ENVIRONMENTAL ASSESSMENT REPORT

VOLUME 2:
APPENDICES 1 TO 5

PNG BIOMASS
MARKHAM VALLEY

MARCH 2017
Report No. 01183B_2_v2

Oil Search

PNG BIOMASS

ERIAS GROUP

ERIAS Group Pty Ltd
ACN 155 087 362

Markham Valley Biomass Limited

PNG Biomass Markham Valley

Environmental Assessment Report

Volume 2 – Appendices 1 to 5

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(Report No. 01183B_2_v2)

Prepared by ERIAS Group Pty Ltd
(ACN: 155 087 362)

13–25 Church Street
Hawthorn, Victoria, 3122
Australia
P +61 3 9023 9281
E info@eriasgroup.com
W eriasgroup.com

Client Contact:	Michael Henson michael.henson@alignedenergy.net

ERIAS Group Contact:	Michael Jones michael.jones@eriasgroup.com
ERIAS Group Alternative Contact:	Michelle Clark michelle.clark@eriasgroup.com

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Appendix 1
Hydrology and Sediment Transport Impact Assessment

PNG Biomass Markham Valley Project

Hydrology and Sediment Transport Impact Assessment

March 2017

ABN	26 096 574 659
GST	The company is registered for GST
Head Office	27 / 43 Lang Parade
	Auchenflower QLD 4066
Registered Office	c/- de Blonk Smith and Young Accountants
	GPO 119
	Brisbane, QLD 4001
Postal Address	PO Box 2151
	Toowong QLD 4066
Phone	61 (07) 3721 0100
Fax	61 (07) 3721 0151
Email Contact	info@hydrobiology.biz
Website	http://www.hydrobiology.biz

PNG Biomass Markham Valley Project

Hydrology and Sediment Transport Impact Assessment

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EXECUTIVE SUMMARY

Background and Purpose

Hydrobiology undertook a Hydrology and Sediment Transport Baseline and Impact Assessment for the proposed PNG Biomass Markham Valley Project ('the Project'), which is to be located on the northern floodplain of the Markham River in Morobe Province, between the Leron River to the west and the Erap River to the east. The Project area included parts of the Leron, Erap, Rumu, and Maralumi River sub-catchments of the Markham River.

The purpose of this study was to understand the existing hydrology and sediment transport conditions, and morphological characteristics, and to assess potential impacts of the Project on these conditions. The study focussed on issues of relevance to the Project, and informed the requirements of the Environmental Assessment (EA).

Methods

The approach used a desktop data review, and industry accepted modelling methods to provide an understanding of the existing environment and to assess potential impacts resulting from the project. The modelling approach was entirely desktop in nature, but was supported by *in situ* condition assessments, photographs and morphological characterisation. The models included a rainfall-runoff model to simulate streamflow in the four sub-catchments and the Markham River, a high-level two-dimensional flood model to provide a high-level flood risk assessment of the four sub-catchments, and a stochastic catchment sediment budgeting model to assess the sediment transport regime of the four sub-catchments.

Existing Environment

Key existing characteristics of the Project area include:

- The Markham River, which consists of a large braided channel (along its entire length), anastomosing reaches, and a longitudinal slope that is considerably higher than for any other plain stream of comparable discharge and catchment area within a PNG context. This morphology is largely due to the very high rates of sediment delivery.
- Alluvial fans of various size and depth in all four sub-catchments. These act as important sediment stores and delivery mechanisms and are deposited by river and debris flows. The largest fan is the Leron Fan, but fans are also present in the remaining three sub-catchments and there are a number of smaller piedmont fans.
- Several highly mobile waterways (Leron, Erap, Rumu), generally consisting of a braided pattern and/or multiple distributaries, and displaying wide, flat beds composed of mostly sands and gravels, with cobbles and boulders observed sporadically. These waterways all had high sediment loads.
- Several smaller, less mobile systems with much lower sediment loads (clear water) that appeared to have origins downslope of the fans produced by the high-energy

headwater streams. The downstream reaches of Maralumi River and Klin Wara (a Leron distributary) are good examples.

- Extensive floodplains that are inundated on a regular basis.
- Several low-lying wetlands that are inundated by overbank flows and groundwater levels during flooding of the main waterways. These areas tend to occur upstream of the clearwater streams and are understood to be dry except during periods of high rainfall, meaning that they do not form permanent wetlands. The wetlands appear to regulate the energy, flooding regimes and suspended sediment loads of the outlet streams and are, therefore, considered sensitive to changes to the hydrologic or sediment regimes.

KEY ISSUES

The major issues with regard to the hydrology, sediment transport, and channel form associated with the Project are:

- Impacts to the very low magnitude events (<10th percentile), including zero flow days, particularly in the Maralumi River and other smaller clearwater streams. These impacts were, however, exaggerated by the uncalibrated rainfall/runoff data and the conservative impact assessment method. As the Project progresses and more detail can be provided with regard to hydrology and planting plans, these predicted impacts will likely reduce.
- The location of the power plant in relation to flooding extents. An assessment should be undertaken that considers the risk posed by inundation (including the development of a calibrated hydraulic model). Results of the model should be used in conjunction with field observations to further inform requirements relating to avoidance, management and mitigation measures for flood events.
- There is a considerable risk of avulsion of all the main waterways within and adjacent to the Project area. While the likelihood of avulsions occurring during the life of the Project was rated as low, the consequences of an avulsion are significant, particularly given the location of the power plant near the Maralumi and Rumu Rivers. Consideration should be given to measures to reduce the risk associated with avulsion.
- All other impacts to hydrological characteristics, sediment yields and channel form were considered low or negligible, provided the proposed mitigation measures were implemented.

PNG Biomass Markham Valley Project

Hydrology and Sediment Transport Impact Assessment

March 2017

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1 INTRODUCTION

1.1 Background

Hydrobiology was commissioned by ERIAS Group (ERIAS) to conduct a Hydrology and Sediment Transport Baseline and Impact Assessment for the proposed PNG Biomass Markham Valley Project ('the Project'). The Project is being proposed by Markham Valley Biomass Limited (MVB). It will be located on the north bank of the Markham River in Morobe Province, Papua New Guinea (PNG) between the Leron River to the west, the Erap River to the east and extending in a northerly direction approximately 20 km across the grassed floodplain to the foothills of the Saruwaged Range to the north (Figure 1-1). The Project involves establishing eucalypt plantations to provide fuel for a 30 MW (2 x 15 MW) power station, and has been defined by the PNG Conservation & Environment Protection Authority (CEPA) as a Level 2 Activity under the *Environment Act 2000*.

1.2 Purpose

The purpose of this study was to understand the existing hydrology and sediment transport conditions, and the existing waterway morphology, and to assess potential impacts of the Project on these conditions. The study focussed on issues of relevance to the Project, and informed the requirements of the Environmental Assessment (EA).

1.3 Objectives

The objectives of the hydrology and sediment transport impact assessment (as defined in the Scope of Works) were to:

- Describe the main sub-catchment/s that may be impacted by the Project activities.
- Characterise the hydrology and sediment transport characteristics of the main watercourses in the Project area that may be impacted by Project activities.
- Characterise the hydrology of proposed plantation areas between or near major drainages, which may be subject to inundation, overbank flow and similar hydrological events.
- Run hydrological and sediment transport models to determine baseline flow rates, suspended sediment concentrations and bed sedimentation rates for a range of exceedance flows in the main watercourses potentially impacted by the Project (within the constraints of available data).
- Review the proposed locations for plantation areas and power plant site options, and identify areas potentially at risk of flooding.
- Conduct the study to satisfy relevant assessment requirements of PNG legislation, the Forest Stewardship Council (FSC) *National Forest Management Standards for Papua New*

Guinea (FSC, 2016; FSC, 2010) and International Finance Corporation (IFC) Environmental and Social Performance Standards (2012), as applicable.

- List and assess the potential impacts of the Project on hydrology and sediment transport during construction and operational periods.
- Recommend appropriate measures to mitigate potential impacts on hydrology and sediment transport as a result of the Project activities.
- Assess residual impacts of the Project on hydrology and sediment transport on the key watercourses and sub-catchments (i.e., those impacts that are still likely to occur following effective implementation of management/mitigation measures).

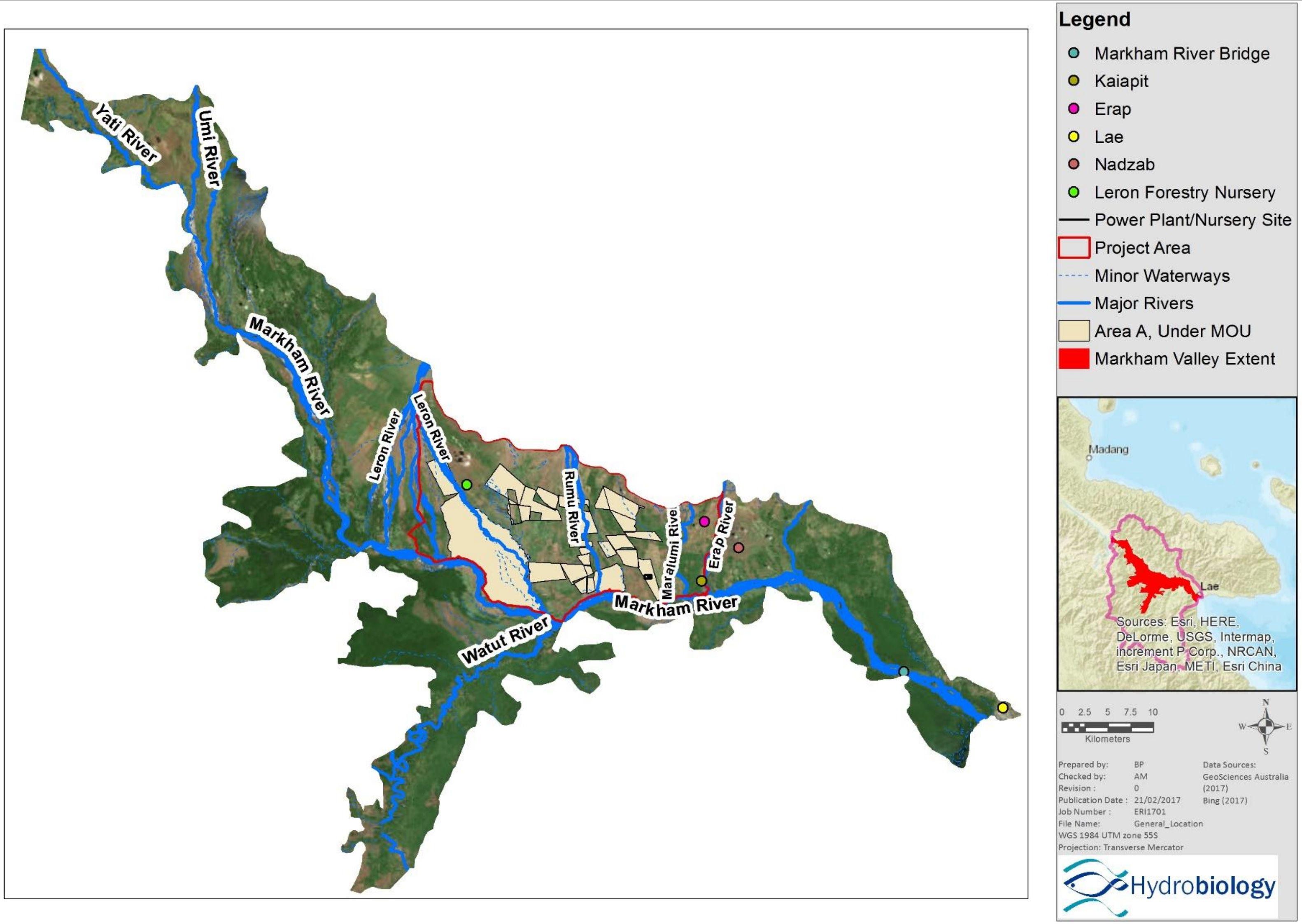

Figure 1-1 Location of the Project area within the Markham Valley

2 PROJECT DESCRIPTION

The Project will involve growing *Eucalyptus pellita* in plantations to provide biomass that will fuel a new 30 MW power plant. The Project is advancing on the basis of plantation areas described as "Area A", these being areas that are under Memoranda of Understanding (MOUs), and a power plant as shown in Figure 1-1. Of the potential plantation area covered by the MOUs (approximately 17,940 ha), the plantations net stocked area (actual planted area not including buffer zones) will cover up to 16,000 ha.

The major components of the Project that are relevant to this report are outlined further below:

- **Plant Nursery –** A central, fit-for-purpose seedling and propagation nursery will be constructed next to the power plant site to utilise common water and power services, security and storage facilities. The nursery will occupy an area of 9.6 ha. MVB proposes to commence construction of the first (temporary) phase of the nursery prior to environment permit approval and Final Investment Decision (FID) (targeted for Q3 2017).
- **Plantations –** Establishment of 16,000 ha of eucalypt plantations within the Project area will occur over a seven-year period between 2017 and 2023, with the plantation area to be maintained indefinitely. The maximum plantation area established in any one year will be 4,500 ha (to occur in 2019), with an average of approximately 2,000 ha/year established during this initial phase. For the purposes of this report, the potential plantation area is defined as those parts of the broader Project area that are under active MOUs with the landowners of Area A, less buffer zones for streams and other environmental (e.g. wetlands) and/or social values (e.g. villages).
- **Road Upgrades –** Prior to site clearing and plantation establishment, road access to the proposed plantation areas will be established or upgraded as per the full Project description.
- **Clearing of Vegetation –** In areas to be planted, all existing vegetation including trees up to 30 cm in diameter will be removed to enable clear and unrestricted access to the site. Tree stumps will be retained to minimise soil disturbance, with planting to occur between these.
- **Harvesting –** Where practicable (and subject to landowner negotiations), plantations will be established (and eventually harvested) in a dispersed pattern across the landscape to reduce localised impacts on environmental and/or socio-cultural values. Plantations will be established progressively across the Project area in 'compartments' of approximately 20 ha each (e.g., 400 x 500 m), ranging from 5 to 50 ha based on local constraints such as watercourses, existing gardens/crops, or areas of unsuitable soils. Within a given compartment, planting (and later maintenance and harvesting) will occur concurrently.

- **Villages –** The largest villages (Chivasing and Tararan) will be surrounded by a buffer zone of at least 50 m within which plantation establishment will not occur. Near smaller hamlets (such as Ganef) and other infrastructure, buffer zones will be negotiated with local landowners/residents.
- **Agroforestry Zones –** In areas immediately outside villages, gardens and food crops (and associated buffers), agroforestry zones may be established by local landowners in areas made available by the Project.
- **Environmental Buffers and Informal Reserves –** The Project will apply the following riparian (streamside) buffer zones:
  - Buffer zones of 100 m from the banks of the Markham, Erap and Ramu Rivers, as well as on all sides of any lakes, lagoons or swamps (the latter being defined by the *Papua New Guinea Logging Code of Practice* (PNGFA/DEC, 1996) as "having surface water present for 6 months of the year").
  - Buffer zones of 50 m on either side of permanent watercourses (streams and rivers other than those listed above) with bed widths greater than 5 m.
  - Buffer zones of at least 30 m on all sides of all bodies of water and watercourses with an average width greater than 1 m but less than 5 m.
  - Buffer zones of at least 15 m on all sides of all bodies of water and watercourses with an average width of less than 1 m.
- **Excluded Activities –** The following activities will be excluded within the riparian buffer zones:
  - Felling plantations or raintrees, or clearing any other vegetation (except where required for bridges or designated crossing points).
  - Establishing plantations.
  - Storing of logs, soil, machinery, fuels, oils, lubricant, herbicides or other chemicals, or placement of any other project-related infrastructure.
  - Construction of roads, except where required for designated stream crossings or bridges.
  - Crossing of harvesting machinery, except for appropriately constructed permanent crossing points (bridges) or at designated temporary crossings for dry watercourses. Harvesting machinery can cross watercourses where log crossings or culverts are provided.
- **Plantation Establishment –** Plantation establishment will in general follow the timeline summarised in the Project description.
- **Harvesting –** The power plant is scheduled to commence operations in Q4 2019. Raintrees cleared between 2019 and 2022 will be the initial source of biomass fuel, although *Acacia* from existing plantations west of Madang may also be used during this period. By 2023, the fuel source will have transitioned to using biomass grown in its eucalypt plantations within the Project area.

- **Power Plant –** The power plant site will cover a total of about 31 ha, including the log yard. Construction of the power plant will involve several sequential steps culminating in commissioning and power delivery to the Ramu Grid, as outlined in the Project description. It will consist of a new 30 MW power plant (consisting of two separate 15 MW units that will be constructed several years apart).
- **Raw Water Supply –**Raw water will be sourced from water bores located near or on the power plant site, or transported to the site from bores near the Markham River using an above-ground pipeline for the distance of about 3 km.
- **Roads –** Plantation roads will comprise main roads, secondary roads and access (tertiary) tracks. Carriageway widths will be 8 m, 6 m and 4 m, respectively, with a total tree clearance of at least 25 m for main roads (and 10 m and 6 m for secondary and tertiary roads, respectively) with 2 m shoulders to the side drains. Road construction will involve a bulldozer for initial formation, with carriageway construction using a grader, roller, water truck and, where required, gravel trucks.
- **Site Runoff –** Site runoff will be managed via a clean and dirty drains system. The clean drains system will collect all the runoff, spills and other discharges from the plant that are within the site discharge limits provided in the environment permit, e.g., steam traps, condensate leaks, feedwater leaks and cooling water leakage in the turbine, condensing and feed heating area. This water will be reused or recycled as much as possible.

3 SUMMARY OF LEGISLATION AND STANDARDS

This section describes a review of relevant literature and laws, treaties and conventions that provide an assessment framework for the Hydrology and Sediment Transport Impact Assessment.

The International Finance Corporation (IFC) Standards (1-8) (IFC, 2012) aim to ensure that all potential environmental impacts are considered and managed to an appropriate level. Performance Standard 1 applies to all projects that have impacts. It details how the impacts should be identified and managed. The application of Standards 2 – 8 is dependent on the nature of the project. Of these remaining standards, the two most relevant are:

- Performance Standard 6 (Biodiversity Conservation and Sustainable Management of Living Natural Resources):
  - Promote sustainable management of living natural resources using practices that integrate conservation needs and development priorities.
  - Consideration should be given to direct and indirect project-related impacts to biodiversity and ecosystem services, taking into consideration hydrological changes.
  - Significant changes or degradation of natural habitat should be avoided.
  - Mitigation should achieve no net loss of biodiversity where feasible.
  - Impacts to critical habitat (those with high biodiversity value) should be avoided where feasible.
  - A long-term biodiversity monitoring program must be incorporated.
- Performance Standard 3 (Resource Efficiency and Pollution Prevention):
  - Covers activities that increase pollution to air, water and land.
  - Aims to reduce impacts and promote sustainable use of resources, including water and reduce project-related emissions.
  - Reference should be given to the World Bank Group Environmental, Health and Safety Guidelines (EHS guidelines).
  - If a project uses a considerable amount of water, measures must be adopted to reduce any impact from this, including consideration of additional water conservation measures within the client's operations, use of alternative water supplies, water consumption offsets and evaluation of other project locations.

The current Forestry Stewardship Council (FSC) *National Forest Management Standards for Papua New Guinea* (FSC, 2010)) contains a range of standards that are relevant to hydrology and sediment transport. These have been added to and improved as part of the review process informing the 2016 revised draft (FSC, 2016). This review process has been informed by the FSC *International Generic Indicators* (FSC, 2015), so many of the generic indicators in FSC (2015) have been included as part of the 2016 draft. Thus, the review has focussed on the standards within the FSC (2016) document. Those standards relevant to hydrology and sediment transport in FSC (2016) include:

- Principle 6 – Environmental Values and Impact:
  - Criterion 6.1.1 – Best Available Information is used to identify environmental values within, and, where potentially affected by management activities, outside of the Management Unit. These environmental values shall be identified and described with participation of the customary landowners.
  - Criterion 6.2.1 – An environmental impact assessment identifies potential present and future impacts of management activities on environmental values, from the stand level to the landscape level, prior to the start of site-disturbing activities. When the Organization uses water ways for the transportation of logs, the EIA specifically includes the impact of this activity.
  - Criterion 6.2.2 – For all harvesting and processing operations the evaluation of the environmental impacts of the management activities include the following aspects:
    - Characterisation of ecosystems within the Management Unit, and outside the Management Unit where potentially affected by management activities, using biological and geo-physical information.
    - Impact on:
      - Physical and chemical soil stability.
      - Water resources including water quality and quantity in catchments.
      - Downstream river and coastal systems.
  - Guidance 2 (former 6.4.4) – Consideration should be given to the configuration of the areas under management (e.g. harvest block shape and size) so that it follows the landforms, favours the movement & breeding of fauna and aims to minimise forest fragmentation.
  - Guidance 3: The Land use planning process should consider connectivity for natural vegetation, e.g. through buffer zones, greenbelts, etc.
  - Criterion 6.7 – The Organization shall protect or restore natural watercourses, water bodies, riparian zones and their connectivity. The Organization shall avoid negative impacts on water quality and quantity and mitigate and remedy those that occur. The operation shall meet or exceed all the standards as contained in the *Papua New Guinea Logging Code of Practice* (PNGFA/DEC, 1996).
    - Criterion 6.7.1 – Conservation measures are implemented to protect natural watercourses, water bodies, riparian zones and their connectivity, including water quantity and water quality. The potential impact of the use of water ways for log transport shall be included.
    - Criterion 6.7.1 – Protection measures are implemented to protect natural watercourses, water bodies, riparian zones and their connectivity, including water quantity and water quality.

    - Criterion 6.7.2 – The Organization has effective mitigation and restoration measures in place if implemented conservation measures do not protect watercourses, water bodies, riparian zones and their connectivity, water quantity or water quality from impacts of forest management.
    - Criterion 6.7.3 – Where natural watercourses, water bodies, riparian zones and their connectivity, water quantity or water quality have been damaged by past activities by The Organization, restoration activities are implemented.
    - Criterion 6.7.4 – Where continued degradation exists to watercourses, water bodies, water quantity and water quality caused by previous managers and the activities of third parties, measures are implemented that prevent or mitigate this degradation.
- Principle 7 Management Planning:
  - Criterion 7.1.1 – The Organization shall engage with each community in the Management Unit to ensure a Participatory Land use planning by the Customary landowners and rights holders has been completed and recorded on maps that include:
    - Watershed protection areas if identified.
    - Ecologically sensitive areas if identified.
- Criterion 7.4 – The management plan shall include verifiable targets by which progress towards each of the prescribed management objectives can be assessed.
  - ANNEX E -Elements of the Management Plan
    - 3) Measures to conserve and/or restore:
      i. Rare and threatened species and habitats.
      ii. Water bodies and riparian zones.
      iii. Landscape connectivity, including wildlife corridors.
      iv. Declared ecosystem services.
      v. Representative Sample Areas.
      vi. High Conservation Values.
- Principle 8 – Monitoring and Assessment:
  - ANNEX G – Monitoring Requirements.
    - 1) Monitoring is sufficient to identify and describe the environmental impacts of management activities, including where applicable:
      - x. The impacts of infrastructural development, transport activities and silviculture to rare and threatened species, habitats, ecosystems, landscape values water and soils.
    - 2) Monitoring procedures are sufficient to identify and describe changes in environmental conditions including where applicable:

    - vi. Water courses, water bodies, water quantity and water quality and the effectiveness of actions implemented to conserve and/or restore them.
    - vii. Landscape values and the effectiveness of actions implemented to maintain and/or restore them.
- Principle 9 – High Conservation Values:
  - Criterion 9.1 – The Organization, through engagement with affected stakeholders, interested stakeholders and other means and sources, shall assess and record the presence and status of the following High Conservation Values in the Management Unit, proportionate to the scale, intensity and risk of impacts of management activities, and likelihood of the occurrence of the High Conservation Values:
    - HCV 4 – Critical ecosystem services. Basic ecosystem services in critical situations, including protection of water catchments and control of erosion of vulnerable soils and slopes.
    - HCV 5 – Community needs. Sites and resources fundamental for satisfying the basic necessities of local communities or Indigenous Peoples (for livelihoods, health, nutrition, water, etc.), identified through engagement with these communities or Indigenous Peoples.
- Principle 10 – Implementation of Management Activities:
  - Criterion 10.1 – After harvest or in accordance with the management plan, The Organization shall, by natural or artificial regeneration methods, regenerate vegetation cover in a timely fashion to pre-harvesting or more natural conditions.
  - Criterion 10.9 – The Organization shall assess risks and implement activities that reduce potential negative impacts from natural hazards proportionate to scale, intensity, and risk:
    - Criterion 10.9.1 – Potential negative impacts of natural hazards on infrastructure, forest resources and communities in and adjacent to the Management Unitare assessed as part of the requirements for Criterion 6.2.

In addition to the above standards, there is a range of legislation and regulations associated with environmental impact assessment and management within PNG. Much of these have little direct relevance to the hydrology and sediment transport component of the Project. Relevant legislation and guidelines include:

- *Environment Act 2000* – Major objectives state that the Act is designed to promote the wise management of PNG natural resources, and sustain the potential of natural and physical resources to meet the reasonable needs of future generations, and safeguard the life supporting capacity of air, water, land, and ecosystem. With regard to water/sediment transport, it attempts to achieve these objectives by regulating the use of freshwater through the issuing of Water Permits. There is little of relevance within the Act relating to sediment control and/or erosion.

- *Environment (Water Quality Criteria) Regulation 2002* – This regulation falls under the *Environment Act 2000* and much of it is of little relevance to hydrology, sediment transport or geomorphology. However, it addresses the requirements for water discharges or use to not lower water quality below the prescribed water quality criteria. This would ostensibly include changes to sediment loads.

Given that most of the IFC Performance Standards (IFC, 2012) and FSC *National Forest Management Standards for Papua New Guinea* (FSC, 2016) appear to comply or exceed the expectations of the PNG legislation, these have been used to guide this assessment.

4 REGIONAL CONTEXT AND SITE DETAILS

4.1 Regional

4.1.1 Climate

The general climate of the area (including Lae) is described as Lowland Perhumid (McAlpine & Keig, 1983). The mean annual temperature at Erap is about 27°C and about 1°C higher than Lae, while both annual and diurnal temperature ranges are also slightly higher compared with values for Lae (Pöyry, 2012). Annual evaporation rates (Class A) are estimated to be 1750 – 2250 mm a^{-1}) (McAlpine & Keig, 1983).

4.1.2 Rainfall

The average annual rainfall of the Markham River catchment is reported to be 2,100 mm a^{-1} (Renagi, et al., 2010). Regional rainfall patterns are affected by the Inter Tropical Convergence Zone (ITCZ), resulting in the 'north-west monsoon' conditions of December to March, while the 'south-east trades' dominate during April to November. During the south-east trade season, the winds' moisture is released as rain along the coastal ranges, while the Markham Valley remains relatively dry. Therefore, there is a notable difference in both annual rainfall totals and seasonality between the coast and the Markham Valley. Figure 4-1 illustrates these differences, showing monthly rainfall totals for three different rain gauges with increasing distances from the coast. The Lae rain gauge (adopted from McAlpine 1983) is located on/near the coast, the Nadzab Airport rain gauge is in the Markham Valley about 35 km north-west of the coastline, and the Leron Forestry Nursery rain gauge is in the Markham Valley about 75 km north-west of the coastline. These locations are shown in Figure 1-1. Pöyry (2012) reported annual rainfall totals of 4,565, 1,275, 1,359 and 2,425 mm for Lae, Erap, Leron and Kaiapit respectively. Annual rainfall totals in the higher relief areas of the catchment are likely to be higher than those of the valley, but little publicly available data are available to substantiate this claim.

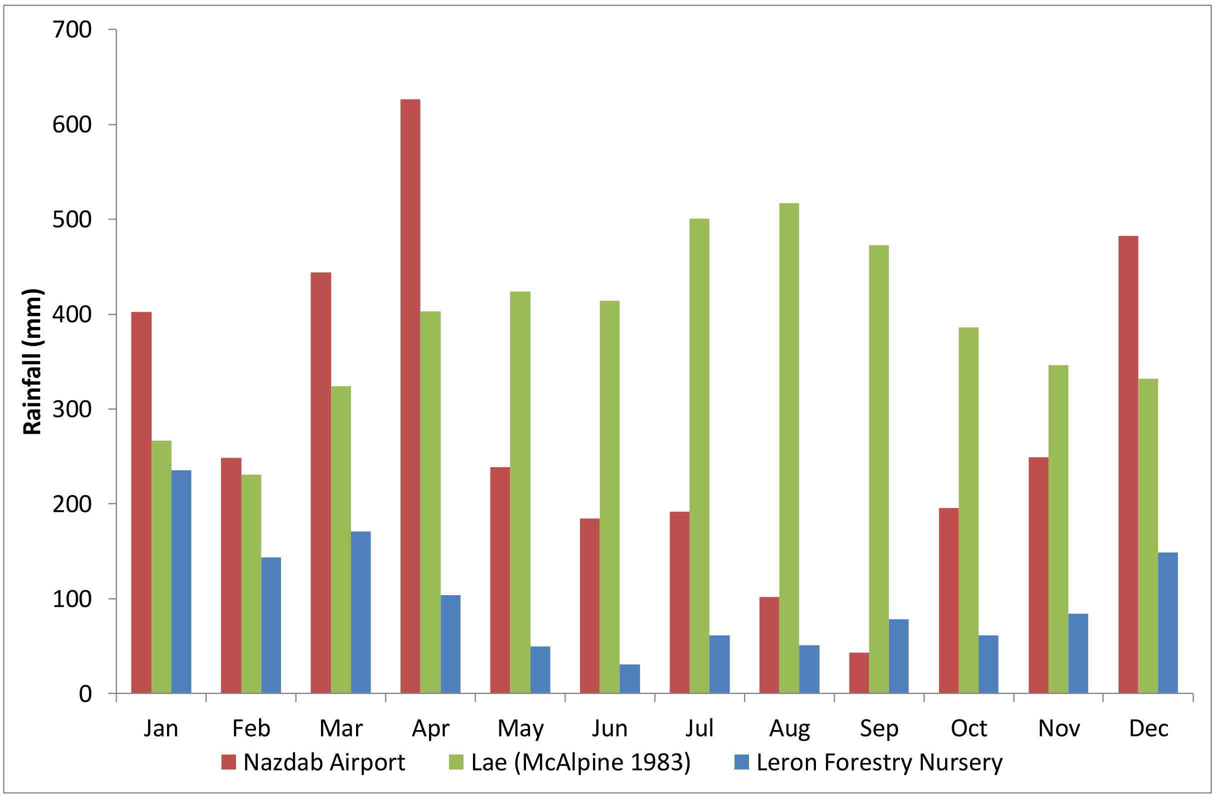

Figure 4-1 Variability of monthly rainfall totals

4.1.3 Markham River

The Markham River is situated in the eastern part of the Markham-Ramu Graben which, in turn, forms part of the Sepik-Markham Depression, a major structural feature of PNG and Papua (Loffler, 1977) which follows a fault zone of approximately 300 km length (Pöyry, 2012). The graben separates the central and northern coastal ranges, with the Finisterre and Saruwaged Ranges to the north, and the Kratke Ranges and Herzog Mountains of the Owen Stanley Range to the south. Loffler (1977) described the Markham River as *quite unusual* due to a braided form along its entire length and a longitudinal slope that is *considerably higher than for any other plain stream of comparable discharge and catchment area* within a PNG context. This morphology is largely due to the very high rates of sediment delivery, often on a catastrophic scale, from upland areas to lowland plains due, mostly, to the combined effect of high rates of rainfall and tectonic activity. Sediment inputs were described by Meynink (1988) as *large by any standard*. The morphology of the river throughout its length shows similarities to alluvial sediment runout fans and the main river channel follows a relatively steep course, discharging to the Huon Gulf at Lae. Selected physiographic characteristics are presented in Table 4-1.

Table 4-1 Selected physical characteristics of the Markham River

Parameter	Value	Source
Catchment area (km^2)	12,000 - 13,000	Loffler (1977), Renagi et al. (2010)
Catchment mean annual rainfall (mm)	2,100	Renagi et al. (2010) & consistent with McAlpine & Keig (1983)
Mean annual discharge (m^3s^{-1})	~350 - 450	Powell & Powell (2000), Meynink (1988), Maunsell (1980)
Maximum recorded discharge (m^3s^{-1})	3,087	SMEC (1990) – recorded at the Markham River bridge crossing (Figure 1-1)
Channel width (km)	0.5 - 2.0	Loffler (1977)
Valley width (km)	3 - 8 (generally)	Tilley *et al* (2005)
Maximum valley width (km)	22	Pöyry (2012)
Plain course length (km)	140	Loffler (1977)
Elevation at source (m)	450	Loffler (1977)
Area of alluvial fan (km^2)	1,800	Meynink (1988)
Gradient, min, max, avg (m/m)	0.001, 0.006, 0.003	Loffler (1977)
Morphology	Anastomosing[1], shallow, wide, braided[2]	Loffler (1977)
Planform	Mostly straight, with some incipient meanders of very long wavelength.	Loffler (1977)
Sediment type	Variable (gravel-clay)	Loffler (1977)
Floodplain sediment grade	65% of material in upper 2 m has a median particle size (D_{50}) of < 0.075 mm	Tilley *et al.* (2005) – recorded in the reach adjacent to the Markham River bridge crossing (Figure 1-1)
Channel sediment grade (bridge reach)	D_{50} ~ 19 mm in upper 0.5 m of bed	Tilley *et al.* (2005) – recorded in the reach adjacent to the Markham River bridge crossing (Figure 1-1)
Channel sediment grade (Markham River mouth)	Sandy gravel, gravelly sand, and boulders up to 50 cm diameter	http://web.vims.edu/margins – recorded at the mouth of the Markham River (Figure 1-1)
Tributary stream types	Fans[3], piedmonts[4]	Loffler (1977)

The entire Markham River system is affected by long-term tectonically induced changes in relief and slope gradients, with mountain uplift contrasting with sea-floor subsidence across a major plate boundary. The Saruwaged Ranges have undergone uplift of at least 4,000 m since the late-Miocene, making the area one of the most tectonically unstable in PNG. There are frequent earthquakes, which trigger landslides, both in the mountains and on the sea floor. These landslides can occur in combination with very heavy rainstorms to cause floods and debris torrents in the mountain catchments.

[1] Anastomosing watercourses are those that comprise two or more interconnected channels, separated by semi-permanent banks formed of cohesive material (Whittow, 2000).

[2] A waterway characterised by a network of interconnected converging and diverging channels. The intervening bars are exposed at low water and are highly mobile/transient (Whittow, 2000).

[3] A fan- or cone-shaped mass of material (usually sand/gravel) deposited by a stream where it emerges from the constriction of a narrow valley at a mountain front and debouches onto a plain or into a wide trunk valley (Whittow, 2000).

[4] Used to describe the gentle slope leading down from the steep mountain slopes to the plains, including the bedrock (pediment) and the accumulated colluvial and alluvial material (bahada) (Whittow, 2000).

Of note, the 1988 Kaiapit (Figure 1-1) event mobilised an estimated 1.8 km^3 of sediment within the Markham River catchment, which is likely still being transported through the river system. Earthquakes occurred in the Finisterre Range on 13 October 1993 with aftershocks persisting for over three months and affecting an area of over 3,000 km^2. The largest earthquake registered 7.1 on the Richter scale. The effects of the earthquake included damming (by debris consisting of residual soil and weathered rock mass) of the upper Leron River (a northern tributary of the Markham River) to a depth of 30 m, thereby forming a large lake which breached three weeks later. Dam breaches such as this one result in pulses of sediment delivered to the coast.

Alluvial fans are a characteristic feature of the Markham Valley and an important sediment store and delivery mechanism. These features represent sediments deposited by river flows, and debris flows resulting from landslide activity typically triggered by ongoing uplift of the northern block and seismic activity. The fans contain alluvium to depths of up to 1,000 m with river channels incised up to 20 m below the fan surface. The largest fan is the Leron Fan (Loffler, 1977), which forms the western boundary of the Project area. The fans, and the rivers that flow over them, are highly mobile and continuously changing in form due to ongoing fluvial processes and intermittent tectonic activity. Other notable alluvial fans include those of the Rumu and Erap Rivers, with the Erap River forming the eastern boundary of the Project area. There are also a number of smaller piedmont fans (those that do not reach the main river channels). The general depth of floodplain alluvium is not known in detail, but likely to be at least 50 m.

The Markham River bed is typically braided and up to 1.5 km wide in places. The main tributaries of the Markham River – the Umi, Maniang, Leron, Rumu and Erap Rivers – flow from the northern ranges. The active alluvial fan deposition in the northern part of the valley forces the Markham River to flow against the southern margin (Pettifer, 1973). Major tributaries on the south side include the Watut River and the Wampit River.

The braids, islands and bars of the Markham River channel are continually changing. The largest recent shift is a major avulsion[5] about half way between the Watut-Markham confluence and the Markham River bridge crossing which occurred in the mid-1990s (Figure 4-2). Aerial imagery suggests that the narrower channel occupied by the Markham River after the avulsion may be limiting downstream flow of sediment and creating a build-up further upstream (Geoff Pickup, *pers. comm.*).

[5] The abandonment of a river channel and the establishment of a new channel. Avulsions occur as a result of channel slopes that are much less steep than the slope that the river could travel if it took a new course. Avulsion typically occurs during large floods which carry the power necessary to rapidly change the landscape (Whittow, 2000; Slingerland & Smith, 1998; Nanson & Knighton, 1996).

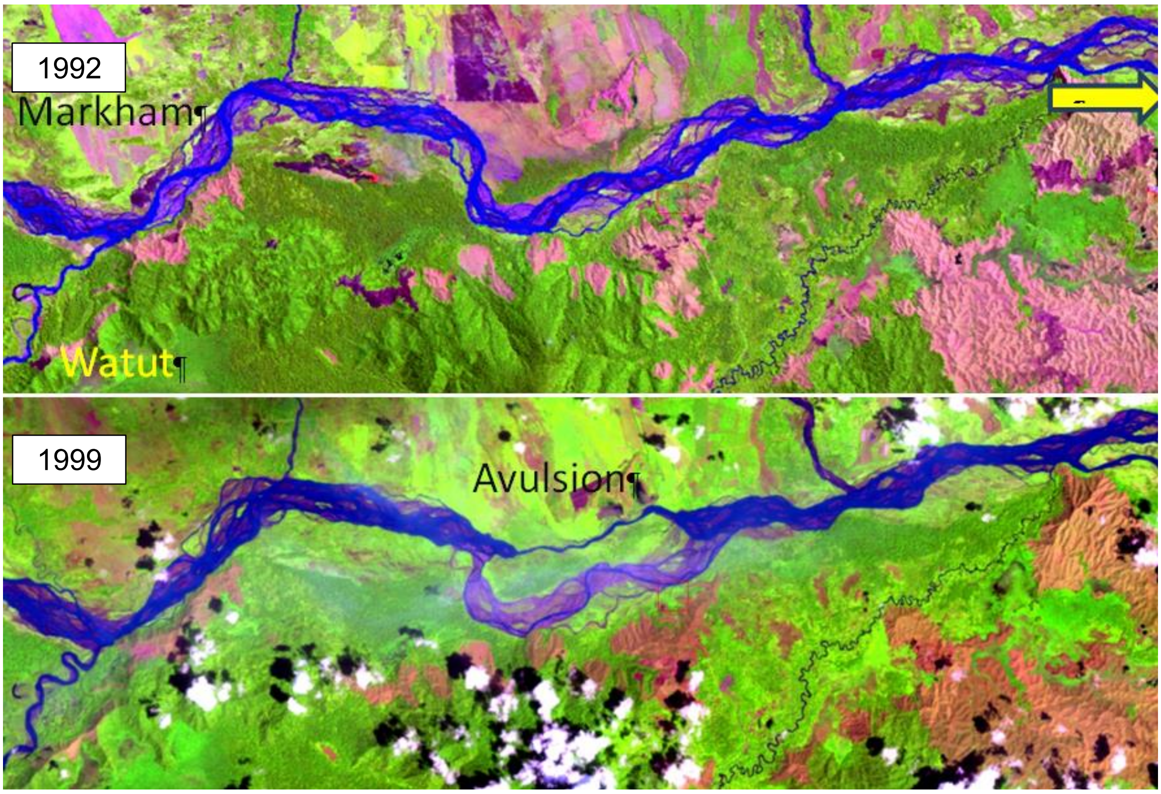

Figure 4-2 Avulsion of Markham River upstream of Markham River bridge crossing (data from Dr Geoff Pickup)

4.1.4 Sediment Delivery

Upland rates of sediment removal (denudation rates) are likely far greater than rates of *in situ* weathering in the Markham River catchment. As such, large amounts of sediment would be delivered from the mountains, through the valley channels and footslope fans to the alluvial plain. Valley channels would serve as conduits for collection and removal of colluvium shed from the slopes in addition to any incision by streams. The colluvium would move down-channel until landslide processes were overtaken by stream erosion and remaining colluvium entrained and removed in suspension or as bed load (Pain, 1972).

PNG is subject to considerable rainfall erosion by virtue of rugged terrain and high rainfall totals and intensities. Turvey (1974), cited by El-Swaify et al. (1982), reported that the rate of denudation for Central Papua was about 1.4 t ha^{-1} a^{-1}. Data from the Fly Basin, PNG, indicate natural sediment yields of up to 8.4 t ha^{-1} a^{-1}. These values are high by world standards and can be attributed primarily to the high rainfall. Background erosion rates for the Strickland River Basin (based on TSS measurements by Porgera Joint Venture) were estimated to be approximately 20 t ha^{-1} a^{-1}. The Strickland River Basin is largely undisturbed, but subject to high rates of natural sediment delivery to the river system through frequent landslides. PSM

(2003) reported erosion rates of 375 – 750 t ha^{-1} a^{-1} for disturbed mining areas in steep upper catchment areas of the Watut River sub-catchment of the Markham River.

Kolola & Samanta (2013) used remote imagery, GIS analysis and the Revised Universal Soil Loss Equation to estimate soil erosion rates from the Markham River catchment. They estimated that the mean basin-wide rate of erosion was 17.7 Mt a^{-1} (or 14 t ha^{-1} a^{-1}) but with rates of around 2 t ha^{-1} a^{-1} for floodplain and areas of low relief. For the Markham Valley specifically, a subsequent paper (Kolola and Samanta (2015) reported a loss rate of 15.1 t ha^{-1} a^{-1} compared to a basin-wide average rate of 21 t ha^{-1} a^{-1}. Renagi et al. (2010) estimated a basin-wide yield rate of 1.5-1.6 t ha^{-1} a^{-1}.

4.1.5 Sediment Transport

From the preceding discussion, it is clear that very large volumes of sediment move through the Markham River catchment and are discharged to the Huon Gulf. Meynink (1988) suggested that, historically, most of the sediment inflows to the Markham Valley would derive from the six major northern catchments that have a combined area of some 3,200 km^2. Although the catchment area on the south side of the Markham River is larger compared to that on the north, most sediment from the south side is delivered from the Watut River system which has a catchment area of about 5,000 km^2. Meynink (1988) argued that landsliding debris from the upper Watut River would probably be stored in the river valleys and valley channels (inferring a lower sediment delivery ratio from the south). Using a desk-based study of Holocene catchment denudation in the Markham Valley, Meynink (1988) estimated long-term (Holocene average) deposition and transport rates, and concluded that that the total silt and clay delivered from the Markham River to the Huon Gulf averaged over the Holocene was between 10 and 40 Mt a^{-1} (refer Table 4-2).

Meynink's method involved assuming a cross section form of the Markham Valley Rift and estimating the Holocene change in the longitudinal profile of the Markham Valley to estimate the volume of material stored in the valley in the last 18,000 years. The method further assumed that the deposited volume represented the coarse fraction of the source material, and that the finer silts and clays had passed through the system as washload. Based on data from alluvial soils of the Sepik River (as no local data were available), it was assumed that 50% of the material would be finer that 50 microns, suggesting a substantial fine fraction. Therefore, limits for washload were considered to be 0.5 to 2.0 times the deposited fraction.

Bed material discharge was not estimated, although is typically assumed to constitute about 10% of the total sediment load. For the case of the Markham River this figure may be higher due to the very high rates of coarse material delivery to the valley floor and the steep slope of the river, even in its lower reaches.

Powell & Powell (2000) used the data of Meynink (1988) to estimate mean annual Total Suspended Sediment (TSS) values in the Markham River of between about 800 and

4,000 mg L^{-1} depending on assumptions made (although the former authors appeared to misinterpret some of Meynink's results). They also cite the results of other studies that indicated TSS values in the mid- to high-100's of mg L^{-1} were quite common in the vicinity of the Markham River mouth. It is likely that TSS values would be generally high and highly variable on a monthly basis as a result of the prevailing flow and sediment processes.

Table 4-2 Estimates of sediment deposition rate and transport in the Markham River catchment (adapted from Meynink (1988))

Deposition Rate (mt a^{-1})	Washload Transport (mt a^{-1}) (Low estimate)	Washload Transport (mt a^{-1}) (High estimate)
From Northern Catchments		
17	8.5	34
From Southern Catchments		
2.7	1.3	6.4
TOTALS		
19.7	9.8	40.4

Elsewhere, Nedeco-Haskoning and Maunsell (1980) (cited in http://web.vims.edu/margins and Renagi et al. (2010)) estimated that about 150-160 tonnes of sediment per square kilometre of catchment was moved annually by the Markham River with an average bedload of about 2 Mt a^{-1} and an estimated suspended load of 9-12 Mt a^{-1}.

4.1.6 Flooding

Figure 4-3 shows areas subject to inundation within the Markham Valley, showing that about 40% of the valley is subject to flooding on a permanent/long-term basis, 36% of the valley is subject to flooding periodically/seasonally, while only 24% of the valley is not subject to flooding. These values are not entirely consistent with anecdotal observations from people on site, with the current proposed power plant location apparently not subject to long-term inundation, despite the map suggesting otherwise. Regardless, the map does provide some indication as to the frequency and extent of flooding.

Landslide damming of flows and subsequent dam breaches can complicate the flooding frequency as they result in substantial amounts of water released over a very short period. While dam breaches are not a regular occurrence, several dammed waterways remain in the catchment that pose a future flooding risk. Tutton and Browne (1994) suggested that a major landslide of similar magnitude to the Finisterre landslide could occur in the 3,000 km^2 affected area every 60 years. Given that much smaller events may still be of sufficient magnitude to cause shifts of the river courses or re-mobilisation of alluvial fan sediments through either the release of the landslide dams or directly through mudflows and debris flows, it may be appropriate to consider that such a threatening landslide event and resulting alterations to the flooding regime may occur every 20 odd years.

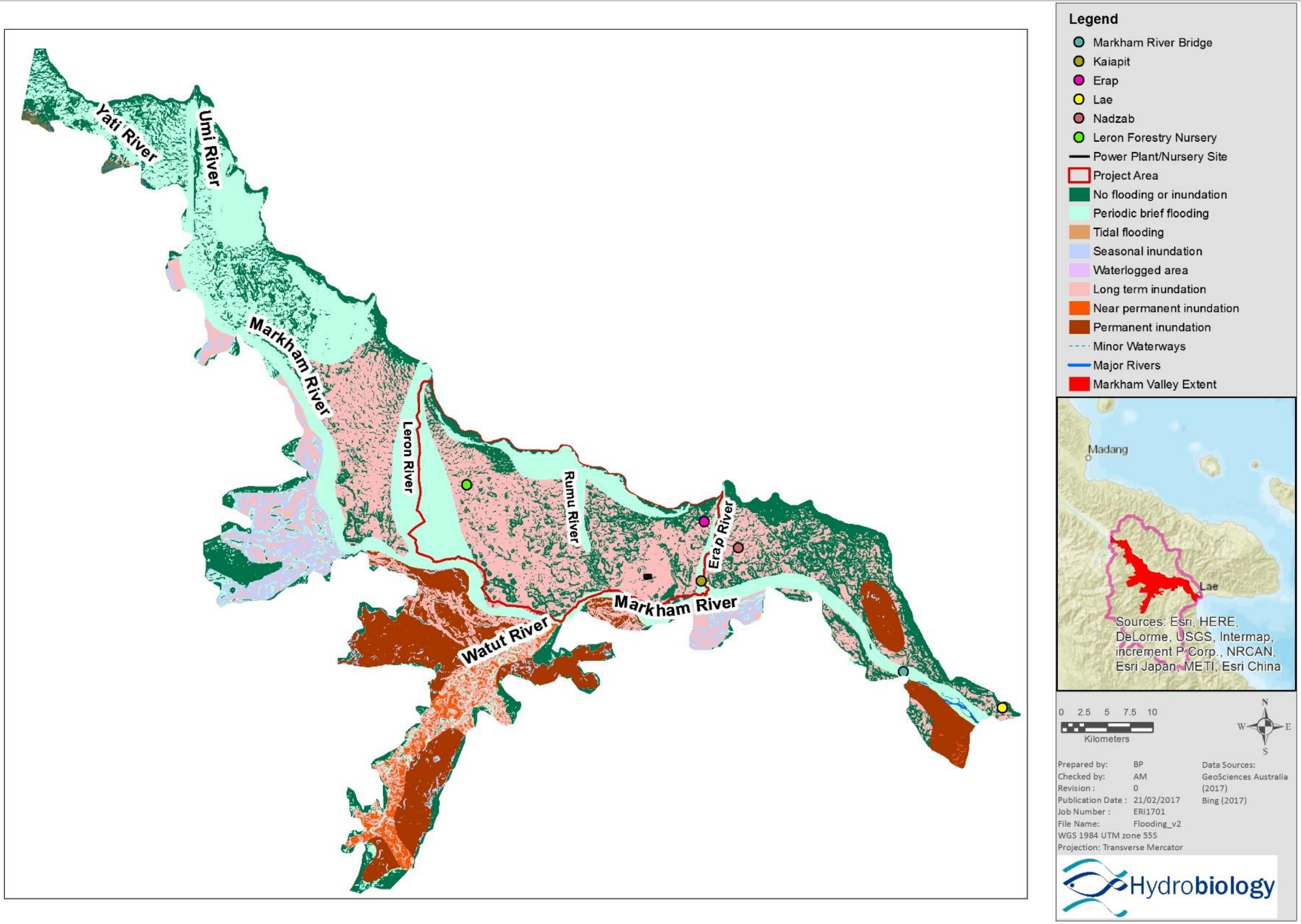

Figure 4-3 Inundation zones within the Markham Valley

4.2 Project Area

4.2.1 Local Sub-Catchments and Waterways

The Project area straddles the northern floodplain of the Markham River between Leron and Nadzab. It encompasses four Markham River sub-catchments – Leron, Erap, Rumu and Maralumi River sub-catchments. Figure 4-4 shows the location of the sub-catchments, while Figure 4-5 shows the longitudinal profile of the main channel for each of the sub-catchments. While channel length and catchment area vary considerably between sub-catchments, all four sub-catchments consist of very steep headwaters, draining onto flat alluvial fans. As described above, the fans consist of considerable sediment deposits and the main waterways draining over the fan are generally highly mobile, consisting of a braided pattern and/or multiple distributaries, and displaying wide, flat beds composed of mostly sands and gravels, with cobbles and boulders observed sporadically. These stream types are indicative of systems with very high sediment loads. Bed material for these waterways is shown in Figure 4-6.

