386.29,751.83)	
	θ	T(0.20132,1.5976,1.5976)	
	w_{FP}	T(50,500,800)	
	H	T(1,3,6)	
	L	U(7,7.8)	
	D	TG(0.25,0.5,1.5,5,95)	
Isaac River (proposed extraction reach)	w	T(30,45,95)	[22]truncated at (0,500) [23]truncate at (0.0025,0.06)
	d	T(0.5,1,2)	
	i	BG[22](0.34357,3.6712,0,540.76)	
	W	T(35,50,100)	
	S	LN[23](0.02127,0.047663)	
	MN	D({0.025,0.03,0.035,0.04},{0.6,0.2,0.1,0.1})	
	w_{FP}	T(200,500,1500)	
	H	T(2,4,10)	
	L	U(8,8.7)	
	D	TG(0.5,1,4,5,95)	

Note:

Variables and parameters: w = excavation width (m); d = excavation depth (m); i = rainfall (mm/month); W = stream width (m); S = stream bed slope (m/m); MN = Manning's hydraulic roughness (dimensionless); R = rainfall-runoff erosivity factor (MJ-mm/ha-hour-year); l_1 = hillslope length (m); θ = hillslope gradient (degree); w_{FP} = floodplain width (m); H = stream bank height (m); L = stream reach length (km); D = scour depth (m), and SDRc = .sediment delivery ratio in channel (dimensionless).

Probability distribution functions: T(20,25,95) = Triangular distribution, 20 indicates minimum, 25 most likely and 95 maximum values; IG(64.8237,18.437) = Inverse Gaussian distribution, 64.8237 indicates mean and 18.437 shape parameters; [1]truncated at (0,809) = a distribution truncated at two bounds; LN(0.35,0.27) = LogNormal distribution, 0.35 indicates the mean while 0.27 standard deviation; E(0.16073) = Exponential distribution with decay constant (mean = 0.16073); D({0.025,0.03,0.035,0.04},{0.1,0.1,0.2,0.6}) = Discrete distribution, 0.025,0.03,0.035,0.04 indicate outcomes while 0.1,0.1,0.2,0.6 their probabilities respectively; Er(4,743.41) = Erlang distribution, 4 indicates an integral shape parameter while 743.41 scale parameter; LL(0.23522,3.0589,1.8134) = Log Logistic distribution, 0.23522 indicates location, 3.0589 scale and 1.8134 shape parameters; U(18,19) = Uniform distribution, 18 indicates minimum and 19 maximum values; TG(0.25,0.5,2,5,95)= Triangular distribution with most likely value (0.5), and bottom (0.25) and top (2) values at 5th and 95th percentiles respectively; BG(0.43156,38.777,0,6483.5) = Beta General distribution, 0.43156 and 38.777 indicate shape parameters while 0 and 6483.5 minimum and maximum values respectively; P_t2(0.04831,1.6824) = Pareto distribution, 0.04831 indicates shape while 1.6824 scale parameters; Lg(3317.65,938.94) = Logistic distribution with location (3317.65) and scale (938.94) parameters; P5(4.4373,17.819, Shift(-1.6665)) = Pearson type V (or Inverse Gamma) distribution, 4.4373 indicates shape and 17.819 scale parameters while Shift(-1.6665) shift in the domain of the distribution.

Appendix Table 2 Distributions of global stochastic variables

Catchment	Probability distribution function		Remarks
	Variables & parameters	Distribution	
All	q_c	LN[1](0.35,0.27)	[1]truncated at (0, 0.75)
	β	T(0.9,1.2,1.5)	
	γ	T(0.9,1.2,1.7)	
	ϕ	T(0.0005,0.002,0.01)	
	K_1	T(218,836,3326) when MN (0.025) Pe(195,750,2981) when MN (0.03) T(178,684,2718) when MN (0.035) T(165,631,2509) when MN (0.04)	
	K	T(0.0001,0.03,0.05)	
	C	T(0.003, 0.2, 1)	
	SDR_h	T(0.001,0.4, 0.75)	
	δ	T(0, 0.14, 0.5)	
	K_3	U(0.0001,0.0005)	
	e	U(0.1, 1.5)	
	f	U(0.5,1)	
	RT	B(1,0.7)	
	RD	D({0.1,0.4,0.7,0.95},{0.05,0.1,0.75,0.1})	
	BD	T(1,1.5,2)	
	C_b	T(0.3,0.4,0.5)	