While most of the major streams and their tributaries described above were mobile and subject to high sediment loads, several smaller, less mobile systems with much lower sediment loads (clear water) were also observed. These smaller, clearwater streams appeared to have origins downslope of the fans produced by the high-energy headwater streams. That is, due to the excess of sediments in the fan, during the dry season, flows were sub-surface and only returned to the surface at the origins of the clearwater streams some distance downstream. The downstream reaches of Maralumi River and Klin Wara (a Leron River distributary) are good examples (Figure 4-7, Figure 4-8). The dissipation of energy and settlement of sediment loads within the fans appear to be contributing to clearwater conditions in subsequent outflows. During the monsoon, these waterways would likely be connected by surface flows and turbidity would be higher. Figure 4-9 provides a schematic of the sources of these streams. Fathom Pacific (2017) noted that this buffering of flow and sediments contributed to a more diverse aquatic and riparian habitat, with riparian vegetation consisting of large trees.

Widths of all the main waterways within the Project area were highly variable, although actual bankfull width was difficult to ascertain within the fan due to the anabranching nature of the distributary channels. Widths of the Leron, Erap and Rumu Rivers were several hundred metres in the most downstream reaches, and narrowed in an upstream direction towards the foothills. Due to the sediment buffering effect of the Maralumi alluvial fan (described above), the Maralumi channel width remained less than 100 m for its entire length.

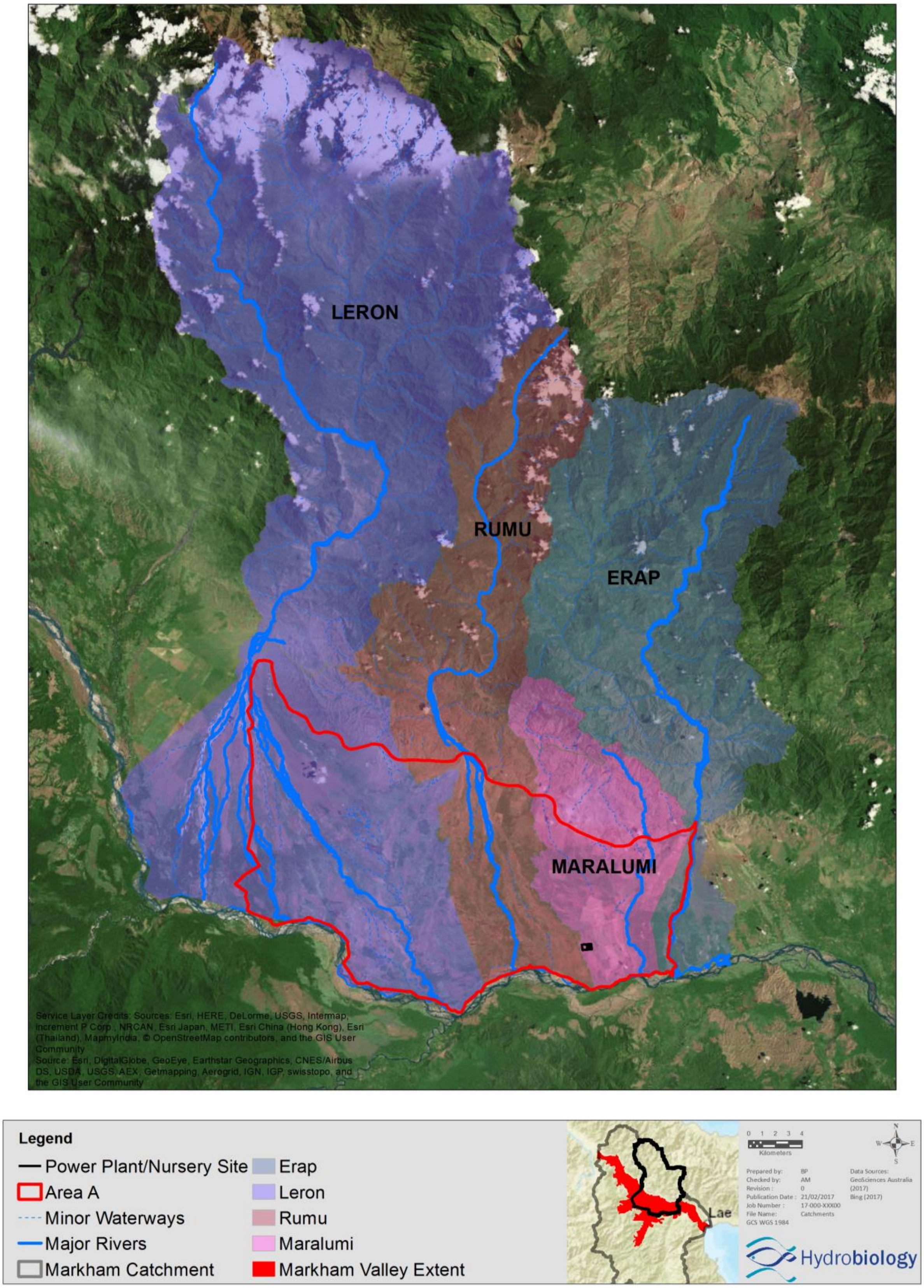

Figure 4-4 Location of the Leron, Rumu, Erap and Maralumi River sub-catchments

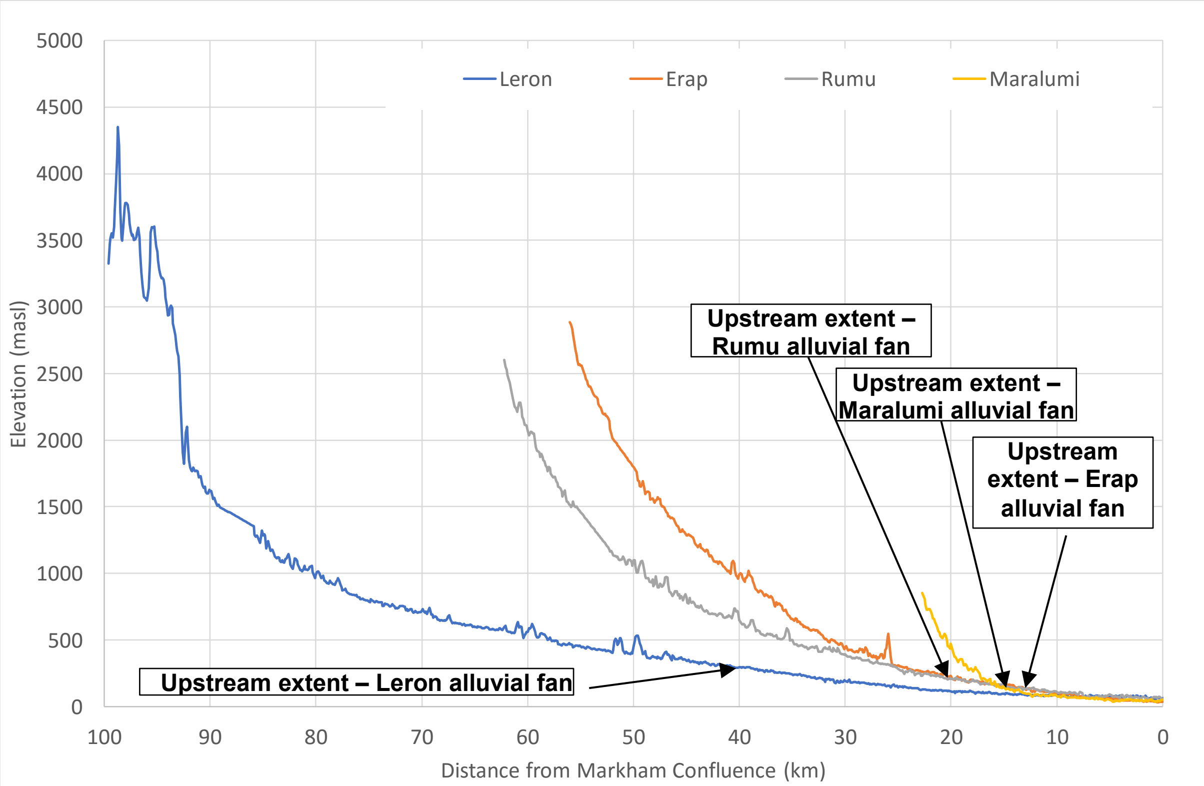

Figure 4-5 Longitudinal profiles of the four major waterways that intersect the Project area

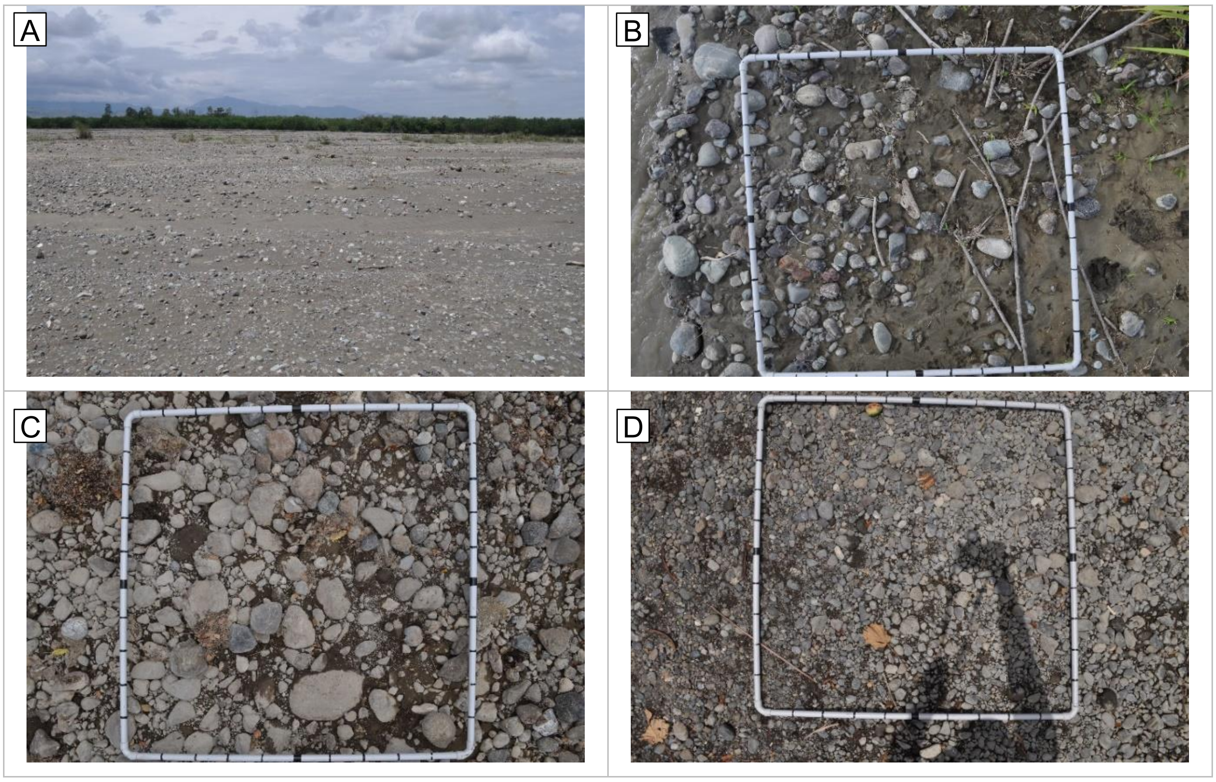

Figure 4-6 Bed material – A: Leron River distributary, B: Rumu, C: Erap, D: Maralumi

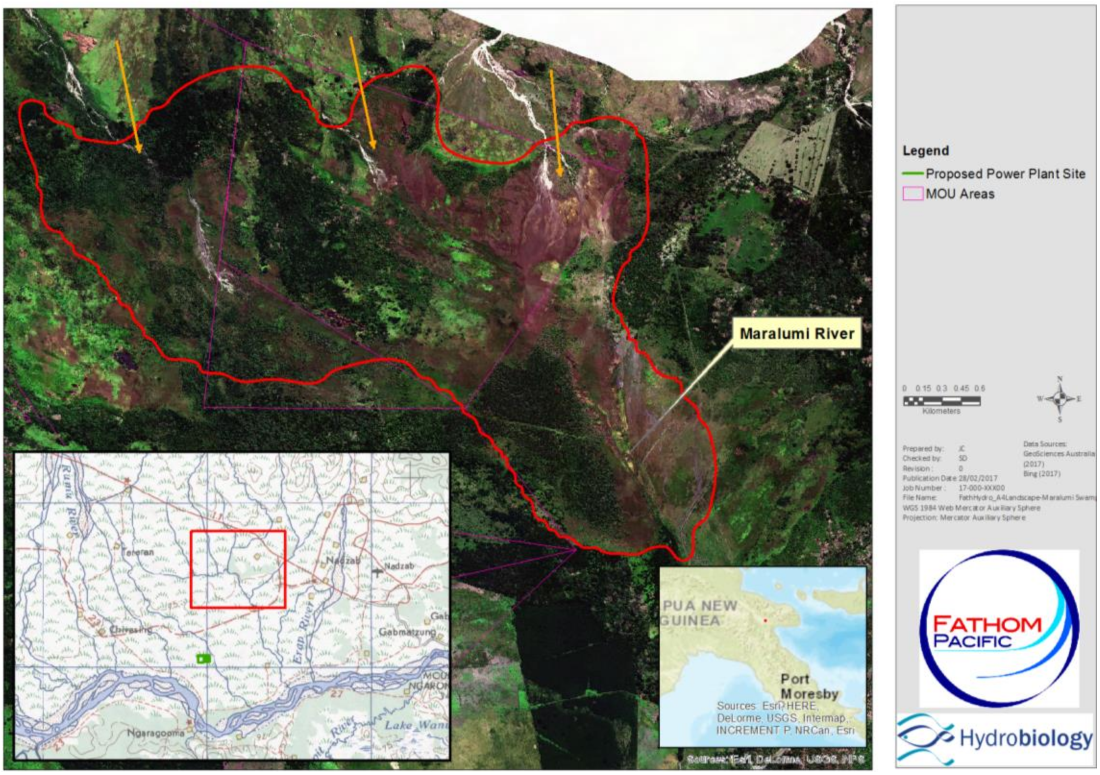

Figure 4-7 Headwater region of the Maralumi River (red polygon). High energy streams indicated by black arrows. (Source: Fathom Pacific (2017))

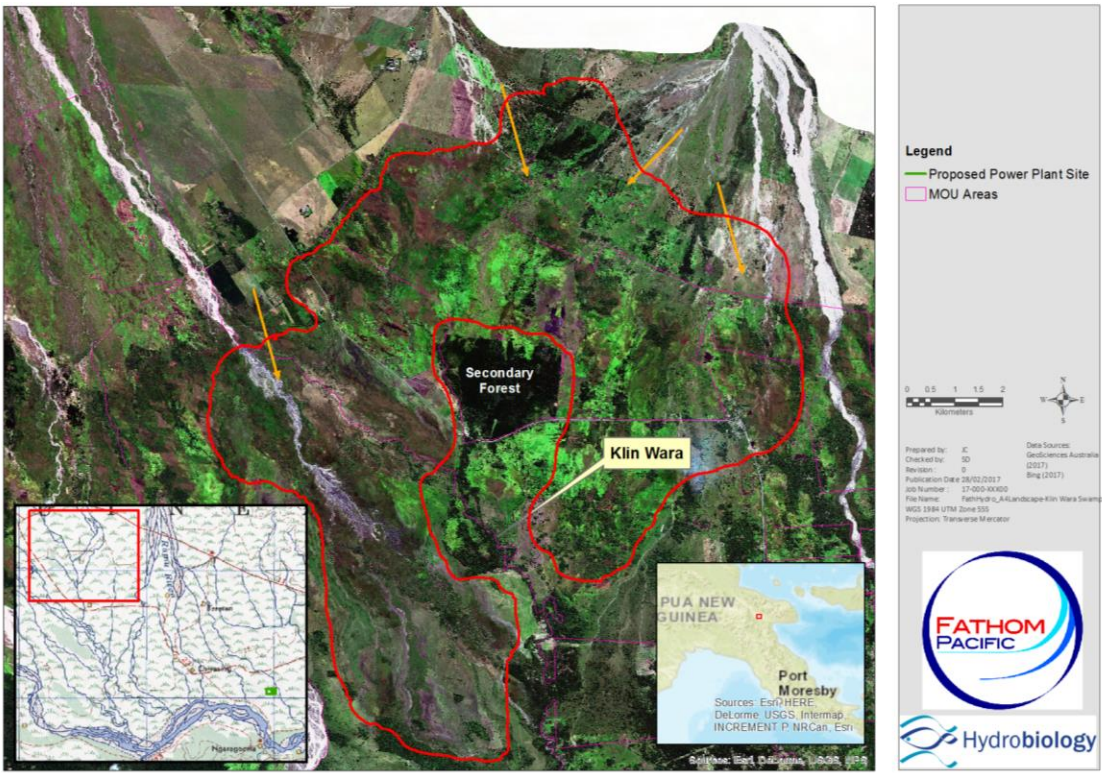

Figure 4-8 Headwater region of Klin Wara (red polygon) in the Leron River sub-catchment. Termination point of the high-energy streams indicated by yellow arrows. (Source: Fathom Pacific (2017))

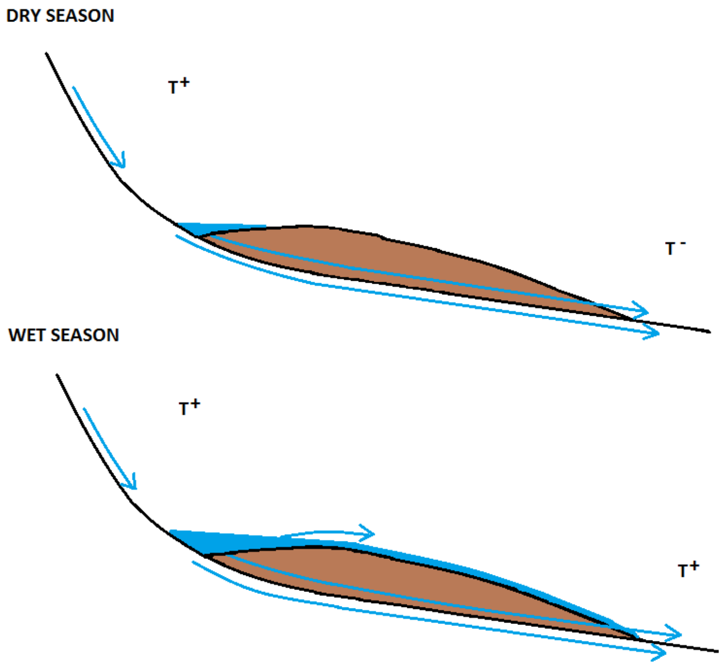

Figure 4-9 Schematic diagram of the source of the clearwater streams, showing flow pathways and changes in turbidity (T = turbidity)

Floodplain widths were also highly variable, with the Leron floodplain extending several kilometres and narrowing towards the foothills. Floodplains were generally intersected by many smaller distributary channels and waterways which varied between turbid waterways with coarse bed material and clearwater streams with finer bed material (as described above). Bank height was also highly variable; however, due to the considerable aggradation of sediments, the majority of banks were generally low (<5 m) and, as a result of the fan-like aggradation, were composed of similar material as the channel bed (Figure 4-10). Riparian vegetation on these banks was dominated by grasses and low shrubs, although there were scattered larger trees providing canopy cover. Given the unconsolidated bank materials, these trees are unlikely to provide any additional resilience to bank erosion.

Fathom Pacific (2017) also noted the presence of smaller ephemeral tributaries within the sub-catchments. They noted that the streams consisted of a boulder-cobble-gravel dominated bed structure and moderate to high sediment loads with high gradient headwaters and ephemeral or episodic flows that dictated relatively low aquatic fauna diversity. They were located in much of the northern sector of the Project area bordering the foothills and the Leron River and draining into the four major waterways.

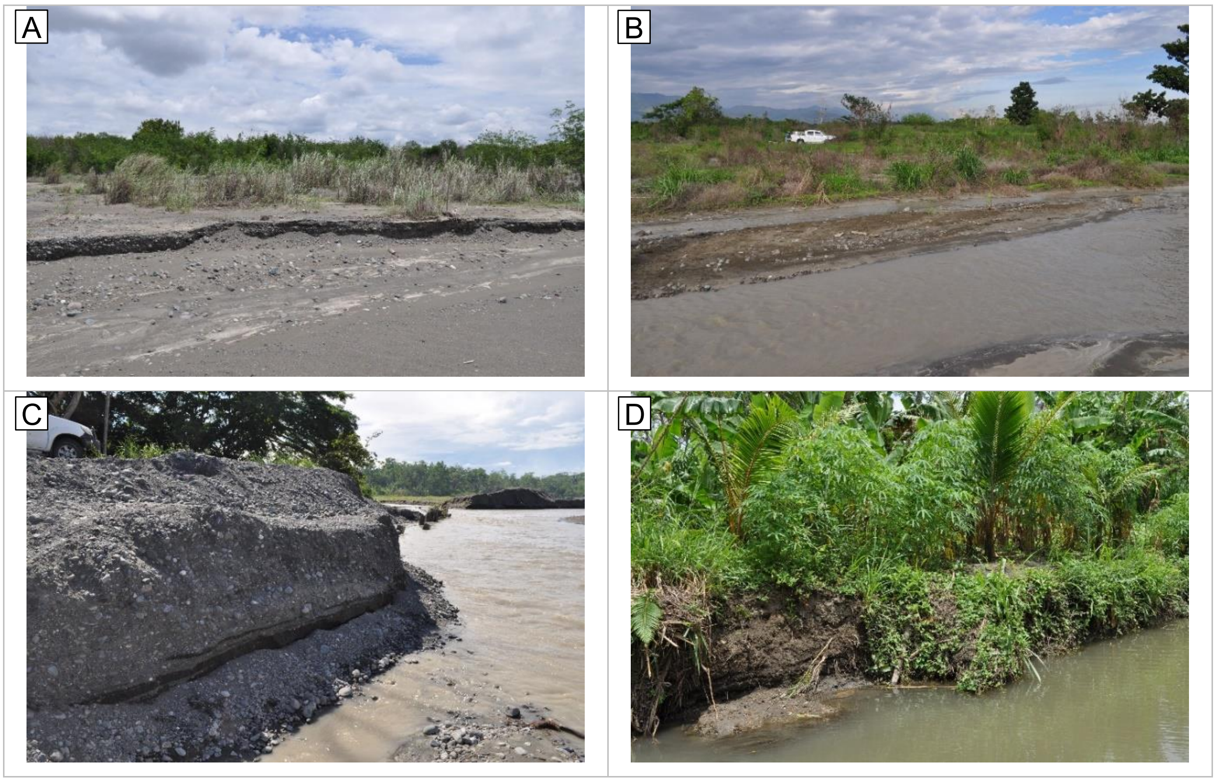

Figure 4-10 Bank material – A: Leron River distributary, B: Rumu, C: Erap, D: Maralumi

4.2.2 General Hydrology

The four main waterways (Leron, Erap, Rumu, Maralumi) were all considered to be permanent waterways. However, based on the Lowland Perhumid climatic descriptions in Section 4.1.1 and outlined in McAlpine & Keig (1983), the available rainfall data, and knowledge of catchments of similar characteristics in similar climates, it is likely that flows cease for short periods during very dry conditions in the smaller catchments. Further, many of the smaller distributary channels of the waterways would dry during the dry season, with only the main channel 'wetted' during these periods. The dry season site visit undertaken as part of Fathom Pacific (2017) supported this classification, with several Leron distributary channels observed to be dry, while Erap, Rumu and Maralumi Rivers were flowing.

4.2.3 General Sediment Transport

Sediment loads are generally very high across the Leron, Erap and Rumu River sub-catchments, attributed to the very high denudation rates within their upper reaches. Sediment is delivered from the mountains, through the valley channels and footslope fans to the alluvial plain. The fans are major depositional features within the Project area and result in the creation of distributary channels that exhibit a variety of features and connectivity. Some are continuous features that continue to convey sediment delivered from up slope, while others (as reported above) initiate from the expression of subsurface flows some way downstream of the fans and exhibit far lower potential to transport sediments.

While similar processes occur in the Maralumi River sub-catchment as those described above, the waterways downstream of the fan were all clear and had low sediment transport capacity. This variation from the other sub-catchments was attributed to Maralumi River catchment's much smaller area and lower headwater slopes.

4.2.4 Flooding

Fugro Consultants (2016) mapped elevation and slope of the Project area, as reproduced in Figure 4-11 and Figure 4-12[6]. They show that the entire Project area is subject to flooding during high flow events, with the south-east corner most prone due to its low slope and elevation. This area forms part of the Maralumi, Erap and Markham floodplains and contains the proposed power plant location. Given the comparatively low bank heights reported above, overbank flows would be expected to occur on a frequent basis, resulting in floodplain inundation. Analysis of Figure 4-3 shows that 51% of the Project area is subject to permanent/long-term inundation, 26% is subject to periodic brief flooding, while only 24% is not subject to flooding, confirming the low-lying floodplain and inter-connectedness between the channels and floodplains.

4.2.5 Other Wetted Areas

Overbank flows and groundwater levels during flooding of the main waterways influence the inundation of several low-lying wetlands within the Project area. These areas tend to occur upstream of the previously discussed clearwater streams. Fathom Pacific (2017) noted that these wetlands are understood to be dry except during periods of high rainfall, meaning that they do not form permanent wetlands. The general hydrological characteristics of the area are consistent with this finding. These wetlands do, however, appear to regulate the energy, flooding regimes and suspended sediment loads of the outlet streams. Therefore, these areas are considered sensitive to changes to the hydrologic or sediment regimes.

[6] The legend of the provided map does not define slope; however, the lack of colour variation over the site suggests that the topography is relatively flat.

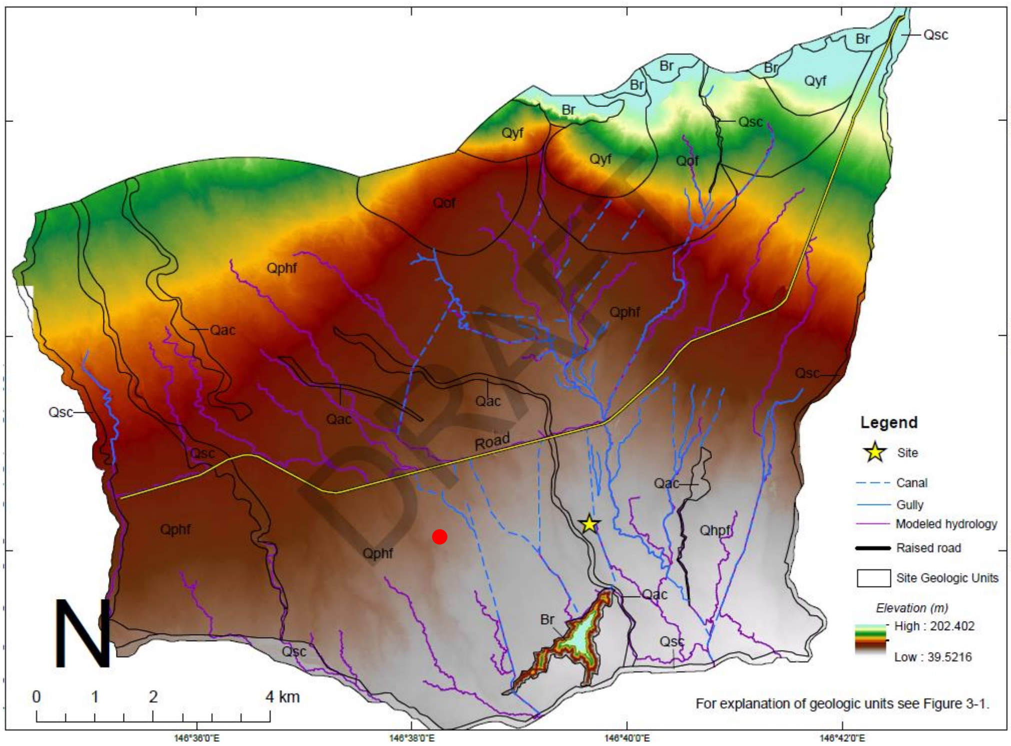

Figure 4-11 Hydrography and elevation of the Project area (Source: Fugro Consultants (2016))
Note that the power plant site has moved since this figure was produced (now indicated by a red circle)

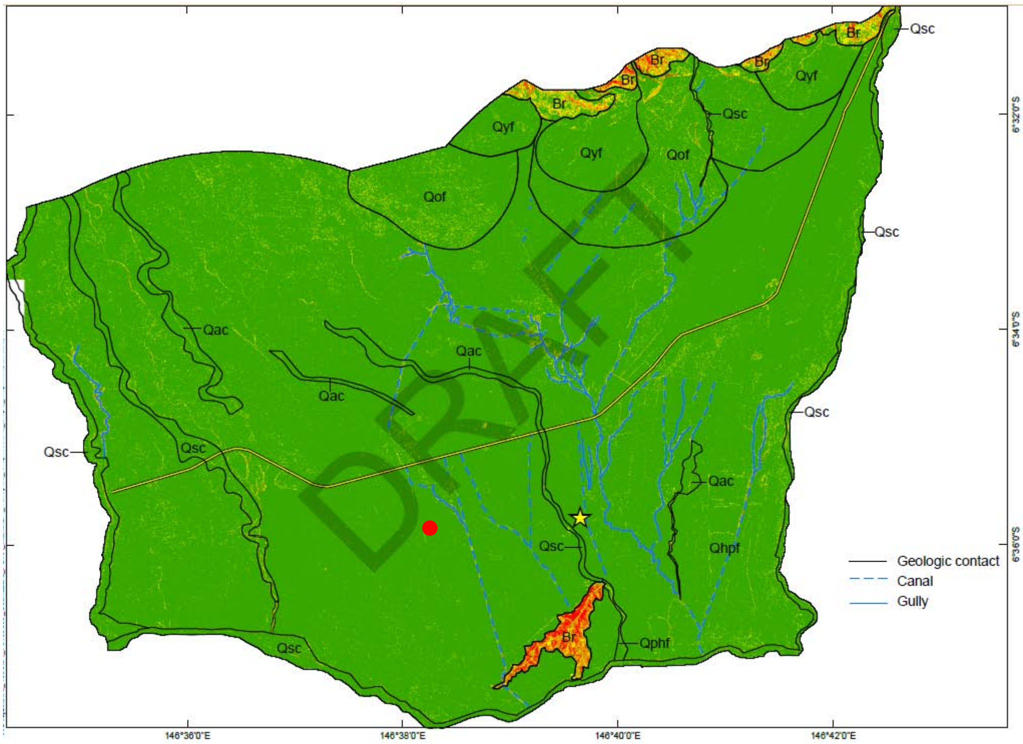

Figure 4-12 Slope of the Project area (Source: Fugro Consultants (2016))
Note that the power plant site has moved since this figure was produced (now indicated by a red circle)

5 METHODS

5.1 Approach

There was very little information available relating to the existing hydrological and sediment transport regimes or the geomorphology of the Project area. As such, the approach used a desktop data review, and industry accepted modelling methods to provide an understanding of the existing environment and to assess potential impacts resulting from the project. The modelling approach was entirely desktop in nature, but was supported by *in situ* condition assessments, photographs and morphological characterisation undertaken by Dr Adrian Flynn as part of the aquatic ecology assessment (Fathom Pacific, 2017), and under direction from Hydrobiology. The approach is described further below.

5.2 Existing Environment

5.2.1 Hydrology

Only limited rainfall data were available for the study area. Therefore, a 100-year synthetic daily rainfall sequence was generated for the Project area using the best available daily data from Nadzab Airport (Nov 2012 to Nov 2015). Methods for developing this synthetic series are contained within the groundwater hydrology report (White, 2017).

There were no available flow data series for the study area, with only flow summary statistics available for Markham River. As such, runoff estimates needed to be generated. Due to the lack of calibration data, it was determined that several techniques should be used to provide a range of potential runoff values that could be used to inform a risk assessment. Three methods were chosen:

1. The Australian Water Balance Model (AWBM) (Boughton, 1996) was used to generate runoff estimates from the synthetic rainfall data. The AWBM is a relatively simple model based on the generation of overland flow from rainfall which occurs because soil is saturated to full capacity, or because rain arrives more quickly than soil can absorb it. The AWBM was developed in the early 1990s and is now one of the most widely used rainfall-runoff models in Australia and has been applied to a range of international locations, including PNG. It is conceptually simple, robust and straightforward to calibrate. The model parameters used were taken from previous runoff modelling of PNG catchments of similar characteristics (Hydrobiology, 2008; Hydrobiology, 2013).
2. An early version of the AWBM (the 'Boughton' model – Boughton (1964)) was adapted for and previously tested on PNG Highland catchments by Dr Geoff Pickup (Pickup, 1976; 1977a; 1977b). This model was run using parameters previously used by Hydrobiology (2008) for PNG catchments of similar characteristics. This model is referred to as the "Pickup model" from hereafter.

3. The Regional Flood Frequency Method, described in SMEC (1990), was used to develop design peak flood discharges for the Markham River. The Markham River catchment is on the boundary of the derivation range for the method, so it is likely to underestimate discharge values.

The first two methods were used for all sub-catchments and Markham River catchment to develop 1-year, 2-year, 5-year, 20-year, 50-year and 100-year average recurrence intervals (ARIs) and to develop flow duration curves. As there were no calibration data for any flow duration curves, these graphs used a monthly time-step as it was considered that more frequent time-steps may be inaccurate. Methods described in SMEC (1990) for estimation of large and extreme floods were then used to derive the 500-year ARI from the 100-year ARI. Method 3 was used only on the Markham River and was used to develop the same design peak flood discharges. No duration curves could be created using this method.

No hydrological parameters were developed for the smaller clearwater streams (except for Maralumi River) as these were considered as part of the four major sub-catchments. Impacts to these would be assessed using the outputs from the groundwater hydrology assessment.

5.2.2 Flooding

Existing flooding extents were modelled using a basic two-dimensional HEC-RAS model, using the Project area digital elevation model (DEM) (30 m resolution) as the base terrain. Flows that closely resembled the 100-year ARI and 500-year ARI were used as input hydrographs for the model, while the BAAM (2016) vegetation assessment was used to estimate Manning's *n* values. The model ignored potential flows from smaller footslope tributaries. Note that this model was uncalibrated, relied on unverified input data, and used a very low resolution DEM, so is presented only as an indicative assessment of flooding risk. The results should not be used for any purpose other than this initial risk assessment.

A further model used the high (1 m) resolution DEM of the Project area. This DEM was limited in its spatial coverage so was only used to model flood heights in the Maralumi sub-catchment. It too was limited in its efficacy as it was also uncalibrated, and relied on unverified input data.

5.2.3 Sediment Transport

Overall Approach

Full details of the approach are contained within Appendix 1. The sediment yields for the four sub-catchments that the Project area overlays were determined using a catchment sediment budget approach, whereby the movement and storage of sediment throughout the contributing catchments were considered rather than just the theoretical transport capacity of the channel.

Note that due to the size of the Markham River catchment, compared with the four sub-catchments, the process described above was initially run only on the four sub-catchments overlain by the Project area to establish a baseline for the Project area and to enable potential impacts to be determined. Markham River sediment transport data described in Section 4.1 were used as the initial existing environment description for the greater Markham River catchment, for reasons described in Section 5.3.

Monte Carlo (MC) Simulation Method

The sediment model described above was set in a Monte Carlo (MC) framework. The MC framework enabled the uncertainty, variability and random nature of sediment generation and transport to be quantified using an iterative process that involved running model scenarios tens of thousands of times, each time using different input variables drawn at random from their pre-defined probability distribution functions (PDFs). The outcome of this process provided probabilities of different outcomes occurring, and the overall risk determined. This technique is particularly useful in situations where there is uncertainty and/or variability associated with input parameters and processes, by means of random sampling.

For each MC simulation, 160,000 sets of input variables were stochastically generated from their respective PDFs. The sediment yield model was run for each of these sets of variables, and the sediment yield evaluated. The computer program @Risk (Palisade Corporation, 2012) was used for the Monte Carlo simulation.

5.2.4 Channel Condition and Behaviour

Remote sensing methods, *in situ* photographs and descriptions provided by Fathom Pacific (2017) and analysis of the baseline hydrology and sediment transport regimes provided broad geomorphic descriptions and expected channel condition and behaviour. This enabled environmental values to be described for the Project area.

5.3 Impact Assessment

5.3.1 Hydrology

Two different sources of data were used to inform the hydrology impact assessment:

- Groundwater drainage[7] values predicted by White (2017) – for the purpose of this impact assessment, it has been assumed that all groundwater drainage was expressed as surface flow, so any impacts to this drainage directly affected surface flow volumes.

[7] Used in groundwater models to describe excess water that is unable to be stored in the soil or used by vegetation. Models are unable to predict its fate – it simply leaves the system. It may drain to the groundwater or become surface water flow. Given the sandy soils in the Markham Valley, most excess water described by the term groundwater drainage will become groundwater, with some expressed as surface water flow. However, actual volumes are unknown, so it has been assumed that all is expressed as surface water.

This is a highly conservative approach as not all would end up as surface water within the four sub-catchments.

- Power plant water balance – In addition to the impacts of vegetation changes, there will be uptake of water from bores near the Markham River that will be transported to the power plant using an above-ground pipeline. Given the proposed proximity of bores to the Markham River, impacts are likely to be only seen in the main river, but potential impacts have been assessed for all waterways. Figure 5-1 shows the water balance for the power plant. Actual volumes vary depending on the stage of the Project and have been described in the different scenarios below.

Using a monthly time step, White (2017) predicted that, at worst, there would be a reduction in groundwater drainage of 200 mm a^{-1} (probability – 0.1), when the planted area was at its greatest. Based on a net planted area of 16,000 ha, this drainage rate converted to approximately -1.01 $m^3 s^{-1}$ (i.e. a reduction). This value was used to develop four different 'developed' scenarios (in addition to the existing scenario), using slightly greater and smaller values based on the amount of planted area to indicate different stages of the Project. It must be noted that clearing and plantation establishment will be progressive over a number of years and the different stages of the Project (e.g. clearing/first rotation/harvesting/second rotation) will form a mosaic rather than occurring throughout in a prescribed order. As such, the different scenarios are, by necessity, simplified and conservative.

Increases/decreases in groundwater drainage (and resulting surface water flow) were initially calculated for each scenario for the entire planted area (16,000 ha) then allocated to the individual sub-catchments based on the proportion of the 16,000 ha of land under MOUs within each sub-catchment, as mapped in Figure 1-1. The following areas were used to calculate impacts to the various sub-catchments:

- Leron – 52.5% of all MOUs were within this sub-catchment (8,400 ha).
- Rumu – 29.5% of all MOUs were within this sub-catchment (4,720 ha).
- Maralumi – 18% of all MOUs were within this sub-catchment (2,880 ha).
- Erap – No MOUs were within this sub-catchment. As Maralumi and Erap River sub-catchments are likely to be somewhat interconnected, to provide a worst-case scenario, it has been assumed that impacts to the Erap River sub-catchment would be the same as those for the Maralumi River sub-catchment.
- Markham – 100% of all MOUs were within the greater Markham River catchment (16,000 ha).

Power plant and other water uses were also considered for the different scenarios. As it was not known which sub-catchment these water uses would affect, they were applied individually to all four sub-catchments and the Markham River.

The scenarios are summarised in Table 5-1 and explained below:

- **Scenario 1: Construction/Vegetation Clearing** – No construction phase was modelled by White (2017), so it was assumed that the entire 16,000 ha would be cleared, so there would be little to no evapotranspiration (except of standing water). In the absence of the above data, as a worst-case scenario, it was assumed there would be an increase in groundwater drainage of the same magnitude as the reduction caused by the fully established plantation (see Scenario 4), and a resulting increase in surface water flow of 200 mm a^{-1} (1.01 $m^3 s^{-1}$) over the 16,000 ha Project area (compared to existing). Also during construction, there will be a total water use of 0.005 $m^3 s^{-1}$ for nursery and construction purposes. This resulted in the following increases in groundwater drainage in the individual sub-catchments:
  - Leron – 0.525 $m^3 s^{-1}$ (52.5% of 1.01 minus 0.005).
  - Rumu – 0.293 $m^3 s^{-1}$ (29.5% of 1.01 minus 0.005).
  - Maralumi – 0.177 $m^3 s^{-1}$ (18% of 1.01 minus 0.005).
  - Erap – 0.177 $m^3 s^{-1}$ (as per Maralumi).
  - Markham – 1.005 $m^3 s^{-1}$ (100% of 1.01 minus 0.005).
- **Scenario 2: Establishment** – This scenario was developed to consider the early stages of the Project (2019-2022) where trees were not fully grown and/or some cleared areas remained. A nominal average increase in drainage (compared to existing) of 60 mm a^{-1} was assumed. The value was selected to provide a conservative estimate between the existing scenario and Scenario 1 that reflected the fact that cleared areas may still be present and that the vegetation that was present was still establishing. This drainage value converted to 0.30 $m^3 s^{-1}$. During this stage, only one power plant will be operational and so, as Figure 5-1 shows, there will be an uptake of 78.12 t h^{-1} (~0.022 $m^3 s^{-1}$) and a return of 21.9 t h^{-1} (~0.006 $m^3 s^{-1}$), resulting in a total power plant usage of 0.016 $m^3 s^{-1}$ (0.022-0.006). This resulted in the following increases in groundwater drainage in the individual sub-catchments:
  - Leron – 0.142 $m^3 s^{-1}$ (52.5% of 0.30 minus 0.016).
  - Rumu – 0.073 $m^3 s^{-1}$ (29.5% of 0.30 minus 0.016).
  - Maralumi – 0.038 $m^3 s^{-1}$ (18% of 0.30 minus 0.016).
  - Erap – 0.038 $m^3 s^{-1}$ (as per Maralumi).
  - Markham – 0.284 $m^3 s^{-1}$ (100% of 0.30 minus 0.016).
- **Scenario 3: Harvesting** – This scenario was developed to consider the stage where trees were not all fully grown and/or stages where there was some harvesting occurring. As such, a nominal average reduction in runoff of 60 mm a^{-1} (compared to existing) was assumed, which converted to -0.30 $m^3 s^{-1}$. The value was selected to provide a conservative estimate between the existing scenario and the fully planted scenario (Scenario 4) that reflected the increased evapotranspiration that would occur during harvesting compared with the existing scenario, and the smaller net planted area (and reduced evapotranspiration) compared with Scenario 4. During this stage, both units of the power plant will be operational and so, as Figure 5-1 shows, there will be an uptake of 156.24 t h^{-1} (~0.044 $m^3 s^{-1}$) and a return of 43.8 t h^{-1} (~0.012 $m^3 s^{-1}$), resulting in

a total power plant usage of -0.032 $m^3 s^{-1}$ (0.044-0.012). This resulted in the following decreases in groundwater drainage in the individual sub-catchments:

- Leron – -0.190 $m^3 s^{-1}$ (52.5% of -0.30 minus 0.032).
- Rumu – -0.121 $m^3 s^{-1}$ (29.5% of -0.30 minus 0.032).
- Maralumi – -0.086 $m^3 s^{-1}$ (18% of -0.30 minus 0.032).
- Erap – -0.086 $m^3 s^{-1}$ (as per Maralumi).
- Markham – -0.332 $m^3 s^{-1}$ (100% of -0.30 minus 0.032).

- **Scenario 4: Established** – This phase considered the impacts during the period where the plantation was well-established, and consisted of a mosaic of tree age classes. As such, it used the value of -1.01 $m^3 s^{-1}$ described above. In all likelihood, this value is very unlikely to occur, but provides a worst-case scenario. During this stage, two power plants will be operational and so, as Figure 5-1 shows, there will be an uptake of 156.24 t h^{-1} (~0.044 $m^3 s^{-1}$) and a return of 43.8 t h^{-1} (~0.012 $m^3 s^{-1}$), resulting in a total power plant usage of -0.032 $m^3 s^{-1}$ (0.044-0.012). This resulted in the following decreases in groundwater drainage in the individual sub-catchments:
  - Leron – -0.562 $m^3 s^{-1}$ (52.5% of -1.01 minus 0.032).
  - Rumu – -0.330 $m^3 s^{-1}$ (29.5% of -1.01 minus 0.032).
  - Maralumi – -0.214 $m^3 s^{-1}$ (18% of -1.01 minus 0.032).
  - Erap – -0.214 $m^3 s^{-1}$ (as per Maralumi).
  - Markham – -1.042 $m^3 s^{-1}$ (100% of -1.01 minus 0.032).

The above values were either subtracted or added to the existing daily flow volumes that were developed as part of the existing environment to develop surface flow duration curves for the different scenarios. These were then used to compare against the existing duration curves to measure potential impact.

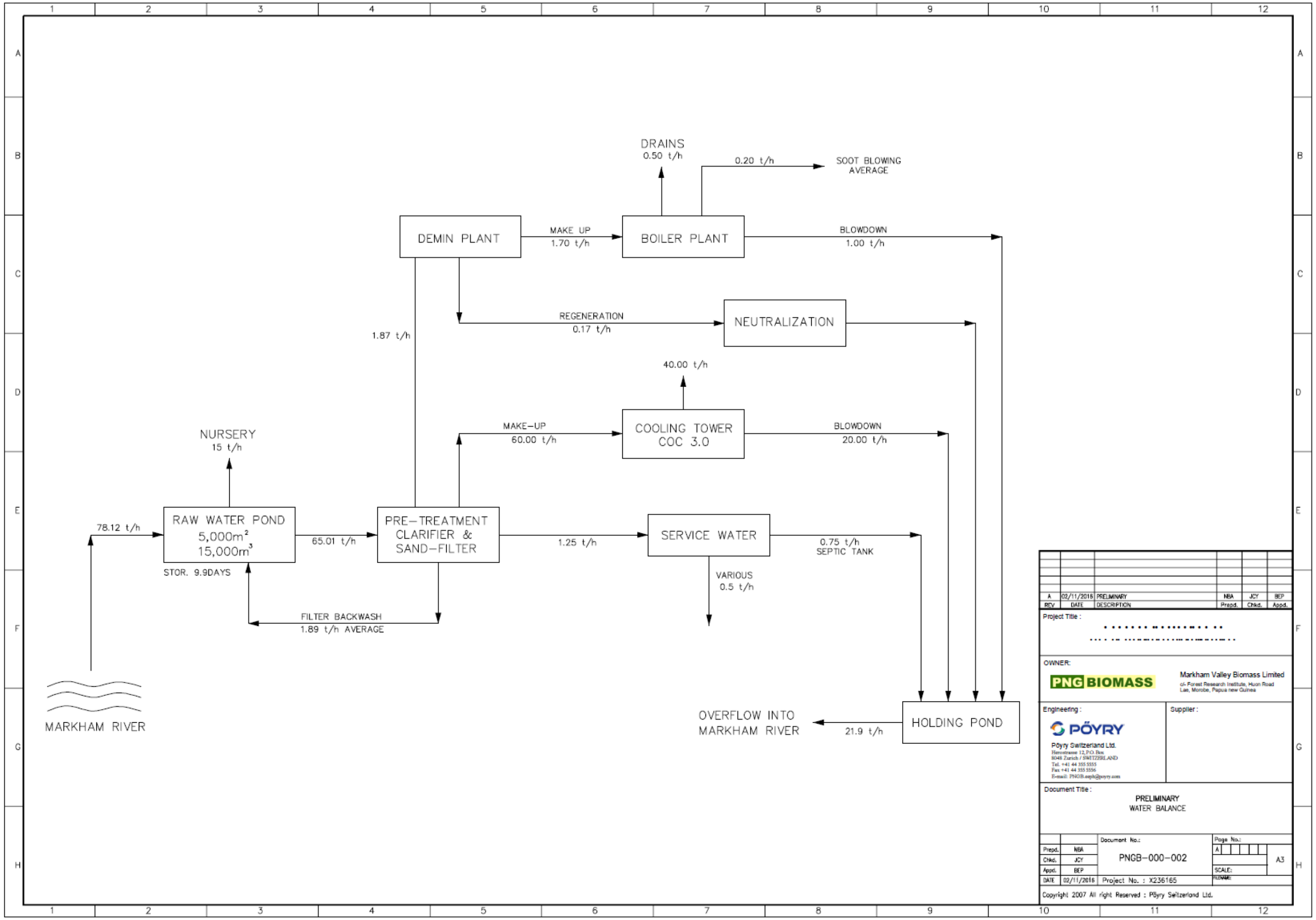

Figure 5-1 Water balance for each 15 MW power plant unit (water balance doubles for two units) (Source: Pöyry (2012))

Table 5-1 Impacts to surface water flow from vegetation and power plant water use for all impact scenarios

Scenario	Vegetation Impacts	Power Plant Impacts			
	Change to Groundwater Drainage (Vegetation Impacts) (m3 s^{-1})	Power Plant Water Uptake from Bores (m3 s^{-1})	Power Plant Water Release into Waterways (m3 s^{-1})	Total Change to Surface Flow from Power Plant Water Use (m3 s^{-1})	Total Change to Surface Water Flow (m3 s^{-1})
Leron River – 52.5% of 16,000 ha (8,400 ha)					
1 – Construction/ Vegetation Clearing	+0.530	-0.005	N/A	-0.005	+0.525
2 – Establishment	+0.158	-0.022	+0.006	-0.016	+0.142
3 – Harvesting	-0.158	-0.044	+0.012	-0.032	-0.190
4 – Established	-0.530	-0.044	+0.012	-0.032	-0.562
Rumu River – 29.5% of 16,000 ha (4,720 ha)					
1 – Construction/ Vegetation Clearing	+0.298	-0.005	N/A	-0.005	+0.293
2 – Establishment	+0.089	-0.022	+0.006	-0.016	+0.073
3 – Harvesting	-0.089	-0.044	+0.012	-0.032	-0.121
4 – Established	-0.298	-0.044	+0.012	-0.032	-0.330
Maralumi River – 18% of 16,000 ha (2,880 ha)					
1 – Construction/ Vegetation Clearing	+0.182	-0.005	N/A	-0.005	+0.177
2 – Establishment	+0.054	-0.022	+0.006	-0.016	+0.038
3 – Harvesting	-0.054	-0.044	+0.012	-0.032	-0.086
4 – Established	-0.182	-0.044	+0.012	-0.032	-0.214
Erap River – as per Maralumi River					
1 – Construction/ Vegetation Clearing	+0.182	-0.005	N/A	-0.005	+0.177
2 – Establishment	+0.054	-0.022	+0.006	-0.016	+0.038
3 – Harvesting	-0.054	-0.044	+0.012	-0.032	-0.086
4 – Established	-0.182	-0.044	+0.012	-0.032	-0.214
Markham River – 100% of 16,000 ha					
1 – Construction/ Vegetation Clearing	+1.01	-0.005	N/A	-0.005	+1.005
2 – Establishment	+0.30	-0.022	+0.006	-0.016	+0.284
3 – Harvesting	-0.30	-0.044	+0.012	-0.032	-0.332
4 – Established	-1.01	-0.044	+0.012	-0.032	-1.042

Note: A + value indicates an increase in surface water flow. A – value indicated a reduction in surface water flow. Green highlighted cells are those used to calculate the total change.

5.3.2 Flooding

The basic two-dimensional HEC-RAS models were re-run using 100-day flow hydrographs that closely resembled the 100-year ARI and 500-year ARI for impact Scenario 4 as input hydrographs for the model. These hydrographs were derived from the daily flow records. BAAM (2016) vegetation assessment was used to estimate Manning's *n* values for those areas not under MOUs, while those areas under MOUs were assigned a Manning's *n* value that reflected their plantation land use. The model ignored potential flows from smaller footslope tributaries.

5.3.3 Sediment Transport

Leron, Erap, Rumu, Maralumi Rivers

To evaluate impacts on sediment yield, the sediment yield model was rerun replacing the *C*-factor within the model for the different MOUs in the Project area with values to represent the land cover of a plantation. The *C*-factor values for the remaining catchment areas were not altered for this assessment. All other parameters were also left unchanged. The same four different impact scenarios described above were investigated to ensure the potential impacts of the different stages of the Project were investigated. As described above, these scenarios were very conservative and provided a worst-case scenario from a sediment transport perspective. The scenarios were:

1. **Scenario 1: Construction/Vegetation Clearing** – no ground cover, including the power plant area.
2. **Scenario 2: Establishment** – Trees are not fully grown and/or some cleared areas remain.
3. **Scenario 3: Harvesting** – low canopy cover, power plant area fully developed. Trees are not all fully grown, and there has been some harvesting.
4. **Scenario 4: Established** – high canopy cover, power plant area fully developed. Plantation is well-established, but there is a mosaic of tree age classes.

The *C*-factor values for each of the above scenarios (and the existing scenario) are provided in Table 5-2. These values were used to develop a discrete PDF of *C*-values across the four sub-catchments from which *C*-factor values could be drawn within the MC framework. The actual planting and harvesting plans were not known during the assessment, so it was impossible to determine how much of each sub-catchment would be planted. As such, the probabilities of different *C*-factor values occurring were calculated for the whole Project area then applied to each individual sub-catchment, based on the area under MOUs within each catchment.

The exact amount of sedimented runoff that would enter different waterways within each sub-catchment will vary according to the proportion of the sub-catchment that is under plantation. As such, as a worst-case scenario, assessments of individual waterways assumed that all sediments generated across the Project area were being delivered to that waterway and no other. This is, of course, unrealistic, but it offers a worst-case scenario *in lieu* of actual data.

Table 5-2 *C*-factor values for the existing and developed scenarios

C-Factor Category	C Value	Existing Probability	Scenario 1 Probability	Scenario 2 Probability	Scenario 3 Probability	Scenario 4 Probability
Development	0.002	0.13	0.13	0.13	0.13	0.13
Forest	0.004	66.18	66.17	66.17	66.17	66.17
Grass	0.050	29.10	23.31	23.31	23.31	23.31
Waterway	0.000	2.49	2.49	2.49	2.49	2.49
Disturbed Forest	0.050	0.91	0.91	0.91	0.91	0.91
Modified Garden Areas	0.125	0.12	0.12	0.12	0.12	0.12
Shrubland	0.050	0.08	0.00	0.00	0.00	0.00
Mixed grass/shrub/wood	0.050	0.22	0.00	0.00	0.00	0.00
Plantation	0.050	0.39	0.39	0.39	0.39	0.39
Disturbed Grassland	0.500	0.19	0.19	0.19	0.19	0.19
Village Area	0.200	0.16	0.16	0.16	0.16	0.16
Woodland: degraded ground cover	0.1000	0.02	0.02	0.02	0.02	0.02
Plantation Initial Growth	0.150	0.00	0.00	3.04	0.00	0.00
Plantation Mid Growth	0.070	0.00	0.00	0.00	3.04	0.00
Plantation Full Growth	0.050	0.00	0.00	0.00	3.04	6.09
Power Plant	0.002	0.00	0.00	0.01	0.01	0.01
Plantation Cleared	0.400	0.00	6.10	3.04	0.00	0.00
Total	N/A	100.00	100.00	100.00	100.00	100.00

Markham River

As discussed earlier, no sediment transport model was developed for the Markham River, as the size of the catchment would have made it difficult to develop a reliable model without considerable (unavailable) data inputs. Instead, the impact assessment initially considered impacts to the four sub-catchments and the following process was followed to measure Markham River impacts and significance:

- Where residual impacts to sediment transport of the four sub-catchments were considered negligible to minor, it was assumed that impacts to the Markham River sediment transport were also negligible to minor.
- If residual impacts were more significant than minor, this would instigate the development of a sediment transport model for the Markham River. This threshold was developed as it enabled a more efficient process and reduced the volume of synthetic data being used for the assessment. It was also logical to assume that if impacts to the sub-catchment were expected to be minor, that there would be similarly negligible impacts to Markham River. As all residual impacts were considered negligible to minor, this step was not undertaken.
- All impacts to off river wetlands were already being considered as part of the impact assessment of the four sub-catchments, so were not considered in this section.

5.3.4 Channel Condition and Behaviour

Remote sensing methods, *in situ* photographs and descriptions provided by Fathom Pacific (2017) and analysis of the hydrology and sediment transport impact assessments enabled the development of predictions of channel response to the Project.

5.3.5 Impact Significance Assessment Method

As with other components of the Project, residual impacts have been assessed by considering both the magnitude of the impact (after the successful application of impact avoidance or management measures) and the sensitivity of the environment (environmental value – EV) being impacted. As defined in the *Environment Act 2000*, a beneficial EV is:

> *a quality or characteristic of the environment or any element or segment of the environment, which (a) is conducive to ecological health, public benefit, welfare, safety, health or aesthetic enjoyment and which requires protection from environmental harm; or (b) is declared in an Environment Policy or permit to be a beneficial value*

The term 'environmental value' has been used in this document to encompass this definition and includes resources, sites, and other receptors as considered relevant. EVs relevant to hydrology and sediment transport environments are provided in more detail in Sections 5.3.6 and 7.4.

This approach has allowed determination of the impact's significance via a matrix, as discussed further below.

Magnitude of Impact

The magnitude of an impact reflects the size and nature of change based on its severity, geographical extent and duration. For the purposes of this assessment, these elements have been defined as follows:

- Severity: the scale or degree of change (both positive and negative) from the existing condition as a result of the impact.
- Geographical extent: the spatial extent of the impact where this is defined as site, local, regional or widespread (provincial, national or trans-boundary).
- Duration: the timescale of the effect, such as short, medium or long term (i.e., effectively permanent), and considers reversibility.

The magnitude of impact has therefore been ranked as high, moderate, low and negligible, as described in Table 5-3, with positive impacts (or benefits) also being included but not ranked. It should be noted that, where the magnitude of impact is ranked as negligible, the overall impact significance is also ranked as negligible regardless of the sensitivity of the EV, resource or receptor that is being impacted.

Table 5-3 Criteria for Magnitude of Impact

• Magnitude	• Description
High	An impact that is long lasting, widespread, and leads to substantial and possibly irreversible change to the value, resource or receptor. With regard to hydrology and sediment transport, this refers to a >15% increase or decrease of volume of water/sediment.
Moderate	An impact that is short term and is contained within the region where the Project is being developed, but that extends beyond the area of disturbance to the surrounding area. With regard to hydrology and sediment transport, this refers to a 10-15% increase or decrease of volume of water/sediment.
Low	An impact that is temporary or short term and localised, and where the change is barely detectable with respect to natural variability. With regard to hydrology and sediment transport, this refers to a 5-10% increase or decrease of volume of water/sediment.
Negligible	An impact that is highly transient or very short term, highly localised, and easily remediated, and where the change is unlikely to be detectable with respect to natural variability. With regard to hydrology and sediment transport, this refers to a <5% increase or decrease of volume of water/sediment.
Positive	A beneficial impact on an environmental value.

Sensitivity of an Environmental Value

The Project has assessed relevant EVs as described in statutory guidelines or policy, or where these are not defined, determined on the basis of experience and accepted practice. The sensitivity of an EV is then determined on the basis of a range of factors such as its:

- Formal status, where this may be assigned by statutory and/or regulatory authorities, or appropriately-recognised national and/or international organisations. This can involve legislation, regulations or international conventions or other mechanisms that attribute a particular status to a value.
- Rarity or uniqueness within and beyond the immediate area of interest, i.e., its vulnerability, and the capacity for the value to be replaced.
- Capacity to adapt to change without adversely effects on the EV's inherent attributes, i.e., its resilience.
- Importance to local communities and society, and/or its iconic or symbolic importance to cultural value systems.

Sensitivity has been ranked as high, moderate or low, as described in Table 5-4.

Table 5-4 Criteria for Sensitivity of an Environmental Value

Sensitivity	Description
High	• The EV is intact and retains its intrinsic attributes • The EV is listed as being of conservation significance on a statutory or recognised international, national or state register • The EV is unique to the environment in which it occurs. It is isolated to the affected area or system, and is poorly represented in the region, territory, country or the world • The EV has not been exposed to threatening processes, or there has not been a noticeable impact on its integrity • Project activities would have an adverse effect on the EV • Potentially affected communities are highly reliant on the EV, e.g., it may be the primary or only source of food or income (i.e., the primary provisioning or regulating ecosystem service) for the community • The EV highly important from a cultural heritage perspective
Moderate	• The EV is recognised as being important at a regional level and may have been nominated for listing on recognised or statutory registers • The EV is in a moderate to good condition and retains many of its key characteristics and structural elements • The EV is relatively well represented in the areas/systems in which it occurs, but its distribution and abundance are limited by threatening processes • Threatening processes have reduced the EV's resilience to change. As such, changes resulting from project activities may lead to degradation • Due to the abundance and distribution of the EV, replacement of unavoidable losses is possible • Potentially affected communities are somewhat reliant on the EV, resource or receptor. The EV is one of a number of food sources or income streams and is not the primary or only provisioning or regulating ecosystem service available to the community • The EV is moderately important from a cultural heritage perspective
Low	• The EV is not listed on any recognised or statutory register, but may be recognised locally by relevant and suitably qualified experts or organisations • The EV is in a poor to moderate condition • The EV is not rare or unique, and numerous representative examples exist throughout the area/system • The EV is widely distributed and abundant throughout the host area or system • Change is not expected to result in further degradation of the EV, or there is no detectable response to change • Replacement of unavoidable losses is assured due to the abundance and wide distribution of the EV • Potentially affected communities are not reliant on the EV, resource or receptor. The EV is not an important or regularly used source of food or income (it is an occasional ecosystem service) for the community • The value is not important from a cultural heritage perspective

Not all the attributes listed in Table 5-3 and Table 5-4 may be applicable to a specific impact EV, or may be contradictory, with the application of these criteria sometimes leading to inconsistent outcomes. For example, impacts that are widespread (with a high magnitude of impact) may also be barely detectable (with a low magnitude of impact). Where this occurs, professional judgement has been used to determine the criteria of most relevance and the overall impact significance.

Impact Significance

The significance of an impact on an EV is determined by combining the likely magnitude of the impact on that EV with its sensitivity via a matrix based on the above criteria. This approach is shown in Table 5-5.

Table 5-5 Significance Assessment Matrix

		Sensitivity of Environmental Value		
		High	**Moderate**	**Low**
Magnitude of Impact	**High**	Major	High	Moderate
	Moderate	High	Moderate	Low
	Low	Moderate	Low	Low
	Negligible	Negligible	Negligible	Negligible
	Positive	Positive	Positive	Positive

The magnitude of an impact is assessed after the application of avoidance and management measures that change the impact's severity, geographical extent or duration. As noted above, this is combined with the EV's sensitivity, which generally remains unaltered unless proposed actions or activities reduce the susceptibility of that EV to adverse effects. The outcome is a determination of the significance of the residual impacts (i.e., the credible impacts associated with Project development.

5.3.6 Environmental Values and Impact Mechanisms

As part of the impact assessment, EVs for the Project area needed to be described. There were no known pre-existing documented EVs for hydrological or fluvial geomorphic features in the local study area. As such, these needed to be determined with regard to hydrology, sediment transport regime and geomorphic form and their contribution to ecological health and human community amenity and safety. This enabled impact mechanisms to be identified from which an impact assessment could be undertaken.

6 EXISTING ENVIRONMENT

6.1 Hydrology

Appendix 2 shows the long-term discharge time series for the Markham, Leron, Erap, Rumu and Maralumi Rivers. These series were created using the AWBM and Pickup rainfall-runoff models described above. The general flow statistics for the Markham River and four sub-catchments are shown in Table 6-1. Monthly flow duration curves were also created to identify the duration over which certain sized flows were exceeded. These curves are shown in Figure 6-1 to Figure 6-5.

It is evident from the table and figures that the two models predicted similar low exceedance flows (higher magnitude values), predicting maximum and 90th percentile flows (i.e. 10% probability of exceedance) of similar magnitude. However, the Pickup model predicted much higher more frequent flows, with the median and 10th percentile flows (i.e. 90% probability of exceedance) being an order of magnitude higher. These differences were likely due to the different runoff parameters within each of the model and, in the absence of any validation data, the two models have been used as an upper and lower limit. Flows are likely to be within the bounds of these two models.

The limited available Markham River flow summary data (Table 4-1) were used to somewhat validate the model results, with the Pickup model predicting similar median discharge. Both models predicted higher maximum flows than those recorded by SMEC (1990); however, the SMEC estimate was based on seven years of data so this was expected considering the smaller temporal variation that would be evident over a seven-year period.

Regardless of the differences between the models, it was evident that all rivers displayed similarly low mean and median flows relative to their higher magnitude flows, and showed high variability. The high range between the 10th and 90th percentiles indicated that there was considerable hydrological seasonality, but this was partly an artefact of the modelling method, although the rainfall records and literature support this finding (McAlpine & Keig, 1983). This is further evidenced by Figure 6-6, Figure 6-7, and Figure 6-8, with clear seasonality in all four sub-catchments and Markham River catchment.

As discussed in Section 4.2.5, the flooding regime of the major waterways heavily influences the wetness of the ephemeral off-river wetlands. The high-level flooding assessment of the four sub-catchments identified that much of the floodplain of the four sub-catchments would be inundated for the 100-year and 500-year ARIs (Figure 6-9 and Figure 6-10). The proposed location of the power plant was shown to not be inundated by both the 100- and 500-year ARIs, but its location is close to the flood extent for both events. The use of the 1 m DEM showed more extensive flooding in the Maralumi catchment, but little risk to the power plant in both the 100- and 500-year ARIs.

Table 6-1 General hydrological statistics for the study sub-catchments

Sub-Catchment	Maralumi Sub-Catchment		Leron Sub-Catchment		Rumu Sub-Catchment		Erap Sub-Catchment		Markham Sub-Catchment		
Model	Pickup	AWBM	Pickup	AWBM	Pickup	AWBM	Pickup	AWBM	Pickup	AWBM	Regional Flood Frequency
General Statistics											
Percentile 10 ($m^3 s^{-1}$)[8]	2.08	0.05	14.94	0.38	4.72	0.12	5.83	0.15	134.58	3.38	N/A
Percentile 90 ($m^3 s^{-1}$)[9]	9.77	9.46	70.05	68.00	22.13	21.49	27.34	26.54	630.96	612.51	N/A
Maximum ($m^3 s^{-1}$)	236.97	203.62	1698.70	1463.75	536.50	462.57	662.97	571.28	15300.30	13183.96	N/A
Mean ($m^3 s^{-1}$)	7.10	3.64	50.86	26.15	16.06	8.26	19.85	10.21	458.14	235.52	N/A
Median ($m^3 s^{-1}$)[10]	5.22	0.83	37.42	5.99	11.82	1.89	14.60	2.34	337.00	53.91	N/A
Standard Deviation ($m^3 s^{-1}$)	10.80	8.61	77.41	61.90	24.45	19.56	30.21	24.16	697.19	557.52	N/A
Mean Daily Baseflow ($m^3 s^{-1}$)	3.88	0.82	27.79	5.88	8.78	1.86	10.84	2.30	250.27	52.95	N/A
Flood Frequency report											
1 Year ARI ($m^3 s^{-1}$)	84.36	46.77	559.40	336.19	176.68	126.86	218.32	156.67	5031.57	3028.04	N/A
2 Year ARI ($m^3 s^{-1}$)	100.78	69.36	692.47	498.59	218.70	174.27	270.26	215.22	6262.01	4490.83	3688.87
5 Year ARI ($m^3 s^{-1}$)	119.67	90.47	835.97	650.39	264.03	218.94	326.27	270.39	7560.24	5858.09	4337.28
10 Year ARI ($m^3 s^{-1}$)	134.38	108.84	970.79	782.41	304.25	247.26	375.97	305.36	8676.71	7047.20	4769.55
20 Year ARI ($m^3 s^{-1}$)	152.52	126.86	1097.01	911.95	345.30	288.19	426.70	355.92	9847.58	8213.89	5177.81
50 Year ARI ($m^3 s^{-1}$)	179.30	153.60	1285.33	1104.21	405.95	348.95	501.64	430.95	11577.02	9945.56	5682.13
100 Year ARI ($m^3 s^{-1}$)	200.07	174.49	1434.21	1254.33	452.97	396.39	555.06	489.54	12918.02	11297.74	6090.39
500 Year ARI ($m^3 s^{-1}$)	270.09	235.56	1936.18	1693.35	611.51	535.13	749.34	660.88	17439.32	15251.95	8222.02

[8] The 10th percentile has a 90% probability of exceedance at any one time. The figures below use 'probability of exceedance' rather than percentiles.
[9] The 90th percentile has a 10% probability of exceedance at any one time. The figures below use 'probability of exceedance' rather than percentiles.
[10] The median flow (50th percentile) has a 50% probability of exceedance at any one time. The figures below use 'probability of exceedance' rather than percentiles.

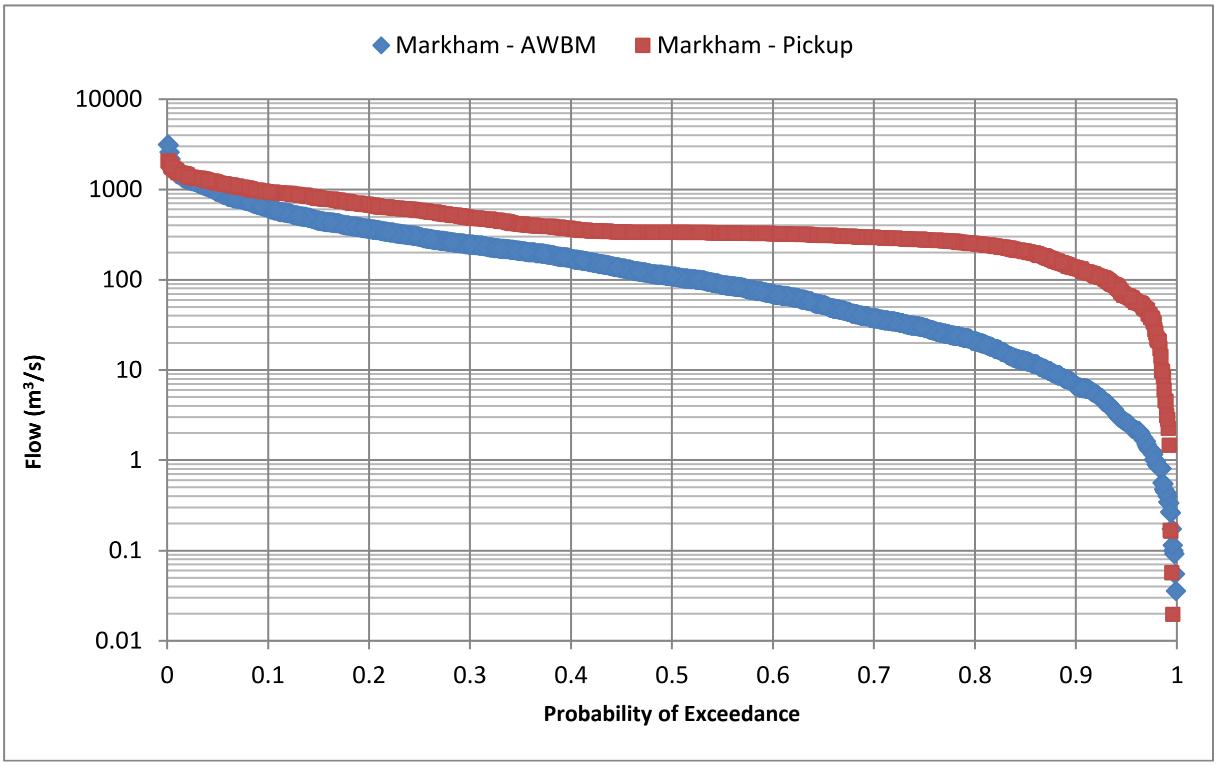

Figure 6-1 Markham River catchment flow duration curves for the two models

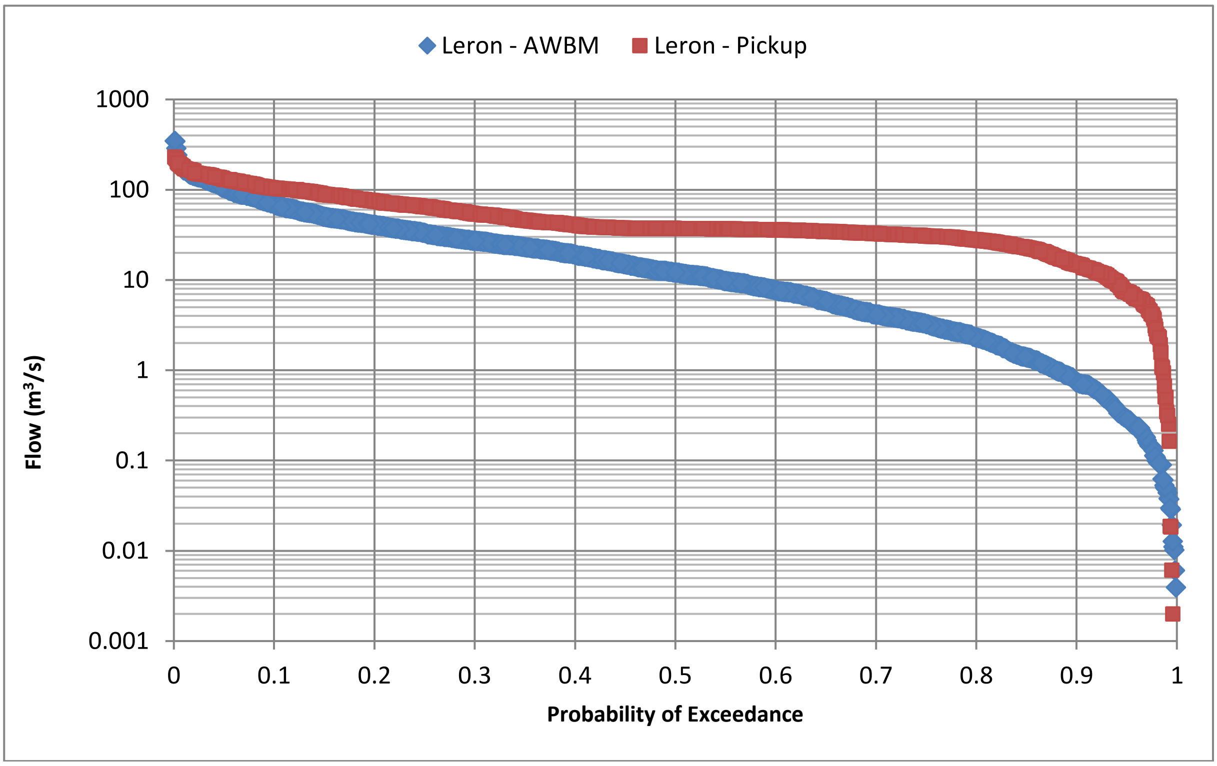

Figure 6-2 Leron River sub-catchment flow duration curves for the two models

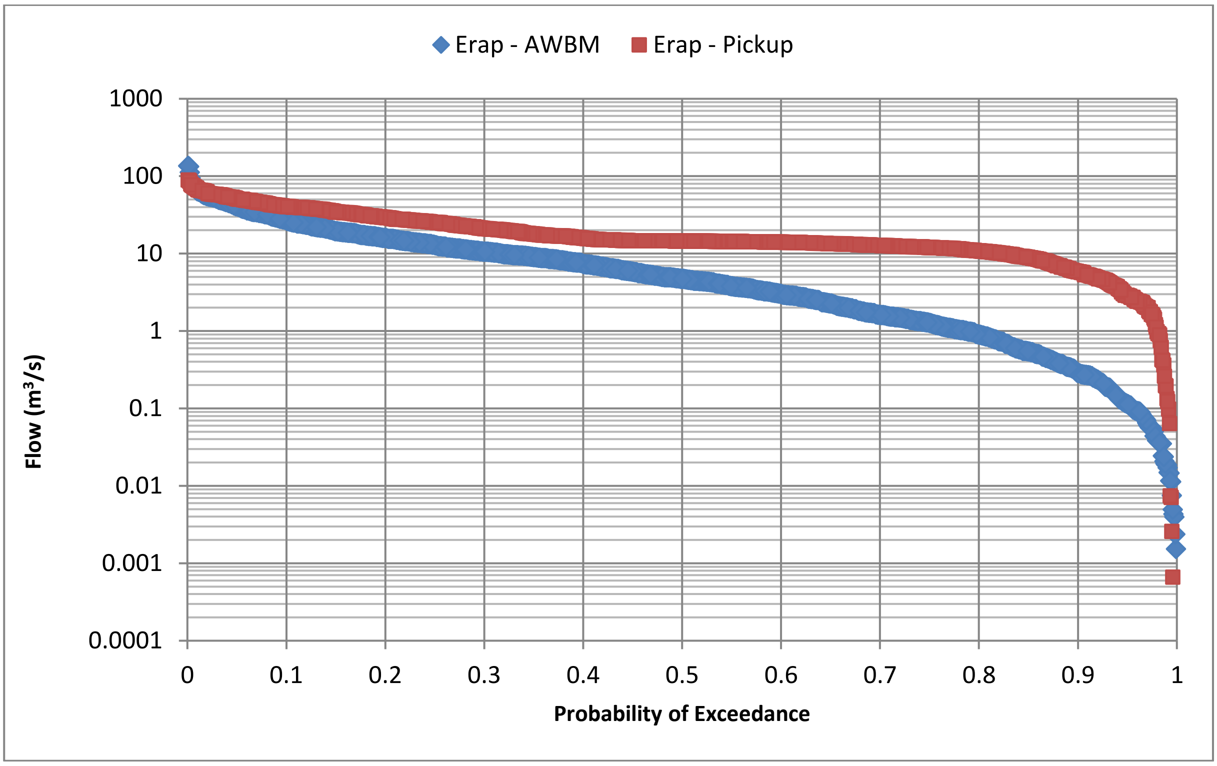

Figure 6-3 Erap River sub-catchment flow duration curves for the two models

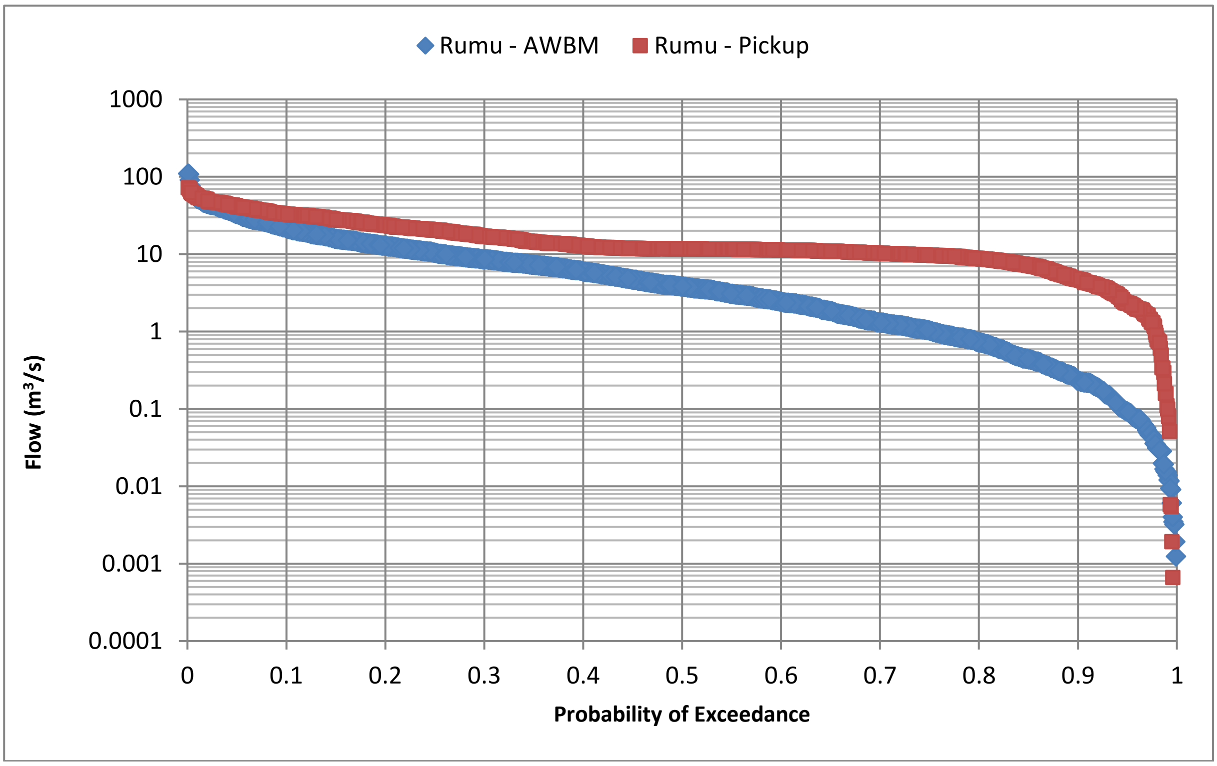

Figure 6-4 Rumu River sub-catchment flow duration curves for the two models

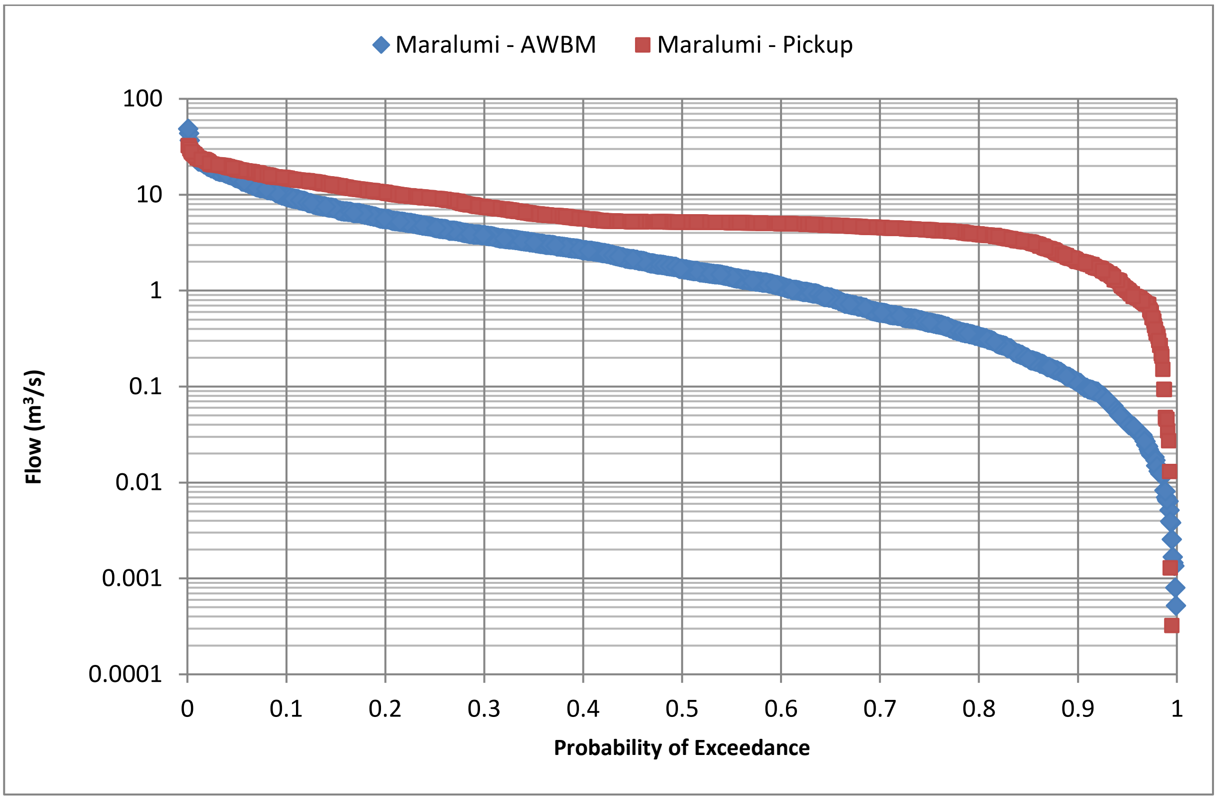

Figure 6-5 Maralumi River sub-catchment flow duration curves for the two models

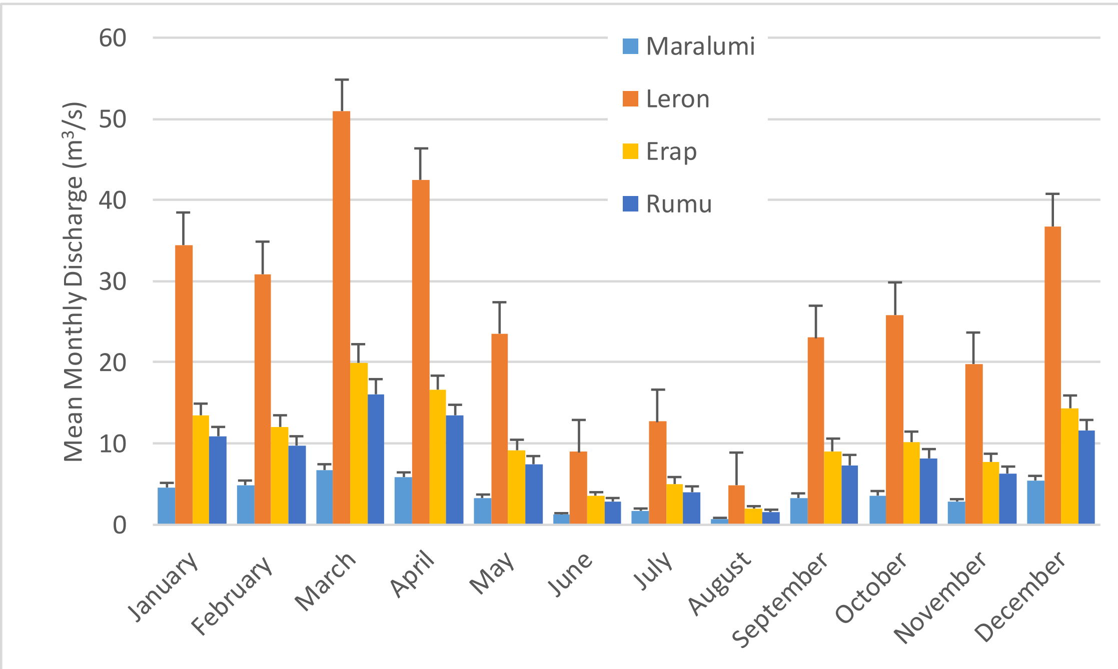

Figure 6-6 Monthly mean daily flows for the four sub-catchments (AWBM model). Error bars show standard error.

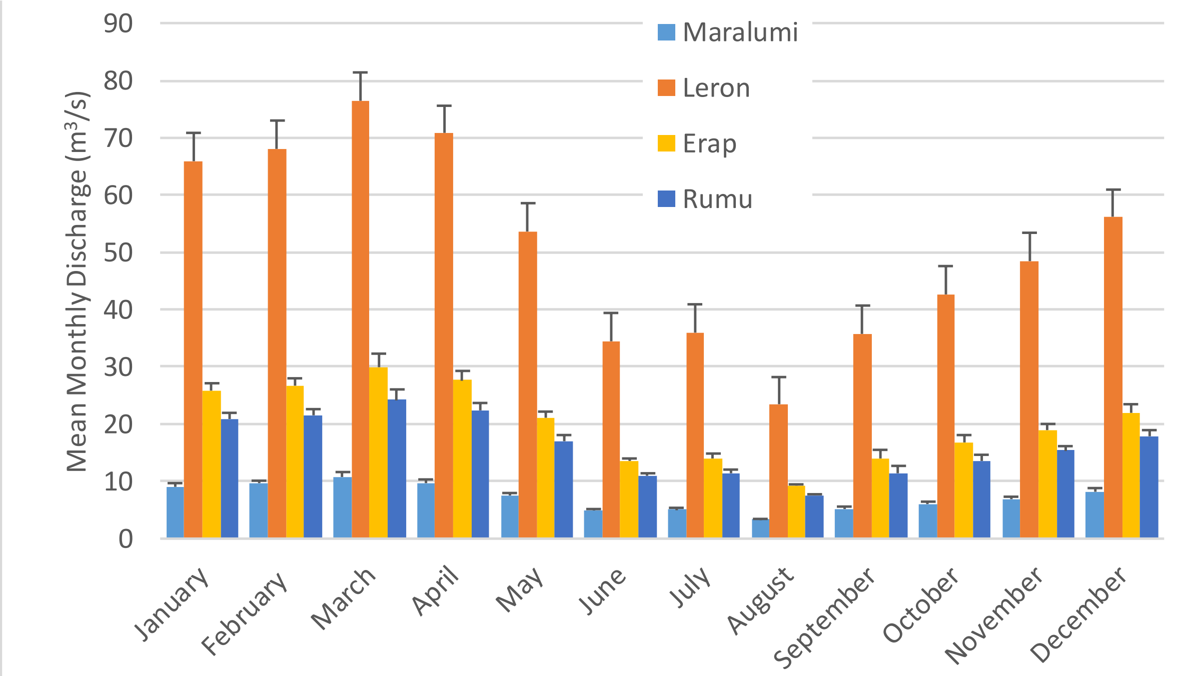

Figure 6-7 Monthly mean daily flows for the four sub-catchments (Pickup model). Error bars show standard error.

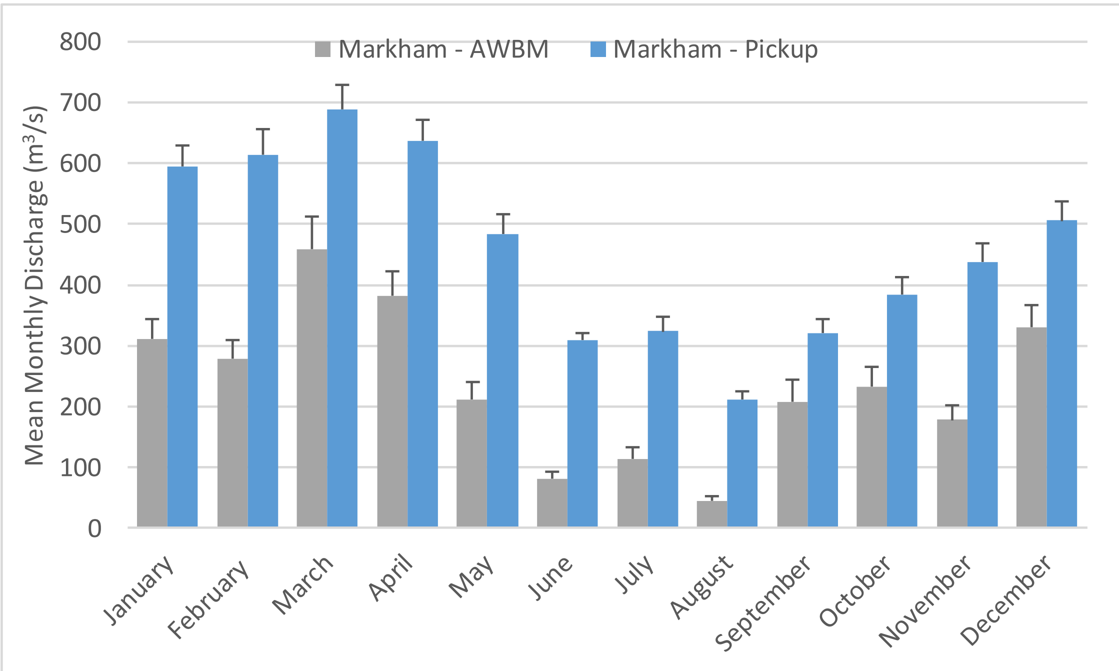

Figure 6-8 Monthly mean daily flows for Markham River (AWBM model). Error bars show standard error.

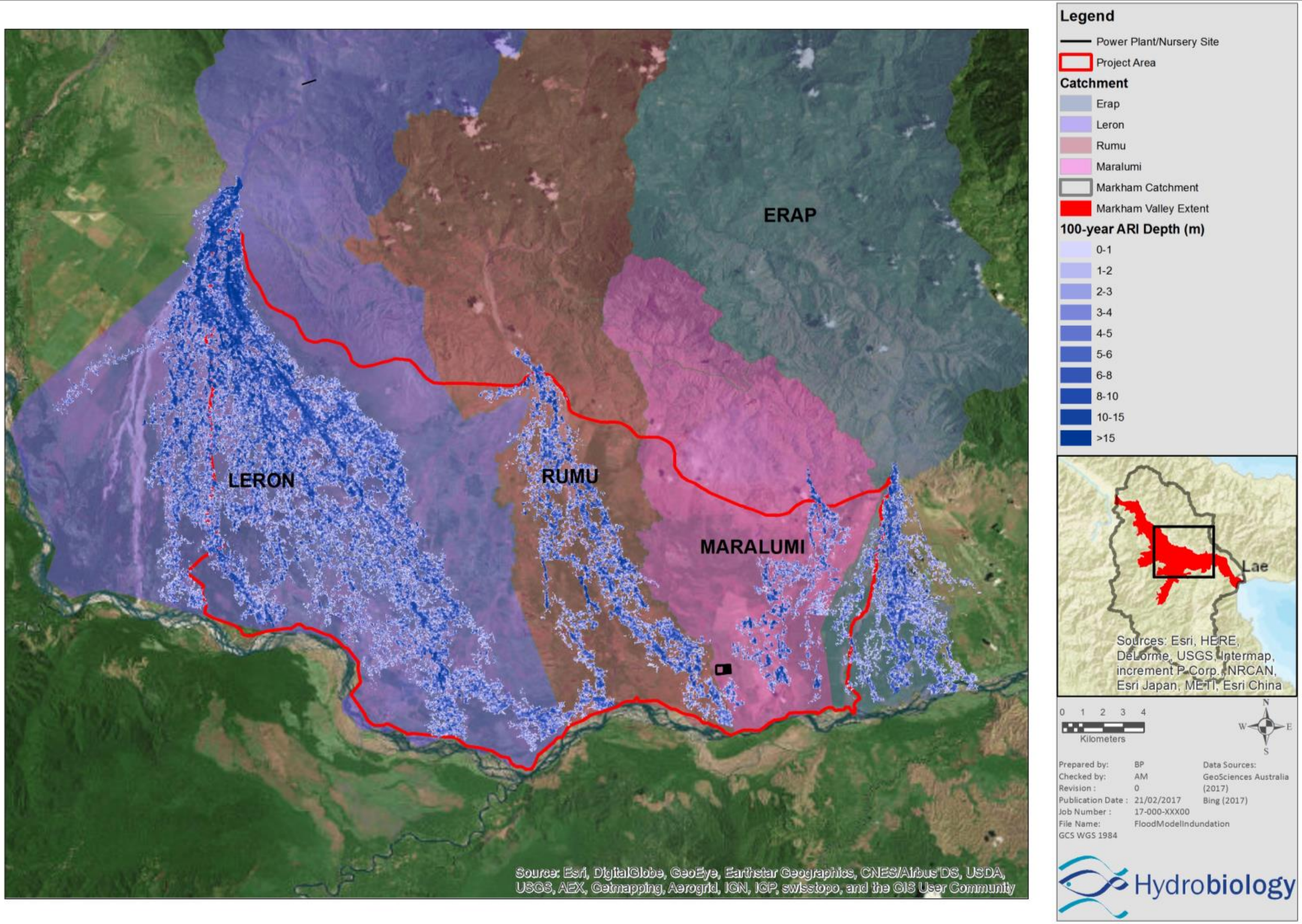

Figure 6-9 Modelled flood inundation extents for the Project area resulting from simultaneous 100-year ARI flows in all four sub-catchments, showing the approximate location of the power plant site and the Project area

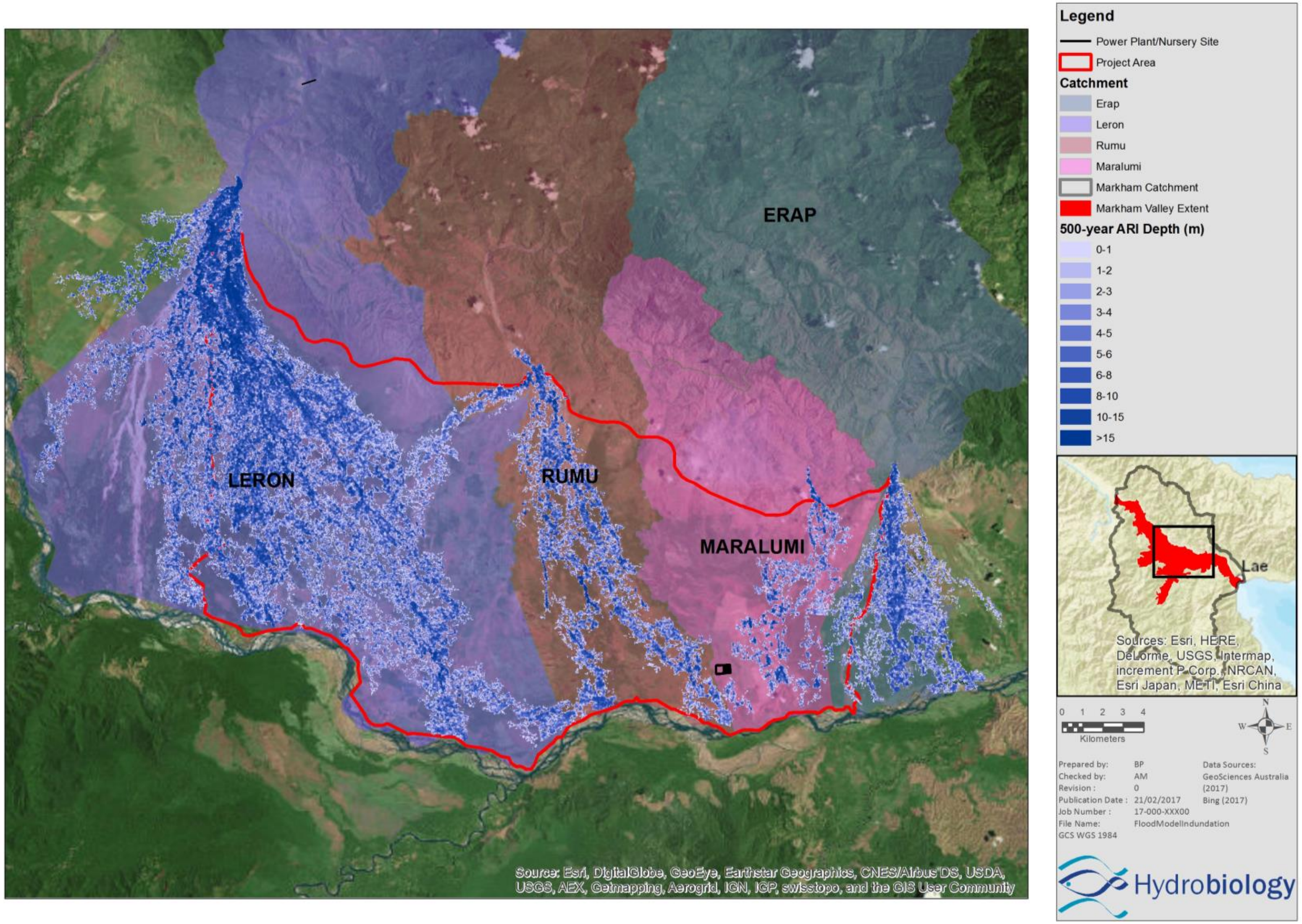

Figure 6-10 Modelled flood inundation extents for the Project area resulting from simultaneous 500-year ARI flows in all four sub-catchments, showing the approximate location of the power plant site and the Project area

6.2 Sediment Transport

Results from the coarse sediment yield model for Leron, Erap, Rumu and Maralumi River sub-catchments are presented in the form of a box-and whisker plot (Figure 6-11). It shows median sediment yields of 1,654,000; 471,000; 518,000; and 132,000 $m^3\ a^{-1}$ respectively, meaning that there is a 50 % chance of these values occurring in any one year. The plots also showed considerable variability around the median value, with highly positively skewed distributions for all model iterations. This implies that very high rates of sediment replenishment would occur during less frequent major flow events. This is typical of environments that are exposed to highly variable rainfall, like this region of the Markham River catchment.

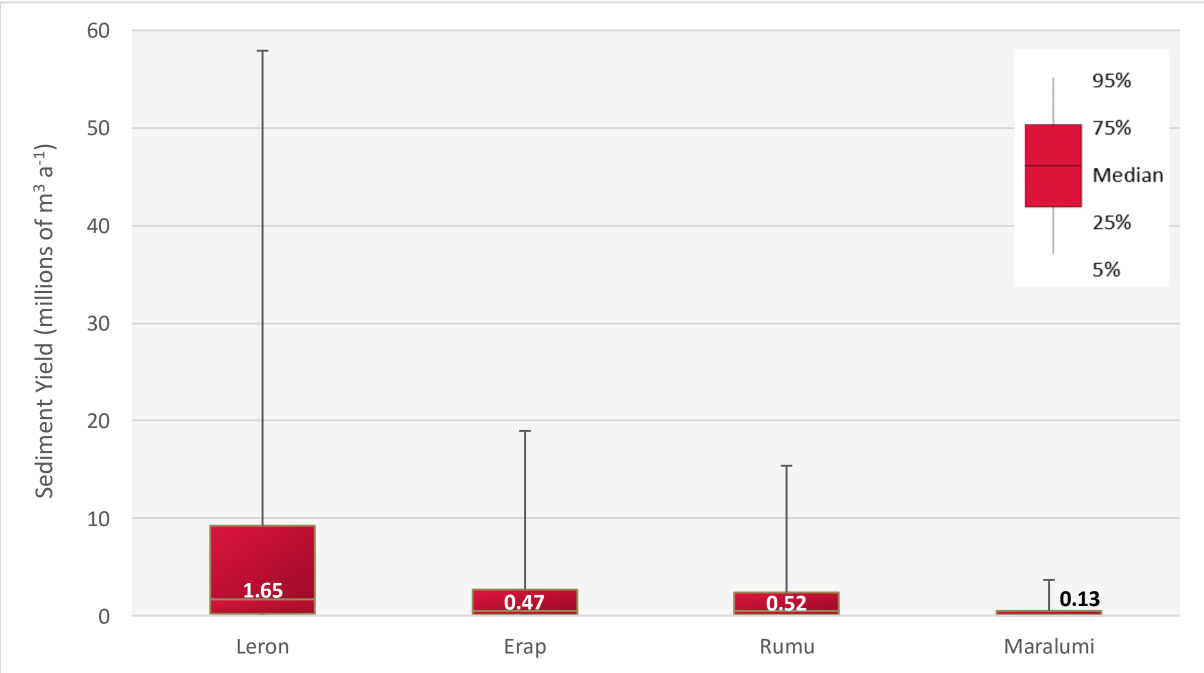

Figure 6-11 Box-and-whisker plot of total coarse sediment yields for the four sub-catchments. Error bars show standard error.

The model only predicts the coarser proportion of the sediment load (i.e. that which is transported partially to totally along the bed) and ignores much of the washload (fines). The coarser proportion would include particles down to the silt fraction at times, but would generally only describe sand particles or larger. Using the estimates of Meynink (1988) that suggested that washload would be 0.5 to 2.0 times the bed load, total sediment yields would be in the order of:

- Leron – 2,481,000 to 4,962,000 $m^3\ a^{-1}$.
- Erap – 706,500 to 1,413,000 $m^3\ a^{-1}$.
- Rumu – 777,000 to 1,554,000 $m^3\ a^{-1}$.
- Maralumi – 198,000 to 396,000 $m^3\ a^{-1}$.

The estimates compare well with whole-of-catchment estimates of Markham River sediment yield. Much of the washload would end up in the Markham River and downstream or on the floodplain or ephemeral wetlands/clearwater tributaries.

Not surprisingly, the model highlighted that catchment erosion processes (as opposed to channel erosion) were the dominant source of sediment, accounting for more than 90% of channel sediments for all the sub-catchments. The model estimated that there would be considerable deposition during periods where the sediment supply from the catchment exceeded the transport capacity of the waterways. This deposition would likely occur within the alluvial fan reaches.