Note:

Variables and parameters: q_c = runoff coefficient (mm/mm); β = exponent of discharge; γ = exponent of stream bed slope; ϕ = particle diameter (m); K_1 = coefficient of coarse sediment transport capacity; K = soil erodibility factor (tonnes-hectare-hour/Mj-mm-hectare); C = cover and management factor (dimensionless); SDR_h = sediment delivery ratio from hillslope into channel and stream (dimensionless); δ = coarse fraction in sediment delivered from the hillslope (dimensionless); K_3 = coefficient of stream bank erosion (dimensionless); e and f= coefficient and exponent of annual flow for estimating bankfull flow; RT = indicator of vegetated stream bank; RD = density of riparian tree (fraction); BD = dry bulk density of coarse sediment (t/m^3); and C_b = proportion of coarse material in stream bank (dimensionless).

Probability distribution function: Pe(195,750,2981) = Pert distribution with minimum (195), most likely (750) and maximum (2981) values; B(1,0.7) = Binomial distribution with 70% probability for true event (1).

A1.3 Topographic factor

The topographic factor reflects the effect of topography (concave, convex, uniform and complex) on soil loss. It combines the effect of hillslope length factor (L_1, dimensionless) (Section A1.3.1) and hillslope gradient factor (S_1, dimensionless) (Section A1.3.2), described below.

A1.3.1 Hillslope length factor (L_1)

The hillslope length factor (L_1, dimensionless) addresses the effect of hillslope length (l_1, m) on soil loss. Generally, as l_1 increases, soil loss increases due to progressive accumulation of runoff down the hillslope. L_1 is defined as the ratio of soil loss from a given hillslope length to that from a 22.1 m length under otherwise identical conditions (of unit plot).

The variability of L_1 factor was simulated by considering hillslopes as being moderately susceptible to both rill and inter-rill erosion processes and was estimated using an equation described by Rosewell (1993), as listed below:

$$L_1 = \left(\frac{x_h}{22.13}\right)^m \qquad \text{(A.5)}$$

where:

x_h = horizontal hillslope length (m), and

m = variable hillslope length exponent, which is related to the ratio (ε) of rill erosion to inter-rill erosion, explained as:

$$m = \frac{\varepsilon}{1+\varepsilon} \qquad \text{(A.6)}$$

For soil moderately susceptible to both rill and inter-rill erosion, ε is calculated as

$$\varepsilon = \frac{\sin\theta}{0.0896 \times \left[3.0 \times (\sin\theta)^{0.8} + 0.56\right]} \qquad \text{(A.7)}$$

where:

θ = hillslope angle (degrees).

Hillslope lengths (l_1) (and gradients, θ, see section A1.3.2) were randomly measured along hillslopes from a DEM of the area, with layers of the stream network and 50-metre contours superimposed. The Methodologies of Dissmeyer and Foster (1980) and RUSLE2 (2008) were used to define starting and finishing points of the overland flow paths respectively. Due to the resolution of the DEM, it was assumed that the hillslopes were uniform and other forms of topography (concave, convex and complex) were not considered. Random samples in pairs (l_1, θ) were created and their variability simulated using the MCS method (as described for the *K* factor), to create a range of simulated L_1 values.

Samples of l_1 were fitted to over 22 different parametric and non-parametric distributions and best-fit tested by the Kolmogorov-Smirnov or K-S method, with exception of Anderson-

Darling or A-D method (Appendix Table 1). Appendix Table 1 shows the variability in hillslope length by catchments, showing that Boothill Creek, Denison Creek and Isaac River catchments have different distributions. The l_1 distributions were used in stochastically simulating their spatial variability by the MCS method. A correlation found between l_1 and θ was preserved during the simulation, thus predicting the realistic variations of l_1 within catchments of Boothill Creek, Denison Creek and Isaac River (Appendix Table 3a).