Confirming field observations of the clearer water in Maralumi River, sediment yield within this sub-catchment was much lower than the remaining sub-catchments. This is a product of the smaller sub-catchment area, and the higher proportion of lower sloping lands. Field observations and analysis of aerial imagery also suggested that much of the sediment carried by the Maralumi River would deposit within the alluvial fan reaches. Comparatively, the flat, sedimented beds of the larger rivers were shown to convey much larger volumes of sediment, particularly Leron River. This would suggest that Maralumi River would be more susceptible to changes in sediment supply, particularly in the reaches downstream of where much of the catchment sediment appears to deposit.

6.3 Channel Condition and Behaviour

The existing channel condition and behaviour is described in Section 4. In general, the Markham, Leron, Erap, Rumu, and ephemeral waterways were subject to major aggradation, bank instabilities, and avulsions. The Maralumi River and other clearwater waterways were generally stable, well-vegetated waterways that are less subject to channel instabilities.

7 IMPACTS

7.1 Hydrology and Flooding

7.1.1 Leron, Erap, Rumu, Maralumi River sub-catchments

Results of the hydrology impact assessment are summarised in tables in Appendix 2. Flow duration curves for all the existing and four impact scenarios for Leron, Erap, Rumu, and Maralumi River sub-catchments and Markham River catchment are provided in Figure 7-1 to Figure 7-5 respectively. Note that some scenarios are not visible on the figures as they are the same or very similar to other scenarios. The following observations can be made regarding the hydrological characteristics of the different scenarios for the four sub-catchments:

- The Pickup model predicted that there would be negligible differences between the different scenarios.
- The AWBM model predicted that there would be negligible differences between the different scenarios for higher magnitude, less frequent flows (>50th percentile). This is shown in both the duration curves and the results of the flood frequency analyses (Appendix 2). This suggests that the Project will not affect these flows.
- Given the lack of impact on the larger flow events, it is unlikely that the Project will impact flood heights. While increased vegetation height and density are likely to result in slowing of flows on the floodplain, based on the available modelled data, this is unlikely to significantly affect flood depths. The HEC-RAS modelling confirmed the negligible impacts on flood inundation, with flood inundation extent not varying between existing and impact scenarios. However, as outlined in Section 4.2.4 and 6.1 there is already a significant risk to infrastructure from flooding, particularly for the larger events (100-year, 500-year ARI), which will need to be further investigated.
- The AWBM model predicted negligible increases to median flows in Scenarios 1 and 2, suggesting that construction of the Project should not affect short-term median flows.
- The AWBM model predicted negligible decreases in median flows in Scenarios 3 and 4, suggesting that operation of the Project should not affect long-term median flows.
- The AWBM model predicted major increases to the more frequent flows (10th percentile) flows in Scenarios 1 and 2 for all sub-catchments, suggesting that construction of the Project may result in increases in these flows in the short-term.
- The AWBM model predicted major decreases to the more frequent flows (10th percentile) flows in Scenarios 3 and 4 for all sub-catchments, suggesting that operation of the Project may result in decreases in the more frequent flows.
- The AWBM model predicted noticeable increases in the number of zero flow days in all four sub-catchments for Scenarios 3 and 4, suggesting that the Project may result in these waterways ceasing to flow for short periods. These impacts are more likely to be seen in the smaller, clearwater streams than the main channels. Note that since actual planting areas for each sub-catchment were not known during the assessment, the

impact assessment applied a reduction in runoff based on the area of land under MOUs within each sub-catchment (except for Erap River – refer to Section 5.3.1 for method), which provided a very conservative, worst-case approach. More detail on actual surface- and groundwater hydrology, and planting plans would lessen the predicted impact.

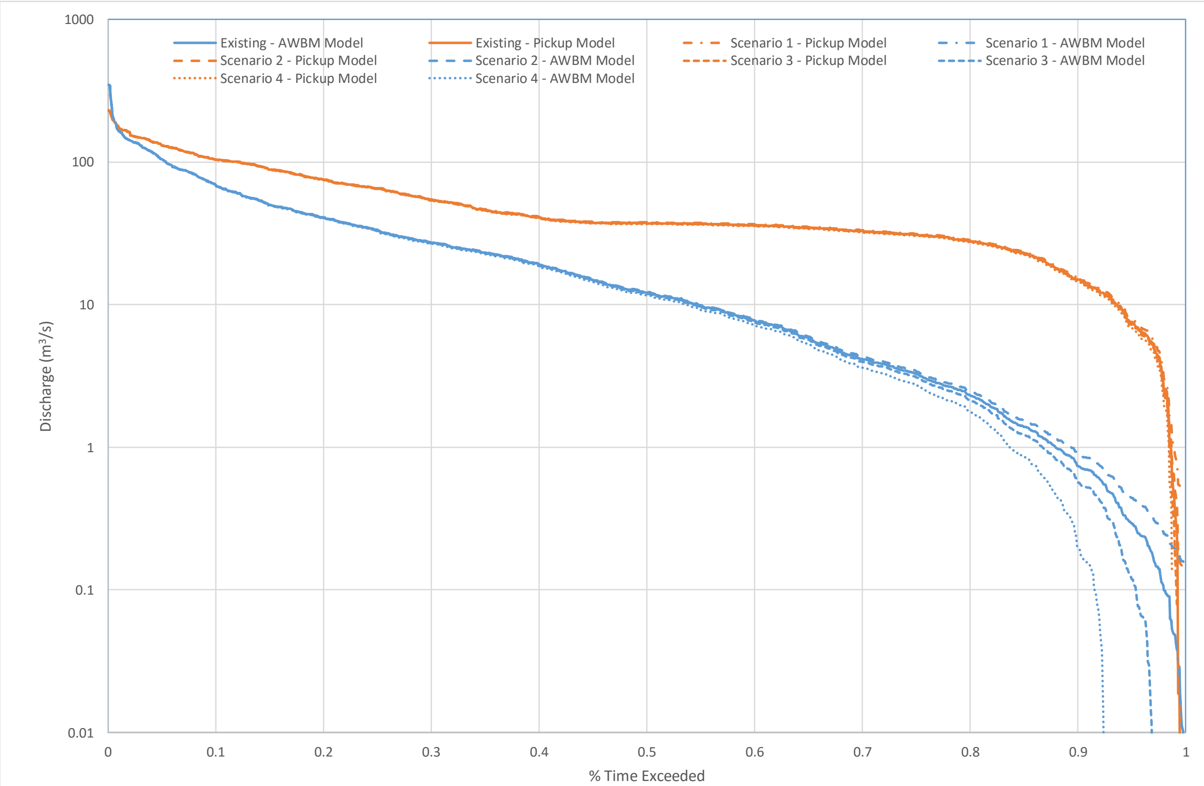

Figure 7-1 Leron River sub-catchment flow duration curves for the two models for all scenarios

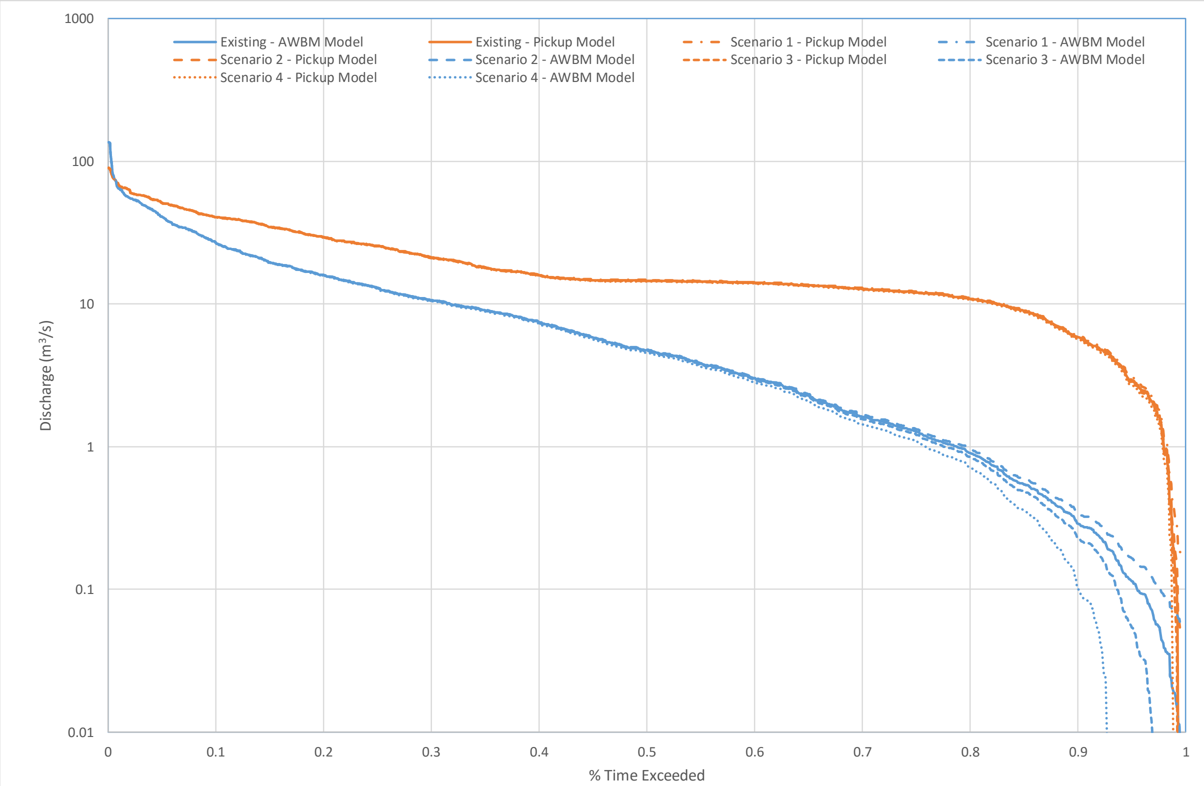

Figure 7-2 Erap River sub-catchment flow duration curves for the two models for all scenarios

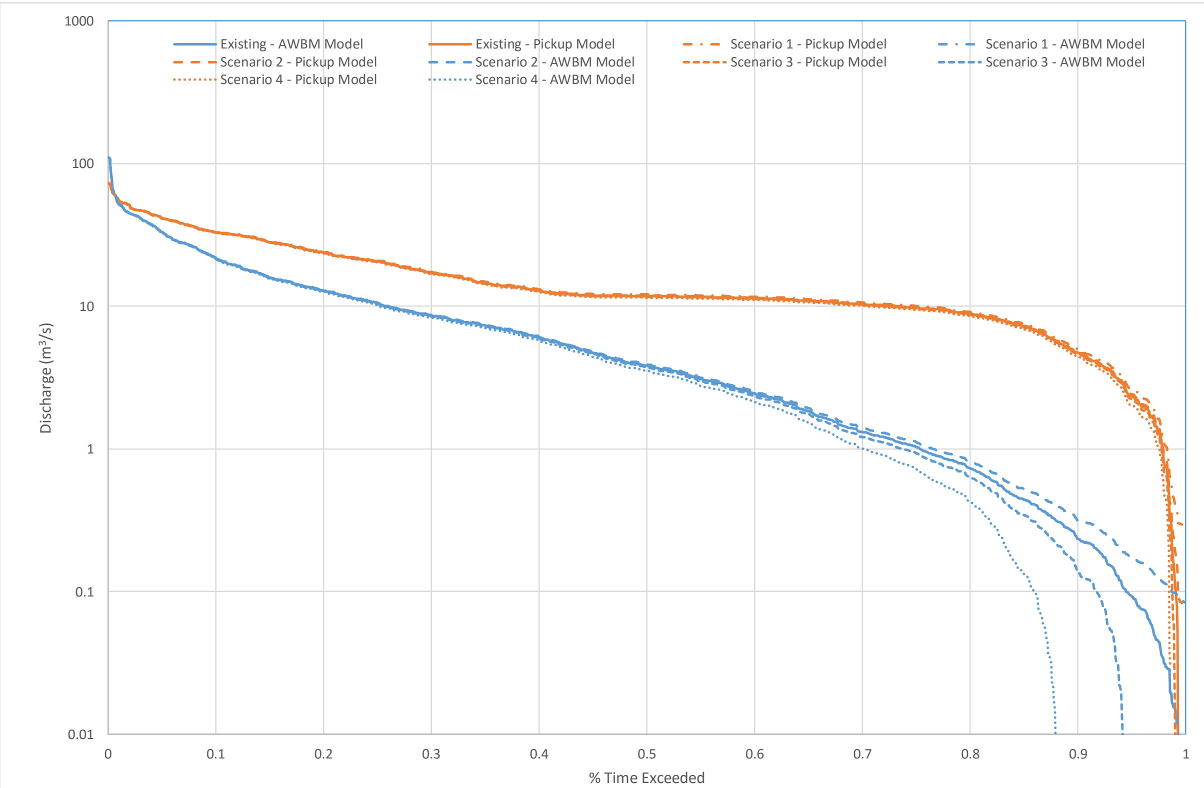

Figure 7-3 Rumu River sub-catchment flow duration curves for the two models for all scenarios

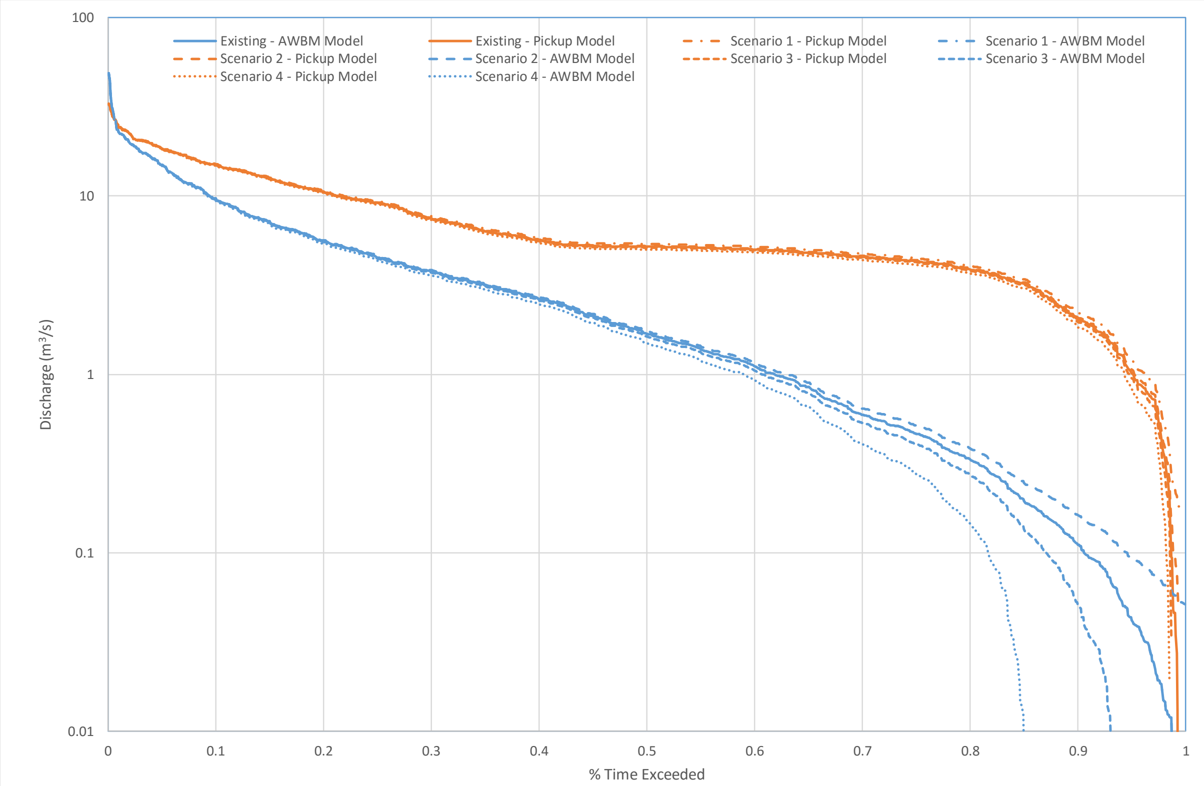

Figure 7-4 Maralumi River sub-catchment flow duration curves for the two models for all scenarios

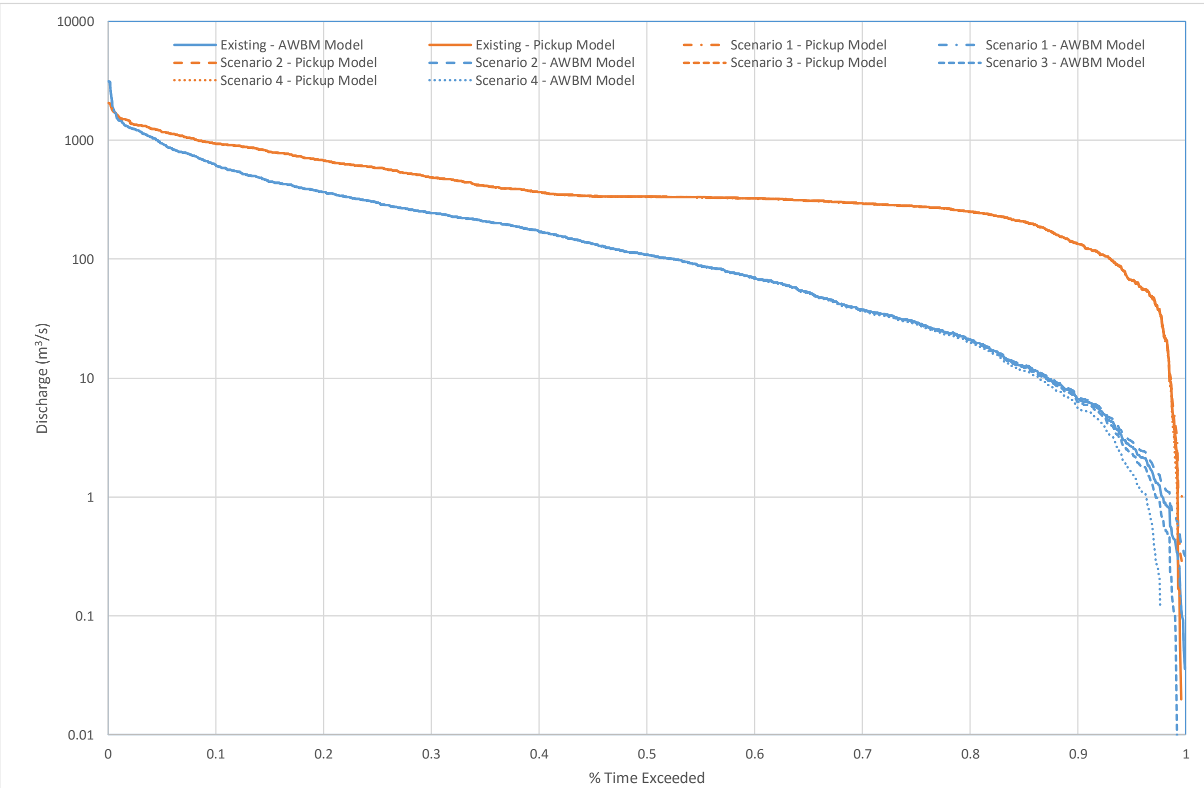

Figure 7-5 Markham River catchment flow duration curves for the two models for all scenarios

7.1.2 Markham River Catchment

The results contained within Appendix 2 and Figure 7-5 suggested that impacts to Markham River hydrology would be negligible.

7.1.3 Clearwater streams and other wetted areas

Given the increased groundwater drainage predicted in White (2017), and the possible increase in the number of zero flow days in all sub-catchments (as predicted by the AWBM model, using a very conservative approach), it is possible that the groundwater-fed clearwater streams will also cease to flow more often. However, provided that plantations are not developed in source areas, the likelihood of this is low. Off-river wetland areas will also be more likely to dry up, although these will be partly fed by overbank flows from the supplying catchments, so will be unlikely to dry for any length of time.

7.2 Sediment Transport

Figure 7-6 to Figure 7-9 show the sediment yields for the existing and impact scenarios for the Leron, Erap, Rumu, and Maralumi River sub-catchments. It is evident that only negligible changes in sediment supply were predicted, with negligible increases during construction/vegetation clearing and establishment, and negligible decreases during harvesting and full establishment. As such, it was predicted that the Project would not affect overall sediment yields from the four sub-catchments. Therefore, it was also predicted that there would be no impacts to Markham River sediment yields.

However, during construction and vegetation clearing, some of the sediment produced will likely be delivered to the clearwater streams and wetlands. It is difficult to quantify volumes entering individual waterways, but left unmitigated, this will impact on water quality and aquatic habitat quality.

7.3 Channel Condition and Behaviour

Given the generally minor impacts on hydrology and sediment transport (except for low flows), it is expected that there will also be minor impacts on channel condition and behaviour. In the absence of mitigation measures, there may be several exceptions, including:

- Localised sediment aggradation during construction and vegetation clearing, and establishment (Scenarios 1 and 2), particularly to the clearwater streams.
- Negligible to low increases to the likelihood of avulsion during construction and vegetation clearing, and establishment, due to negligible to low increases to the lower frequency (high magnitude) events (Scenarios 1 and 2).
- Continued risks of avulsion and bank instabilities, regardless of the Project (all Scenarios).

7.4 Environmental Values and Impact Mechanisms

Environmental values and potential impact mechanisms are identified in Table 7-1.

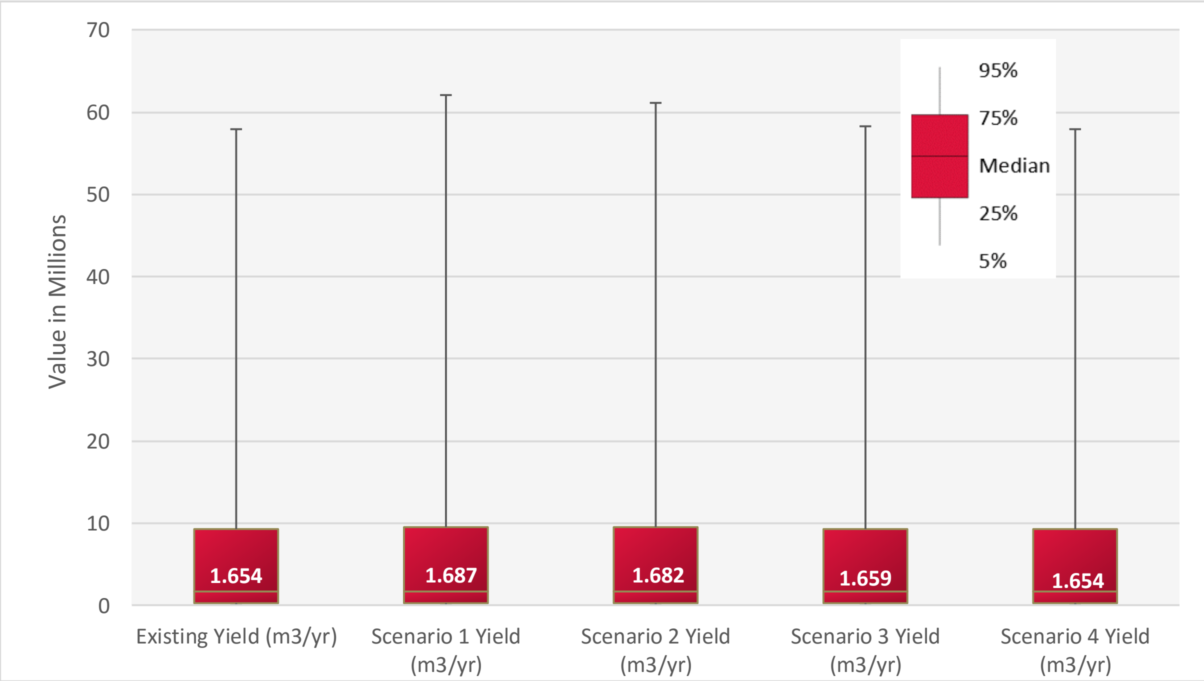

Figure 7-6 Box-and-whisker plot of total channel sediment yield for the existing and four impact scenarios – Leron River sub-catchment

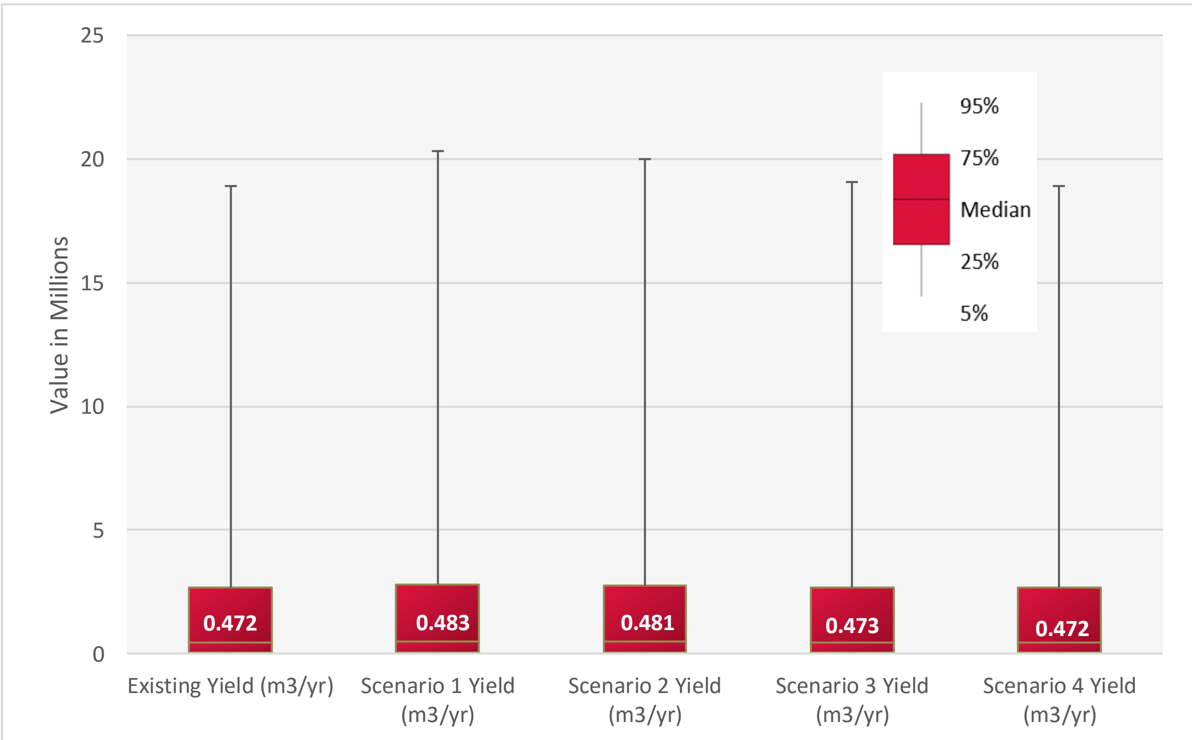

Figure 7-7 Box-and-whisker plot of total channel sediment yield – Erap River sub-catchment

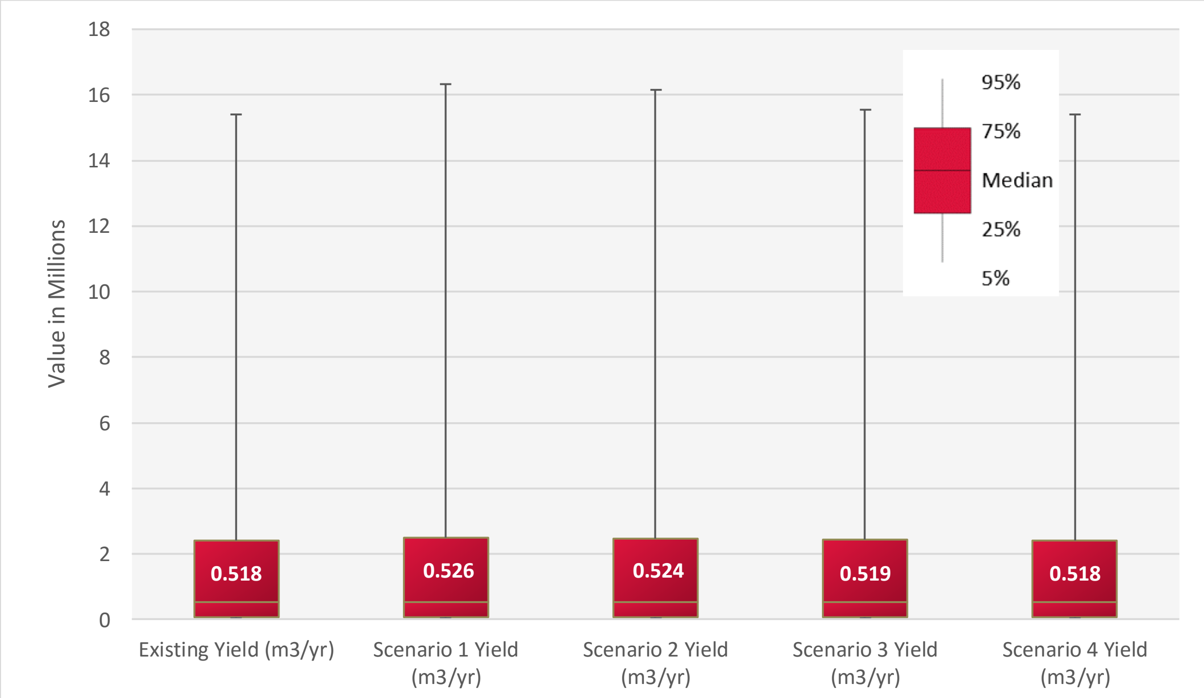

Figure 7-8 Box-and-whisker plot of total channel sediment yield – Rumu River sub-catchment

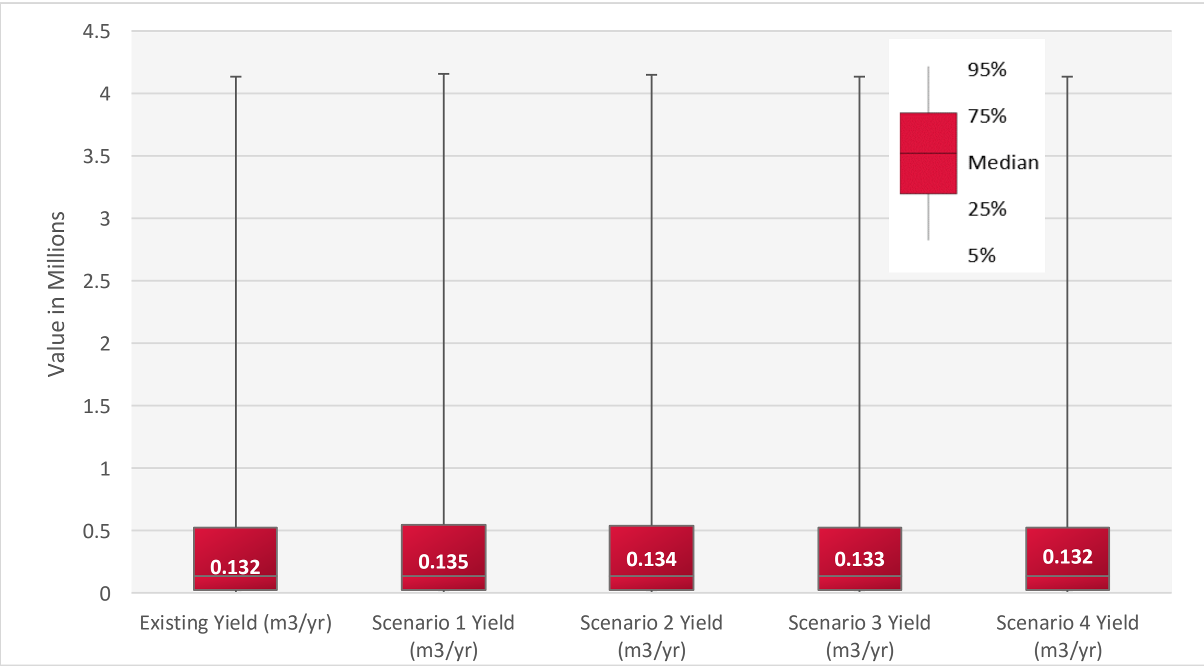

Figure 7-9 Box-and-whisker plot of total channel sediment yield – Maralumi River sub-catchment

Table 7-1 Environmental Values for the Project area and corresponding impact mechanisms

Environmental Value	Impact Mechanisms
Protection of Surface Water Flow Volumes The hydrology values vary according to the four different channel forms seen in the Project area: • Ephemeral foothill tributaries. • Perennial high flow energy, high sediment supply rivers (Leron, Rumu, Erap). • Clearwater streams (Maralumi and others). • Markham River. The more ephemeral waterways and the clearwater streams are highly sensitive to changes in the hydrology. Those more turbid, perennial streams are less likely to be sensitive, although if impacts result in a threshold cross from perennial to ephemeral, sensitivity would increase	**Scenario 1: Construction/Vegetation Clearing** Increased surface water runoff during construction due to lower vegetation densities **Scenario 2: Establishment** Increased surface water runoff during construction due to lower vegetation densities **Scenario 3: Harvesting** Decreased surface water runoff during operation due to increased vegetation densities **Scenario 4: Established** Decreased surface water runoff during operation due to increased vegetation densities
Floodplain and Wetland Flooding Regimes The floodplain contained in the Project area is subject to regular inundation that feeds the off-river wetland water levels. These are important refugia for aquatic species and will be highly sensitive to changes in flooding regime.	**Scenario 1: Construction/Vegetation Clearing** Decreased flooding levels due to lower floodplain vegetation densities **Scenario 2: Establishment** Decreased flooding levels due to lower floodplain vegetation densities More frequent inundation of wetlands due to higher surface water flows **Scenario 3: Harvesting** Increased flooding levels due to higher floodplain vegetation densities Less frequent inundation of wetlands due lower surface water flows **Scenario 4: Established** Increased flooding levels due to higher floodplain vegetation densities Less frequent inundation of wetlands due lower surface water flows
Channel Form and Processes Channel form and behavior varies across the Project area. The ephemeral foothill tributaries, and Leron, Rumu, Erap, and Markham Rivers are less sensitive to changes in channel form and processes as they are naturally highly mobile systems due to the extremely large volumes of sediment conveyed through the systems. They support aquatic fauna at all times but diversity of aquatic and riparian fauna is limited by tolerances to sediment conditions and habitat availability. These waterways are prone to aggradation and avulsion. The clearwater streams are more sensitive to changes in channel form and processes as they are naturally exposed to low turbidity for long periods of time (except during high flows). The lower flow and sediment supply contributes to the development of more diverse aquatic habitats. Riparian vegetation with a relatively high diversity of vegetation structural forms including large trees. These streams support a relatively high diversity of aquatic species and at downstream reaches, are likely to provide important refugia for populations in the Markham River during times of episodic high flow and high sediment conditions.	**Scenario 1: Construction/Vegetation Clearing** Increased sediment delivery to channels from construction activities (e.g. bridge construction, road clearance, vegetation clearing) Disturbance of channels via construction activities that influence channel stability or avulsion risk. **Scenario 2: Establishment** Short-term, localised increases to sediment delivery to channels from operation activities (e.g. plantation harvesting, road runoff) Increased sediment delivery to channels from increased vegetation density Disturbance of channels via operational activities that influence channel stability or avulsion risk. **Scenario 3: Harvesting** Short-term, localised increases to sediment delivery to channels from operation activities (e.g. plantation harvesting, road runoff) Overall reduced sediment delivery (long-term, catchment-scale) to channels from increased vegetation density Disturbance of channels via operational activities that influence channel stability or avulsion risk. **Scenario 4: Established** Reduced sediment delivery to channels from increased vegetation density Disturbance of channels via operational activities that influence channel stability or avulsion risk.

7.5 Mitigation Measures

The Project has committed to a number of mitigation measures that will ameliorate hydrology and sediment yield impacts. These measures are reflected in, or exceed, the *Papua New Guinea Logging Code of Practice* (PNGFA/DEC, 1996), and the current and revised (draft) *National Forest Management Standards for Papua New Guinea* (FSC, 2010; FSC, 2016). These measures are outlined below. Additional measures that reflect the current knowledge of the hydrology and sediment transport environments the Project area and experience from other projects are also provided.

7.5.1 Buffer Zones

As outlined in Section 2, the Project will apply riparian buffer zones sized according to the size of watercourses. These zones will have a positive effect on bank stability, assist in filtering of sediment-laden runoff and reduce impacts of overbank flows. As outlined in the Project description, the following activities will be excluded within the riparian buffer zones:

- Establishment of plantations.
- Felling of trees or clearing of any vegetation except where required for designated stream crossings.
- Storing of logs, soil, machinery, fuels, oils, lubricant or herbicides, or placement of any other project-related infrastructure.
- Construction of roads, except where required for designated stream crossings or bridges.
- Crossing of harvesting machinery, except at designated temporary crossings over dry watercourse beds. Where practicable, these should be located where low banks or natural fords facilitate crossing without significant earthworks to modify the bank, and located to minimise clearing of vegetation required to construct the crossing.
- Where harvesting machinery is required to cross watercourses, log crossings or culverts will be constructed. Where such construction occurs, crossings should be planned at locations of riparian grassland where practicable to minimise the clearing of vegetation through the buffer zone. Where culverts are used, the crossing construction will be subject to specific environmental and technical feasibility assessment and culvert designs will adopt the principals of the *Papua New Guinea Logging Code of Practice* (PNGFA/DEC, 1996). Where culverts are used or bridges built, construction practices will be adopted to mitigate physical impacts to watercourse bank and in-stream bed, to stabilise banks from ongoing erosion, to control sediment release during construction and to mitigate potential impacts associated with stockpiling and spillages.

7.5.2 Power Plant and Nursery

Although the sediment yield assessment suggested that overall impacts during construction and operation would be negligible, construction of the power plant and nursery will require vegetation clearing and earthworks that have the potential to increase sediment-laden runoff. Any impacts will be mitigated using the buffer zones and the adoption of the principals of the *Papua New Guinea Logging Code of Practice* (PNGFA/DEC, 1996) with regard to vegetation clearance. Fathom Pacific (2017) also recommended the use of bunds and silt fences downslope from earth stockpiles to reduce sediment-laden runoff. While the gentle topography of the area is likely to minimise runoff risk, these recommendations are good practice and should be implemented. Other mitigation measures that should be considered include timing of construction during drier periods to minimise risk of sedimented runoff, light sprinkling of water on exposed earth (i.e. roads, construction site) in dry conditions for dust suppression, installation of rumble grids at the entry/exit points of the construction site to minimise the amount of sediment leaving the site, covering of stockpiles, and redirection of surface runoff into settling ponds or other suitable areas. A *Construction Management Plan* that includes an *Erosion and Sediment Control* sub-plan should be developed for all construction-related activities that adopts the above mitigation measures and conforms with PNGFA/DEC (1996).

7.5.3 Power Plant Water Abstraction

The impact assessment assumed that any water abstraction for the power plant would directly impact on all the four sub-catchments. To minimise these impacts, it is recommended to follow the measures suggested by White (2017):

- Location of a suitable number of bores as close to the Markham River as practicable to ensure reliable groundwater supply and to mitigate potential impacts to groundwater dependent ecosystems which may be associated with smaller watercourses.
- Location of bores downslope of plantations and the water supplies of villages and hamlets.

7.5.4 Hydrology and Flooding

The hydrology and flooding assessments were based on synthetic data and uncalibrated model outputs that do not provide an accurate representation of the local conditions. However, the method of using several datasets to establish worst-case scenarios enabled potential impacts to be identified. Generally, impacts were minor or negligible, but the increase in zero flow days may affect the habitat of the waterways and wetlands within Project area. The actual increase may well be exaggerated, so flows should be monitored during construction and operation to determine whether zero flow days occur.

Flooding extents and depths should be investigated further, with flow gauges established in the major waterways to provide more understanding of actual flows and flood depths. These data can then be used to establish calibrated models. Floodplain flood depths should be recorded (with aerial imagery or GPS-enabled cameras) during any flows within Leron, Erap, Rumu or Maralumi Rivers that overtop the channel banks to assist in calibration of models.

Given the identified flood risks to the power plant using the uncalibrated model, design of the plant should involve an assessment that considers the risk posed by inundation (where this might involve the development of a calibrated hydraulic model). Results of the model should be used to assess the suitability of the proposed location for the power plant and to develop appropriate management and mitigation measures.

A Water Management Plan should be developed that outlines the above tasks and considers additional water conservation measures within the Project area (e.g., use of Markham River as an alternative water supply during drier periods), and water consumption offsets (e.g. water allocation scheme).

7.5.5 Monitoring Requirements

The recommended management plans described above should include monitoring measures that are consistent with Principle 8 of FSC (2016), as described in Section 3. These measures may include the consideration of the following:

- Installation of flow and water quality gauges in selected major and/or clearwater rivers/streams within the Project area. The successful installation of gauges in Leron, Rumu, and Erap Rivers will be limited by the highly mobile nature of these systems. As such, gauges should only be installed where channel morphology allows, and any potential gauge site should have prior approval from a hydrographer.
- Establishment of geomorphology/hydrology monitoring sites within the potentially impacted major waterways (Leron, Erap, Rumu, and Maralumi Rivers).
- Establishment of monitoring sites within selected clearwater and/or ephemeral waterways and wetlands.
- Flow and water quality gauges should be operational before construction begins and should be monitored regularly to ensure mitigation measures are effective.
- All water/sediment infrastructure on the power plant / nursery construction site (e.g. settling ponds, stockpiles, silt fences) should be inspected regularly to ensure that they are operating effectively.
- The monitoring sites established prior to construction should be monitored at least once during construction of the power plant.
- Flow gauges should be monitored regularly to ensure mitigation measures are effective. This can be set up to occur automatically.
- The monitoring sites established prior to construction should be monitored annually.

7.6 Impact Significance

Table 7-2 summarises the potential hydrology and sediment yield impacts from the Project that were described in detail above. Assessment of the magnitude, sensitivity and significance of impacts within this table was based on Section 5.3.5. Residual impacts are included in the table and assume the mitigation measures identified above have been implemented. It is evident that, with the exception of potential impacts of floods to the power plant, all residual impacts are negligible or low. The potential impacts of floods to the power plant need further investigation prior to finalising the assessment of impact.

7.7 Cumulative Impacts

Given that the residual significance of all hydrology and sediment transport related impacts have been rated as either negligible or low, the Project is unlikely to exacerbate any existing impacts in the Markham Valley.

Table 7-2 Assessment of potential hydrology and sediment transport impacts in the Project area

Type of Impact	Potential Impact / Consequence	Magnitude of Impact	Sensitivity of Impact	Significance of Impact	Residual Magnitude	Residual Sensitivity	Residual Significance
Hydrology	Existing flood risk to proposed infrastructure for flows in excess of 100-year ARI	High	High	Major	Low	High	Moderate
	Change to high magnitude events (>50th percentile) and flooding and resulting impacts on infrastructure	Negligible	High	Negligible	Negligible	High	Negligible
	Change in low magnitude events (10th to 50th percentile)	Low	Low-Moderate	Low	Low	Low-Moderate	Low
	Change in very low magnitude events (<10th percentile) – Leron, Erap, Rumu	High	Low	Moderate	Negligible	Low	Negligible
	Change in very low magnitude events (<10th percentile) – Maralumi, clearwater streams and wetlands	High	Moderate	High	Low	Moderate	Low
	Change in very low magnitude events (<10th percentile) – Markham	Moderate	Low	Low	Negligible	Low	Negligible
Sediment yield	Elevated sediment yields in receiving watercourses during construction/ vegetation clearing and establishment – Leron, Erap, Rumu, Markham	Negligible	Low	Negligible	Negligible	Low	Negligible
	Elevated sediment yields in receiving watercourses during construction/ vegetation clearing and establishment – Maralumi, clearwater streams and wetlands	Low	Moderate	Low	Negligible	Moderate	Negligible
	Reduced sediment yields in receiving watercourses during harvesting and established plantation (Scenarios 3 and 4) – Leron, Erap, Rumu, Markham	Negligible	Low	Negligible	Negligible	Low	Negligible
	Reduced sediment yields in receiving watercourses during harvesting and established plantation – Maralumi, clearwater streams and wetlands	Negligible	Moderate	Negligible	Negligible	Moderate	Negligible
	Localised sediment-laden runoff from construction activities (bridges, power plant) – Leron, Erap, Rumu, Markham	Low	Low	Low	Negligible	Low	Negligible
	Localised sediment-laden runoff from construction activities (bridges, power plant) – Maralumi, clearwater streams and wetlands	Low	Moderate	Low	Negligible	Moderate	Negligible

Type of Impact	Potential Impact / Consequence	Magnitude of Impact	Sensitivity of Impact	Significance of Impact	Residual Magnitude	Residual Sensitivity	Residual Significance
Channel Form	Localised sediment aggradation during construction/vegetation clearing, and establishment (Scenarios 1 and 2), particularly to the clearwater streams.	Low	High	Moderate	Negligible	High	Negligible
	Minor increases to the likelihood of avulsion during construction (Scenarios 1 and 2)	Negligible	High	Negligible	Negligible	High	Negligible
	Continued risks of avulsion and bank instabilities – Leron, Erap, Rumu, Markham	Moderate	Low	Low	Moderate	Low	Low
	Continued risks of bank instabilities – Maralumi, clearwater streams and wetlands	High	High	Major	Negligible	High	Negligible

8 CONCLUSIONS

This assessment used a desktop data review, and industry accepted modelling methods to provide an understanding of the existing hydrology, sediment transport conditions, and channel morphology, and to assess potential impacts to these resulting from the Project. The modelling approach was supported by *in situ* condition assessments, photographs and morphological characterisation. The models included a rainfall-runoff model to simulate streamflow in the four sub-catchments and the Markham River, a high-level two-dimensional flood model to provide a high-level flood risk assessment of the four sub-catchments, and a stochastic catchment sediment budgeting model to assess the sediment transport regime of the four sub-catchments.

The approach identified several key risks that would need to be addressed. These issues included potential impacts to the very low magnitude events (<10th percentile), including zero flow days, particularly in the Maralumi River and other smaller clearwater streams; potential flooding risks to proposed infrastructure; and considerable risk of avulsion of all the main waterways within and adjacent to the Project area; all other impacts to hydrological characteristics, sediment yields and channel form were considered low or negligible.

Provided all recommended mitigation measures are implemented, the majority of impacts can be reduced to low or negligible. Of particular note though is the remaining moderate flood risk and its potential impacts on proposed infrastructure. The proposed location of the power plant is outside (but close to) the 100-year and 500-year ARI flood extents. Design of the plant should involve an assessment that considers the risk posed by inundation, assesses the suitability of the proposed location for the power plant and develops appropriate management and mitigation measures. Further, there remains a risk of avulsion throughout the Project area from the Markham River and the larger waterways. The overall risk of this remains low within the Project life, but the location of the power plant close to the Maralumi and Rumu Rivers increases its susceptibility to these processes.

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APPENDIX 1 MODEL VARIABLES AND PARAMETERS

A1 General Approach

The sediment budget approach used a model that was supported by several sub-models. The model was defined as follows:

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

$$Y = STC \ [if \ CSS \geq STC] \qquad (1.2)$$

$$y = CSS - STC \ [if \ CSS \geq STC] \qquad (1.3)$$

where:

Y = Sediment yield (t/year);

CSS = catchment sediment supply (t/year);

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

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

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

Several separate sub-models/equations were used to determine the parameters of the above model. They were used to predict supply of sediment to the channel and transport of sediment within the channel. These models/equations are described in Appendix 1 and outlined below:

- *CSS* was estimated as:

$$CSS = HE + BE + BedE \qquad (1.4)$$

where:

HE = coarse sediment from hillslope erosion (t/year). This was calculated using the Revised Universal Soil Loss Equation (RUSLE) (Wischmeier & Smith, 1978).

BE = coarse sediment from stream bank erosion (t/year). This was calculated using an extension of the SedNet bank erosion equation (Wilkinson, et al., 2004). This equation has been used throughout Australia to calculate catchment-scale bank erosion sediment yields.

BedE = coarse sediment from stream bed erosion (t/year). Stochastic generation of bed erosion based on probability distributions was undertaken based on literature values and knowledge of similar PNG systems, including Markham and Watut Rivers.

- *STC* was calculated by extending Yang (1973) equation (Prosser, et al., 2001) as

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

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).

Variables and parameters of the above model (Equations 1.1 to 1.5) are highly variable and uncertain. Field observations, literature, geographic information system (GIS) layers, a digital elevation model (DEM), local information and expert knowledge were used in defining the variables and parameters of the model. Professional judgement was used where no information was available. A stochastic approach (Monte Carlo (MC) 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 further below. The MC method was applied in three steps. They were:

1. The variables and parameters of the sediment yield model (Equations 1.1-1.13) were considered stochastic variables and their PDFs were parameterised. The exception was catchment area, which was considered as a deterministic variable.
2. The sediment yield model (Equations 1.1-1.13) was developed in a spreadsheet format and set in to the MC framework. Any interdependency between and among the factors, variables and parameters of the model was maintained.
3. A MC of the sediment yield model (Equations 1.1-1.13) was run.

A2 Hillslope Erosion (HE)

Coarse sediment yield from the hillslopes was estimated by using modified plot-scale Revised Universal Soil Loss Equation (RUSLE) (Wischmeier & 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 0). The plot scale RUSLE model is defined by:

$$A = RKL_1S_1CP \qquad (A.1)$$

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).

P = support practice factor (dimensionless).

P was set to one to reflect the assumption that there were limited soil conservation measures adopted in the sub-catchments. Consequently Equation A.1 was reduced to:

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

Total soil loss from each sub-catchment was estimated as:

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

where:

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

C_a = sub-catchment area (ha).

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

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

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).

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

A2.1 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 the four sub-catchments using the Australian R map (Rosewell 1993, Figure, P.80) and transferring R values from catchments of similar rainfall characteristics (e.g. wet and wet-dry tropics of northern Australia). 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 1 show the probability distribution of R (and other stochastic variables and parameters) of the model.

A2.2 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 & G.R., 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).

The four sub-catchments were considered to be actively eroding. Discrete values of K were obtained from Markham River catchment RUSLE assessment reported in Kolola & Samanta (2013; 2015). K-values are shown in Appendix Table 1. Likely correlation of K with rainfall and other factors, based on limited information, professional judgement and consistency, was maintained during the simulation.