A1.3.2 Hillslope gradient factor (S_1)

The hill slope gradient factor (S_1, dimensionless) is defined as the ratio of soil loss from a hillslope gradient to that from a 9 % slope under identical conditions. Its limit is $0 \leq S_1 \geq 1.0$. $S_1 = 1.0$ shows soil loss from a 9 % hillslope gradient, $S_1 < 1.0$ indicates soil loss from a hillslope < 9% slope and $S_1 > 1.0$ suggests soil loss from a hillslope > 9% slope. $S_1 = 0.0$ % reflects absolute flat ground and that there would be no soil loss. A 100% slope = Tan 45^0.

As hillslope gradient (θ, degree) increases, the shear stress of the surface runoff increases leading to more chance of increased erosion. Soil loss is higher for a unit increase in θ compared with hillslope length (l_1), and therefore sound knowledge of θ is desirable.

The S_1 factor in Boothill Creek, Denison Creek and Isaac River was estimated using the following equation described by Nearing (1997):

$$S_1 = -1.5 + \frac{17}{1 + e^{(2.3 - 6.1 Sin\theta)}} \qquad \text{(A.8)}$$

Elevations of each of the starting and finishing points of the overland flow paths were recorded when measuring the hillslope length (l_1) (see Section A1.3.1 for details), from which θ was calculated as:

$$\theta = Sin^{-1}\left[\frac{y_i - x_i}{x_h}\right] \qquad \text{(A.9)}$$

where:

y_i and x_i = elevations at starting and finishing points of the overland flow paths (m)

Samples of θ were tested against various distributions for the best fit as described for l_1 (Section A1.3.1) (Appendix Table 1). Appendix Table 1 shows the variability of θ in these three catchments, illustrating that there was no unique pattern of θ across the catchments. The spatial variability in θ and, thus, the spatial variability in S_1 values, were simulated using the MCS method by using the respective θ curve for each catchment and following the method as described for the K factor (Section A1.2).

Appendix Table 3a Correlation between and among stochastic variables and parameters

	P	q_c	R	K	I	θ	C	SDR_h	δ
P	1								
q_c	0.5094	1							
R	0.9312	0.5852	1						
K	0.9673	0.5427	0.9594	1					
I	0	0	0	0	1				
θ	0.0095	0.5625	0	0	-0.3686	1			
C	-0.2923	0.2055	-0.2431	-0.2769	0	0	1		
SDR_h	0.4637	0.4863	0.4641	0.4676	-0.1453	0.4297	-0.1227	1	
δ	0	0	0	0	0	0	0	0.7676	1

Appendix Table 3b Correlation between and among stochastic variables and parameters

	β	Q	w	W	H	D	d
β	1						
Q	0.0011	1					
w	0	0.6633	1				
W	0	0.6656	1	1			
H	0	0.4966	0	0.0017	1		
D	0	0.7405	0	0.003	0.7637	1	
d	0	0.7405	0	0.003	0.7635	1	1

Appendix Table 3c Correlation between and among stochastic variables and parameters

	ϕ	MN	BD	C_b
ϕ	1			
MN	0.94	1		
BD	0.73	0.54	1	
C_b	0.53	0.55	0.75	1

Appendix Table 3d Correlation between the variable and parameter

	S	γ
S	1	
γ	0.3	1

Appendix Table 3e Correlation between variables

	TCL	SDR_c
TCL	1	
SDR_c	0.17	1

A1.4 Surface cover and management factor (C)

The cover and management factor (*C*, dimensionless) reflects the effect of any vegetation, management and erosion control practices on soil loss. It estimates the combined effect of prior land use, canopy cover, surface cover, surface roughness, soil biomass and soil disturbing activities on soil loss. It is defined as the ratio of soil loss from a specified condition to soil loss from continuous bare fallow. *C* varies mostly between 0 and 1.0 ($0 \leq C \leq 1.0$). $C = 0$ suggests there is no soil loss, whereas $C = 1.0$ indicates there is no reduction in soil loss rates.

There is no known information about the typical distribution of the *C* factor for these or other catchments. Therefore, the spatial variability of *C* was predicted using a triangular distribution (Appendix Table 2) by the same MCS method as specified for the K factor (Section A1.2).

A1.5 Sediment Delivery Ratio (SDR_h) and coarse material (δ)

Not all eroded sediment from hillslopes will be transported into the concentrated channels downstream, partially due to the topographic complexity. Rather, it will be redeposited on the land surface. The proportion of eroded sediment transported from hillslopes to creek and stream (sediment yield) is described by the hillslope Sediment Delivery Ratio (SDR_h). SDR_h is variable between catchments, but lies between 0 and 1 with a value of 0.0 indicating no sediment transported to the stream network, while a value of 1 indicates all eroded material is transported downstream. As with other model parameters, the variability of SDR_h was predicted stochastically (Appendix Table 2). Similarly, variability and uncertainty in the proportion of coarse material (δ) in the sediment yield from hillslope was stochastically simulated (Appendix Table 2) based on limited information (Sheridan and Noske 2005).

A1.6 Catchment area (C_a) and reach length (L)

Catchment area (C_a, ha) and reach length (L, Km) were considered deterministic variables and they were calculated from the DEM using standard GIS tools.

A1.7 Bank erosion (BE)

Coarse material from bank erosion in Boothill Creek, Denison Creek and Isaac River was predicted simplistically by extending Wilkinson *et al* (2004) method. It is defined as

$$BE = K_3 * Q_b * (1 - PR) * (1 - FP) * H * L * BD * C_b \qquad \text{(A.10)}$$

where:

BE = coarse sediment from banks of creek and stream (t/ year);

K_3 = coefficient of bank erosion (dimensionless);

Q_b = bankfull discharge (ML/ year);

PR = proportion of riparian tree along the banks of creek and stream (dimensionless);

FP = floodplain factor (dimensionless);

H = height of bank (m); and

C_b = proportion of coarse material in banks.

A1.7.1 Coefficient of bank erosion (K_3)

Coefficient of bank erosion (K_3) was simulated stochastically. It was assumed to follow uniform distribution. Data from Wilkinson et al. (2004, P. 91) was utilised to define its bounds and its variability was simulated by Monte Carlo method as for *R* (Section A1.1).

A1.7.2 Bankfull discharge (Q_b)

Bankfull discharge (Q_b) was estimated as

$$Q_b = e(12 * Q_m)^f \tag{A.11}$$

where:

Q_b = bankfull discharge (ML/year)

e & *f* = coefficient and exponent of discharge.

e and *f* were stochastically simulated by Monte Carlo method by utilising data from Wilkinson et al (2004, P. 54)(Appendix Table 2). Monthly discharge (Q_m, ML) was also simulated stochastically (Section A1.9.2 below).

A1.7.3 1.7.2 Floodplain factor (*FP*)

Floodplain factor (*FP*) was estimated as (DeRose et al 2003)

$$FP = 1 - e^{(-0.0008 * w_{FP})} \tag{A.12}$$

where:

w_{FP} = width of floodplain along *L* (m).

Width of flood plain (w_{FP}) along the reach was randomly measured from the map of Boothill Creek, Denison Creek and Isaac River obtained from Google Earth search (http://www.google.com/earth/index.html). Samples of w_{FP} were fitted for its best PDF as for topographic factor (Section A1.3) and its spatial variability and uncertainty was simulated by the Monte Carlo method (Appendix Table 2).

A1.7.4 1.7.2 Bank height (*H*), dry bulk density(*BD*) and proportion of coarse material (C_b)

Bank height (*H*, m) is also among the highly variables in these three creeks and river. Accordingly, its spatial variability and uncertainty was considered to be captured by triangular distribution (Appendix Table 1). Similarly, dry bulk density (*BD*, t/m^3) and proportion of coarse material in the bank material (C_a) are also highly variable and as such spatial variabilities and uncertainties of *H*, *BD* and C_a were stochastically simulated after retaining their correlations found and deemed necessary (Appendix Table 3b and 3c) by the Monte Carlo method.

A1.8 Bed erosion (Bed)

Coarse material from bed erosion was predicted simplistically as not enough information was available to utilise general bed scoring equation. Variability in scour depth (D, m) was assumed to follow triangular distribution, whose bounds were defined based on field observation and professional experience. And its spatial variability and uncertainty was predicted stochastically as other stochastic inputs (Appendix Table 1).