Appendix Table 1 Distributions of stochastic variables in the four sub-catchments

Catchment	Probability distribution function		Remarks
	Variables & parameters	Distribution	
Leron (301 km2)	i	Invgauss(124.71,117.5)	Truncated (0,865)
	W	Pareto2(203.96,2.4105)	Truncated (5,450)
	S	Exponential (0.11325)	Truncated (0, 0.8)
	MN	Discrete ({0.025,0.03,0.035,0.04}, {0.1,0.1,0.2,0.6})	

Catchment	Probability distribution function		Remarks
	Variables & parameters	Distribution	
	R	Triangular (2000,8000,30000)	
	l_1	Gamma (1.1978,547.87)	Truncated (5,1000)
	θ	Uniform (-0.27448,89.754)	Truncated (0, 70)
	WFP	Exponential (2871.6)	Truncated (15,5000)
	H	Triangular (0.5, 20, 3)	
	L	Uniform (18,19)	
	D	Triangular (0.25,0.5,2,5,95)	
	q_c	Lognormal (0.371,0.2)	
	β	Triangular (0.9,1.2,1.5)	
	γ	Triangular (0.9,1.2,1.7)	
	ϕ	Triangular (0.0000005, 0.512, 0.032)	
	K_1	Triangular (218,836,3326) when MN (0.025) Pert (195,750,2981) when MN (0.03) Triangular (178,684,2718) when MN (0.035) Triangular (165,631,2509) when MN (0.04)	
	K	Discrete K Value Probability 0.07 0.25 0.17 0.02 0.27 0.25 0.37 0.48	
	C	Discrete C-Factor Probability Development - 0.002 0.14 Forest - 0.004 66.18 Grass - 0.05 29.1 Waterway - 0 2.49 Dvpt Plantation Initial Growth - 0.15 0 Dvpt Plantation Mid Growth - 0.07 0 Dvpt Plantation Full Growth - 0.05 0 Dvpt Plantation - Dvpd Area - 0.002 0 Dvpt Plantation Cleared - 0.4 0 Disturbed Forest - 0.05 0.91 Garden areas with evidence of recent modification - 0.125 0.12 Shrubland - 0.05 0.08 Grass/shrub/wood - 0.05 0.22 Plantation - 0.05 0.39 Disturbed Grassland - 0.5 0.19 Village Area - 0.2 0.16 Woodland with severely degraded ground cover - 0.1 0.02	
	SDR_h	Triangular (0.001,0.4, 0.75)	
	δ	Triangular (0, 0.14, 0.5)	
	K_3	Uniform (0.0001,0.0005)	
	e	Uniform (0.1, 1.5)	
	f	Uniform (0.5,1)	
	RT	Binomial (1,0.7)	
	RD	Discrete ({0.1,0.4,0.7,0.95}, {0.05,0.1,0.75,0.1})	
	BD	Triangular (1,1.5,2)	
	C_b	Triangular (0.3,0.4,0.5)	
Erap ($498 km^2$)	I	Invgauss (124.71,117.5)	Truncated (0, 865)
	W	Log norm (72.463,159.57)	Truncated (5,450)
	S	Exponential (0.11325)	Truncated (0,0.8)
	MN	Discrete ({0.025,0.03,0.035,0.04}, {0.1,0.6,0.2,0.1})	
	R	Triangular (2000,8000,30000)	

Catchment	Probability distribution function		Remarks
	Variables & parameters	Distribution	
	I1	Pert (3.3449,41.772,3362)	Truncated (5,1000)
	θ	Exponential (44.44)	Truncated (0,70)
	WFP	Exponential (737.7)	Truncated (15,5000)
	H	Triangular (0.5, 20, 3)	
	L	Uniform (19,20)	
	D	Triangular (0.25,0.5,2,5,95)	
	q_c	Lognormal (0.371,0.2)	
	β	Triangular (0.9,1.2,1.5)	
	γ	Triangular (0.9,1.2,1.7)	
	ϕ	Triangular (0.0000005, 0.512, 0.032)	
	K_1	Triangular (218,836,3326) when MN (0.025) Pert (195,750,2981) when MN (0.03) Triangular (178,684,2718) when MN (0.035) Triangular (165,631,2509) when MN (0.04)	
	K	Discrete K Value Probability 0.07 0.25 0.17 0.02 0.27 0.25 0.37 0.48	
	C	Discrete C-Factor Probability Development - 0.002 0.14 Forest - 0.004 66.18 Grass - 0.05 29.1 Waterway - 0 2.49 Dvpt Plantation Initial Growth - 0.15 0 Dvpt Plantation Mid Growth - 0.07 0 Dvpt Plantation Full Growth - 0.05 0 Dvpt Plantation - Dvpd Area - 0.002 0 Dvpt Plantation Cleared - 0.4 0 Disturbed Forest - 0.05 0.91 Garden areas with evidence of recent modification - 0.125 0.12 Shrubland - 0.05 0.08 Grass/shrub/wood - 0.05 0.22 Plantation - 0.05 0.39 Disturbed Grassland - 0.5 0.19 Village Area - 0.2 0.16 Woodland with severely degraded ground cover - 0.1 0.02	
	SDR_h	Triangular (0.001,0.4, 0.75)	
	δ	Triangular (0, 0.14, 0.5)	
	K_3	Uniform (0.0001,0.0005)	
	e	Uniform (0.1, 1.5)	
	f	Uniform (0.5,1)	
	RT	Binomial (1,0.7)	
	RD	Discrete ({0.1,0.4,0.7,0.95}, {0.05,0.1,0.75,0.1})	
	BD	Triangular (1,1.5,2)	
	C_b	Triangular (0.3,0.4,0.5)	
Rumu (403 km^2)	i	Invgauss (124.71,117.5)	Truncated (0, 865)
	W	Exponential (112.89)	Truncated (5,450)
	S	Exponential (0.11325)	Truncated (0,0.8)
	MN	Discrete ({0.025,0.03,0.035,0.04}, {0.1,0.6,0.2,0.1})	
	R	Triangular (2000,8000,30000)	

Catchment	Probability distribution function		Remarks
	Variables & parameters	Distribution	
	I1	Gamma (1.0966,646.29)	Truncated (5,1000)
	θ	Triangular (0, 0, 89)	Truncated (0,70)
	wFP	Exponential (565.91)	Truncated (15,5000)
	H	Triangular (0.5, 20, 3)	
	L	Uniform (19,20)	
	D	Triangular (0.25,0.5,2,5,95)	
	q_c	Lognormal (0.371,0.2)	
	β	Triangular (0.9,1.2,1.5)	
	γ	Triangular (0.9,1.2,1.7)	
	ϕ	Triangular (0.0000005, 0.512, 0.032)	
	K_1	Triangular (218,836,3326) when MN (0.025) Pert (195,750,2981) when MN (0.03) Triangular (178,684,2718) when MN (0.035) Triangular (165,631,2509) when MN (0.04)	
	K	Discrete K Value Probability 0.07 0.25 0.17 0.02 0.27 0.25 0.37 0.48	
	C	Discrete C-Factor Probability Development - 0.002 0.14 Forest - 0.004 66.18 Grass - 0.05 29.1 Waterway - 0 2.49 Dvpt Plantation Initial Growth - 0.15 0 Dvpt Plantation Mid Growth - 0.07 0 Dvpt Plantation Full Growth - 0.05 0 Dvpt Plantation - Dvpd Area - 0.002 0 Dvpt Plantation Cleared - 0.4 0 Disturbed Forest - 0.05 0.91 Garden areas with evidence of recent modification - 0.125 0.12 Shrubland - 0.05 0.08 Grass/shrub/wood - 0.05 0.22 Plantation - 0.05 0.39 Disturbed Grassland - 0.5 0.19 Village Area - 0.2 0.16 Woodland with severely degraded ground cover - 0.1 0.02	
	SDR_h	Triangular (0.001,0.4, 0.75)	
	δ	Triangular (0, 0.14, 0.5)	
	K_3	Uniform (0.0001,0.0005)	
	e	Uniform (0.1, 1.5)	
	f	Uniform (0.5,1)	
	RT	Binomial (1,0.7)	
	RD	Discrete ({0.1,0.4,0.7,0.95}, {0.05,0.1,0.75,0.1})	
	BD	Triangular (1,1.5,2)	
	C_b	Triangular (0.3,0.4,0.5)	
Maralumi ($178\ km^2$)	i	Invgauss (124.71,117.5)	Truncated (0, 865)
	W	Invgauss (20.161,6.246)	Truncated (10,200)
	S	Exponential (0.11325)	Truncated (0,0.8)
	MN	Discrete ({0.025,0.03,0.035,0.04}, {0.1,0.6,0.2,0.1})	

Catchment	Probability distribution function		Remarks
	Variables & parameters	Distribution	
	R	Triangular (2000,8000,30000)	
	I1	Log Logistic (-37.165,964.41,1.8623)	Truncated (5,1000)
	θ	Log Logistic (-4.4323,13.146,3.4749)	Truncated (0,70)
	wFP	Invgauss	Truncated (15,5000)
	H	Triangular (0.5, 20, 3)	
	L	Uniform (19,20)	
	D	Triangular (0.25,0.5,2,5,95)	
	q_c	Lognormal (0.371,0.2)	
	β	Triangular (0.9,1.2,1.5)	
	γ	Triangular (0.9,1.2,1.7)	
	ϕ	Triangular (0.0000005, 0.512, 0.032)	
	K_1	Triangular (218,836,3326) when MN (0.025) Pert (195,750,2981) when MN (0.03) Triangular (178,684,2718) when MN (0.035) Triangular (165,631,2509) when MN (0.04)	
	K	Discrete K Value Probability 0.07 0.25 0.17 0.02 0.27 0.25 0.37 0.48	
	C	Discrete C-Factor Probability Development - 0.002 0.14 Forest - 0.004 66.18 Grass - 0.05 29.1 Waterway - 0 2.49 Dvpt Plantation Initial Growth - 0.15 0 Dvpt Plantation Mid Growth - 0.07 0 Dvpt Plantation Full Growth - 0.05 0 Dvpt Plantation - Dvpd Area - 0.002 0 Dvpt Plantation Cleared - 0.4 0 Disturbed Forest - 0.05 0.91 Garden areas with evidence of recent modification - 0.125 0.12 Shrubland - 0.05 0.08 Grass/shrub/wood - 0.05 0.22 Plantation - 0.05 0.39 Disturbed Grassland - 0.5 0.19 Village Area - 0.2 0.16 Woodland with severely degraded ground cover - 0.1 0.02	
	SDR_h	Triangular (0.001,0.4, 0.75)	
	δ	Triangular (0, 0.14, 0.5)	
	K_3	Uniform (0.0001,0.0005)	
	e	Uniform (0.1, 1.5)	
	f	Uniform (0.5,1)	
	RT	Binomial (1,0.7)	
	RD	Discrete ({0.1,0.4,0.7,0.95}, {0.05,0.1,0.75,0.1})	
	BD	Triangular (1,1.5,2)	
	C_b	Triangular (0.3,0.4,0.5)	

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); 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 functions: Triangular(20,25,95) = 20 indicates minimum, 25 most likely and 95 maximum values; Invgauss(4.8237,18.437) = Inverse Gaussian distribution, 64.8237 indicates mean and 18.437 shape parameters; Truncated (0,809) = a distribution truncated at two bounds; Lognormal(0.35,0.27) = 0.35 indicates the mean while 0.27 standard deviation; Exponential(0.16073) = Exponential distribution with decay constant (mean = 0.16073); Discrete({0.025,0.03,0.035,0.04},{0.1,0.1,0.2,0.6}) = 0.025,0.03,0.035,0.04 indicate outcomes while 0.1,0.1,0.2,0.6 their probabilities respectively; Erlang(4,743.41) = 4 indicates an integral shape parameter while 743.41 scale parameter; Log Logistic(0.23522,3.0589,1.8134) = 0.23522 indicates location, 3.0589 scale and 1.8134 shape parameters; Uniform(18,19) = 18 indicates minimum and 19 maximum values; Triangular(0.25,0.5,2,5,95)= most likely value (0.5), and bottom (0.25) and top (2) values at 5th and 95th percentiles respectively; Beta General(0.43156,38.777,0,6483.5) = 0.43156 and 38.777 indicate shape parameters while 0 and 6483.5 minimum and maximum values respectively; Pareto2(0.04831,1.6824) = 0.04831 indicates shape while 1.6824 scale parameters; Logistic(3317.65,938.94) = location (3317.65) and scale (938.94) parameters; PearsonType5(4.4373,17.819, Shift(-1.6665)) = 4.4373 indicates shape and 17.819 scale parameters while Shift(-1.6665) shift in the domain of the distribution; Pert(195,750,2981) = minimum (195), most likely (750) and maximum (2981) values; Binomial(1,0.7) = 70% probability for true event (1).

A2.3 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 A2.3.1) and hillslope gradient factor (S_1, dimensionless) (Section A2.3.2), described below.

A2.3.1 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:

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

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:

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

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

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

where:

θ = hillslope angle (degrees).

Hillslope lengths (l_1) (and gradients, θ, see section A2.3.2) were randomly measured along hillslopes from a DEM of the area, with layers of the stream network superimposed. The methods 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, 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 (Appendix Table 1). Appendix Table 1 shows the variability in hillslope length by catchments, showing that the four sub-catchments had different distributions. The l_1 distributions were used in stochastically simulating their spatial variability by the MC method. A correlation found between l_1 and $\theta$was preserved during the simulation, thus predicting the realistic variations of l_1 within the four sub-catchments.

A2.3.2 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 $\theta$is desirable.

The S_1 factor in the four sub-catchments was estimated using the following equation described by Nearing (1997):

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

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 A2.3.1 for details), from which θ was calculated as:

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

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 A2.3.1) (Appendix Table 1). Appendix Table 1 shows the variability of θ in the sub-catchments, illustrating that there was no unique pattern of θ across the sub-catchments. The spatial variability in θ and, thus, the spatial variability in S_1 values, were simulated using the MC method by using the respective θ curve for each sub-catchment and following the method as described for the *K* factor (Section A2.2).

A2.4 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 ($0 \le C \le 1.0$). $C = 0$ suggests there is no soil loss, whereas $C = 1.0$ indicates there is no reduction in soil loss rates.

Land cover for the Project area and supplying catchments was derived from the terrestrial vegetation surveys undertaken by BAAM (2016) (Project area) and aerial imagery analysis (greater catchments). *C* factor values for the surveyed land cover were developed from values within the literature, particularly from the Markham River catchment surveys undertaken by Kolola & Samanta (2013; 2015) and several other assessments of C factor in tropical environments (Kuok, et al., 2013; Farhan, et al., 2013; Bonilla, et al., 2010). Spatial variability of C was thus determined to be discrete. The discrete *C* values are shown in Appendix Table 1.

A2.5 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 1). Similarly, variability and uncertainty in the proportion of coarse material (δ) in the sediment yield from hillslope was stochastically simulated (Appendix Table 1) based on limited information (Sheridan & Noske, 2005).

A2.6 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.

A3 Bank erosion (BE)

Coarse material from bank erosion in the four sub-catchments was predicted simplistically by extending the Wilkinson et al. (2004) method. It is defined as

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

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.

A3.1 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 the MC method.

A3.2 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 MC method by utilising data from Wilkinson et al (2004, p. 54) (Appendix Table 1). Monthly discharge (Q_m, ML) was also simulated stochastically (Section A3.6.2 below).

A3.3 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 aerial imagery and maps the four sub-catchments. Samples of w_{FP} were fitted for their best PDF as for topographic factor (Section A2.3) and its spatial variability and uncertainty was simulated by the MC method (Appendix Table 1).

A3.4 Bank height (*H*), dry bulk density(*BD*) and proportion of coarse material (C_b)

Bank height (*H*, m) was also highly variables in the four sub-catchments. 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) were also highly variable and as such spatial variabilities and uncertainties of *H*, *BD* and C_a were stochastically simulated after retaining their correlations by the MC method.

A3.5 Bed erosion (Bed)

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

A3.6 Discharge (Q_m)

Monthly discharge (Q_m ML) in the four sub-catchments was estimated based on mass balance and black-box approach. It was calculated as

$$Q_m = 100 * q_c * i * C_a \tag{A.13}$$

where:

Q_m = discharge (ML/month);

q_c = runoff coefficient (dimensionless); and

i = rainfall (mm/month).

A3.6.1 Runoff coefficient (q_c)

There was little information regarding the runoff coefficient (q_c) within the four sub-catchments. 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 sub-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 1). The truncated Lognormal distribution was defined based on limited information in the sub-catchments and professional judgement. A correlation between q_c and rainfall was also set for realistic simulation of runoff.

A3.6.2 Rainfall (i)

Monthly rainfall data were derived from the rainfall dataset described in the main text. Both spatial and temporal variabilities and uncertainties of rainfall were predicted stochastically. They were tested with over 22 distributions for best fit (Appendix Table 1). Given the absence of sub-catchment specific rainfall datasets, the same PDF was used for each sub-catchment. The PDF used is shown in Appendix Table 1.

A4 Sediment Transport Capacity

STC was calculated by extending Yang (1973) equation (Prosser, et al., 2001) as:

$$STC = K_1 \frac{12 * Q_m^{\beta} * S^{\gamma}}{W^{\beta-1}} \quad (1.6)$$

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).

A4.1 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 the four sub-catchments were stochastically simulated by utilising data from Wilkinson et al. (2004, Table 5, P. 90), information from the field, aerial imagery, literature, and professional judgement. Appendix Table 1 shows the distributions of K_1, which were utilised in simulating the spatial variability and uncertainty in K_1 through the MC method. Correlation between particle size and Manning's roughness, found based on global knowledge, was maintained during the simulation for realistic K_1 simulations.

A4.2 Channel bed slope (S)

Variability and uncertainty in bed slope of each of the sub-catchments were predicted stochastically. Lengths of creek were overlaid on the DEM, with start and end elevations noted. Samples of elevation drop versus distance were thus obtained and used to create samples of channel slope (S, m/m) for its stochastic generation. Channel slope was calculated as

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

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 each of the sub-catchments which were used in stochastically simulating the spatial variability of *S*, and thus the spatial variability in sediment transport capacity (STC).

A4.3 Exponents of discharge (β) and channel bed slope (ϒ), and channel width (W)

STC is highly sensitive to the exponent of discharge (β). There was little information available about the behaviour of both β and the exponent of slope (Υ) of rivers (Prosser & Rustomji, 2000). This information was utilised to set their PDFs for their stochastic simulation (Appendix Table 1). Variability in the channel width (*W*, m) was considered to follow triangular distribution with bounds defined based on field observations, imagery analysis, and professional experience (Appendix Table 1). Spatial variabilities and uncertainties in them were simulated by the MC method by retaining plausible correlation in them and other dependent stochastic variables and parameters.

A5 Impact Assessment

Most parameters within the model were kept the same for each of the scenarios run (existing, several impact scenarios). The major exception was the *C*-factor value. This is because the major potential source of impacts on sediment transport from the Project are from changes to land cover and their effects on sedimented runoff, evapotranspiration, and infiltration. Changes to the C-factor values are described in the main text.

APPENDIX 2 LONG TERM DISCHARGE TIME SERIES

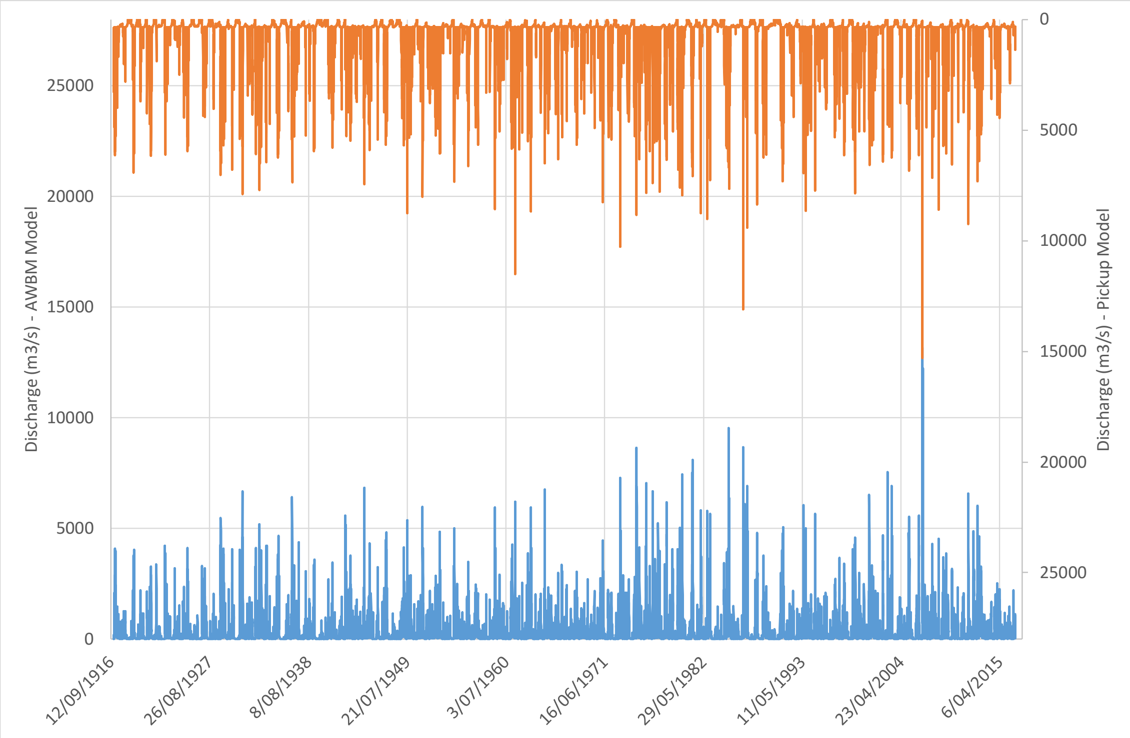

Figure A1-9-1 Modelled Markham River Hydrograph

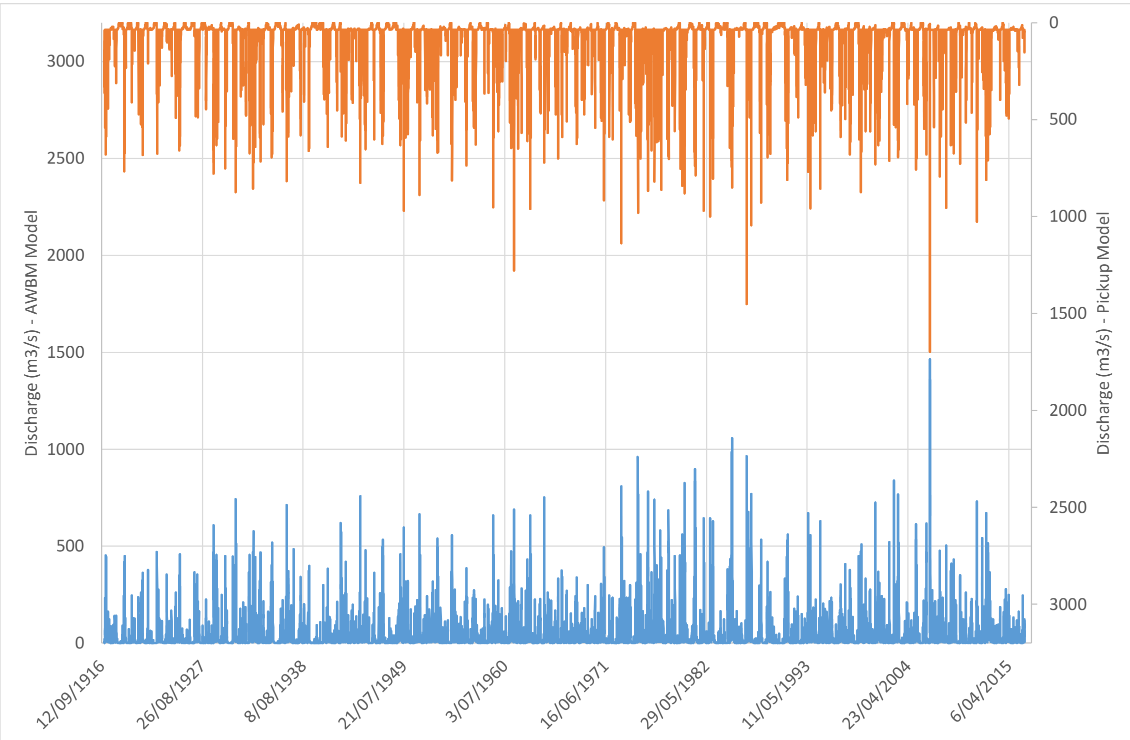

Figure A1 -9-2 Modelled Leron River Hydrograph

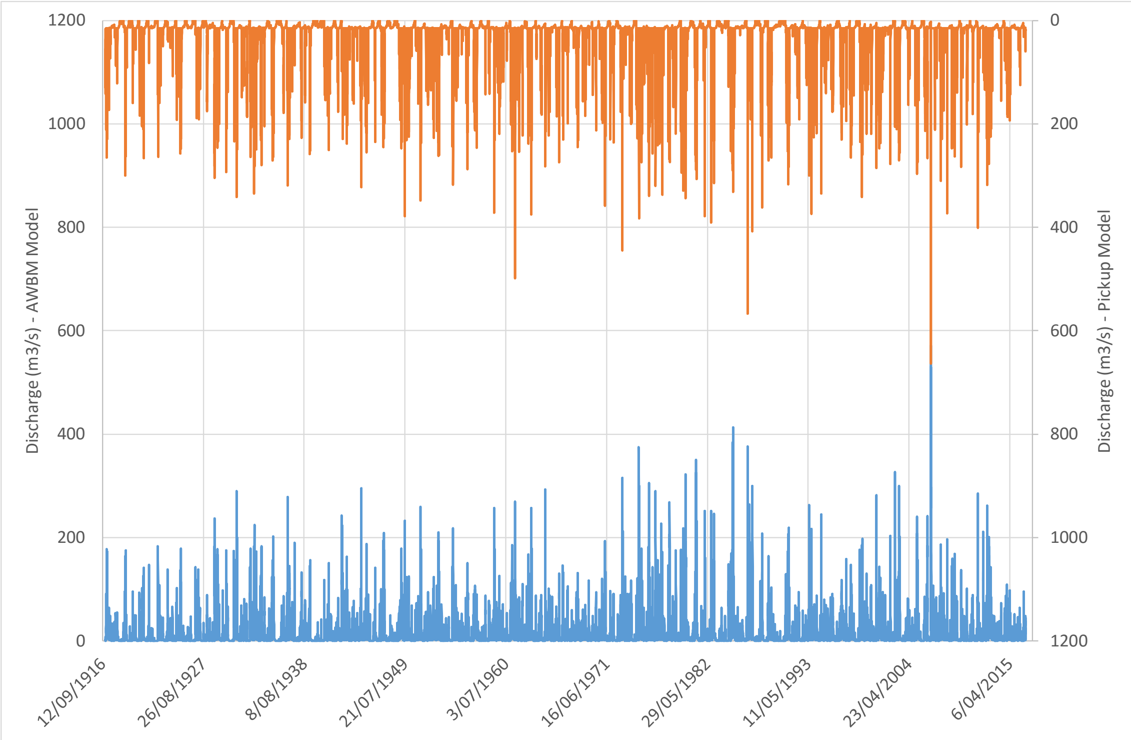

Figure A1-9-3 Modelled Erap River Hydrograph

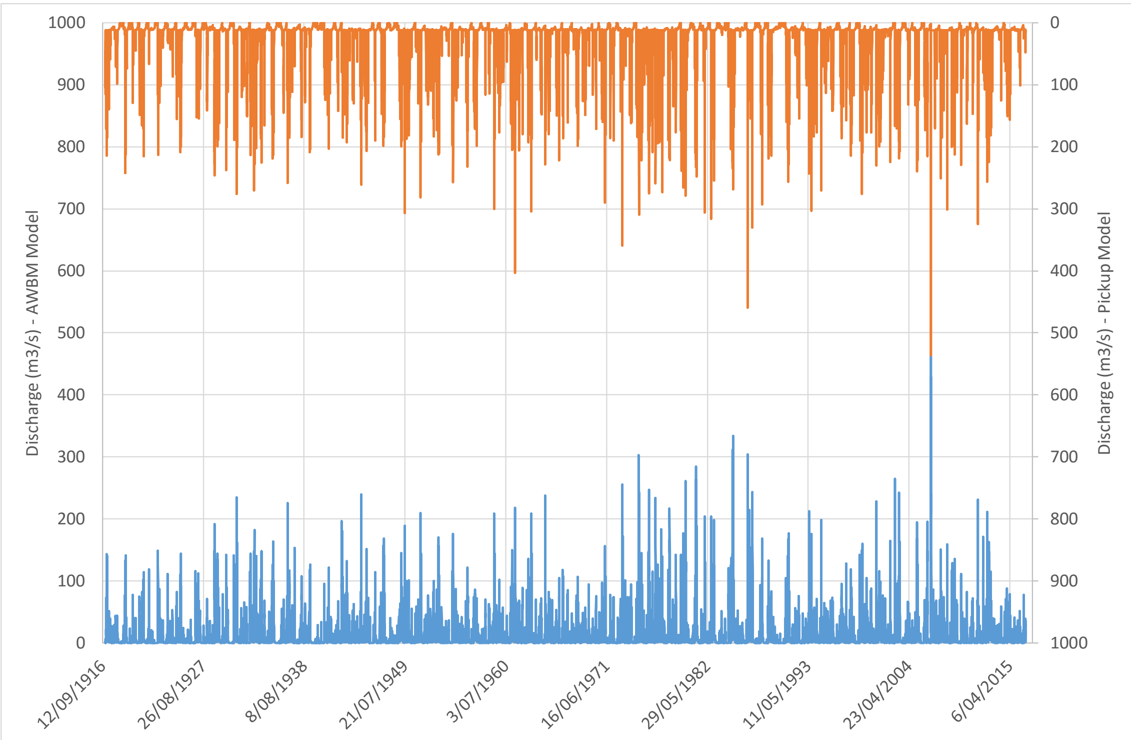

Figure A1-9-4 Modelled Rumu River Hydrograph

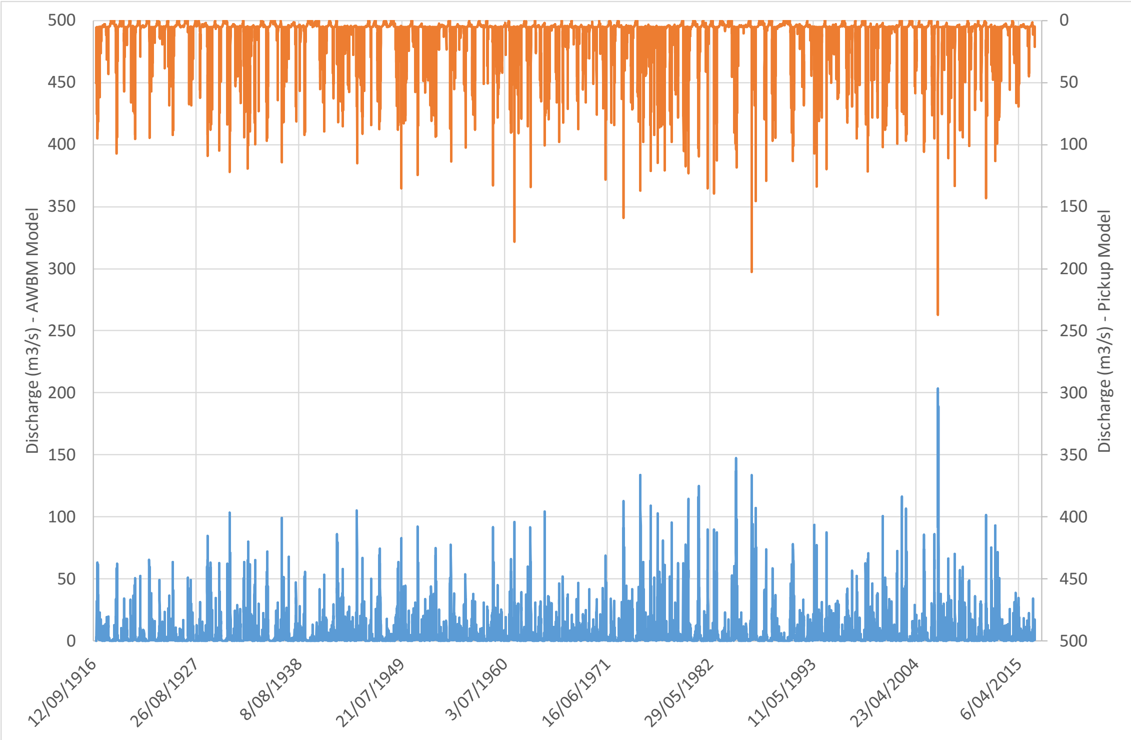

Figure A1-9-5 Modelled Maralumi River Hydrograph

APPENDIX 3 HYDROLOGY IMPACTS TABLES

Leron Summary Table

Scenario Catchment Model	Existing Leron Pickup	Existing Leron AWBM	Scenario 1 Leron Pickup	Scenario 1 Leron AWBM	Scenario 2 Leron Pickup	Scenario 2 Leron AWBM	Scenario 3 Leron Pickup	Scenario 3 Leron AWBM	Scenario 4 Leron Pickup	Scenario 4 Leron AWBM
General Statistics										
Maximum	1698.70	1463.75	1699.23	1464.27	1698.84	1463.89	1698.51	1463.56	1698.14	1463.19
Percentile 10	14.94	0.38	15.47	0.90	15.08	0.52	14.75	0.19	14.38	0.00
Percentile 90	70.03	68.00	70.56	68.53	70.17	68.15	69.84	67.81	69.47	67.44
Mean	50.86	26.15	51.38	26.68	51.00	26.29	50.67	25.97	50.32	25.63
Median	37.42	5.99	37.94	6.51	37.56	6.13	37.23	5.80	36.85	5.42
CV	1.52	2.37	1.51	2.32	1.52	2.35	1.53	2.38	1.54	2.41
Standard Deviation	77.40	61.90	77.40	61.90	77.40	61.90	77.39	61.90	77.39	61.88
Mean Daily Baseflow	27.67	5.89	28.20	6.42	27.82	6.04	27.50	5.71	27.16	5.40
Flood Frequency report										
Partial series 1 Yr ARI	559.40	336.19	559.16	395.70	559.55	336.33	558.43	336.00	558.82	335.62
Partial series 2 Yr ARI	692.47	498.59	695.76	547.68	692.61	498.74	695.05	498.40	691.91	498.03
Partial series 5 Yr ARI	835.97	650.39	839.90	690.44	836.11	650.54	839.18	650.20	835.40	649.82
Partial series 10 Yr ARI	970.79	782.41	954.83	796.12	954.56	807.56	957.42	774.60	953.84	774.22
Partial series 20 Yr ARI	1097.01	911.95	1086.41	914.02	1086.02	925.64	1085.69	913.30	1094.54	912.93
Partial series 50 Yr ARI	1285.33	1104.21	1280.58	1120.80	1280.15	1120.43	1280.50	1120.11	1279.49	1119.76
Partial series 100 Yr ARI	1434.21	1254.33	1431.16	1261.49	1429.44	1282.70	1430.54	1260.81	1430.19	1282.07
Partial series 500 Yr ARI	1936.18	1693.35	1932.06	1703.00	1929.74	1731.65	1931.23	1702.09	1930.75	1730.79

Erap Summary Table

Scenario Catchment Model	Existing Erap Pickup	Existing Erap AWBM	Scenario 1 Erap Pickup	Scenario 1 Erap AWBM	Scenario 2 Erap Pickup	Scenario 2 Erap AWBM	Scenario 3 Erap Pickup	Scenario 3 Erap AWBM	Scenario 4 Erap Pickup	Scenario 4 Erap AWBM
General Statistics										
Maximum	662.97	571.27	663.15	571.45	663.01	571.31	662.88	571.19	662.76	571.06
Percentile 10	5.83	0.15	6.01	0.32	5.87	0.18	5.74	0.06	5.62	0.00
Percentile 90	27.33	26.54	27.51	26.72	27.37	26.58	27.24	26.46	27.12	26.33
Mean	19.85	10.21	20.03	10.38	19.89	10.24	19.77	10.12	19.64	10.01
Median	14.60	2.34	14.78	2.51	14.64	2.37	14.51	2.25	14.39	2.12
CV	1.52	2.37	1.51	2.33	1.52	2.36	1.53	2.39	1.54	2.41
Standard Deviation	30.21	24.16	30.21	24.16	30.21	24.16	30.21	24.16	30.20	24.15
Mean Daily Baseflow	10.80	2.30	10.98	2.48	10.84	2.34	10.72	2.22	10.61	2.11
Flood Frequency report										
Partial series 1 Yr ARI	218.32	156.67	218.50	131.39	218.36	131.25	218.23	131.12	218.10	130.99
Partial series 2 Yr ARI	270.26	215.22	270.44	194.77	270.30	194.63	270.17	194.51	270.05	194.38
Partial series 5 Yr ARI	326.27	270.39	326.44	254.02	326.30	253.88	326.18	253.75	326.05	253.62
Partial series 10 Yr ARI	375.97	305.36	372.67	302.57	379.94	302.43	372.36	302.30	372.27	308.54
Partial series 20 Yr ARI	426.70	355.92	423.98	356.70	428.99	356.56	423.67	364.07	424.55	361.11
Partial series 50 Yr ARI	501.64	430.95	499.76	440.23	499.62	437.27	499.00	437.15	499.37	437.03
Partial series 100 Yr ARI	555.06	489.54	558.53	500.73	558.39	500.60	558.30	500.49	558.76	500.37
Partial series 500 Yr ARI	749.34	660.88	754.01	675.98	753.83	675.81	753.71	675.66	754.32	675.50

Rumu Summary Table

Scenario Catchment Model	Existing Rumu Pickup	Existing Rumu AWBM	Scenario 1 Rumu Pickup	Scenario 1 Rumu AWBM	Scenario 2 Rumu Pickup	Scenario 2 Rumu AWBM	Scenario 3 Rumu Pickup	Scenario 3 Rumu AWBM	Scenario 4 Rumu Pickup	Scenario 4 Rumu AWBM
General Statistics										
Maximum	536.50	462.57	536.79	462.86	536.57	462.64	536.38	462.45	536.17	462.24
Percentile 10	4.72	0.12	5.01	0.41	4.79	0.19	4.60	0.00	4.39	0.00
Percentile 90	22.12	21.49	22.41	21.78	22.19	21.56	22.00	21.37	21.79	21.16
Mean	16.06	8.26	16.36	8.56	16.14	8.34	15.95	8.15	15.75	7.97
Median	11.82	1.89	12.11	2.18	11.89	1.96	11.70	1.77	11.49	1.56
CV	1.52	2.37	1.50	2.29	1.52	2.35	1.53	2.40	1.55	2.45
Standard Deviation	24.45	19.56	24.45	19.56	24.45	19.56	24.44	19.56	24.44	19.55
Mean Daily Baseflow	8.74	1.86	9.03	2.16	8.81	1.94	8.63	1.75	8.44	1.60
Flood Frequency report										
Partial series 1 Yr ARI	176.68	126.86	177.18	106.54	181.69	126.93	192.75	106.12	176.34	105.91
Partial series 2 Yr ARI	218.70	174.27	219.02	157.86	224.96	174.34	229.66	157.44	218.38	157.24
Partial series 5 Yr ARI	264.03	218.94	264.30	205.84	270.05	219.02	272.07	205.41	263.69	205.20
Partial series 10 Yr ARI	304.25	247.26	301.73	245.15	301.51	255.15	307.31	244.73	302.11	244.51
Partial series 20 Yr ARI	345.30	288.19	343.25	294.20	346.21	288.75	342.79	294.74	342.62	288.35
Partial series 50 Yr ARI	405.95	348.95	404.57	354.32	404.35	354.10	404.16	353.92	405.91	353.72
Partial series 100 Yr ARI	452.97	396.39	452.13	402.36	451.94	405.38	451.75	404.08	451.52	405.02
Partial series 500 Yr ARI	611.51	535.13	610.37	543.19	610.11	547.27	609.86	545.51	609.56	546.78

Maralumi Summary Table

Scenario	Existing	Existing	Scenario 1	Scenario 1	Scenario 2	Scenario 2	Scenario 3	Scenario 3	Scenario 4	Scenario 4
Catchment	Maralumi	Maralumi	Maralumi	Maralumi	Maralumi	Maralumi	Maralumi	Maralumi	Maralumi	Maralumi
Model	Pickup	AWBM	Pickup	AWBM	Pickup	AWBM	Pickup	AWBM	Pickup	AWBM
General Statistics										
Maximum	236.97	203.62	237.15	203.79	237.01	203.66	236.88	203.53	236.76	203.40
Percentile 10	2.08	0.05	2.26	0.23	2.12	0.09	1.99	0.00	1.87	0.00
Percentile 90	9.77	9.46	9.95	9.64	9.81	9.50	9.68	9.37	9.56	9.25
Mean	7.10	3.64	7.27	3.82	7.13	3.68	7.01	3.56	6.89	3.46
Median	5.22	0.83	5.40	1.01	5.26	0.87	5.13	0.75	5.01	0.62
CV	1.52	2.37	1.49	2.26	1.51	2.34	1.54	2.42	1.57	2.49
Standard Deviation	10.80	8.61	10.80	8.61	10.80	8.61	10.80	8.61	10.79	8.60
Mean Daily Baseflow	3.86	0.82	4.04	1.00	3.90	0.86	3.78	0.75	3.67	0.66
Flood Frequency report										
Partial series 1 Yr ARI	84.36	46.77	78.11	54.11	78.08	46.80	77.84	46.68	77.82	46.55
Partial series 2 Yr ARI	100.78	69.36	97.16	76.02	96.64	69.40	96.90	69.27	96.39	69.14
Partial series 5 Yr ARI	119.67	90.47	117.27	96.15	116.66	90.51	117.00	90.39	116.40	90.26
Partial series 10 Yr ARI	134.38	108.84	133.32	107.96	133.18	107.82	133.05	112.19	132.91	107.56
Partial series 20 Yr ARI	152.52	126.86	151.66	129.64	151.52	127.11	151.39	126.99	151.26	126.86
Partial series 50 Yr ARI	179.30	153.60	178.74	156.01	178.60	156.09	178.48	155.76	178.35	155.32
Partial series 100 Yr ARI	200.07	174.49	199.74	178.57	199.61	178.45	198.26	178.34	199.38	178.22
Partial series 500 Yr ARI	270.09	235.56	269.65	241.07	269.47	240.91	267.65	240.75	269.16	240.60

Markham Summary Table

Scenario Catchment Model	Existing Markham Pickup	Existing Markham AWBM	Scenario 1 Markham Pickup	Scenario 1 Markham AWBM	Scenario 2 Markham Pickup	Scenario 2 Markham AWBM	Scenario 3 Markham Pickup	Scenario 3 Markham AWBM	Scenario 4 Markham Pickup	Scenario 4 Markham AWBM
General Statistics										
Maximum	15300.30	13183.96	15301.31	13184.97	15300.58	13184.25	15299.97	13183.63	15299.26	13182.92
Percentile 10	134.57	3.38	135.58	4.38	134.86	3.66	134.24	3.04	133.53	2.33
Percentile 90	630.80	612.52	631.81	613.52	631.08	612.80	630.47	612.18	629.76	611.47
Mean	458.09	235.53	459.09	236.54	458.37	235.82	457.76	235.20	457.07	234.51
Median	337.00	53.91	338.01	54.92	337.28	54.19	336.67	53.58	335.96	52.87
CV	1.52	2.37	1.52	2.36	1.52	2.36	1.52	2.37	1.53	2.38
Standard Deviation	697.13	557.52	697.13	557.52	697.13	557.52	697.12	557.52	697.11	557.52
Mean Daily Baseflow	249.26	53.09	250.26	54.09	249.54	53.37	248.95	52.76	248.29	52.08
Flood Frequency report										
Partial series 1 Yr ARI	5031.57	3028.04	5045.33	3029.06	5031.86	3491.86	5038.20	3027.70	5030.50	3026.98
Partial series 2 Yr ARI	6262.01	4490.83	6238.94	4491.84	6262.29	4911.23	6236.78	4490.50	6260.97	4489.79
Partial series 5 Yr ARI	7560.24	5858.09	7530.00	5859.12	7560.52	6214.26	7529.29	5857.76	7559.19	5857.03
Partial series 10 Yr ARI	8676.71	7047.20	8597.47	6979.56	8596.74	6978.83	8596.12	6978.20	8595.40	6977.48
Partial series 20 Yr ARI	9847.58	8213.89	9781.60	8228.83	9803.13	8404.24	9780.24	8376.52	9779.52	8226.77
Partial series 50 Yr ARI	11577.02	9945.56	11530.51	10091.46	11529.40	10090.77	11528.79	10090.18	11528.08	10089.50
Partial series 100 Yr ARI	12918.02	11297.74	12874.77	11400.29	12886.23	11358.00	12885.64	11551.84	12872.79	11551.20
Partial series 500 Yr ARI	17439.32	15251.95	17380.93	15390.39	17396.41	15333.29	17395.61	15594.98	17378.26	15594.11

Appendix 2
Hydrogeological Impacts Assessment

MARKHAM VALLEY POWER PROJECT

HYDROGEOLOGICAL IMPACTS ASSESSMENT

Don White[1] and Richard Silberstein[2]

[1]Whitegum Forest and Natural Resources Pty Ltd
PO Box 3269, Midland, WA 6056

[2]HydroEnviro Pty Ltd
255 Hay St, Subiaco, WA 6008

SUMMARY, EXPECTED IMPACTS AND RECOMMENDATIONS

SCOPE

This report presents estimates of the impact of a proposed *Eucalyptus pellita* plantation, and pumping to the associated power plant, on aquifers and streams. These estimates are used to quantify the potential effect of the plantation and pumping for the power plant, on groundwater dependent ecosystems and local water supply wells. The plantation and power plant will be located in the Markham Valley, Morobe Province, Papua New Guinea.

The potential hydrogeological impacts of the plantation were assessed against the Forest Stewardship Council (FSC) criteria for certification of plantations and the IFC Performance Standards 3 and 4. In the context of these criteria, the proponent is required to quantify the water use of the plantation and any change in the groundwater that might affect local water supply or existing water users. The project should also aim to make the most efficient use possible of resources, including water, and protect community health and wellbeing.

METHODS

A relationship between the crop factor (ratio of evapotranspiration to potential evaporation) and plant-available soil water, and the process-based model 3PG, were used to model the water balance of the existing grassland and savannah and the proposed plantation. The net water balance was calculated on a monthly time step and these outputs were used to estimate the change in groundwater depth, assuming a one-dimensional water balance and a specific yield of 10%. The water balance of the existing tall Kunai grassland was compared with *E. pellita* plantations with access to a range of soil depths from 3 m to 20 m.

The aim was to quantify the probability of a given change in depth to groundwater due to the plantation. The approach taken was to quantify the 'potential' impact on groundwater and streams. This conservative approach is prudent until a comprehensive data set on depth to groundwater and soil physical properties is available.

For the proposed pumping, analyses of simulated pumping were undertaken using the analytic solution for Laplace´s equation and spreadsheets available from the United States Geological Survey (https://pubs.er.usgs.gov/). Data from both the drawdown phase and recovery phase of the test as supplied were used to derive two estimates of the mean saturated hydraulic conductivity and to quantify drawdown associated with one, three and five bore options.

RESULTS

The modelling suggests the maximum possible increase in seasonal fluctuation in groundwater level is 4.5 m, and that in 60% of years the change would be between 0 and 2 m (Figure I). This would be observed as an increase in the seasonal dynamics. This study finds little cause for concern that the plantation will result in a trend of continuous decline in the groundwater given rainfall within the historical range. The plantation, at its maximum area, will use between 10,000 and 30,000 ML more water per year than the existing land uses. This is considerable amount of water, but is negligible in the context of the catchment of the Markham River (Jacobson, 1971).

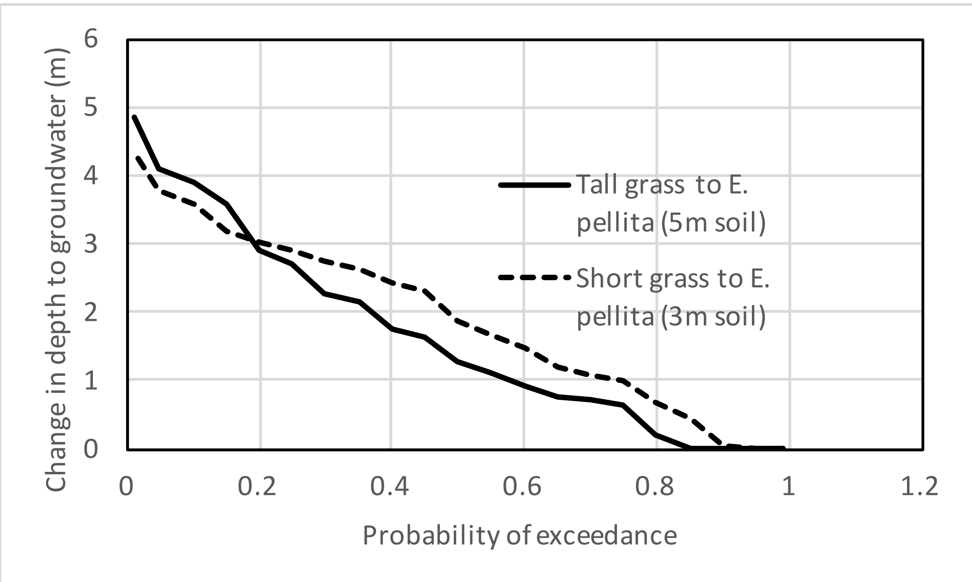

FIGURE I): THE RELATIONSHIP BETWEEN CHANGE IN GROUNDWATER DEPTH AND THE PROBABILITY A VALUE IS EXCEEDED. THE RELATIONSHIP IS PLOTTED FOR TWO CASES: I) A PLANTATION REPLACING SHORT GRASSLAND AND II) A PLANTATION REPLACING TALL, KUNAI GRASSLAND WITH ACCESS TO 5 M SOIL. THESE SCENARIOS REPRESENT THE MOST EXTREME IMPACT ON GROUNDWATER DEPTH THAT IS BIOPHYSICALLY POSSIBLE.

The pumping analysis concluded that, assuming the aquifer is 50 m thick, the water required can not be reliably or safely supplied from fewer than 5 bores separated by 1 km.

RECOMMENDATIONS

1. The sandy soils of the region are likely be very transmissive in which case the groundwater drawdown due to the plantation will diminish within a relatively small distance from the plantations edge (10 to 20 m). The proposed streamside reserves (100 m for the Markham River, 60 m for the Erap and Leron Rivers, 30 m for streams wider than 5 m, 20 m for streams 1 to 3 m and 5 m for streams less than 1 m) are therefore adequate to protect the streams and associated vegetation from the changes in groundwater depth associated with the plantation.
2. It is further recommended that large plantations (more than 100 ha) should not be located within 1 km of the upslope side of local water supply wells. The local network of wells should also be monitored for depth and water quality. These data can be used to improve the modelling presented here.
3. The proposed pumping bores for the power plant should be sited downslope of the plantation and close to the Markham River to ensure continuity of supply and to avoid any impact of these bores on local water supply wells or on groundwater-dependent ecosystems. The maximum rate of pumping (for the two 15 MW units) will be 156,000 L per hour. This equates to 375 mm per day if it all comes from a ground area of 1 ha. This is a large amount of water and is approximately 120 times the maximum possible impact of the plantation per unit land area. Pumping at this rate from a single well will cause a drawdown at least one km from the bore centre. It is therefore essential that further aquifer testing be undertaken to determine: i)the full depth of the reliable aquifer and ii) the specific yield and hydraulic conductivity of the aquifer.
4. If changes in ground water depth of less than 3 m are unacceptable then the results of this study indicate that a detailed field data collection and associated modelling study is warranted.
5. Based on the limited amount of data available and the data from the pumping test, which did not reach steady state, the amount of water that the proponents wish to pump cannot be reliably supplied from fewer than 5 wells approximately 1 km apart. To reduce these specifications a detailed study of the soil physics, lithology and pumping tests with a network of observation bores would be required.

6. There is great deal of uncertainty surrounding the climate data, groundwater depth and dynamics and key soil properties needed to model the growth, water balance and groundwater impacts of the plantation and pumping bores. We recommend that a monitoring program be commenced at the site. As well as measurements of plantation growth the proponents should commence measuring weather variables including rainfall, radiation and temperature. Groundwater monitoring bores should also be installed in transects within the plantation and extending 100 m beyond the plantations edge.
7. That a project be initiated to explore the relationship between management and the wood productivity (wood per water) of the project.
8. That a full life cycle analysis be conducted of the water impacts and efficiency of using biomass to produce energy.

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1. Scope and Context

1.1. Objectives

This document forms part of a broader environmental assessment of a proposal to establish a *Eucalyptus* plantation estate of approximately 16,000 ha in the Markham Valley, Morobe Province, Papua New Guinea. The trees will be harvested on a 7 to 9-year cycle to provide biomass for a power plant. This report quantifies the impact of the plantations and associated processing plant on the local groundwater and streams including:

1. The establishment of 16,000 ha of *Eucalyptus* (*E. pellita* or hybrids) plantations.
2. The extraction of up to 156 m^3 hr^{-1} of water for the power plant from bores i) within the power plant boundary or ii) adjacent to the Markham River.

1.2. Methodology

The effect of plantations on groundwater resources were assessed using models of the vegetation water balance. This involved:

1. Describing the current condition of the groundwater and vegetation in the area.
2. Identifying the models that are best suited to quantifying the water balance of plantations at the stand and catchment scale.
3. Assembling data sets for i) model inputs and ii) to constrain the model outputs.
4. Using the models to quantify the potential effect of plantations on the groundwater and streams of the region. The criteria for this assessment were those defined in Principle 5 and 6 of the Forest Stewardship Council (FSC) International Generic Indicators (see section 2.3 for details) and consistent with the IFC performance standards 3 and 4.

The effect of groundwater extraction by the biomass-fired power plant on local and regional groundwater depth was assessed by:

1. Quantifying the rate of extraction.
2. Describing relevant soil physical properties of the soils at the bore sites.
3. Modelling groundwater dynamics at the bore sites.

2. Assessment Criteria

The local Papua New Guinea (PNG) regulations regarding land use and industrial impacts on groundwater do not provide an adequate basis for assessing the impact of a development of this type on groundwater resources. Instead, FSC certification guidelines and standards, together with the IFC Performance Standards 3 and 4, were used as the basis for quantifying the impact of the plantation establishment.

FSC International Generic Indicators (FSC, 2015), Principles 5 and 6 consider the impact of plantations on water resources (Appendix 1). In summary, certification of this activity by FSC would require that the proponent should quantify water demand by the activity and areas of stress and conflict with existing use. If the current state is not considered natural there is a responsibility to quantify the change in the state of the system; specifically, the change in depth to groundwater and the proximity of this change to local wells, groundwater dependent ecosystems (including crops) and streams.

IFC Performance Standard 3 and 4 (IFC, 2012) pertain, respectively, to the efficient use of Resources and Community Health and Safety. For compliance the project must demonstrate that it will not adversely affect the health of the local community through adverse changes in water quality or security and that efficient use is being made of water resources.

The impact of the plantation and proposed pumping on i) the total water balance of the Markham River valley, ii) depth to groundwater and iii) water used for biomass production (efficiency) were quantified with respect to the current land use. The region of the Markham Valley where Markham Valley Biomass (MVB) proposes to establish a biomass plant and plantation is mostly degraded grazing land with a sparse scattering of rain trees (less than 50 per ha). Within this area, streams should be protected from forestry operations by adequate buffer zones.

To meet the FSC standard for assessing the impact of new plantations on water resources the change in water balance associated with the change in land use should be quantified compared to an agreed ‘baseline condition’. The dominant land use of the Markham Valley where PNGB proposes tree-planting is cattle grazing, on relatively poor pastures among remnant rain trees. There are also sugar cane plantations, oil palm plantations and some other tree plantations in the lower parts of the valley. None of these represent the natural condition of the valley. In a study where grazing was excluded from a series of sites in the valley (Saulei et al., 1992), there was a rapid succession from perennial grasses including *Imperata* spp. to trees and shrubs which reached an average height of 6 m within three years. Thus, the natural vegetation of the region would appear to be a savannah with much higher biomass density in both the understorey and overstorey than occurs presently.

In the following sections the water use of a pasture system and plantation are quantified. These two vegetation types represent the current and proposed state of an area of 16,000 ha in the Markham Valley. These alternative land uses will subsequently be referred to as plantations and grassland.

3. Existing and Future Conditions in The Proposed Plantations

The effect of plantations on the annual and monthly water balance was quantified using both 3PG (Physiological Principles of Plantation Growth, (Landsberg and Waring, 1997) and a model of the crop factor or ratio between plantation water use and potential evaporation (White et al., 2016). The outputs of these models were used to quantify the potential change to groundwater depth due to the proposed plantation.

This section describes the conditions of the plantation area in the past, present and future as a basis for the modelling in the following sections.

3.1. Current and Proposed Land Use

The drier central and northern parts of the Markham Valley are dominated by grasslands with scattered trees appearing at the northern margins (< 50 per ha). Two types of grassland, tall and short, were recognized by Holloway et al., (1973). The proposed planting area is dominated by the taller of these two grasslands, known locally as Kunai, in which the dominant species is *Imperata cylindrica*, while about 15% of the area is open woodland with introduced rain trees (*Samanea saman*). Tall Kunai grassland is known to occupy the more stable surfaces in the Markham Valley (Holloway et al., 1973). The dominant land use on all these lands is grazing, although there are some sugar cane and oil palm plantations in the valley. For water use modelling the key features of the Kunai grassland are that it is a perennial, C4, grass species up to 2 m tall and is relatively deep rooted with roots known to extend at least 2 m in the sandy subsoils.

The proposed plantations of *Eucalyptus pellita (E. pellita)* and hybrids will total 16,000 ha. The area that will be converted under the current Memoranda Of Understanding (MOU) is immediately west and northwest of the Nadzab Airport. The proponents have estimated that within this area, approximately 16,000 ha will be planted after exclusions; including streamside buffers and areas for the power plant, associated roads and infrastructure.

The plantations will be established at 1,333 stems per hectare and will be managed on a 7 to 9-year rotation. The fallow between rotations will be brief. Alternate rotations will be established by replanting with seedlings or coppicing (re-sprouting) from the stumps. This will result in a 14 to 18 year repeated management cycle (plant – harvest – coppice – harvest – replant). The proposed schedule of planting and harvesting will result in a plantation estate with the total area and age profile shown in Figure 1.

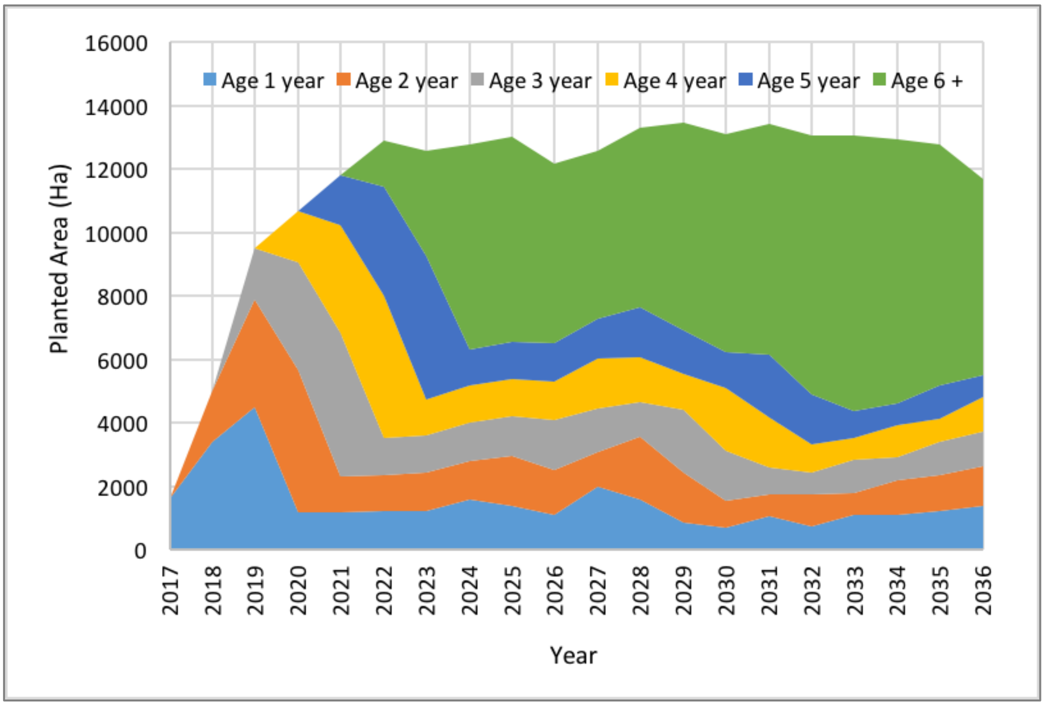

FIGURE 1. AREA AND AGE PROFILE OF PROPOSED PLANTATION ESTATE BETWEEN 2017 AND 2036 (APPROXIMATELY FOUR ROTATIONS AND TWO COMPLETE MANAGEMENT CYCLES).

3.2. Current and Future Climate

3.2.1. The Past and Present

Climate data is a critical input for any modelling of plantation growth or water use. Modelling the water balance at stand and catchment scale requires monthly or daily data for radiation, temperature, rainfall, potential evaporation and air saturation deficit. Of these variables, rainfall and temperature are the most important. Reasonable estimates of radiation, air saturation deficit and potential evaporation can be made from maximum and minimum temperature, latitude, longitude and time of year.

Historical variability within and between years is also an important consideration for quantifying the effect of plantations and of pumping on local groundwater resources. There will not be a single outcome from change but rather a distribution of possible changes with varying likelihoods. A long historical record, together with an understanding of the likely future changes will allow probabilities to be attached to the range of variation in key state variables such as rainfall, evaporation and drainage and runoff. A historical record of monthly rainfall, radiation, maximum and minimum temperature and potential evaporation, that spans the years 1900 to 2014 was constructed using local data and a synthetic record acquired from the

University of East Anglia Climate Research Unit[1]. This 114-year record allowed the use of models to quantify historical variation in the water balance of plantations and alternative land uses. It is acknowledged that this record is based on very limited sequences of measurement from within the plantation area. It will therefore be ´different´ from local records from within and near to the proposed planting area for any given year or month. These limitations notwithstanding, the representation of variation within- and between-year rainfall is sufficiently precise and realistic to allow us to represent the variability of the water balance under plantation and the grassland.

In a water balance, rainfall is the most critical variable. With radiation, it drives all the processes in the water balance. It also has greater variation between days, months and years and spatially than either radiation or potential evaporation. During the dry season, when water availability is most likely to be an issue for local communities, rainfall is a more important limit to both productivity and evaporation than radiation (see section below on limits to evaporation for an explanation).

The length and spatial coverage of the rainfall data available from the plantation area is extremely limited. There are seven weather stations in the Markham Valley with four (Nadzab, Bampu, Umi, and Chivasing) within the proposed plantation area. The most complete year of rainfall data from these stations was collected in 2014, although there are large gaps at some stations even during this year. As well as these more recent records, there are rainfall records of varying lengths from 1960 to 1975 from various locations in the valley. The most complete rainfall set relevant to this project is a continuous rainfall record from 1961 to 1973 from the Leron Plains station, which is northwest of the proposed plantation area. There is also a five-year data set from the Leron forestry nursery collected between 2005 and 2010.

A monthly record of temperature, rainfall, humidity, rain days and FAO56 Potential Evaporation was downloaded from the University of East Anglia Climate Research Unit. The location specified was the Nadzab Airport. However, each grid cell is 0.5 degrees x 0.5 degrees so that Nadzab falls in the same cell as Lae. The average annual rainfall varies within this cell by more than 200%. In 2014, the annual rainfall in the ´Lae´ record acquired from the University East Anglia Climate Research Unit (2263 mm) was 81 % greater

[1] University of East Anglia Climatic Research Unit; Harris, I; Jones, P.D. (2015): CRU TS3.23: Climatic Research Unit (CRU) Time-Series (TS) Version 3.23 of High Resolution Gridded Data of Month-by-month Variation in Climate (Jan. 1901- Dec. 2014). Centre for Environmental Data Analysis, *09 November 2015*. doi:10.5285/4c7fdfa6-f176-4c58-acee-683d5e9d2ed5. http://dx.doi.org/10.5285/4c7fdfa6-f176-4c58-acee-683d5e9d2ed5

than the average from the stations within the plantation area (1249 mm). The difference between the ´Lae´ synthetic data record and observed rainfall during was most pronounced during the dry season.

The average rainfall for the plantation area was calculated for each month of 2014 using the data from Umi, Bampu, Nadzab, Chivasing and Leron. This notional spatial average for the plantation area is plotted in Figure 2, alongside the data for the same year for Lae that was downloaded from the East Anglia Climate Research Unit.

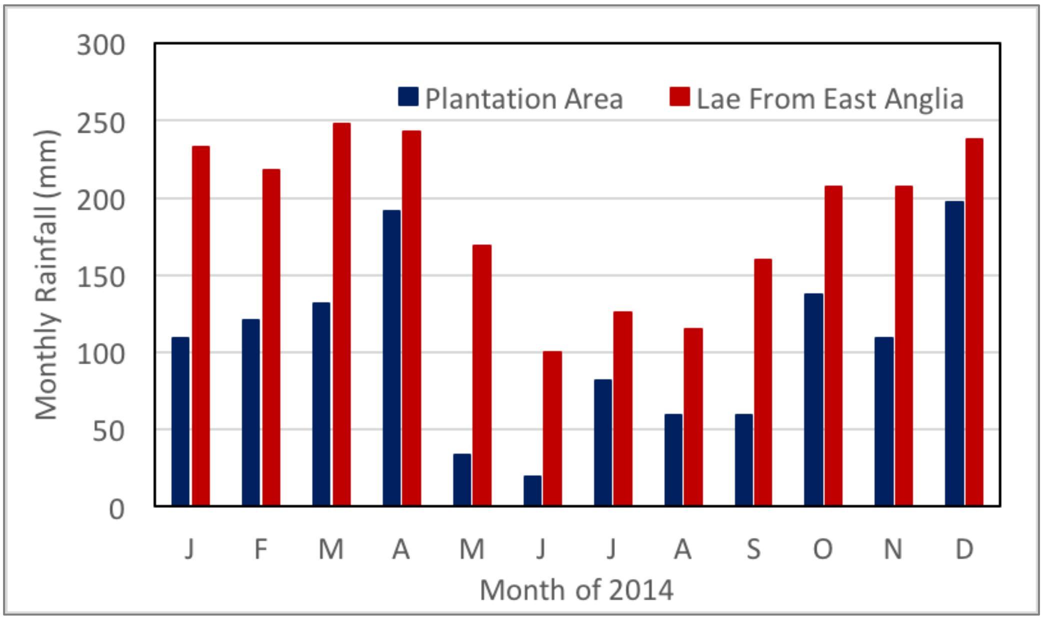

FIGURE 2. MONTHLY RAINFALL DURING 2014, THE AVERAGE FOR THE PROPOSED PLANTATION AREA WAS CALCULATED FROM AN INCOMPLETE RECORD FROM THE FOUR STATIONS WITHIN THIS AREA, WHILE 'LAE FROM EAST ANGLIA' IS FOR A CELL WHICH INCLUDES LAE AND NADZAB AIRPORT.

This notional monthly value for the plantation area was plotted against the estimate for ´LAE´ from the University of East Anglia Climate Research Unit for the same year (Figure 3). The ratio of Nadzab to Lae rainfall was lower in the dry than the wet season. A power function was therefore fitted to this small data sample and explained 68% of the variation in monthly rainfall in the plantation area. In a similar way monthly rainfall data from between 2006 and 2013 at Leron Forestry Nursery was plotted against the synthetic ´Lae´ record. The fit was not as good as for the 2014 data from the plantation region ($r^2 = 0.43$) but the parameters were not significantly different from those in the relationship shown in Figure 3. This model was used to calculate monthly rainfall from January 1900 to December 2014. This calculation gave an average annual rainfall for this period of 1405 mm. This is higher than the values reported recently for the plantation region but included a period between 1940 and 1970 with higher rainfall than has been observed recently.

The average annual rainfall since 1970 in this synthetic record is 1280 mm which is comparable with observed values at the Leron Nursery (1250 mm).

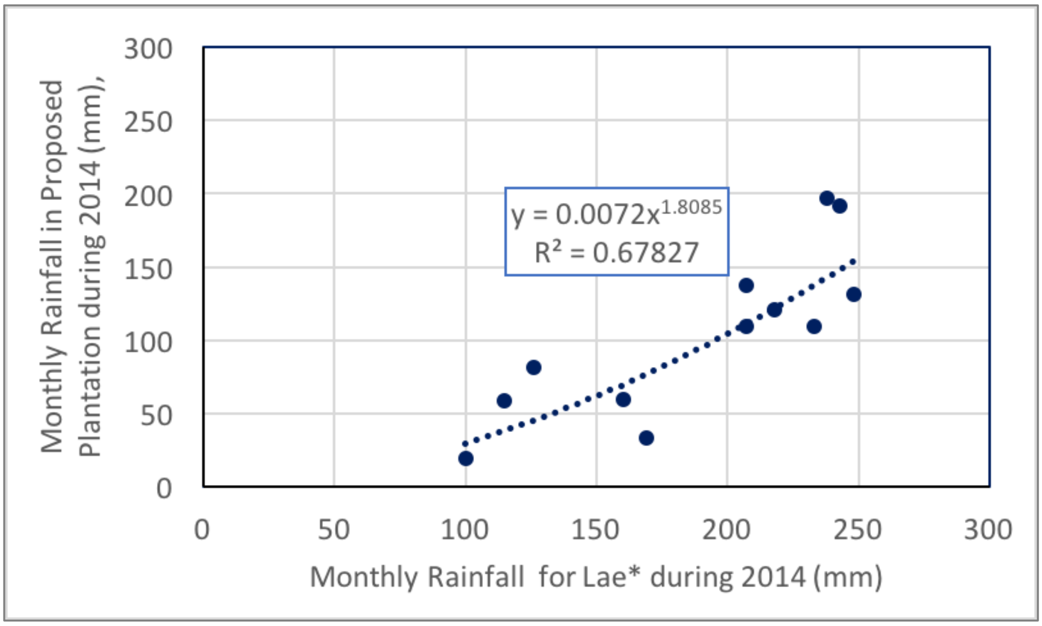

FIGURE 3. MONTHLY RAINFALL RECORDS FOR THE PLANTATION AREA AS A FUNCTION OF THE SYNTHETIC RECORD FROM LAE-NADZAB IN 2014. THE POWER RELATIONSHIP FITTED TO THIS DATA WAS USED TO ADJUST ALL OF THE MONTHLY RAINFALL DATA IN THE SYNTHETIC RECORD TO CREATE A LONG TERM DATA SET FOR THE PLANTATION AREA.

The average of total solar radiation (MJ day^{-1}) was calculated using Equation 1 after Hargreaves and Samani (1985) and as described in Allen et al., (1998.)

$$R_s = \left(0.16\sqrt{T_{max} - T_{min}}\right)R_a$$

EQUATION 1

where R_a is extraterrestrial radiation (the radiation received by the outer atmosphere) which is in turn a function of time of year, declination angle of the sun and latitude (see Allen et al., 1998.). Net radiation (R_n) was calculated (after Green et al., 1995; Alados et al., 2003) as 0.7 times total solar radiation and potential evaporation was calculated after Priestley and Taylor (1972) as described in Section 4 of this report.

The monthly averages for maximum temperature, minimum temperature, daily radiation and the average monthly rainfall for the climate sequence from 1900 to 1914 that was used in all the subsequent analyses are all shown in Figure 4.

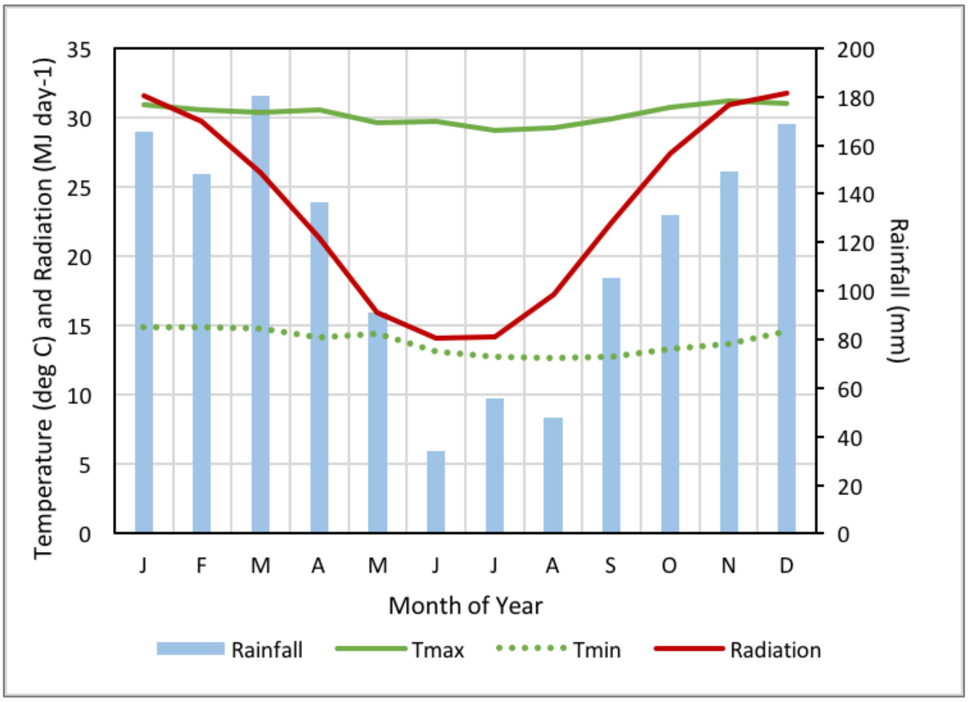

FIGURE 4. LONG TERM AVERAGE MONTHLY CLIMATE DATA FOR THE PLANTATION REGION. TOTAL RAINFALL, AVERAGE DAILY TOTAL RADIATION AND MAXIMUM AND MINIMUM TEMPERATURE ARE ALL SHOWN. THE VALUES WERE ESTIMATED AS DESCRIBED IN THE TEXT. THE LONG TERM AVERAGE ANNUAL RAINFALL ESTIMATED FROM THE PLANTATION AREA WAS 1280 MM.

3.2.2. The Future

It is not certain how the future rainfall will relate to this historical record. However, this is the only means we have for quantifying variation in rainfall and is the best available method for assessing the impact of this variability on plantation water use. Any impact of the proposed plantation estate on hydrogeology of the Project area will be realised in the medium to long term. It is therefore important to consider the likely effect of future climate projections on this historical analysis.

In the next 50 years, large changes in average annual rainfall are not predicted for the region. However, Jakka (2009) highlighted the importance of climatic extremes for water security in regions such as PNG without well-developed water storage infrastructure. In El Niño years, PNG does not necessarily have lower average annual rainfall than at other times but experiences much more variation between months with longer dry periods and individual months with very high rainfall. These events are predicted to increase in frequency due to global climate change.

3.3. Soils

The rate of transfer of rain to groundwater is determined both by a) the rate of evaporation from the land surface and vegetation cover and b) by the amount of water that can be stored in the catchment. This water is stored in the soil and in the groundwater. The amount of water stored in the soil is the product of soil depth and the amount of plant-available water that can be stored per unit of depth, which varies with soil texture. Loams and clay loams store more plant available water (140-170 mm m^{-1}) than either sandy soil or clays (70-100 mm m^{-1}).

The soils of the alluvial plains of the Markham Valley, where the plantations will be established, are primarily deep (>10 m) fluviosols. The surface soil is commonly silt loam while the sub soil is coarse-textured. These soils are deposited by the streams that flow to this area from the adjoining Finisterre and Saruwaged ranges. The coarser material is deposited closest to the ranges but the sub-soils are generally coarse sands with a variable proportion of rounded stones. This material can be quite fertile, although repeated cropping with sugar cane can result in important declines in key fertility indices (Hartemink and Kuniata, 1996; Hartemink, 1998; Hartemink and Bourke, 2000). For modelling with 3PG, and with the other model employed here, we have assumed a fine textured surface soil of 30 cm depth and a course textured sub-soil.

3.4. Groundwater dynamics

It is important to define an effective rooting depth for the plantation and for alternative vegetation and crops. Most trees, grasses and commercial crops cannot grow roots in saturated soil because there is not enough oxygen for root respiration and growth. Thus the depth to groundwater is an alternative method for defining effective rooting depth for the plantation. This, together with soil texture, determines the amount of water available to the trees in the unsaturated zone.

There was no data available from continuously monitored bores. The only information that could be used to assess the current condition of the groundwater systems was a sequence of four records of depth to groundwater made between June 2013 and February 2016. These observations were made in a series of 15 water supply wells within and outside the proposed plantation area. The most complete sequences of observations were made in the Wawin Rd area in the northern central part of Area 1, the Nowa-Leron area nearer to the Leron River and toward the western edge of area 1 and the Clean Water and Tararan area within Area 2.

The wells from each of these four regions fall into two groups with respect to the relationship between height above sea level and depth to groundwater (Figure 5).

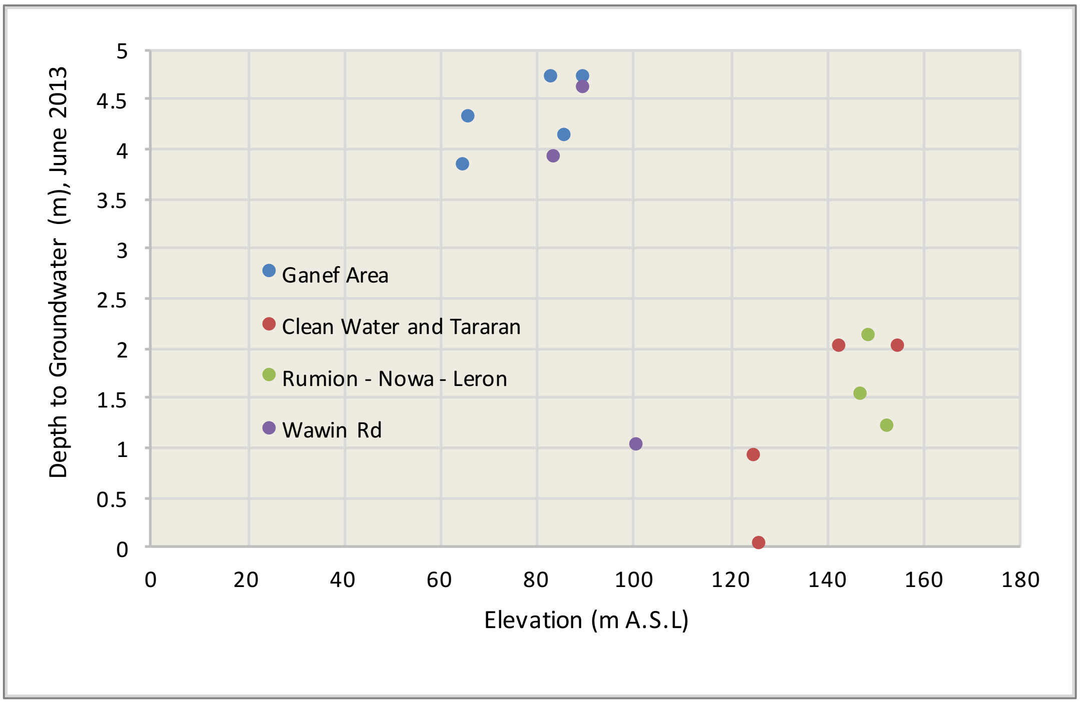

FIGURE 5. THE RELATIONSHIP BETWEEN HEIGHT ABOVE SEA LEVEL AND DEPTH TO GROUNDWATER FOR THE MAIN GROUNDWATER MEASUREMENT AREAS IN THIS PROJECT

The groundwater in the wells was 3.7 to 4.8 m below the surface in the Wawin Road and Ganef areas, which are between 80 and 100 m above sea level (ASL). The wells in the Cleanwater – Tararan and Rumion – Nowa areas were between 125 and 153 m ASL and the groundwater was about 2 m closer to the surface. The Wawin Road and Ganef areas are further from the Leron River or any other major watercourses than either the Clearwater – Tanaran or the Rumion – Nowa areas.

There was a small decrease in the average depth to groundwater between June 2013 and June 2015 (Figure 6). Thereafter there was a general increase in groundwater depth in the lower areas further from the Leron River and a pronounced dry season dip followed by a recovery of the groundwater in the Clearwater – Tararan area (Figure 6).

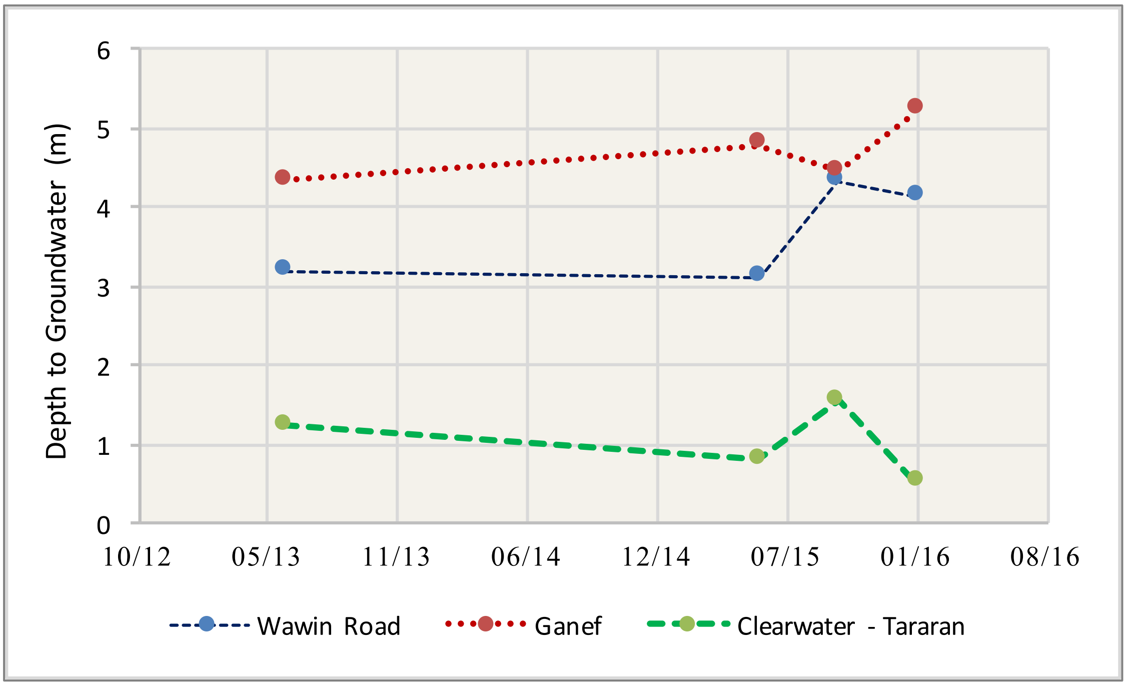

FIGURE 6. TIME TRENDS IN DEPTH TO GROUNDWATER FOR THE MAIN MONITORING AREAS

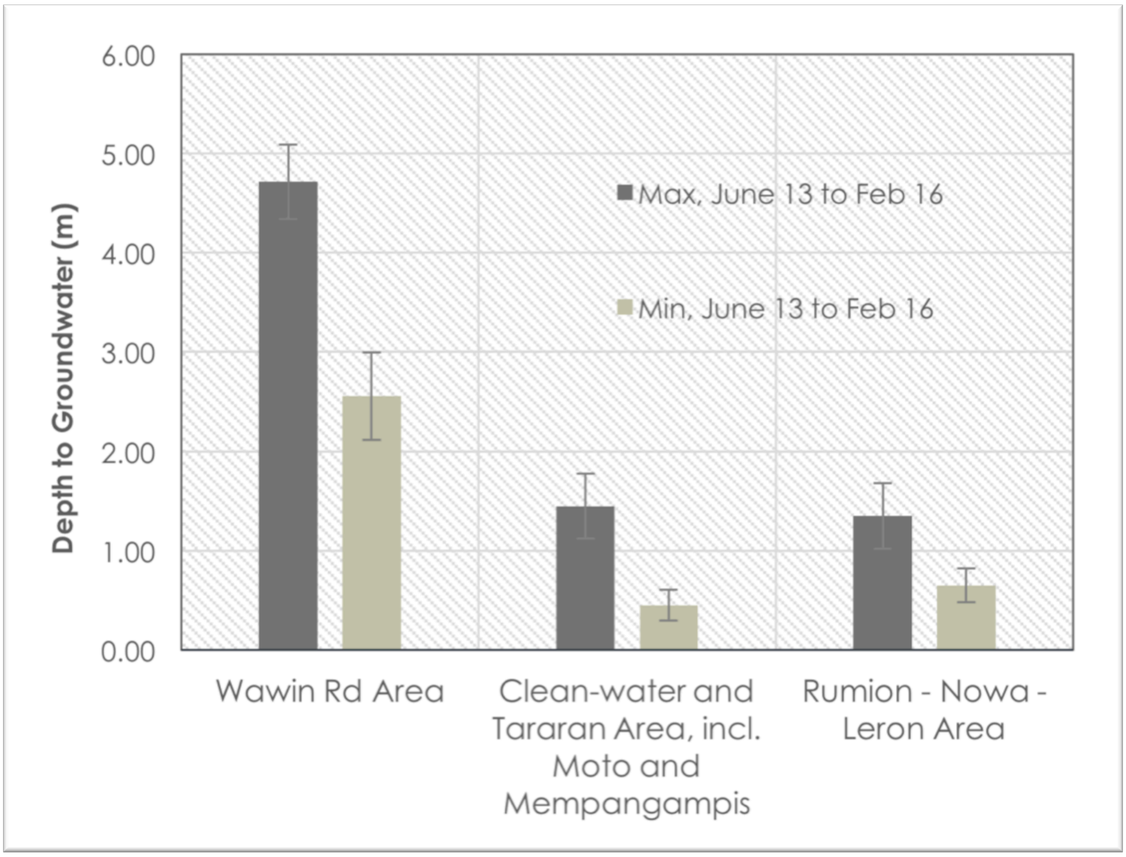

FIGURE 7. AVERAGE MAXIMUM AND MINIMUM DEPTH TO GROUNDWATER RECORDED IN THREE AREAS NEAR THE PROPOSED PLANTATION BOUNDARY.

Although there is very little recent information on depth to groundwater, a study was made in the late 1960s of more than 70 bores on the Leron and

Erap alluvial fans and on the Piedmont (Jacobson, 1971; summarised in the PNG land resources assessment). In the 66 bore holes that could be analysed the depth to groundwater varied from less than two metres to more than 40 m. The average depth to groundwater on the Leron fan was 29 m and on the Erap fan was 23 m. The bores were able to supply between 3000 and 7000 litres per hour from surface pumping. This was considered an underestimate, for reasons summarized in Jacobson (1971); deep aquifers in this type of unconsolidated sediments can typically supply much larger amounts of water (up to 700, 000 litres per hour). There were a number of perched, shallow groundwater systems associated with layers of sediments with low hydraulic conductivities. It is possible that the very shallow wells reported above are in fact perched local groundwater systems.

It would not be wise to draw general conclusions about the effects of site characteristics (altitude, region, soil type or season) on groundwater depth, based on recent measurements. There was no clear trend of either an increase or decrease in depth to groundwater and the data sequence was far too short to draw robust conclusions about the effects of rainfall or aquifer characteristics. The maximum increase in groundwater depth during the dry season was observed in a couple of wells in the Wawin Road area and was a little more than 2 m (Figure 7). The recent data from village wells, and the data from the well pumped by Golders used for this impact assessment (see section 7 for a description and analysis), indicate much shallower groundwater systems than those reported by Jacobson (1971). To resolve these apparent inconsistencies between recent observations and historical records we recommend installing an extensive network of groundwater monitoring bores in the plantation area. In particular, uncertainty regarding the depth to groundwater affects the available depth of the unsaturated zone for a growing plantation and the depth of the aquifer for pumping (see later sections for a description of the implications).

3.4. Plantation Access to Groundwater

It is well established that trees from a range of genera can use water from the capillary fringe of aquifers that they can reach with their roots. This has been observed in temperate, sub tropical, Mediterranean climate and tropical species of *Eucalyptus* and *Pinus* (Benyon et al., 2006; Eamus and Froend, 2006; Petrone et al., 2010; Brooksbank et al., 2011; O'Grady et al., 2011). The rate of groundwater use by trees seems to depend on depths to groundwater and on soil texture and strength in the capillary fringe of the aquifer.

The conditions in the Markham Valley are conducive to root growth and direct use of groundwater by *E. pellita*. There is no data with which to quantify the potential groundwater interactions of *E. pellita*, but experience with *E. grandis*, *E. globulus* and *E. kochii* in Australia (Carter and White, 2009; Benyon and Doody, 2015) suggests that while rates of direct groundwater use by *Eucalyptus* species will be affected by the rate at which water moves from the saturated to the unsaturated zone and the thickness of the capillary fringe, the difference between potential evaporation and rainfall will impose an absolute limit. Rates of between 1 and 2 mm per day are possible when potential evaporation exceeds supply from the unsaturated zone (Benyon and Doody, 2015).

4. The Water Balance – Definitions and Ground Rules

The global debate about the effect of plantations, particularly of eucalypts, on water resources is hindered by confusion about the definition of the components of the water balance and by inconsistent use of terminology. We are not custodians of any 'standard terminology', but to avoid confusion regarding the conclusions of this report, we will define the terminology as applied here at the outset.

4.1. The Catchment Water Balance

Streamflow (Q) over a given time period can be calculated by subtracting evapotranspiration (E_T) and the change in catchment storage (ΔM) over the same period from rainfall (P) (Equation 2, where an increase in storage is positive and a decrease is negative).

$$Q = P - E_t - \Delta M$$

EQUATION 2

Evapotranspiration (E_T) by any land use is the sum of all sources of evaporation from the land surface. For a plantation, total water use or evapotranspiration (E_T) includes transpiration by crop trees (T_{TREE}), soil evaporation (S), canopy interception (I), and understory or weed transpiration (T_{WEED}) (Equation 3). Transpiration (T) is the evaporation, through the leaf surface, of water that has been taken up from the soil by roots and transported to the leaves via stem and branches. Canopy interception (I) is the evaporation of rainfall that is caught in the canopy of either the crop trees or weeds and does not reach the ground. Soil evaporation is the loss of water by evaporation directly from the soil surface.

$$E_t = T_{TREE} + I + S + T_{WEED}$$

EQUATION 3

Many published reports of 'plantation water use' only include transpiration and do not account for other fluxes, which can make up more than 50% of total evapotranspiration (e.g. White et al. 2016). In this report plantation water use refers to evapotranspiration as defined in Equation 3.

4.2. Potential or Reference Evaporation

Potential or reference evaporation (E_0) is a measure of the potential or maximum energy limited rate of evaporation. A useful, albeit imperfect, way of thinking about reference evaporation is as the rate of evaporation from a free water surface under a given set of conditions.

There are many measures of potential evaporation but only two are used in this report. They have been selected because they are widely used, thus providing a ready benchmark against which other similar projects can be compared, and their modest data requirements mean they can be calculated with readily available climate data. The FAO56 reference evaporation (Allen et al., 1998.) is calculated using the Penman-Monteith equation (Monteith, 1965) for 0.12 m tall grass with a constant conductance and albedo (reflectance). For forests and plantations, potential evaporation is more closely approximated by Priestley-Taylor potential evaporation (Priestley and Taylor, 1972) which is on average about 1.2 times FAO56. FAO56 is freely available via FAO LocClim which can be downloaded from the Food and Agriculture Organization of the United Nations (FAO) website (Grieser, 2006). Priestley-Taylor potential evaporation can be calculated using Equation 4, where R_n is net radiation (about 70% of total solar radiation; Alados et al., 2003), s is the slope of the relationship between saturated vapor pressure and temperature and γ is the psychrometric constant or the slope of the relation between the partial pressure of water vapour and air temperature.

$$E_0 = 1.26\left(\frac{s}{s+\gamma}\right)R_n$$

EQUATION 4

4.3. THE CROP FACTOR AND CLIMATE WETNESS INDEX

Potential evaporation is useful in the consideration of water use by different vegetation types. It provides a reference against which to compare data from different crops at the same or from different locations. The ratio of evapotranspiration (E_t) to reference evaporation is called the crop factor (*k*, Equation 5) and will be used here as the basis for comparing plantations with other land uses.

$$k = \frac{E_t}{E_0}$$

EQUATION 5

Rainfall (*P*) and potential evaporation (E_0) both affect the water use of vegetation (see next section for details). Their combined effects are integrated in the climate wetness index (*CWI*, Equation 6), which is the ratio of rainfall to potential evaporation

$$CWI = \frac{P}{E_0}$$

EQUATION 6

4.4 Water security

Sustaining a secure water supply for communities is a complex allocation problem with biophysical and social dimensions. The quantity of allocatable water is usually defined as stream flow under a reference land use, less an allocation for environmental flow and an allowance for inter-annual variation. Changes in land use affect stream flow via changes in evapotranspiration. Addressing the effect of plantations on water security is an issue to be considered by those responsible for local natural resource management. This report aims to provide information and tools to facilitate the consideration of *Eucalyptus* plantations in this allocation process.

4.5. Water Productivity

Quantifying water use does not provide a sufficient basis for making land use decisions. Wood production and value generated from water use must also be considered, particularly where allocatable water is limited. IFC Performance Standard 3, requires that the project 'apply technically and financially feasible resource efficiency and pollution prevention principles.' Plantation management to maximize the production per unit water used is a 'systems' problem that is too often tackled through a narrow focus on selection of plant material to maximize transpiration efficiency.

A lot has been written about 'water-use efficiency' of plantations. Most of the published data on 'water-use efficiency' are actually transpiration efficiency of net carbon assimilation (Ngugi et al., 2003; Searson et al., 2004; Grossnickle et al., 2005) or above-ground biomass growth. If the aim is to design water use efficient plantations then it is very important to understand the distinction between wood production per unit of evapotranspiration (Plantation Water Productivity) and transpiration efficiency.

Wood yield of a plantation (*W*, g) can be expressed as the product of transpiration (T_{TREE}, kg H_2O), the transpiration efficiency of dry matter accumulation (TE_{DM}, expressed in g DM kg^{-1} H_2O) and the proportion of this dry matter partitioned to wood or useable biomass (*HI*, g g^{-1}) and is given by Equation 7 which is adapted from (Passioura, 1977).

$$W = TE_{DM} \times T_{TREE} \times HI$$

EQUATION 7

The water productivity of a plantation (PWP_{WOOD}) is the ratio of wood (or usable biomass) production to evapotranspiration and is given by Equation 8. This expression can be transposed to Equation 9 in which the effects of the transpiration efficiency of dry matter, the harvest index and the ratio of other evaporative fluxes to crop tree transpiration can be easily visualized (White et al., 2014).

$$PWP_{WOOD} = \frac{TE_{DM} \times T_{TREE} \times HI}{T_{TREE} + I + S + T_{WEED}}$$

EQUATION 8

$$PWP_{WOOD} = \frac{TE_{DM} HI}{1 + \left(\frac{T_{WEED} + I + S}{T_{TREE}}\right)}$$

EQUATION 9

Transpiration efficiency of dry matter production is one of several factors that affect Plantation Water Productivity. To design water productive landscapes and ensure water security for local people requires an understanding of the effect of available water and plantation management on all the factors that affect productivity and on all the components of evapotranspiration.

Increasing the transpiration efficiency of dry matter production, increasing the proportion of dry matter that is allocated to stem wood or decreasing the ratio of evaporative losses to crop tree transpiration are all potential mechanisms for increasing plantation yield and plantation water productivity (Equation 9). Managing these processes in isolation from one another might create unintended consequences, as they are not independent. For example increased transpiration efficiency of dry matter production will often be associated with water limitation and a reduced proportional allocation of dry matter to wood (Ryan et al. 2010). Thus transpiration efficiency of dry matter production is often negatively correlated with plantation water productivity (White et al. 2009).

Evaporative losses due to soil evaporation, weed transpiration and canopy interception can make up more than half of the total stand water (White et al. 2016) and reducing their contribution to evapotranspiration is perhaps the most straightforward means for improving water productivity

Evapotranspiration (the total water use of the system) is conservative over the longer term (Kelliher et al., 1995) and difficult to influence through plantation management. It is largely a function of rainfall and available energy and the components of evapotranspiration tend to compensate for one another. For example, changes in management may reduce evapotranspiration in the short–term (for example by reducing leaf area through thinning or pruning) but changes in the system (increased understory leaf area) mean that over longer periods total water use remains similar. It may be best to focus efforts on maximising productivity on land where plantations are grown and to manage water use through landscape design at larger scales. This approach will minimise evaporative losses and maximise plantation water productivity.

Rather than focus on transpiration efficiency it is more effective to target water productivity (wood or usable biomass production per unit of evapotranspiration), which integrates the effect of management on all of the components of evapotranspiration as well as on the transpiration efficiency of dry matter production and the allocation of dry matter to wood and other biomass components. Recent research in temperate (White et al., 2014a) and tropical (Stape et al., 2004b) systems has shown that plantation water productivity is correlated with both production and water use. This is important as it offers potential for plantation managers and water planners to reconcile wood production from *Eucalyptus* plantations with the allocation of limited water resources. Maximising productivity through tree breeding or silviculture will also maximise plantation water productivity.

One of the outputs from the modelling included here is an estimate of the amount of dry matter, above and below ground, and wood produced per unit of evapotranspiration.

5. Water Use by the Proposed and Existing Vegetation

Measurement of pasture and plantation water use is difficult and time consuming. Moreover, any data is constrained to a limited number of management scenarios and a unique combination of climatic and soil conditions. Rates of vegetation water use are 'situation specific' and it is unwise to draw conclusions from a single measurement. Fortunately, research comparing plantations with alternative land uses began more than a century ago and a number of excellent reviews, syntheses and meta analyses have been published recently (Zhang et al., 2001; Whitehead and Beadle, 2004; Brown et al., 2005; Farley et al., 2005; Dye and Versfeld, 2007; van Dijk and Keenan, 2007; Dye, 2013). These reviews and analyses show that useful generalities exist that can guide land use and natural resource management decisions.

In recent decades, since the mid 1980s, a number of process-based models of water use by vegetation (including plantations) have been developed. Most of these models are limited to representing the interaction of plants with the soil in the unsaturated zone. These models consider water that drains beyond the root zones of plants as a loss or leakage from the system. There are however, some models that describe the interactions of this leakage with groundwater and streams.

This section presents a brief summary of the literature on plantation water use and describes the main limits on water use and observed differences between alternative land uses.

5.1. General Principles of Water Use by Plantations and Alternative Land Uses

In a recent Australian Centre for International Agricultural Research (ACIAR) report, White et al. (2016) estimated and discussed the potential water use of *Eucalyptus* plantations in Southeast Asia and Southern China. The report did not attempt to present an exhaustive review but drew on the work of others in reviewing the literature to establish some general principles of plantation water use. These are summarized here:

1 The global effort on plantation water use has historically focused on temperate environments. Research on the water use by tropical and sub-tropical *Eucalyptus* plantations has occurred mostly in Brazil (e.g., Almeida et al. 2007; Stape et al. 2010) and China (e.g. Zhou et al., 2002; Lane et al., 2004). The results from studies in tropical *Eucalyptus* plantations make contrasting conclusions about the effect of *Eucalyptus* plantations on water resources. This highlights the limitations of empirical water balance studies; plantation water use is situation-

specific and it is unwise to draw general conclusions about plantations being a positive, neutral or negative influence on water resources from individual studies.

2 Debate on the effect of plantations on water resources is neither new nor unique to Southeast Asia and has accompanied the establishment of *Eucalyptus* species throughout the world and particularly in Australia (Greenwood et al., 2013) and South Africa (Dye et al., 2013). Markets for carbon may create additional impetus for planting and have therefore intensified concerns (Jackson et al., 2005).

3 In order of decreasing influence, the factors affecting evaporation from the land are: rainfall (water limit), potential evaporation (energy limit, defined in section 1), topography and geology (storage), and vegetation (resistance).

4 <u>Although vegetation cover is a secondary determinant of evapotranspiration it can have an important effect on water availability if stream flow is a small proportion of rainfall.</u>

5 At any given time, water use by plantations, and by alternative land uses, is either water- or energy-limited (Budyko, 1974), (Figure 8). Over long time periods, assuming there is no change in catchment storage, the Budyko (1974) framework can be used to partition rainfall into evapotranspiration and runoff.

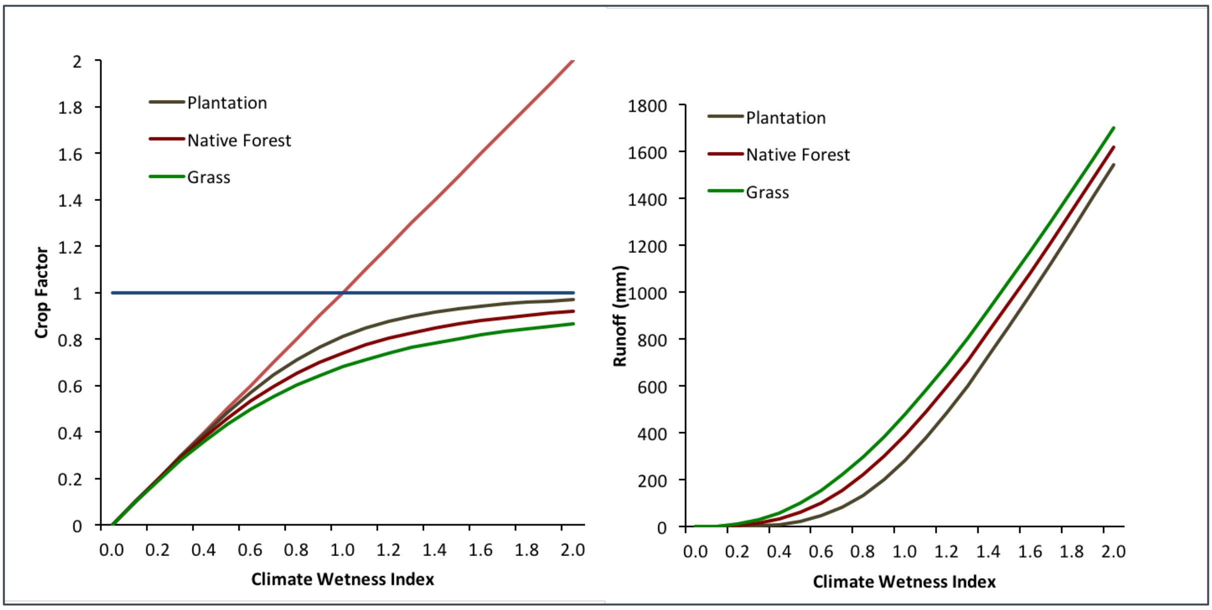

FIGURE 8. A) THE RELATIONSHIP BETWEEN THE CROP FACTOR (K, THE RATIO OF EVAPOTRANSPIRATION TO POTENTIAL EVAPORATION – EQUATION 5) AND THE CLIMATE WETNESS INDEX (CWI, THE RATIO OF RAINFALL TO POTENTIAL EVAPORATION EQUATION 6) SHOWING THE ENERGY AND WATER LIMITS TO EVAPOTRANSPIRATION. THE CURVED LINES ARE POTENTIAL EVAPORATION LINES FROM ZHANG ET AL (2004) FOR DIFFERENT VALUES OF THE CATCHMENT PARAMETER (W - GIVEN VALUES OF 4 FOR PLANTATION, 3 FOR NATURAL FOREST AND 2.5 FOR GRASS BY (ZHANG ET AL., 2004). B) THE RELATIONSHIP BETWEEN RUNOFF AND THE CLIMATE WETNESS INDEX ASSUMING POTENTIAL EVAPORATION OF 1500 MM.

6 The Budyko framework has been adapted to account for the effects of catchment characteristics, including vegetation cover, on evaporation. Zhang et al. (2004) analysed a global data set and fitted relationships between the crop factor and climate wetness index for plantations, natural forest and grassed catchments. These relationships (Figure 8) expressed the crop factor (*k*) as a function of the climate wetness index (*CWI*) and an empirical catchment characteristic parameter (z) that integrated the effects of vegetation type, storage (depth x texture) and topography on evapotranspiration. This model is described in detail in the next section. It is sufficient to note here that the catchment characteristic was significantly different between plantations, native forests, and grasslands. On average the rate of evapotranspiration, on an annual time step, is significantly greater from a commercial plantation than from either natural forest or grassland.