A1.9 Discharge (Q_m)

Monthly discharge (Q_m ML) in Boothill Creek, Denison Creek and Isaac River was estimated based on mass balance and black-box approach. It was calculated as

$$Q_m = 100 * q_c * i * C_a \qquad \text{(A.13)}$$

where:

Q_m = discharge (ML/ month);

q_c = runoff coefficient (dimensionless); and

i = rainfall (mm/ month).

A1.9.1 Runoff coefficient (q_c)

There was little information regarding the runoff coefficient (q_c) within the catchments of Boothill Creek, Denison Creek and Isaac River. q_c varies greatly in a catchment and is one of the most difficult parameters to accurately estimate (Haan et al. 1994). For example, overall error in estimating q_c is in the order of -50 to > +100% of the mean q_c (SMEC 1990). As such, the variability of q_c in these catchments was simulated stochastically. Literature about the distribution of q_c provides very conflicting information. For example, Gottschalk and Weingartner (1998) predicted the variability of q_c by Beta distribution, while Jha et al. (2007) found q_c behaving Lognormally. In this report, a truncated Lognormal distribution (Jha et al. 2007) was arbitrarily utilized in simulating the spatial variability of q_c by the MCS method (Appendix Table 2). The truncated Lognormal distribution was defined based on limited information in Denison Creek and professional judgement. A correlation between q_c and rainfall was also set for realistic simulation of runoff (Appendix Table 3a).

A1.9.2 Rainfall (i)

Both spatial and temporal variabilities and uncertainties of rainfall were predicted stochastically. Monthly rainfall data from all rain gauges within (and close to) catchments of Boothill Creek, Denison Creek and Isaac River were extracted from Bureau of Meteorology (http://www.bom.gov.au/climate/data/index.shtml?zoom=1&lat=-26.9635&lon=133.4635&layers=00B00TFFFFFFFFTFFFFFFFFFFFFFFFFFFFTTT&dp=IDC10002-

d&p_nccObsCode=136&p_display_type=dailyDataFile) (Appendix Table 4). They were fitted over 22 distributions for best fit tested by K-S method with exception of A-D and Chi-Squared (X^2) methods (Appendix Table 1). Appendix Table 1 clearly suggests the varying characteristics of rainfall in them that rainfall is complex in these three catchments, marked by different PDFs and also the different shape and location parameters of the same PDF (Beta General distribution). These distributions were utilised in stochastically simulating the variability of monthly rainfall, necessary for predicting the annual variability of discharge thus the STC and TCL in them.

A1.10 Coefficient of sediment transport capacity (K_1)

Coefficient of sediment transport capacity (K_1) depends upon the particle size and shape, and hydraulic roughness. Variability and uncertainty in K_1 in Boothill Creek, Denison Creek and Isaac River were stochastically simulated by utilising data from Wilkinson et al. (2004, Table 5, P. 90), information from the field, air photos, report (Golder Associates 2009) and professional judgement. Sand was considered as predominant coarse material in those creeks. Appendix Table 2 shows the distributions of K_1, which were utilised in simulating the spatial variability and uncertainty in K_1 through the Monte Carlo method. Correlation between particle size and Manning's roughness, found based on global knowledge, was maintained during the simulation for realistic K_1 simulations (Appendix Table 3c).

Appendix Table 4 Rainfall record by catchments

Description	Rainfall		Remarks
	Gauge	Period	
Boothill Creek	33185	1888 - 1995	
	33131	2003 - 2008	All months with records included
	33083	1953 - 2010	
Denison Creek	33054	1870 - 2010	
	33193	1944 - 1972	
	33106	2002 - 2010	
	34074	1907 - 2010	
	33087	1949 - 2010	
Isaac River (catch I)	34077	1973 - 1995	
	33195	2005 - 2010	
Isaac River (rest of the catchments)	34014	1900 - 1975	
	34039	1972 - 1975	
	34038	1972 - 2010	

A1.11 Channel bed slope (S)

Variability and uncertainty in bed slope of Boothill Creek, Denison Creek and Isaac River were predicted stochastically. Length of reach was measured against contour lines crossing the main trunk of the creek and river from stream network and 50 m contour maps superimposed. Samples of elevation drop versus distance thus obtained were utilised to create samples of channel slope (*S*, m/m) for its stochastic generation. Channel slope was calculated as

$$S = Tan\left(Sin^{-1}\left(\frac{\Delta d_1}{l_2}\right)\right) \qquad (A.14)$$

where:

S = slope of the bed of creek and stream (m/m);

Δd_1 = elevation difference between two contours (m); and

l_2 = length of reach between the two contours (m).