7 The crop factor, evapotranspiration and runoff are most sensitive to vegetation cover for a climate wetness index of 1. Sensitivity decreases steeply for values of the climate wetness index below 1. The catchment water balance is relatively sensitive to vegetation cover in situations where the climate wetness index is between 0.7 and 1.3.

8 These broad differences between vegetation types are based on analysis of large global data sets that only include catchments where more than 80% of the land is covered by a given vegetation type (Zhang et al., 2004). In most parts of Southeast Asia and PNG this is not the case; catchments are usually a mosaic of land uses. In an analysis of catchments with multiple land uses, Zhang and Chiew (2012) found that using an area-weighted average of water use estimated for different land uses gave an unbiased prediction of stream flow and evapotranspiration from the set of catchments. This is a reasonable approach for large scale water planning, particularly in areas where data on vegetation characteristics and local hydrogeology is limited (Zhang and Chiew, 2012).

5.2. How Do Plantations Differ From Grass and Native Forest?

Tree plantations for wood or biomass production have, on average, a higher annual rate of evapotranspiration than either grass, crops or native forest (Zhang et al., 2001). These differences are greatest when the rainfall is uniform throughout the year and the climate wetness index (ratio of rainfall to potential evaporation) approximates 1 (Zhang et al., 2004). Under these circumstances, evapotranspiration is about 10% greater in a plantation than a native forest, while a 15 to 20 % difference is evident between plantation and grass. Observed and predicted differences between these alternative land uses diminish when the climate wetness index is less than one and are often undetectable when it is less than 0.5. When the climate wetness index is greater than 1.5, the rate of evapotranspiration is still greater in plantations than alternatives but the amount of annual runoff from all land uses is large.

Why do plantations use more water than alternative land uses? What differences between these vegetation types affect their relative water use?

The most obvious differences are that they are evergreen, while many native forests are deciduous, and perennial while grasses are annual. Water use by vegetation is correlated with net energy balance which is correlated with leaf area index (Linder, 1985; Smethurst et al., 2001). Even when the local native forest is not deciduous (which is the case in or near the Project area), plantations tend to have a higher leaf area index (ratio of single sided leaf area to ground area) than native forest in a given situation. This is because plantations are often fertilized, are younger, and the leaf area index is affected by forest age and limited by both nutrients and water in natural systems (White et al., 2010).

Seasonal variation in leaf area of different vegetation types is linked to differences in effective rooting depth. Annual grasses have shallow root systems and suffer a terminal drought in late spring or early summer (dry season) (Ward and Dunin, 2001). Perennial grasses will also lose vigor or 'hay off' in the dry season but are generally deeper rooted than their annual counterparts. Trees and deeper-rooted plants are able to sustain higher rates of water use for longer periods during the dry season due to their greater access to soil-stored water (Ward and Dunin, 2001).

Plantations, when compared to crops or pastures, are also aerodynamically rough. This means that the long crown elements that protrude above the canopy create a more turbulent airflow above and within the canopy than occurs above the smoother canopies of pastures and agricultural crops. This turbulence increases the rate of exchange of moist air from within the canopy with the atmosphere.

Together these are the principal differences between plantations and alternative land uses. They mean that when the soil is wet, plantations tend to have a slightly higher maximum crop factor than alternative land uses. Although crop factors of one have been observed in pastures, wheat, lucerne, and in corn, sugar cane and rice (Tomar and O'Toole, 1980; Ward and Dunin, 2001; Watanabe et al., 2004), the reference evaporation used is usually the FAO56 or Penman-Monteith equation for crops (Monteith, 1965), which is 10 to 20% lower than the reference often used for trees (Priestley and

Taylor, 1972). During the dry season the plantations are able to maintain higher rates of water use for longer than annual crops and pastures due to their access to larger amounts of soil-stored water (White et al., 2016).

5.3. Are *Eucalyptus* Plantations a Special Case?

No consideration has so far been given to the difference between *Eucalyptus* species and alternative plantation crops. There is considerable hype and misinformation surrounding water use by *Eucalyptus* plantations. It is true that *Eucalyptus* species tend to exhibit faster rates of transpiration on a sapwood or ground area basis than either *Pinus* species (Benyon and Doody, 2015) or deciduous hardwoods. Conversely, it is also generally true that for a given latitude or climate wetness index, *Pinus* plantations have a higher leaf area index (leaf area / ground area) than *Eucalyptus* and significantly greater interception. Surprisingly, as far as we are aware only one study has made a direct, empirical comparison of the total water balance of *Eucalyptus* and *Pinus* plantations. This study, by Benyon and Doody (2015) concluded that there was no significant difference between the total water use (evapotranspiration as described by Equation 3) of *Pinus* and *Eucalyptus* plantations. It is also noteworthy that because transpiration tends to be a greater proportion of evapotranspiration in *Eucalyptus* than in *Pinus* plantations, it is probable that *Eucalyptus* plantations produce more biomass and wood per unit of evapotranspiration than *Pinus* species (White et al., 2009; White et al., 2014) (Equation 9).

5.4. What is known about water use by tropical *Eucalyptus* species and *E. pellita* in Particular?

Published studies of *Eucalyptus* water use focus primarily on transpiration. While transpiration is generally the largest component of the evapotranspiration, it can be less than half of total evapotranspiration (White et al., 2016). To our knowledge there has only been one study in tropical *Eucalyptus* plantations in which all of the components of evapotranspiration were measured. This study, on the Leizhou Peninsula in Southern China, concluded that plantations of *E. urophylla* x *grandis* did not have an important effect on drainage or local water balance (Lane et al., 2004). In contrast, studies in *E. grandis, E. urophylla* and hybrids in Brazil, in which some components are modelled, report large proportional reductions in already low rates of streamflow (Almeida et al., 2007).

The apparent contradiction between these two studies can be explained by important differences between the climates in the two regions. In both areas the rainfall is relatively uniformly distributed. The difference between these climates lies in the amount of radiation and therefore the amount of potential evaporation. On the Leizhou Peninsula in China, monthly potential evaporation only exceeds rainfall in one or two months a year while in the Cerrada region of Brazil, evaporation is greater than rainfall in every month of the year. The plantations in Brazil are nearly always water limited, while on Leizhou Peninsula they are nearly always energy-limited.

Specific studies cannot be used as a basis for quantifying the impact of a eucalypt plantation in a new location. If direct local measurement is not possible, then any assessment of likely local impact of plantations should be based on an understanding of the relationship between site, climate, species and growth, and water balance. There are numerous studies of transpiration by *Eucalyptus* in tropical and monsoonal environments (Calder, 1986; Roberts and Rosier, 1993; Almeida et al., 2004; Stape et al., 2004a; Almeida et al., 2007; Stape et al., 2010). Collectively these studies show that transpiration by trees and stands of *Eucalyptus* varies diurnally, seasonally, with stand age, and responds to fertiliser and to thinning. They suggest that maximum rates of water use are similar in plantation eucalypts in temperate and tropical environments. We could not find any studies of water use, water balance or transpiration in *E. pellita*.

6. Modelling Forest Growth and Water Use

6.1. What Models?

The choice of model for quantifying plantation water use will be largely determined by the availability of input data and the type and amount of data available for model testing and calibration. The confidence in any subsequent analysis made using the model will be greatly enhanced if local data is used for calibration and testing.

The choice of model will always be a balance between complexity, and accompanying parameter requirements, and realism of the process representations. Simple models have fewer equations, fewer parameter requirements and are, usually, relatively easily calibrated on historical data. The more comprehensive the model process representations, the greater will be the data requirement, both for *a priori* parameter data sets and for calibration and testing datasets. For a given purpose the most suitable model will be the one that predicts the desired output variable with sufficient accuracy and precision. It will need to represent the processes that give rise to this variable with an appropriate balance of realism and simplicity.

The following section presents some modelling options and considers their suitability for the task in terms of this balance of simplicity and realism but they will also need to have been tested in systems similar to those in which we will apply them. There are many models that describe the water balance of vegetated land at plot, hill slope and catchment scale. This section is not intended as a review of these models. The aim is to identify models that can be used to assess the impact of a large *Eucalyptus* plantation on the local groundwater and streams. Such a model must describe the water balance of the site at annual and monthly time resolution. The rainfall at the Markham Valley site is strongly seasonal and a monthly water balance will be required to describe the changes in storage, evaporation and deep drainage that will be needed to quantify the effect of trees on the system. Figure 9) copied from the WAVES (Water, Atmosphere, Vegetation, Energy and Salt) manual includes the processes that a model for quantifying the impact of a plantation would include.

The inputs to the system are energy (solar radiation) and water (rain and irrigation). These inputs are partitioned by the vegetation and the soil. At a minimum the models must estimate evapotranspiration but many models predict the component processes of transpiration, soil evaporation and canopy interception (see equations 2 and 3) separately (WAVES, 3PG (Landsberg and Waring, 1997) and CABALA (Battaglia et al., 2004) do this to varying degrees. In a managed system it is usually desirable to link transpiration with growth. Growth data is more often available than water balance data and can be used to constrain a water balance prediction if the feedbacks amongst the environment, growth and evaporative processes are included.

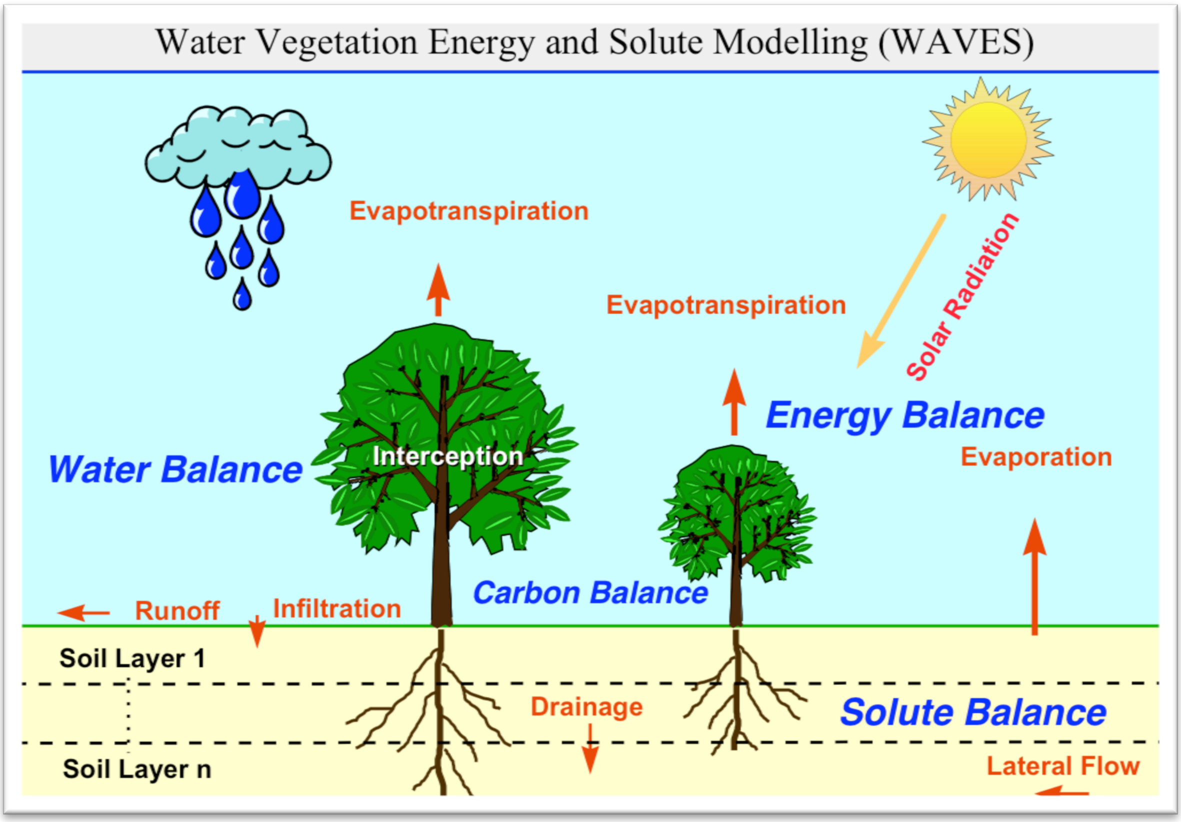

FIGURE 9. THE VEGETATION WATER BALANCE INCLUDED IN THE STAND SCALE MODEL WAVES.

There are a number of models available that model evaporation from forests and other systems reasonably well. In models that are designed to predict the productivity of crops, including plantations, the partitioning of throughfall (rain that reaches the forest floor) between evaporation and ´drainage´ is often treated fairly crudely. These models usually assume that all throughfall infiltrates the soil and is stored in one or multiple soil layers which have a maximum storage capacity. Once this maximum storage capacity is reached then water is lost from the system as ´drainage´. The readily available versions of 3PG describe the soil as a single layer with a maximum available soil water and a lumped ´fertility´ index. The CABALA model does allow for the inclusion of multiple.

In reality, most stand-scale models of plantation productivity, predict drainage (CABALA) or runoff (3PG) as the residual of a daily (CABALA) or monthly (3PG) water balance. In the real biophysical world this lumped residual is made up of runoff (overland flow), interflow at textural discontinuities, drainage and base flow. Few models that have been built to describe vegetation, attempt to describe all of these processes. This is largely because the physical description of the soil that is necessary to parameterise such a model is quite onerous. One model that attempts to describe these processes and their interaction with dynamic vegetation is WAVES. WAVES is a single-cell model, but a spatial version that moves water between cells in the catchment has been developed and is known as TOPOG.

The impact of a change in land use on evapotranspiration and net water balance can in principle be modelled using any of WAVES, 3PG, or a simpler model that represents the differences between the existing vegetation and the proposed plantation. The description of the soil and terrain that is required to run WAVES is not available within the current project. Similarly, we do not have sufficient information on the physiology or carbon balance of *E. pelllita* to parameterize CABALA. We have therefore elected to use a model of the crop factor (White et al., 2016) and 3PG to describe the water balance of the existing rangeland and the proposed plantation:

1. The first model used predicts the crop factor or ratio of evapotranspiration to potential evaporation as a function of relative plant-available soil water.
2. 3PG-PJS (a spreadsheet version of the model Physiological Principles of Plantation Growth). This model discounts light use efficiency as a function of a range of site and stand factors and allocates carbon to three pools including foliage. Photosynthesis and evaporation by the resultant canopy are then modelled independently.

6.2. *Eucalyptus pellita* – Parameterising and Calibrating Models

The project is planning to establish about 16, 000 hectares of *E. pellita* or hybrids. *Eucalyptus pellita* grows naturally in North Queensland and PNG. The species has been cultivated in Brazil, South Africa, India and Indonesia (Bernardo et al., 1998). In the next decade it is likely to become much more important in neighboring Indonesia, where it is being planted as an alternative where *Acacia* plantations have been badly affected by root rot disease (Hardiyanto, 2003). Provenance trials in PNG and the Torres Strait Islands indicate that local provenances outperform provenances from Queensland and that the wood of *E. pellita* has a higher density than other species of *Eucalyptus* commonly planted in tropical plantations (Harwood et al., 1997; Hung et al., 2015).

There have not been any detailed studies of water use or hydrology in plantations of *E. pellita*. In Brazil and Southeast Asia, the allometric relationships (biomass allocation) and growth have been studied in a series of tree improvement and spacing experiments (Bernardo et al., 1998; Hung et al., 2015). The most important difference between *E. pellita* and other tropical Eucalyptus species is a slightly lower specific leaf area and denser wood then other tropical plantation species. In this project we have elected to use a parameter set for 3PG developed by (Almeida et al., 2004) but have made small changes to the parameters associated with specific leaf area and with the relationship between wood biomass and volume.

3PG has been extensively tested in plantations of *E. grandis*, *E. urophylla* and hybrids in Brazil and in China (Almeida et al., 2004; Dye et al., 2004; Stape et al., 2004c; Esprey and Smith, 2007; Almeida and Sands, 2015). Notwithstanding the experience and resultant confidence in the capacity of the model to predict growth, publically available versions have well known limitations for modelling of water balance and runoff. These limitations were recently addressed by (Almeida and Sands, 2015) but this version of the model was not available for this study. The public domain version of the model was recently tested using water balance data from *E. urophylla* in Southern China, which predicted evapotranspiration with acceptable accuracy in seedling and coppice regeneration of this species. It is acknowledged that the model has not been tested directly using water balance data from *E. pellita* plantations. White and Shiqi (unpublished data) recently found that 3PG (standard version) generated acceptable results when used to model evapotranspiration of a coppiced *E. urophylla* x *grandis* plantation in Southern China.

6.3. Estimating the Change in Water Use with a Simple Ramp Function or Vegetation Characteristic

6.3.1. The Crop Factor Model

One approach to modeling seasonal variation in water use and quantifying the difference between plantations and other land uses is to use a relationship between the crop factor (k, the ratio of evapotranspiration to potential evaporation) and relative plant-available soil water to estimate evapotranspiration. These relationships, also known as ‘vegetation characteristics’ or ‘ramp functions’, were described by (White et al., 2000) for a range of planted forests. The crop factor integrates the effect of soil and atmospheric drought on transpiration, interception and soil evaporation through changes in leaf area and canopy conductance. There is sufficient information in the literature to construct very good models of this type for the major temperate plantation species and defensible models for tropical plantation eucalypts.

6.3.2. PARAMETERISING A RAMP FUNCTION FOR TROPICAL PLANTATIONS

This type of model was used by (Battaglia and Sands, 1997) in the plantation model PROMOD to quantify the effect of water stress on water use and the maximum mean annual increment (total volume/age) of *E. globulus* in plantations. Recently, (White et al., 2016) adapted this approach for predicting the water use of tropical plantations of *Eucalyptus grandis*, *E. urhophylla* and hybrids. The functions fitted by these authors to data for *E. globulus* are included as Figure 10, which also includes some data for *E. urophylla* x *grandis* from southern China. The curves are described by equation 7, where the independent variable, w, is the relative available soil water, w_0 is the soil water content for which the crop factor (*k*) is 0.5 and a_w is the slope of the linear portion of the curve.

$$\boldsymbol{k = \frac{w^2 e^{a_w w}}{w_0 e^{a_w w_0} + w^2 e^{a_w w}}}$$

EQUATION 10

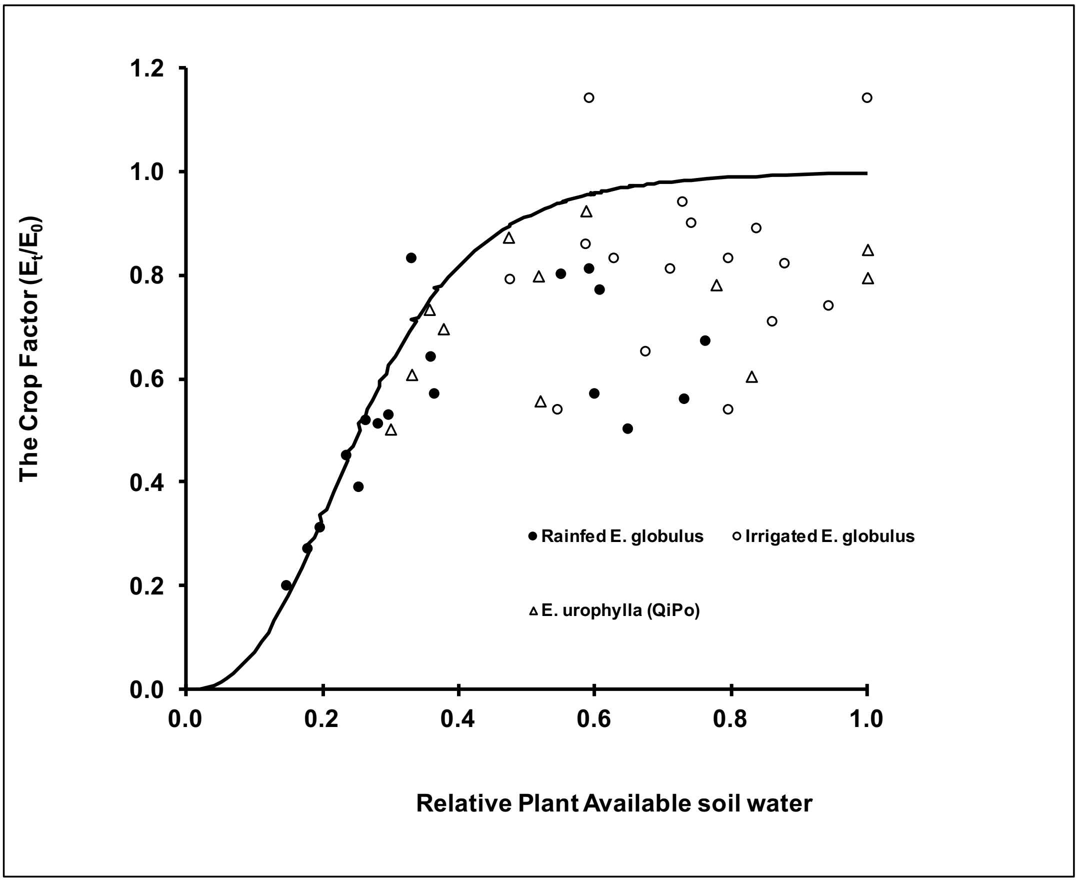

FIGURE 10 THE RELATIONSHIP BETWEEN THE CROP FACTOR (K) AND RELATIVE PLANT AVAILABLE SOIL WATER FOR *E. GLOBULUS* IN TASMANIA, AUSTRALIA. THE FIGURE ALSO INCLUDES DATA FROM E. UROPHYLLA X GRANDIS FROM SOUTHERN CHINA.

6.3.3. Initialising The Crop Factor Model

As with all the modelling in this project, we have elected to be conservative in predicting the potential impacts. Given the uncertainty about the input data, the modelling has been conducted to quantify the maximum possible impact of the plantation. The model is constructed in the following way:

1. The initial relative plant available soil water (*w*) is calculated using Equation 8, where ASW_i is the initial soil stored water and ASW_{max} is the maximum amount of water that can be stored.

$$w = {}^{ASW_i}/_{ASW_{max}}$$

EQUATION 11

2. The crop factor for that month is calculated using Equation 10
3. The evapotranspiration (E_T) for that month is calculated from Equation 5
4. The value for ASW at the end of the month (ASW_f) is calculated from Equation 9, where P is rainfall

$$ASW_f = min(ASW_{max}, ASW_i - E_T + P)$$

EQUATION 12

5. Drainage (excess water) is then calculated using Equation 13

$$Q = min(0, RHS \text{ Equation } 2)$$

EQUATION 13

The differences between the vegetation types were captured by setting maximum soil depth to 1 m for short grassland, 2 m for tall (Kunai) grassland and at 3, 5 and 10 m for the *E. pellita* plantation. These are based on unpublished data for Kunai in Indonesia and recent observations of the depth to groundwater in the study area. Note that trees will grow roots to depths of 3, 5 or 10 metres depending on the actual depth to groundwater. In very shallow groundwater areas the root systems will be limited to 3 m, to 5 m in the slightly deeper sites and to 10 m for the depths to groundwater reported by Jacobsen (1971).

A maximum value of 0.8 was set for the crop factor for the grassland (about 1.0 x FAO56 but 0.8 x Priestley Taylor) and about 0.95 for plantations. As noted above, the settings for these two parameters tend to maximize the difference between plantations and grassland and reflect differences in aerodynamic roughness between these two vegetation types.

Monthly and annual values were calculated for Q, E_T for pastures and grassland. The model was run for 114 years. A fallow of 2 and 6 months was assumed between rotations (2 for coppice, 6 for replant). This was always during the wet season and evapotranspiration was assumed to proceed at 0.8 x potential evaporation during this stage.

6.3.4. Results for Monthly and Annual Evapotranspiration and Drainage Estimated Using The Crop Factor Model

Data in this section is often presented as ´duration curves´. These curves plot values against the probability that a given value is exceeded. They are a useful way of visualising change in hydrology. The net water balance in the following section is described as ´drainage`. In fact this is simply excess water that cannot either be stored in the soil or used by the vegetation. This water leaves the system in the models. It may drain to the groundwater and become base flow or interflow, or it might flow over the land in extreme events as storm flow. The fate of this water is not specified by the models and we have used the term ´drainage' to refer to this ‘net water balance’.

Comparing *E. pellita* Over Shallow Groundwater with short *T. australis* grassland

For this simulation, the soil depth for grassland was 1 m, while *E. pellita* could access 3 m of soil. The maximum annual drainage between 1900 and 2014 was 1182 mm from the grassland, compared to 908 mm for the *E. pellita* plantation (Figure 11). The median values for annual drainage from the same two land uses were 419 and 211 mm. In 2 in every 100 years, annual drainage from the plantations was predicted to be zero while the minimum annual drainage from the grassland was 111 mm (Figure 11).

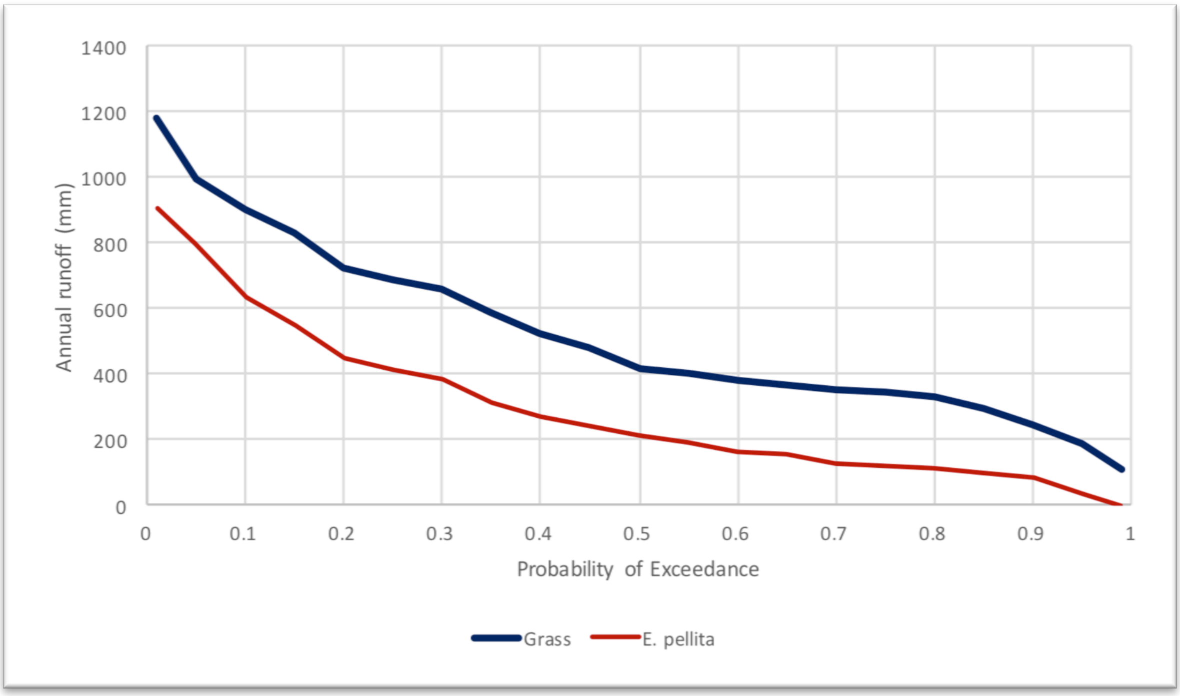

FIGURE 11. ANNUAL DRAINAGE DURATION CURVES FOR E. PELLITA WITH 3 M OF SOIL AND A SHORT GRASS WITH 1 M OF SOIL. THESE ´DURATION´CURVES PLOT THE VALUE OF DRAINAGE (REFERRED TO AS 'RUNOFF' IN THE GRAPH) AGAINST THE PROBABILITY THAT VALUE IS EXCEEDED.

There is a strong relationship between annual rainfall and predicted drainage for both land uses. The slope of this relationship is greater for the grassland than *E. pellita* but this difference is not significant. The x and y intercepts are significantly different between the land uses. Approximately 225 mm more rain is required per year to generate drainage from an *E. pellita* plantation with 3 m of soil (980 mm) than for a short grassland (755 mm) (Figure 12). The difference between the land uses occurs mainly in the transition from dry to wet periods when the soil under the plantations requires more rain to saturate and start draining to the groundwater.

While the effect on annual drainage is important, it is the seasonal variation that will drive fluctuations in groundwater depth. The modelling predicts that the probability that monthly drainage exceeds a given value will be reduced by between 10 and 20% due to the plantation. It also predicts an increase of about 20 % in the number of months with zero drainage due to this land use change (Figure 13).

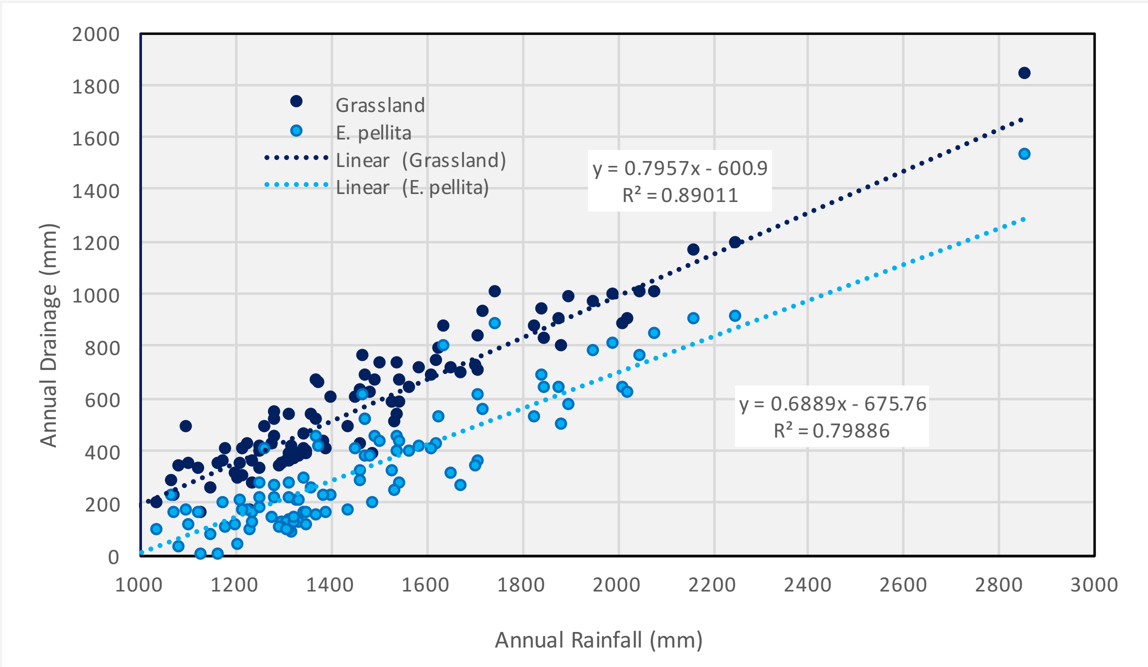

FIGURE 12. ANNUAL DRAINAGE FROM E. PELLITA PLANTATIONS (3 M SOIL DEPTH) AND SHORT GRASSLAND (1 M) PLOTTED AS A FUNCTION OF ANNUAL RAINFALL. DRAINAGE FROM GRASS. THE AMOUNT OF RAIN REQUIRED TO GENERATE RUNOFF OR DRAINAGE IS PREDICTED TO BE 755 MM FOR GRASSLAND AND 980 MM FROM THE PLANTATION. THIS IS THE ONLY SIGNIFICANT DIFFERENCE BETWEEN THE LAND USES.

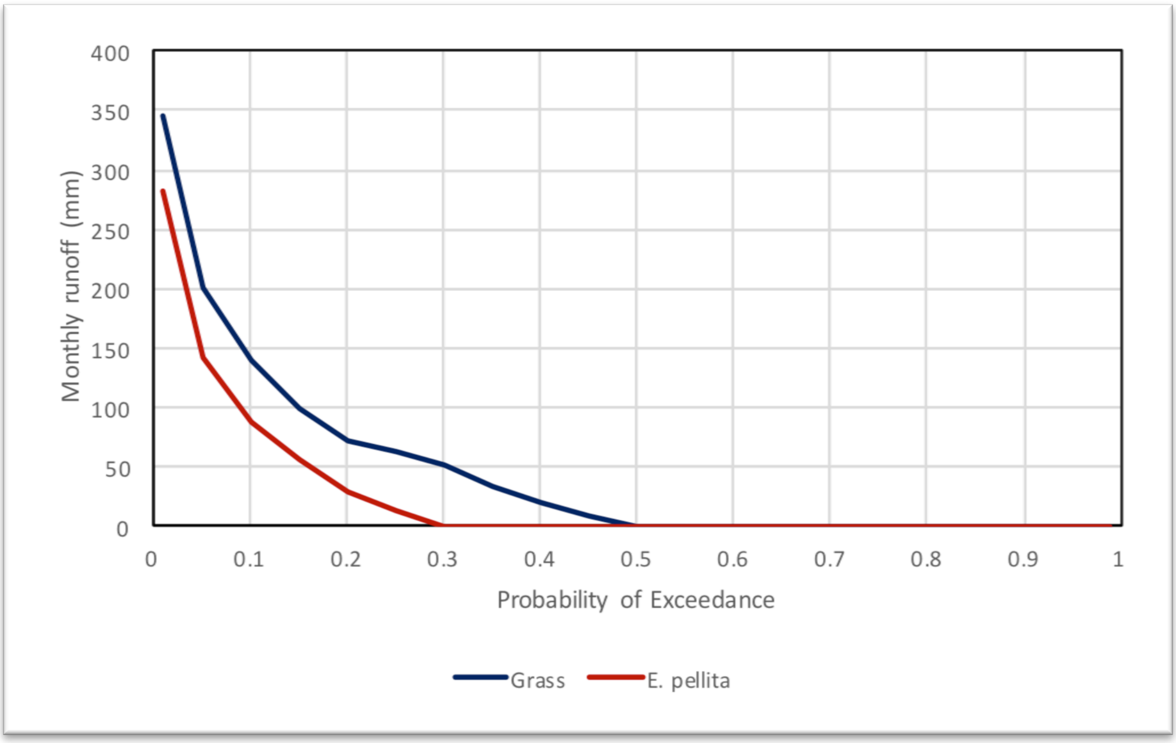

FIGURE 13. MONTHLY DRAINAGE (REFERRED TO AS 'RUNOFF' IN THE GRAPH) DURATION CURVES FOR E. PELLITA WITH 3 M OF SOIL AND A SHORT GRASS WITH 1 M OF SOIL. THESE ´DURATION´ CURVES PLOT THE VALUE AGAINST THE PROBABILITY THAT VALUE IS EXCEEDED.

It is instructive to look at the different patterns of rainfall and drainage in the 10th (2000) and 90th percentile (1917) rainfall years (Figure 14). In the dry and wet years, the rainfall between June and October (dry season) is very similar as are the number of months with some drainage. The main difference between the years is the presence of three or four very wet months in the wet year. These months generate large amounts of runoff which does not stay in the system for very long.

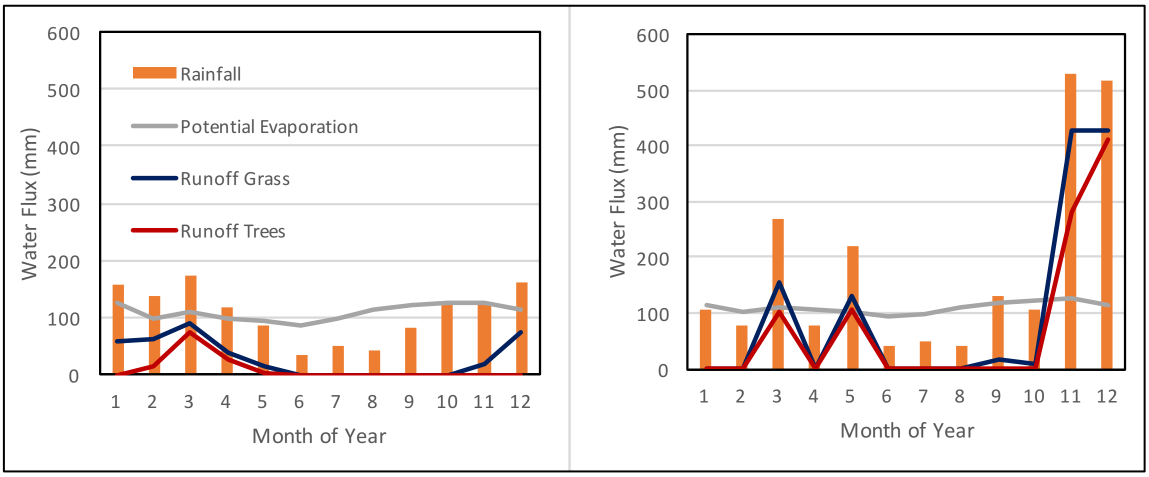

FIGURE 14. MONTHLY RAINFALL, POTENTIAL EVAPORATION AND RUNOFF (DRAINAGE) FROM PLANTATIONS OF E. PELLITA AND SHORT GRASSLAND IN A DRY (LEFT PANEL, 10TH PERCENTILE RAIN, 2000) AND WET (RIGHT PANEL, 90TH PERCENTILE RAIN, 1917) YEAR.

In summary, this modelling predicts a 20% decrease in the amount of annual groundwater recharge that occurs from land occupied by a plantation compared to land occupied by short grassland. Importantly, it also predicts that the number of months with zero recharge will increase by about 20%. This is not to say that the groundwater level will fall as the aquifers are also fed from upslope of the plantation. The effect on groundwater will be estimated later. This section only considers the change in the net water balance.

COMPARING E. PELLITA WITH TALL I. CYLINDRICA GRASSLAND

The short *E. themeda* grassland is not common in the project area; tall, Kunai (*Imperata cylindrica*) grasslands dominate the project area. The magnitude of the predicted difference between *E. pellita* and grassland is diminished if this grassland is given access to 2 m such as might be the case for the tall grassland. The difference between the land uses is reduced to about 10% and in this simulation annual drainage can also be zero under the grassland (Figure 15).

In this situation, the amount of rainfall required to generate runoff in any given year is still 980 m under the plantation but is now 860 mm for the taller grassland (Figure 15). If the grassland can access 3 m of soil, which is possible, then this is predicted to increase to 910 mm (Figure 16). At this point the difference between the land uses is non-significant.

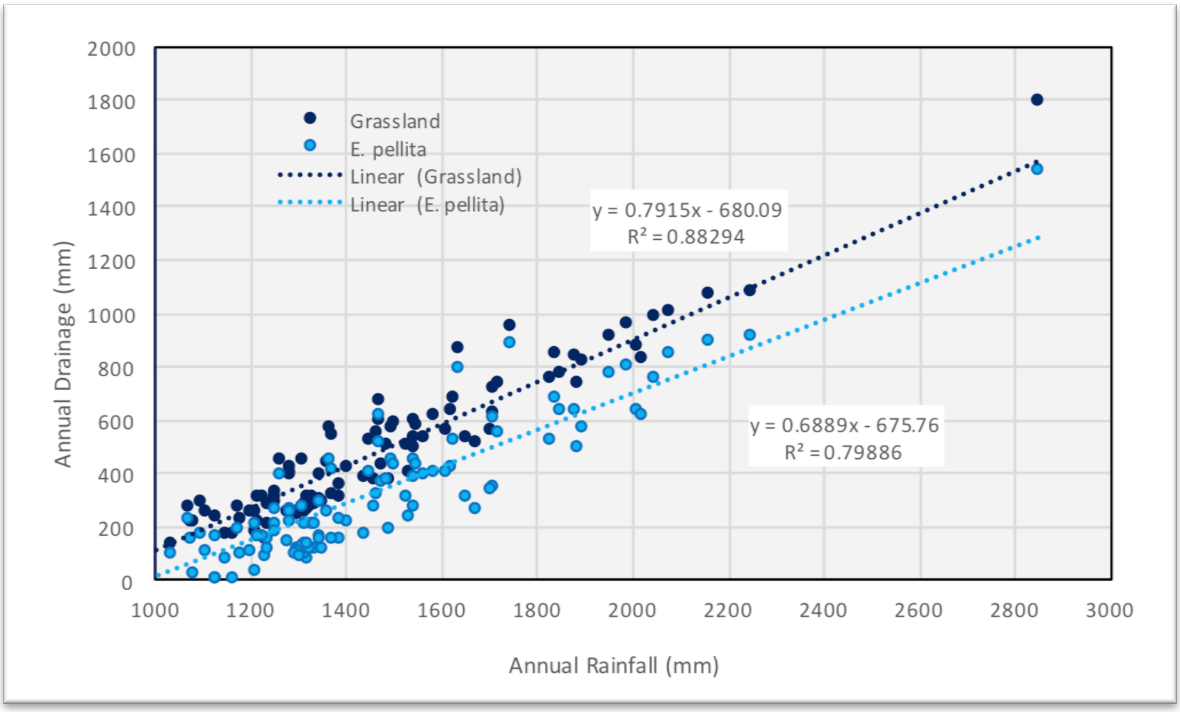

FIGURE 15. ANNUAL DRAINAGE FROM E. PELLITA PLANTATIONS (3 M SOIL DEPTH) AND TALL GRASSLAND (2 M SOIL DEPTH) PLOTTED AS A FUNCTION OF ANNUAL RAINFALL. DRAINAGE FROM GRASS. THE AMOUNT OF RAIN REQUIRED TO GENERATE RUNOFF OR DRAINAGE IS PREDICTED TO BE 860 MM FOR GRASSLAND AND 980 MM FROM THE PLANTATION. THIS IS THE ONLY SIGNIFICANT DIFFERENCE BETWEEN THE LAND USES.

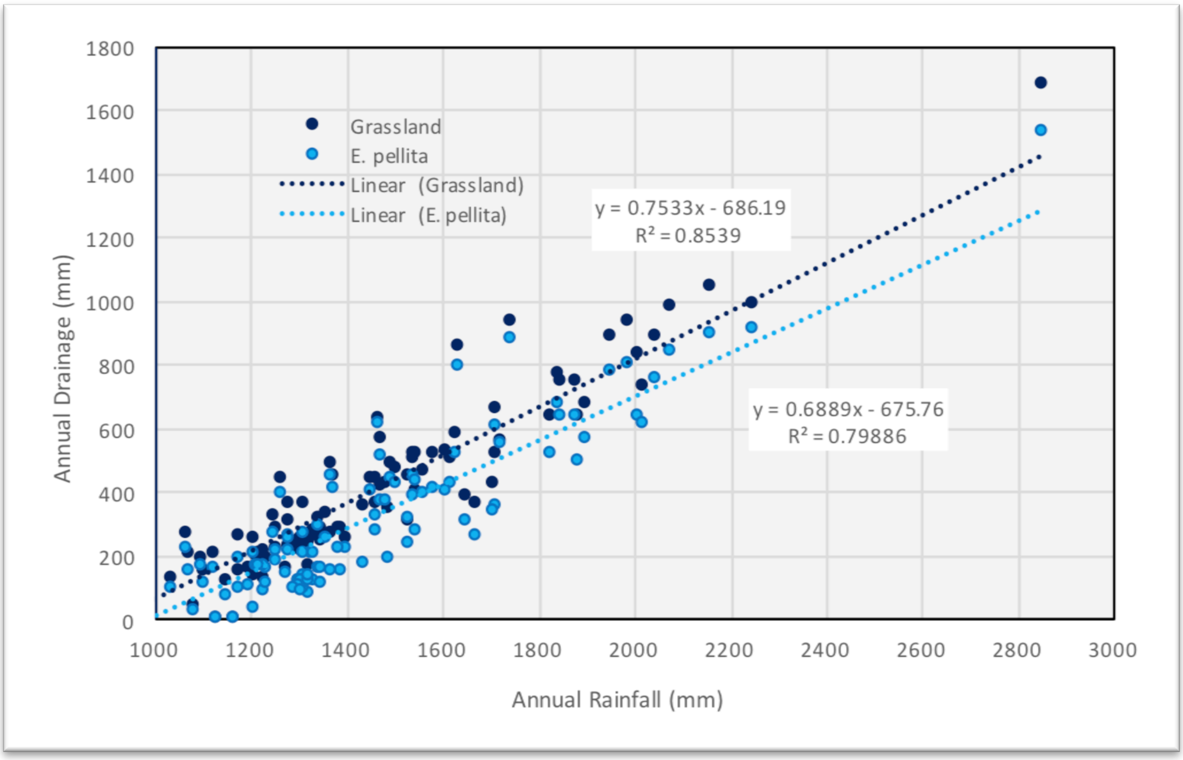

FIGURE 16. ANNUAL DRAINAGE FROM E. PELLITA PLANTATIONS (3 M SOIL DEPTH) AND TALL GRASSLAND (3 M SOIL DEPTH) PLOTTED AS A FUNCTION OF ANNUAL RAINFALL. DRAINAGE FROM GRASS. THE AMOUNT OF RAIN REQUIRED TO GENERATE RUNOFF OR DRAINAGE IS PREDICTED TO BE 860 MM FOR GRASSLAND AND 980 MM FROM THE PLANTATION. THIS IS THE ONLY SIGNIFICANT DIFFERENCE BETWEEN THE LAND USES

Comparing E. pellita with tall I. cylindrica grassland, The Effect of Soil Depth

In the previous section, the water balance of two types of grassland (short and tall, where tall is the most common in the study area) were compared with *E. pellita* growing in 3 m of soil. This scenario was chosen as the base case because recent measurements in the area, at the water supply wells and the test drilling site, suggest that depth to groundwater is approximately 3 m.

There is however some uncertainty about the depth of the groundwater and the depth of the unsaturated soil. While recent measurements suggest there is about 3 m of unsaturated soil, a larger study in the 1970s reported depths to groundwater of between 10 and 30 m. Published studies in Western Australia (Robinson et al., 2006; Mendham et al., 2011) suggest that *Eucalyptus* species, if they are water limited, can grow roots to between 10 and 15 m within a single 10 year rotation. Soil depth was therefore varied in a series of simulations (3 m – base case, 5 m, 7.5 m, 10 m and 20 m). The relationships between annual and monthly drainage and 'the probability of exceedance' for these simulations are shown in Figures 17 and 18.

There was very little predicted change in annual or monthly drainage for soil depths between 5 and 20 m. This is because the 5 m deep soil profile stored enough water to fill the gap between rainfall and potential evaporation during the dry season.

This means that a scenario comparing *E. pellita* with a 5 m soil and Kunai grassland with a 2 m soil will approximate the largest possible difference between the water balance of the two land uses. For this comparison the median annual drainage was 315 mm for the Kunai grassland compared to 153 mm for the *E. pellita*. The median monthly drainage from both land uses was zero mm (Figure 18). An annual rainfall of approximately 871 mm and 1031 mm was needed to generate drainage from, respectively, the Kunai grassland and the *E. pellita* plantation.

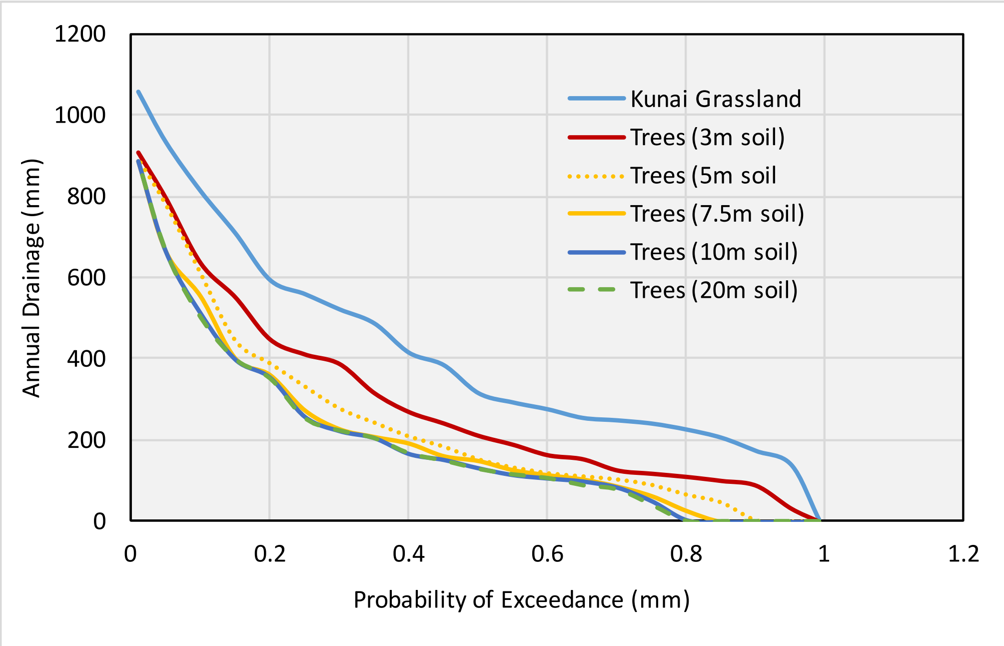

FIGURE 17. ANNUAL DRAINAGE DURATION CURVES FOR E. PELLITA WITH 3 M OF SOIL AND A TALL GRASS WITH 2 M OF SOIL. THESE ´DURATION´ CURVES PLOT THE VALUE OF DRAINAGE AGAINST THE PROBABILITY THAT VALUE IS EXCEEDED.

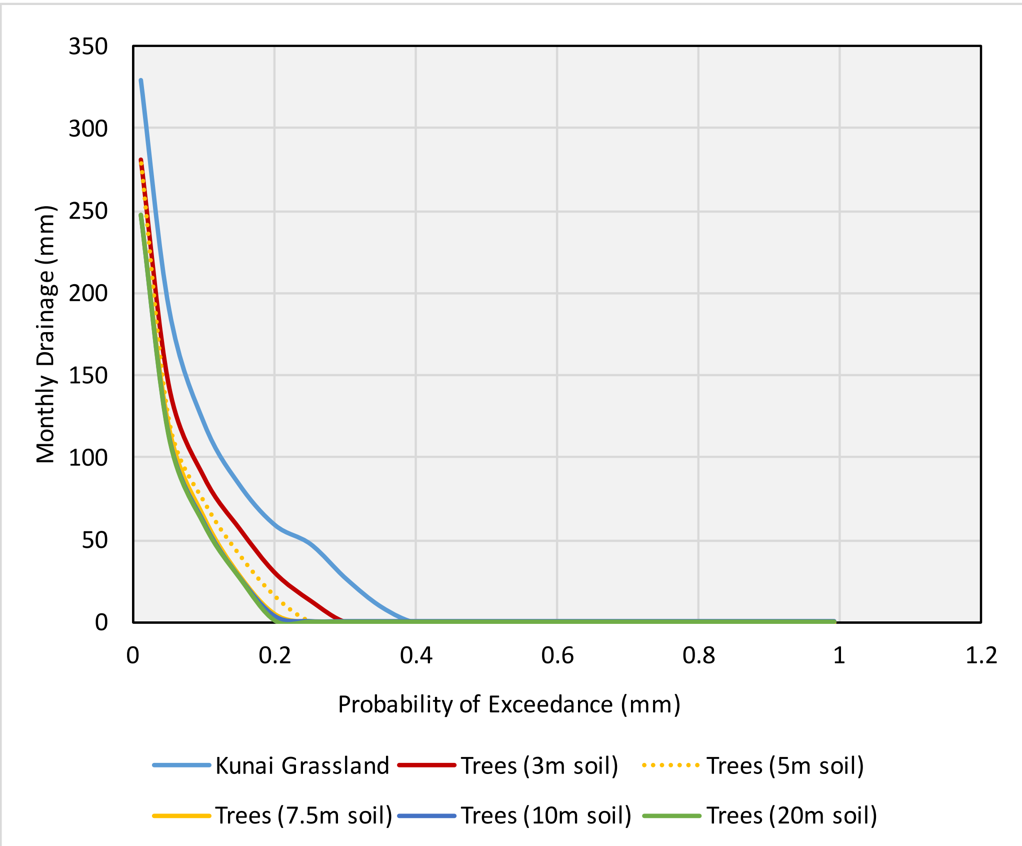

FIGURE 18. ANNUAL DRAINAGE DURATION CURVES FOR E. PELLITA WITH 3 M OF SOIL AND A TALL GRASS WITH 2 M OF SOIL. THESE ´DURATION´ CURVES PLOT THE VALUE OF DRAINAGE AGAINST THE PROBABILITY THAT VALUE IS EXCEEDED.