Appendix Table 1 shows the variability of channel slope in Boothill Creek, Denison Creek and Isaac River, which were utilised in stochastically simulating the spatial variability of *S*, and thus the spatial variability in sediment transport capacity (STC).

A1.12 Exponents of discharge (β) and channel bed slope (ϒ), and channel width (W)

Among others, sediment transport capacity (STC) is highly sensitive to the exponent of discharge (*β*) (e.g. Scenario analysis for STC > 75th percentile in Boothill Creek). There was little information available about the behaviour of both *β* and the exponent of slope (*ϒ*) of river (Prosser and Rustomji, 2000, Figure 1c, P 188). This information was utilised to set their PDFs for their stochastic simulation (Appendix Table 2). Variability in the channel width (*W*, m) was considered to follow triangular distribution with bounds defined based on report (Golder Associates 2009), filed observation, map (http://www.google.com/earth/index.html), and professional experience (Appendix Table 2). Spatial variabilities and uncertainties in them were simulated by Monte Carlo method by retaining plausible correlation in them and other dependent stochastic variables and parameters (Appendix Table 3b and 3d).

A1.13 Extraction pit

Field observation and images suggested distribution of accumulated material did not always match the variability of channel width (*W*). Also, depth of accumulated bed material was not uniform across the channel. Accordingly, the variability in the width (*w*, m) and depth (*d*, m) of bed material to be extracted were simulated stochastically. Appendix Table 1 shows the PDFs of *w* and *d*, which were utilised in stochastically simulating the variability in the extraction of bed material from Boothill Creek, Denison Creek and Isaac River.

In the model, length of extraction pit was considered as deterministic variable; 3500, 2000 and 3000 m long extraction pits (*l*, m) were arbitrarily considered in estimating available bedding material for extraction from Boothill Creek, Denison Creek ad Isaac River respectively.

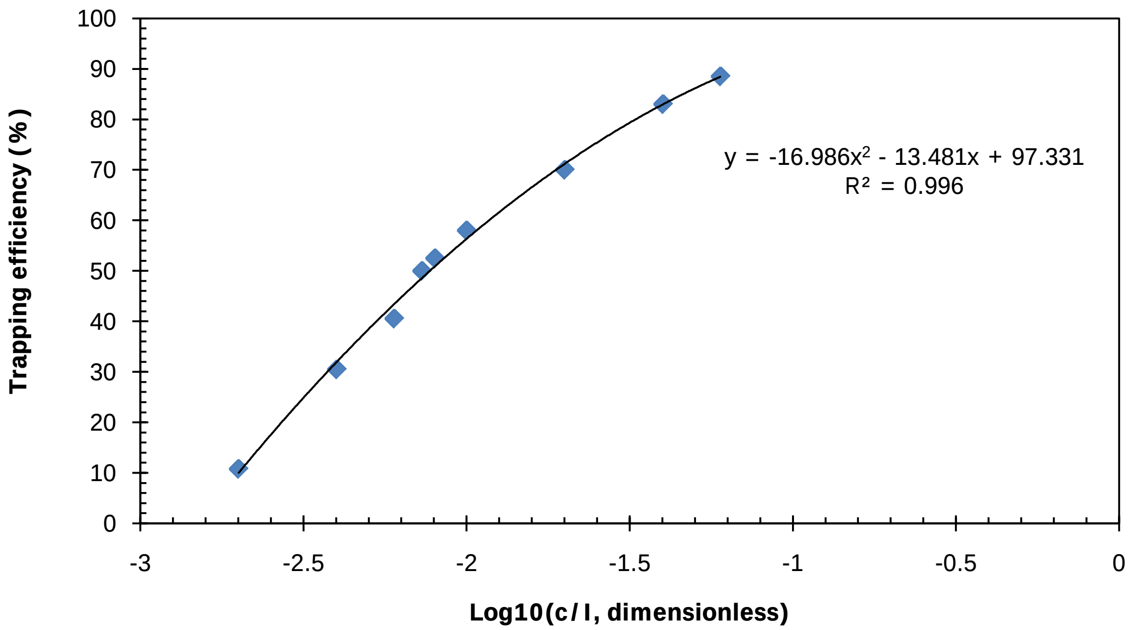
A1.14 Sediment delivery ratio in channel (SDR_c)

There was not much information available to characterise highly variable behaviour of sediment yield from extraction sites in a stream system. Alternatively, knowledge from Boothill Creek and Denison Creek was utilised to simulated the sediment yield from the current existing entitlement pits upstream of the proposed extraction site in Isaac River (Appendix Table 1). Appendix Table 1 suggested SDR_c followed Logistic distribution, which was utilised in its stochastic simulation, necessary in calculating an excess sediment load for potential extraction(catch II d/ s).

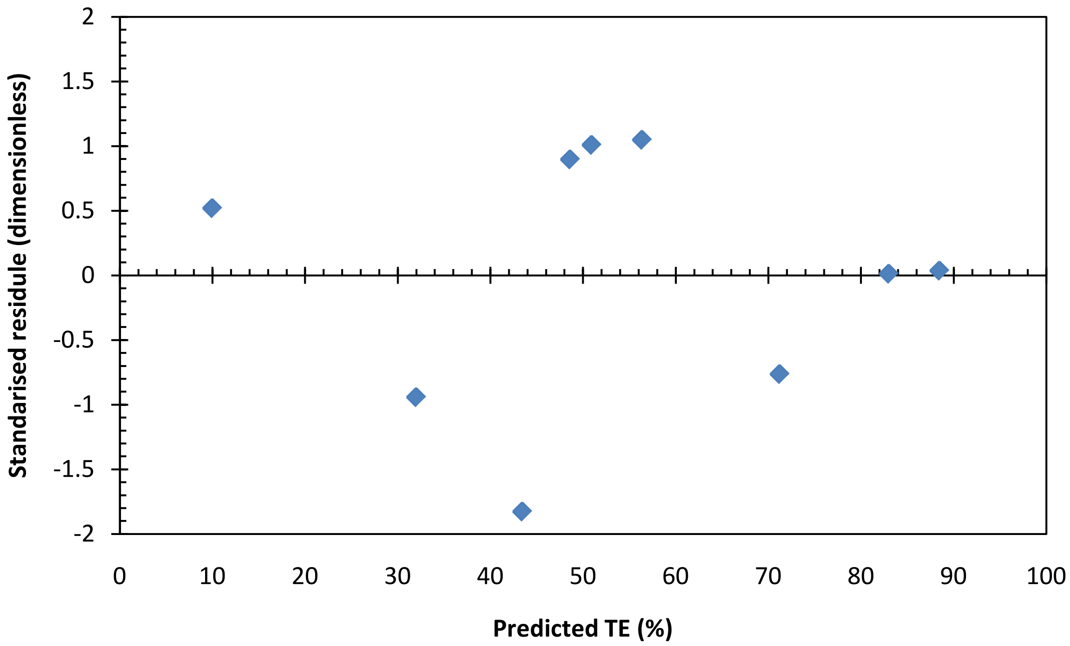
A1.15 Trapping efficiency (TE)

No information was available for estimating trapping efficiency of excavation pit of bed material. Alternatively, Brune's (1953) upper envelop of trapping efficiency (TE, %) was utilised (Heinemann 1984) which identifies the importance of capacity/ inflow (discharge) ratio (c/ I) in trapping sediment.

Coordinates of TE and c/ I were randomly created from the upper curve of TE of Brune (1953). From these samples, four regression equations were developed to closely simulate the polynomial behaviour of TE. Regression equations (1.13-1.14) were checked for their soundness (Appendix Figure 1 and Appendix Figure 2). Appendix Figure 2 is an example (Equation 1.14), which suggested that the equation was statistically sound, marked by non-systematic behaviour of the residual; alternatively error was very much scattering around zero residual error line.



Appendix Figure 1 Scatter plot between Log_{10}(capacity/inflow) and trapping efficiency with fitted regression line



Appendix Figure 2 Standarised residual plot against significant explanatory variable.