6.4. Estimating the Change in Water Use with 3PG

In the above modelling it was not possible to take full account of the effect of the fallow between plantations or to quantify the effect of access to groundwater on plantation water balance. While this approach has previously worked well in small catchments with very shallow soils in China, some reservations remained about the generality of the approach. In this next section, predictions from 3PG are first presented and then compared with those in the previous section.

There are many models that can predict the growth and water use of stands (BIOMASS, GDAY, 3-PG, CABALA, CenW, WAVES and others). In this study a version of 3PG has been used which is freely available, enabling analysis to be repeated as new information becomes available.

3PG (PHYSIOLOGICAL PRINCIPLES OF PLANTATION GROWTH) 3PG, Landsberg and Waring (1997) calculates gross primary production as the product of light interception (calculated using the Beer Lambert law), and light use efficiency which is discounted for the effects of soil fertility, plant available soil water, air saturation deficit, temperature and age. Net primary production is a constant proportion of Gross Primary Productivity (GPP) and is allocated to stems, roots and leaves using rules developed from published literature. Evapotranspiration is calculated as the sum of transpiration and interception. Transpiration in this case uses a conductance which is affected by air saturation deficit, stand age and by soil water content. This is a good estimate of total conductance (plantation plus soil) when the leaf area index is large but may underestimate total water use in fallow periods.

6.4.1. Assumptions and Parameters

For the following simulations, and as noted in section 5, the parameter set published by (Almeida et al., 2004) was used with a minor modification to parameters that calculate wood volume and leaf area from wood and leaf dry matter. These are based on published valued for wood density (Bernardo et al., 1998; Hung et al., 2015).

The model was initialized for an October planting of 1500 stems per hectare[2]. Each seedling was 5 g, 40% of which was foliage, 30% stem and 30% roots. The soil was 3 m deep and stored 100 mm per meter. The fertility index was 0.8 (maximum possible is 1), which White and Ren (unpublished data) found

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[2] The plantations will actually be established at 1333 stems per hectare. A single modelling run using the average annual climate data, indicated that the modeled stocking of 1500 will occupy the site more quickly (3 to 4 months) than the operational system but that this will not affect the modelled annual water use or drainage.

predicted growth and water use of a coppiced *E. urophylla* x *grandis* plantation within +/- 5% up to age 5 years old. Some growth data was available for *E. pellita* in PNG but it was not possible to link actual growth rates with soil properties and as yet most growth data is for very young stands (maximum 18 months).

The plantation was grown for 5 years[3]. The value of root biomass at the end of the first rotation was used to initialize the second rotation. This biomass (approx. 25 t/ha) was allocated 92% to roots, 1% to leaves and 7% to stems. At the end of this rotation the plantation was re-established with the same values used for the first rotation. The program was re-initialised every five years, alternating between the values of initial biomass for a coppice and seedling crop. Atmospheric CO_2 was set at a constant 400 ppm.

6.4.2 Predicted growth, water use and net water balance (Drainage)

The 3PG model predicts that with a present day value for atmospheric CO_2 and using historic values for rainfall, radiation and temperature, predicted dry matter production varied between rotations from 90 to 140 t/ha per rotation. This variation in growth was very strongly correlated with average annual water use for the rotation which varied with rainfall (Figure 19). At the end of every second rotation the plantation was re-established from seedlings. At this time between 32 and 37 t/ha of root biomass had accumulated. The rate of growth from 2010 to 2015 was very similar to that observed in an *E. urophylla* x *grandis* plantation in Southern China.

[3] The actual rotation length will be seven to nine years and the total crop cycle 14 to 18 years. Modelling a single scenario using average annual weather conditions, indicated that there will be a closer correspondence between evapotranspiration predicted using 3PG and the crop factor model for these longer rotations than for those modelled for this report..

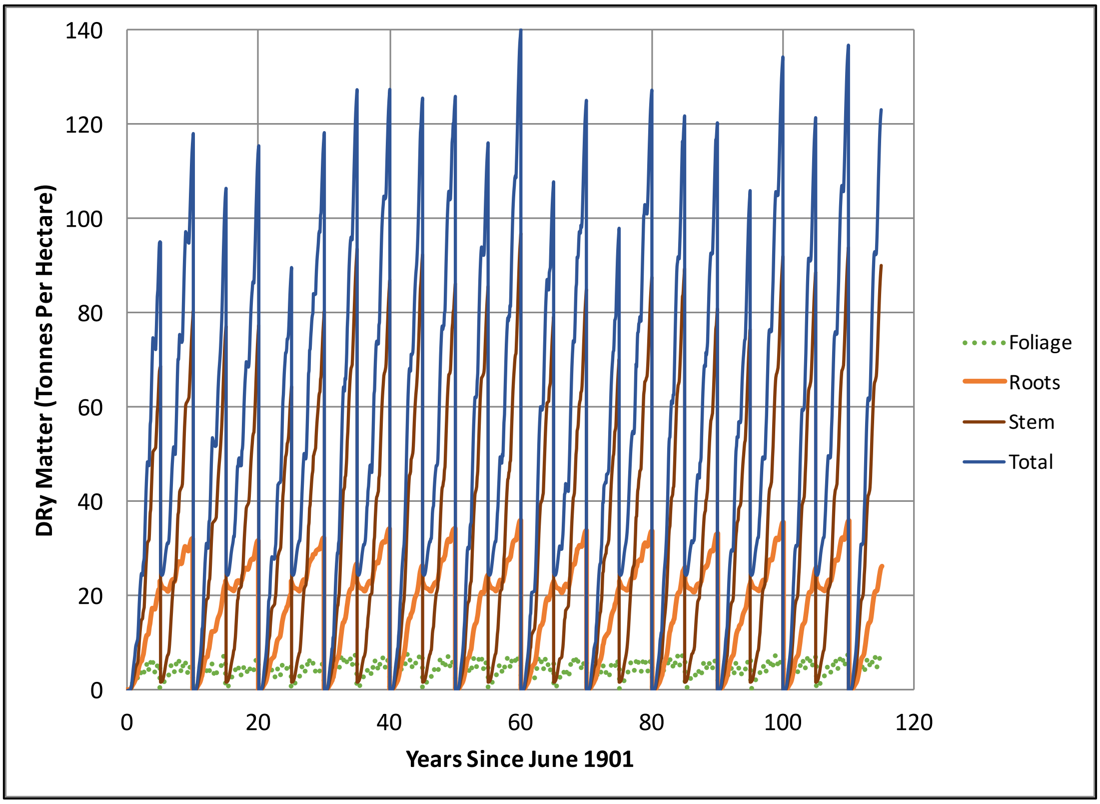

FIGURE 19. TOTAL, ROOT, FOLIAGE AND STEM BIOMASS IN A PLANTATION OF E. PELLITA. FOR THESE SIMULATIONS THE PLANTATION WAS HARVESTED EVERY FIVE YEARS. EVERY SECOND CROP WAS COPPICED WITH ALTERNATE CROPS REPLANTED. ATMOSPHERIC CO_2 CONCENTRATION WAS 400 PPM.

The predicted amount of water used annually (evapotranspiration) to produce the biomass was between 600 mm and 1500 mm (Figure 20). This range of variation was greater than predicted using the ramp function. This reflects the different treatment of the fallow period in the two modelling approaches. The low water use years predicted by 3PG coincide with the re establishment of seedlings (Figure 20).

For some years there are clear differences in the annual evapotranspiration predicted using the ramp function model and 3PG, there is nonetheless a very strong relationship between evapotranspiration by these two models (Figure 21. Over the 114-year sequence modeled, cumulative runoff from the plantations predicted using the ramp function and 3PG was nearly identical (Figure **22**).

We stress that all of the outputs here are modelled and that there are no local growth or water balance data with which to test the models. The models have been tested in similar environments (White et al., 2016; Almeira et al., 2004). The modelled values are within previously reported values for water use in tropical environments and provide a useful basis for planning. It is also encouraging that the two models give similar results. Annual evapotranspiration varies more between years when predicted using 3PG than the ramp function. Nonetheless, the cumulative runoff predicted using the two models is nearly identical over 114 years.

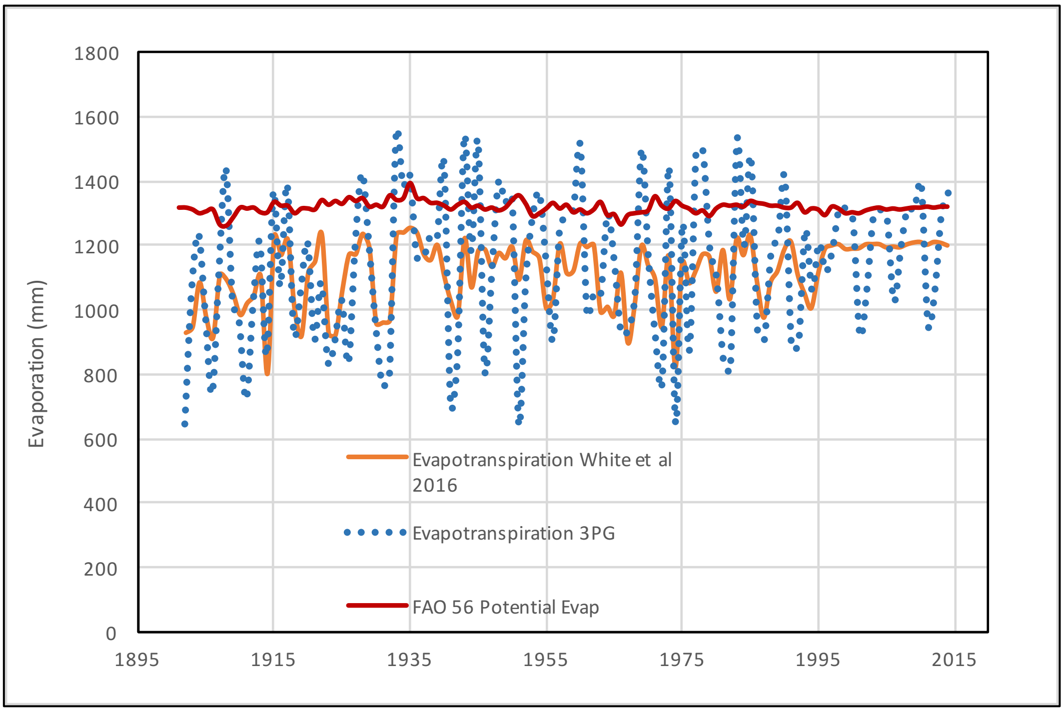

FIGURE 20. ANNUAL POTENTIAL EVAPORATION AND EVAPOTRANSPIRATION FROM PLANTATIONS PREDICTED USING THE RAMP FUNCTION MODEL AND 3PG.

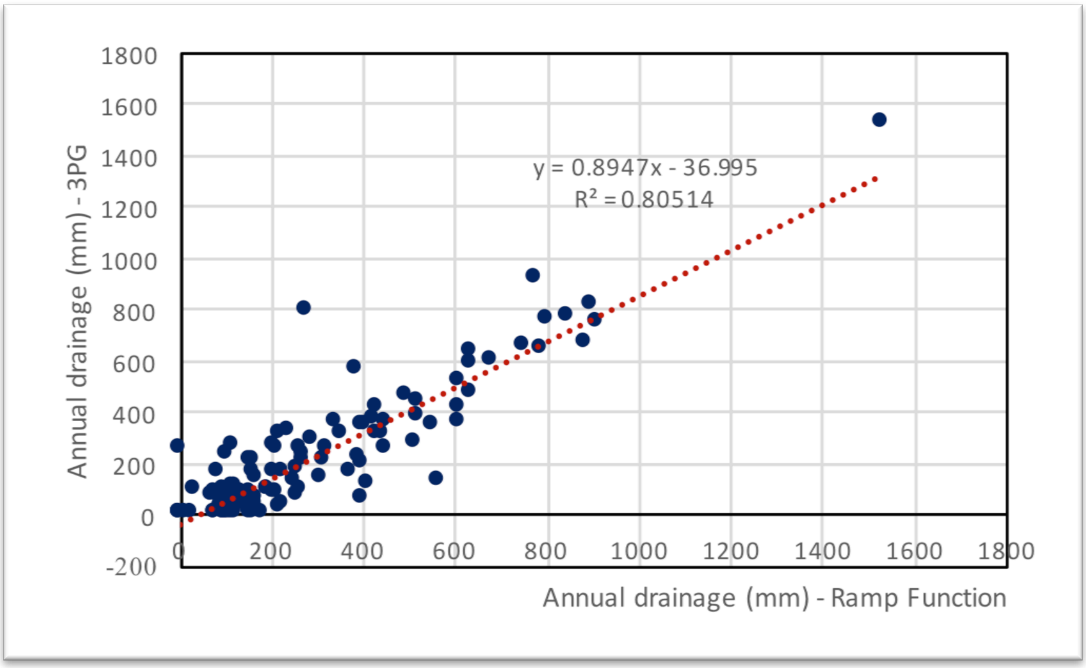

FIGURE 21. ANNUAL RUNOFF PREDICTED USING 3PG PLOTTED AS A FUNCTION OF ANNUAL RUNOFF PREDICTED USING THE RAMP FUNCTION.

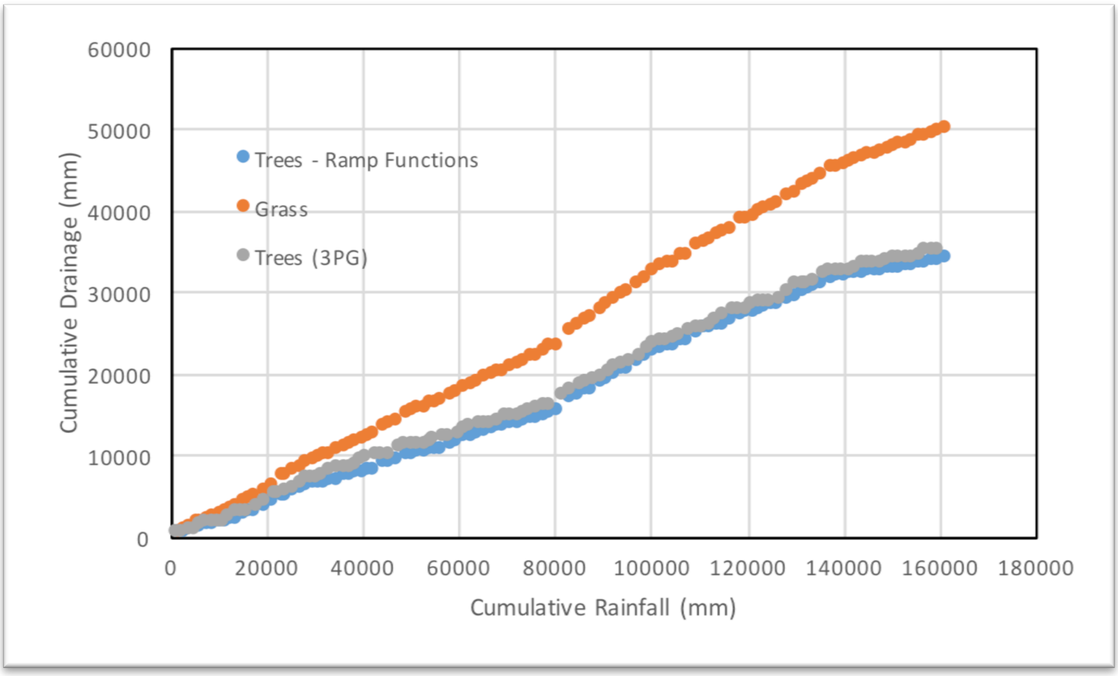

FIGURE 22. CUMULATIVE EVAPOTRANSPIRATION FOR A SHORT GRASS AND FOR AN E. PELLITA PLANTATION PREDICTED USING THE RAMP FUNCTION AND 3PG PLOTTED AS A FUNCTION OF CUMULATIVE RUNOFF.

Except for the first year of each rotation, when the water productivity of biomass production was low, annual vwater productivity values of between 1 and 3 g DM kg^{-1} H_2O were predicted by 3PG. These are either superior to or similar to previously reported values s for temperate systems (White et al. 2014; White et al. 2016).

7. Changes in Depth to Groundwater

7.1 Effect of Plantation on Groundwater

The proponents of the biomass-fired power plant in the Markham Valley wish to plant approximately 16,000 hectares of *Eucalyptus* plantations between Nadzab Airport and the Leron River. These plantations will mostly replace degraded grazing lands of tall Kunai grasslands with scattered trees.

In the previous sections, the variation in growth and water use was modelled using a ramp function and the process based growth model 3PG. These models predicted a very similar effect of plantations on annual water balance. Compared to the short stature grass, a *Eucalyptus* plantation will decrease runoff by up to 200 mm while compared to a taller stature grass the difference will be approximately 50 to 100 mm in a 3 m deep soil and up to 200 mm in a 5 m deep soil. The effect of plantations will be to increase evapotranspiration, decrease runoff and increase the number of months where no water drains to the groundwater by two or three per year. The total effect across the Project area will be to prevent between 7,000 and 30,000 ML per year from reaching the Markham River. The effect on flow in the Markham River will nonetheless be negligible given the capacity of the river. The maximum annual water use equates to between 20 and 80% of the average daily flow of the river.

The more pertinent issue is the effect of this change in water balance on the recharge of the groundwater and therefore on seasonal patterns of groundwater depth. This has the potential to affect groundwater dependent ecosystems and local water supply wells.

To quantify the effect of the plantation on groundwater we assumed that the local groundwater system is one-dimensional so that groundwater is recharged by local rainfall without any inputs from upslope. In the same way, there are no losses downslope from the point of interest. This assumption will maximize the predicted effect of land use change on groundwater. It is in effect the worst-case scenario. Under this assumption, to calculate the effect of a change in recharge on groundwater, the specific yield of the aquifer must be known. In the subsequent modelling a value of 10% has been used. If the specific yield is 10%, one metre of soil in the saturated state can store approximately 100 mm (10%) of water above field capacity. Thus, a change in the net water balance (with no additional inputs or losses) of 100 mm will increase the depth to groundwater by one metre.

For every month from 1900 to 2014, the net change in groundwater depth was calculated along with the maximum annual change of groundwater depth under a plantation and the alternatives of short and tall (shallow- and deep-rooted) grassland. This modelling predicted a seasonal fluctuation of groundwater of 3 m under long grass in the period between 2013 and 2016. This is slightly larger (by about 0.5 m) than the fluctuation currently observed in local wells (see Section 3.3). This is not surprising since we have assumed that the only input is from rainfall and it is unlikely that all rainfall from upslope bypasses the aquifers on the piedmont to the north of the Markham River.

Using the approach described above, and outputs from modelling, the change in groundwater depth when either a short or tall grassland is replaced by a plantation of *E. pellita* was calculated. In Figure 23, the results of this modelling are plotted as a function of the probability that a given change is exceeded. For example, noting again that the predicted changes are probably an overestimate, the probability of a change in groundwater more than 1 m is 0.4 when tall grassland is replaced by plantation and 0.7 when short grass is replaced by plantation on a 3 m soil.

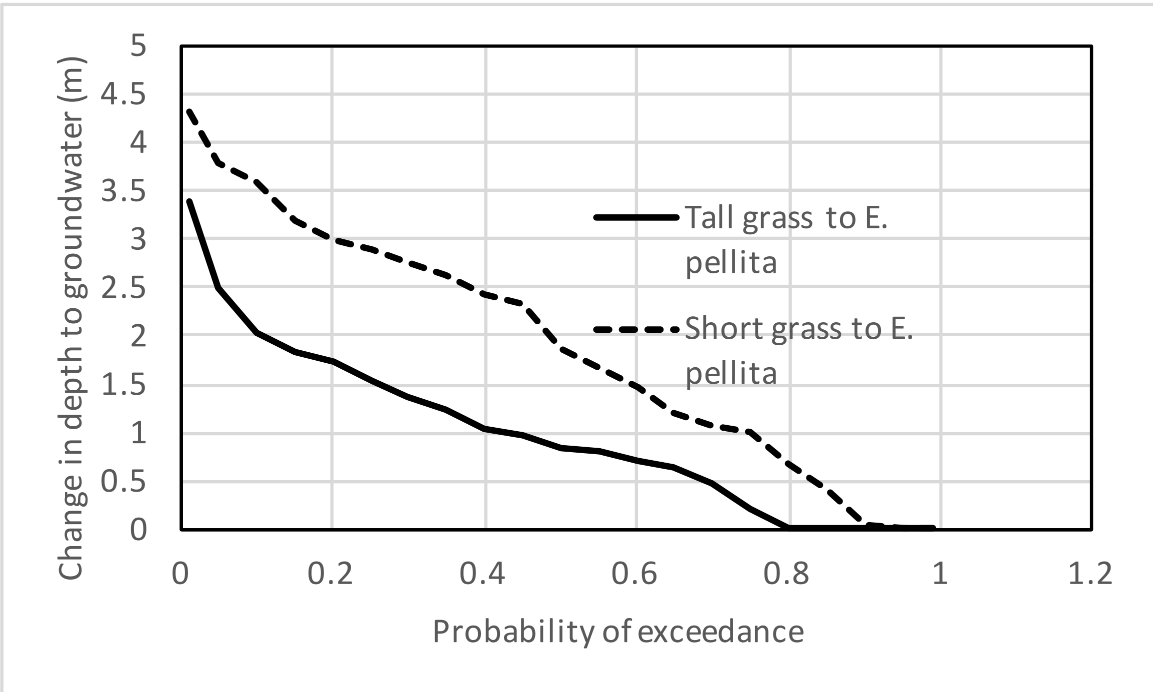

FIGURE 23. THE RELATIONSHIP BETWEEN CHANGE IN GROUNDWATER DEPTH AND THE PROBABILITY THAT A VALUE IS EXCEEDED. THE RELATIONSHIP IS PLOTTED FOR TWO SCENARIOS: I) A PLANTATION REPLACING SHORT GRASSLAND AND II) A PLANTATION REPLACING TALL GRASSLAND. BOTH SCENARIOS ASSUME A MAXIMUM ROOTING DEPTH OF 3 M.

When tall Kunai grassland was compared to a plantation with access to 5 m of soil, which gives the maximum possible effect on water balance, the model predicted changes of groundwater depth between 0 m and 4.5 m. In fact the predicted change was very similar to that predicted from a change from short grassland to a plantation in 3 m of soil (Figure 24).

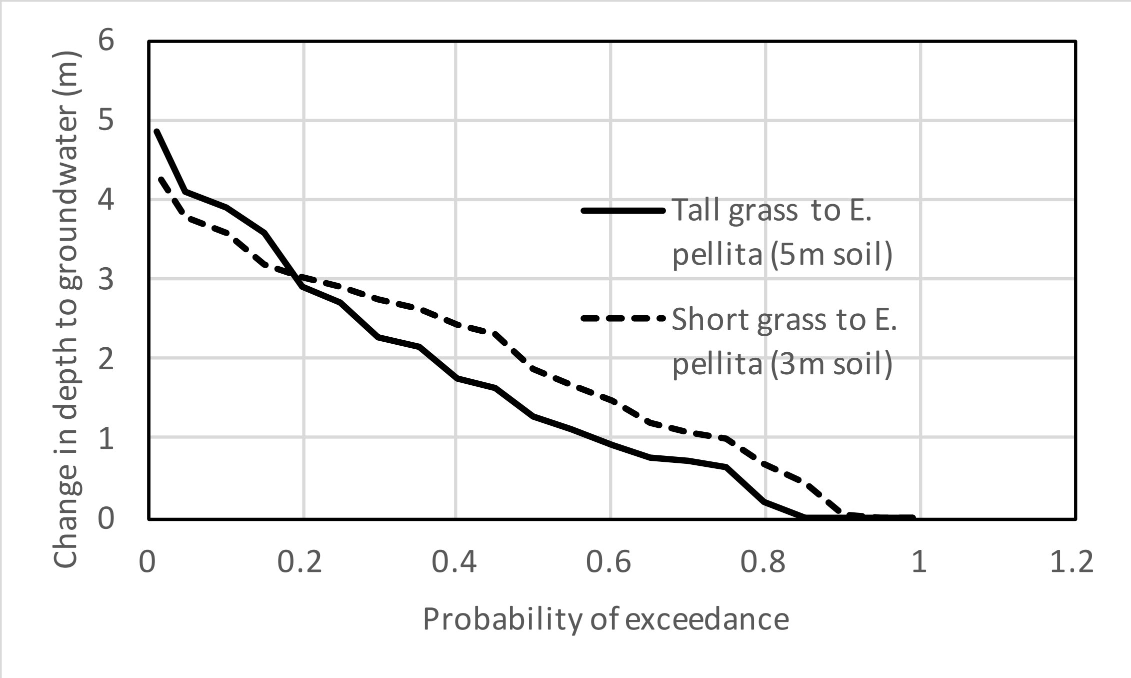

FIGURE 24. THE RELATIONSHIP BETWEEN CHANGE IN GROUNDWATER DEPTH AND THE PROBABILITY THAT A VALUE IS EXCEEDED. THE RELATIONSHIP IS PLOTTED FOR TWO SCENARIOS: I) A PLANTATION REPLACING SHORT GRASSLAND AND II) A PLANTATION REPLACING TALL GRASSLAND.

Drops in ground water have the potential to affect groundwater dependent ecosystems and local water supply wells:

1. In most years the predicted changes for this project are smaller than those that resulted in the death of Banksia woodland species in Western Australia (Eamus and Froend, 2006; Eamus et al., 2006; Froend and Drake, 2006). The predicted changes will only occur directly underneath a block of trees and will diminish towards the edge. The proposed streamside buffers (100 m for the Markham, 60 m for the Leron and Erap rivers, lakes, lagoons and swamps, 30 m for other permanent watercourses greater than 5 m wide, 20 m for streams 1 to 5 m wide, and 5 m for smaller streams) will be sufficient to protect these ecosystems from any changes in groundwater depth caused by the plantation.
2. In our experience in Laos, Vietnam and India, a 3 m drop in groundwater is likely to cause concern for villages dependent on wells for water supply. However, in most situations a drop of 1 m seems acceptable. The modelling predicts that in the worst case scenario of a change from tall Kunai to *E. pellita* with access to 5 m of soil, that the change in groundwater depth near the centre of the plantation may exceed 3 m one in every 5 years. The change will also be less than 1 m in three of every 5 years. These changes may occur under the

plantations and will diminish to zero within 50 m of the edge of the plantation.

It is also noteworthy that we have not accounted for potential changes in climate in the long term. Increases in seasonality of rainfall may increase drainage, or vice versa. Moreover, the runoff coefficient has varied from 16% to 30% in the last 114 years (Figure 25). A return to a higher runoff coefficient will diminish these predicted effects of plantations on groundwater while a further decrease (which is not predicted) will result in a greater effect of plantations on groundwater.

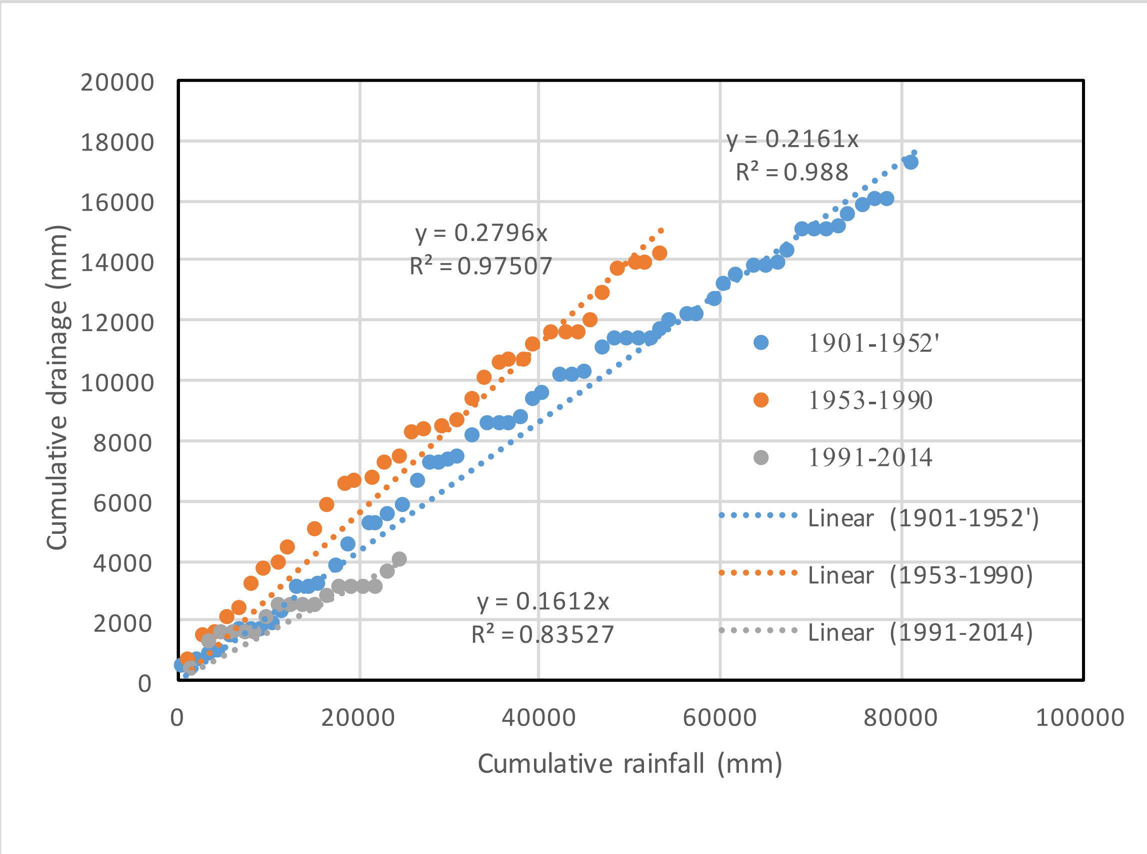

FIGURE 25. THE RELATIONSHIP BETWEEN CUMULATIVE DRAINAGE AND CUMULATIVE WATER BALANCE FOR THREE SEPARATE PERIODS IN THE LAST 114 YEARS. THE RUNOFF COEFFICIENT HAS VARIED FROM ABOUT 15% TO 30% IN THE LAST CENTURY WITH STEP CHANGES IN SLOPE OCCURRING IN 1953 AND 1990.

7.2. Pumping from Bores to Supply the Power Plant

When the plant is complete (2 x 15 MW units), the maximum rate of groundwater pumping required will be 156,000 L hr^{-1} (the same as 156 t hr^{-1}, 156 kL hr^{-1} or 156 m^3 hr^{-1}). The first 15 MW unit will be established in advance of the second. In this initial configuration, the plant and nursery will require a maximum of 78,000 L hr^{-1}.

This section assesses the possibility of pumping groundwater to supply the processing plant and quantifies the likely effect of this pumping on the groundwater. Recommendations are then made regarding number and layout of bores for the initial (1 x 15 MW) and final (2 x 15 MW) configuration. Data from a preliminary pumping test have been used in the quantitative analysis; however, it is stressed that the analysis would have substantially more confidence with additional information. Aspects that could be improved are discussed in more detail later.

7.2.1. Methodology

For flow in an unconfined aquifer, direct analytical solution of Laplace's equation is not possible, and the most common form uses Dupuit's approximation that the velocity of flow is proportional to the piezometric gradient and, across a vertical section, flow is uniform and horizontal. The error in flow field decreases with distance from the discharge point, or pump well in the case here. These assumptions do not hold close to the bore, where the curvature on the watertable is high. They also require pumping to have proceeded long enough that a steady state has been reached. Nevertheless, correct calculation of the discharge rate is maintained and drawdown, a reasonable distance from the bore, will not be greatly in error. The error will be slightly conservative, that is the drawdown calculated will be slightly greater than the actual drawdown, which means our estimates here will be worse than the actual case.

Using the analytic solution described above (Cooper and Jacob, 1946; Todd, 1980) and spreadsheets available from the United States Geological Survey (https://pubs.er.usgs.gov/), we estimated the groundwater drawdown at the pumping site, and the various distances from the site, that might result from pumping 156 kL/hour using 1, 3, or 5 bores or 78 kL/hour using 1 or 2 bores. Data from both the drawdown phase and recovery phase of the test as supplied were used to derive two estimates of the mean saturated hydraulic conductivity. This analysis was undertaken assuming:

I. A coarse alluvial sand.

II. Uniform, homogeneous, isotropic aquifer. This is not realistic but, since we have very limited on-site data on the aquifer characteristics, is a necessary approximation until better information is available.
III. A fully penetrating well into an unconfined aquifer.
IV. The aquifer is assumed to be 50m thick, and the watertable is 3m from the surface.
V. The aquifer is unconfined, uniform, homogenous and isotropic and effectively of infinite extent.
VI. The watertable is horizontal prior to the start of the pump.
VII. Pumping is carried out at a constant rate.
VIII. The bore penetrates the entire depth of the aquifer, thus in the case here we have assumed the entire depth is approximately 50m. This assumption has a significant impact on the results.

The pump test data supplied to the groundwater team indicate a saturated hydraulic conductivity of the order of 1 to 1.5 m/day. From the drawdown phase the value was about 1.2 m/day and from the recovery phase about 1.5 m/day. This is low for a coarse sand but is reasonable for a mixed sand/silt/clay aquifer. However, it should be noted that the test did not appear to get to steady state and, as such, has considerable uncertainty.

Assuming 1.5 m/day as the hydraulic conductivity, then steady state drawdown at the pump test rate (1200 L/min) will not be reached until drawdown at the well is over 30 m. Drawdown might be expected to be measurable (estimated about 1 m) out to a radius of about 1000 m.

7.2.2. Results

The results of the modelling are summarized in Figure 26. The curves in this figure were fitted to the results of a limited number of scenarios but give a useful impression of the relationship between the rate of pumping and groundwater drawdown at two locations.

Scenario 1, A single bore supplying 156 kL hr^{-1}

If a single bore was pumped at the desired specifications of 2600 L/min the drawdown cone would be substantially wider than predicted for the pump test (1200 L/min). Estimates based on the information supplied show that it is not possible to supply the required pump rate from a single bore in a 50 m thick aquifer with hydraulic conductivity of 1.5 m/day. It is unlikely that the bore could deliver this rate of supply if the aquifer is only 50 or 60 m deep.

Scenario 2, A single bore supplying 78 kL/hr

This rate of pumping (1300 L/min) is very similar to the test rate of 1200 L/min, which we estimate will result in more than 30 m drawdown at the pumping site and a measurable drawdown of more than 1 m at a distance of 1 kilometer from the site. To safely supply this amount of water from a single bore will require an aquifer well in excess of 50 m.

Scenario 3, 3 bores (each at 52 kL/hr) supplying 156 kL/hr

If the plant installs three bores, and each pumps 52 kL/hr then, assuming 10 m drawdown in each bore, drawdown would be about 4 m at a 300 m radius and negligible at 1000 m from each bore. This would require the bores to be nearly 2000 m from each other to preserve this status.

Scenario 4, 2 bores (each at 39 kL/kr) supplying 78 kL/hr

This is similar to the previous scenario, but with expected drawdown at the pumping site of approximately 5 m and 2 m at a distance of 300 m from the site. The drawdown would be negligible 500 m from the site.

Scenario 5, 5 bores (each at 31 kL/hr) supplying 156 kL/hr)

With five bores, the rate required from each to supply a total of 156 kL/hr reduces to 31 kL/hr, and drawdown outside 300 m from the bores would be less than about 1.5 m.

Scenario 6, 3 bores (each at 26 kL/hr) supplying 78 kL/hr)

Similar to, and less disruptive than scenario 5.

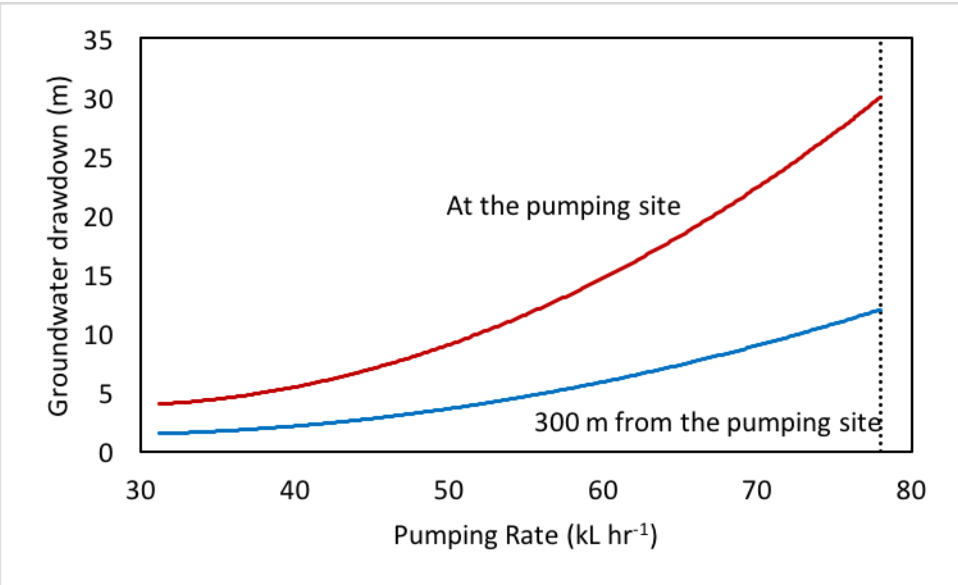

FIGURE 26. APPROXIMATE GROUNDWATER DRAWDOWN AT THE PUMPING SITE AND 300 M FROM THE PUMPING SITE AS A FUNCTION OF PUMPING RATE. THE DASHED, THE VERTICAL LINE INDICATES THE PUMPING RATE FOR A SINGLE 15 MW PLANT (78 T HR^{-1}), A RATE SIMILAR TO THE PUMPING TEST COMPLETED AT THE SITE.

7.2.3 Implications

In all cases, the drawdowns from multiple bores are additive, thus in order to preserve drawdown less than any given allowance, the distance from each bore must be known and the sum of all drawdowns from each calculated.

Without better information on both the actual depth of the aquifer and the specific yield, estimates of the impact of the final configuration are only speculative. A more detailed modelling exercise would be warranted once sufficient information is available. Nonetheless, our assumption of a one dimensional water balance is conservative.

If the aquifer is only 50 m thick, and saturated hydraulic conductivity is 1.5 m/day then the analysis undertaken indicates that it will be difficult to extract the initial amount of 78 kL/hr without at least two wells and that final configuration would require 5 bores, well spaced, that are approximately 1000 m apart. Further aquifer testing is required to determine:

i. The full depth of the reliable aquifer
ii. The specific yield and hydraulic conductivity of the aquifer

Thus a pumping test should be repeated with observation bores, preferably in several directions from the pumped bore and at several distances.

What may be considered an acceptable impact is largely subjective. However, as noted earlier, a drawdown of 3 m is likely to be considered unacceptable if it was to affect village wells or other users' water supplies.

Furthermore, the level of proposed abstraction is high, and if focussed in a small area over a prolonged period could cause other issues such as possible subsidence of the area around the bore and entrainment of water from other aquifers with unknown properties.

We recommend that at least three bores be constructed (scenario 6 above), 1 km apart, for the first phase of the project and that this be increased to 5 for the second stage (scenario 5 above). However, it should be stressed that observation wells should be installed before pumping begins so that the properties of the aquifer can be better understood and estimates of impact will have much greater confidence.

8. Recommendations

1. The sandy soils of the region are likely be very transmissive in which case the groundwater drawdown due to the plantation will diminish within a relatively small distance from the plantations edge (10 to 20 m). The proposed streamside reserves (100 m for the Markham River, 60 m for the Erap and Leron rivers, lakes, lagoons and swamps, 30 m for streams wider than 5 m, 20 m for streams 1 to 5 m wide, and 5 m for streams less than 1 m wide) are therefore adequate to protect the streams and associated vegetation from the changes in groundwater depth associated with the plantation.
2. It is further recommended that large plantations (more than 100 ha) should not be located within one km of the upslope side of local water supply wells. The local network of wells should also be monitored for depth and water quality. These data can be used to iteratively improve the modelling presented here.
3. The proposed pumping bores for the power plant should be sited downslope of the plantation and close to the Markham River to ensure continuity of supply and to avoid any impact of these bores on local water supply wells or on groundwater-dependent ecosystems. The maximum rate of pumping estimated will be 156,000 L per hour. This equates to 375 mm per day if it all comes from a ground area of 1 ha. This is a large amount of water and is approximately 120 times the maximum possible impact of the plantation per unit land area. Pumping at this rate from a single well will cause a drawdown at least one km from the bore centre. It is therefore essential that further aquifer testing be undertaken to determine: i)the full depth of the reliable aquifer and ii) the specific yield and hydraulic conductivity of the aquifer.
4. Should changes in ground water depth of less than 3 m be considered unacceptable then the results of this study suggest that a detailed field data collection and modelling study is warranted.
5. Based on the limited amount of data available and the data from the pumping test, which did not reach steady state, the amount of water that the proponents wish to pump cannot be safely supplied from fewer than 5 wells approximately 1 km apart. To reduce these specifications a detailed study of the soil physics, lithology and pumping tests with a network of observation bores will be required.
6. There is great deal of uncertainty surrounding the climate data, groundwater depth and dynamics and key soil properties needed to model the growth, water balance and groundwater impacts of the

plantation and pumping bores. We recommend that a monitoring program be commenced at the site. As well as measurements of plantation growth the proponents should commence measuring weather variables including rainfall, radiation and temperature. Groundwater monitoring bores should also be installed in transects through the plantation.

7. That a project be initiated to explore the relationship between management and the wood productivity (wood per water) of the project.
8. That a full life cycle analysis be conducted of the water impacts and efficiency of using biomass to produce energy.

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Appendix 1. Relevant FSC Criteria

Principle 5, Annex C: Additional Requirements for Ecosystem Services*.

II – Management Indicators

A. All Services

1. Management indicators for all Ecosystem Services* ensure:
- Peatlands* are not drained;
- Wetlands*, peatlands*, savannahs or natural grasslands* are not converted to plantations* or any other land use;
- Areas converted from wetlands*, peatlands*, savannahs or natural grasslands* to plantation* since November 1994 are not certified, except where:
  . a) The Organization* provides clear and sufficient evidence that it was not directly or indirectly responsible for the conversion; or
  . b) The conversion is producing clear, substantial, additional, secure, long-term* conservation* benefits in the Management Unit*; and
  . c) The total area of plantation* on sites converted since November 1994 is less than 5% of the total area of the Management Unit*.
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iv. Knowledgeable experts independent of The Organization* confirm the effectiveness of management strategies and actions to maintain and/or enhance the identified High Conservation Value* areas.

D. Watershed Services

1) In addition to measures to protect water in Principle* 6 and measures to reduce the impact from natural hazards* in Principle* 10, where promotional claims are made regarding watershed services:

i. An assessment identifies

a) Hydrological features and connections, including permanent and temporary water bodies*, watercourses*, and aquifers*;

b) Domestic water needs for Indigenous Peoples* and local communities* within and outside of the Management Unit* that may be impacted by management activities;

c) Areas of water stress* and water scarcity*; and

d) Consumption of water by The Organization* and other users.

2) Measures are implemented to maintain, enhance or restore* permanent and temporary water bodies*, watercourses*, and aquifers*;

3) Chemicals, waste and sediment are not discharged into water bodies*, watercourses* or aquifers*; and

4) Management activities and strategies respect universal access to water, as defined in the UN resolution on the human right to water and sanitation.

PRINCIPLE 6 – ENVIRONMENTAL VALUES AND IMPACTS

The Organization* shall* maintain, conserve* and/or restore* ecosystem services* and environmental values* of the Management Unit*, and shall* avoid, repair or mitigate negative environmental impacts. (P6 P&C V4)

6.7 The Organization* shall* protect* or restore* natural watercourses, water bodies*, riparian zones* and their connectivity*. The Organization* shall* avoid negative impacts on water quality and quantity and mitigate and remedy those that occur. (C6.5 and 10.2 P&C V4)

INSTRUCTIONS FOR STANDARD DEVELOPERS: Standard Developers shall* identify protection measures that include the following, and may include existing regulations and/or best practices where they provide sufficient protection:

- Buffer zones and other measures to protect natural watercourses* and water bodies*, their connectivity*, in-stream habitat*, and fish, invertebrates, and other aquatic species;
- Measures to protect native vegetation in riparian zones* of watercourses and water bodies*, including feeding, breeding, or cover habitat* for terrestrial and aquatic species, and needed inputs of wood and leaf litter into aquatic areas;
- Measures to prevent negative changes in water quantity and quality, including through maintaining stream shading sufficient to protect against temperature changes beyond natural limits;
- Measures to maintain natural hydrological patterns and stream flows;
- Measures to prevent impacts from road location, construction, maintenance and use;

- Measures to prevent sedimentation of water bodies and soil erosion from harvesting, roads, and other activities; and
- Measures to prevent negative impacts from chemicals or fertilizers*.

6.7.1 Protection* measures are implemented to protect natural watercourses*, water bodies*, riparian zones* and their connectivity*, including water quantity and water quality.

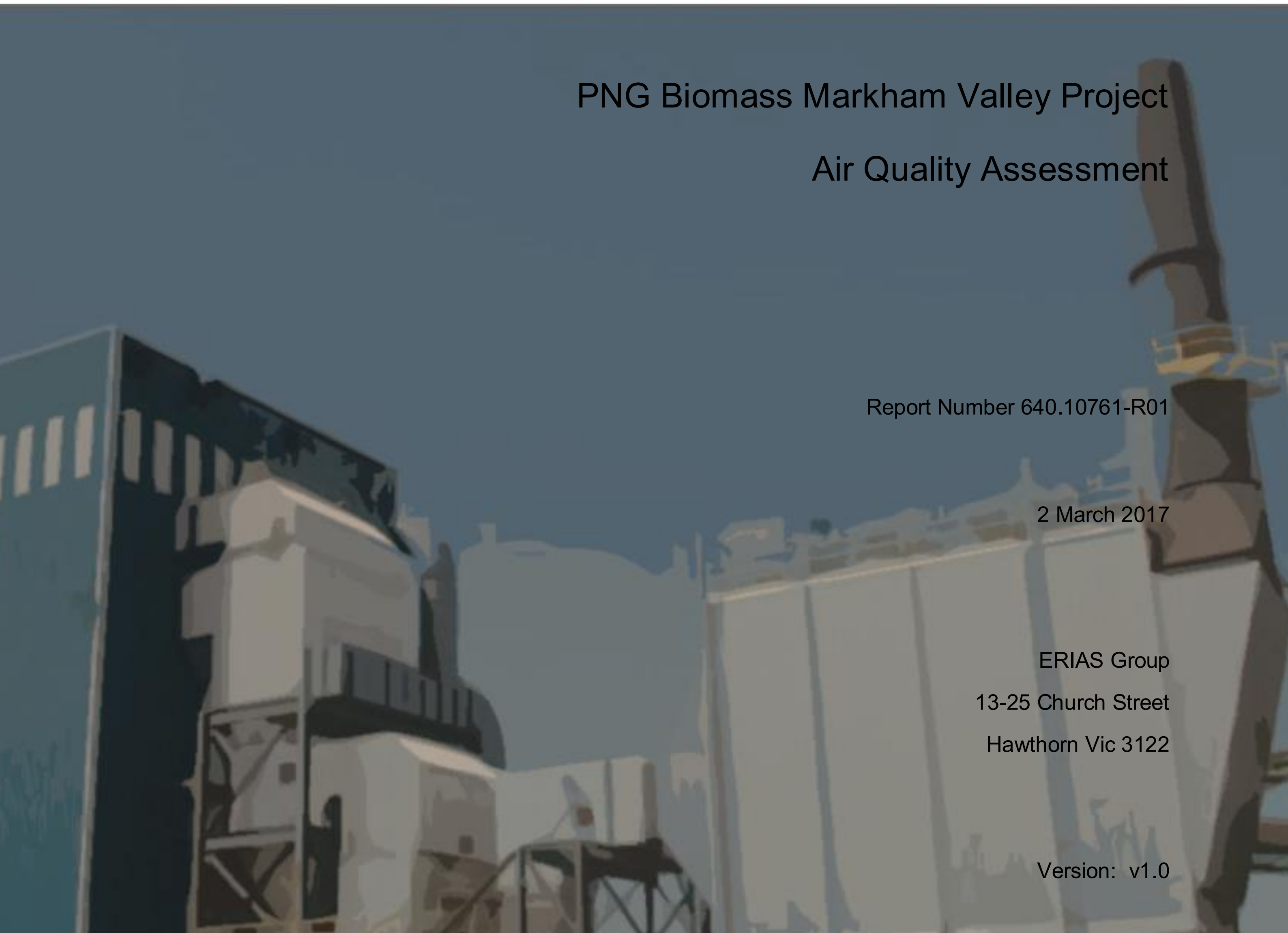
6.7.2 Where implemented protection* measures do not protect watercourses*, water bodies*, riparian zones* and their connectivity*, water quantity or water quality from impacts of forest* management, restoration activities are implemented.

6.7.3 Where natural watercourses, water bodies*, riparian zones* and their connectivity*, water quantity or water quality have been damaged by past activities on land and water by The Organization*, restoration activities* are implemented.

6.7.4 Where continued degradation exists to watercourses*, water bodies*, water quantity and water quality caused by previous managers and the activities of third parties, measures are implemented that prevent or mitigate this degradation.

Appendix 3
Air Quality Assessment

SLR
global environmental solutions



PNG Biomass Markham Valley Project

Air Quality Assessment

Report Number 640.10761-R01

2 March 2017

ERIAS Group
13-25 Church Street
Hawthorn Vic 3122

Version: v1.0

PNG Biomass Markham Valley Project

Air Quality Assessment

PREPARED BY:

SLR Consulting Australia Pty Ltd
ABN 29 001 584 612
Suite 2, 2 Domville Avenue
Hawthorn VIC 3122 Australia

T: +61 3 9249 9400   F: +61 3 9249 9499
melbourne@slrconsulting.com   www.slrconsulting.com

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Reference	Date	Prepared	Checked	Authorised
640.10761-R01-v1.0	2 March 2017	Alison Radford Fardaus Rahaman	Kirsten Lawrence	K Lawrence

Executive Summary

Background

ERIAS Group commissioned SLR on behalf of Markham Valley Biomass Limited (MVB) to perform a detailed Air Quality Assessment study for the proposed PNG Biomass Markham Valley project ('the Project'), located near the confluence of the Watut and Markham rivers approximately 50 kilometres (km) northwest of the provincial capital Lae in Morobe Province, Papua New Guinea (PNG). MVB requires an assessment of the Project addressing the relevant PNG regulatory requirements and international standards related to air quality assessments.

The Project has two related major components:

- Construction and operation of a new 30 MW power plant consisting of two separate 15 MW biomass-fired units that will be constructed several years apart; and
- Establishment of up to 15,000 hectares (ha) of eucalypt plantations to provide biomass (wood) that will be used as fuel for the power plant.

Additional components include a plant nursery and ancillary infrastructure (e.g. log yard, roads, water pipeline corridor).

Air Quality Assessment

A comprehensive study of potential air quality impacts from both construction and operational activities associated with the Project has been performed using a mixture of quantitative and qualitative assessment techniques.

Design data available for the Project were reviewed to identify the key Project activities that have the greatest potential for impacts on local air quality, which were then assessed quantitatively. The emissions to air from these activities were estimated and atmospheric dispersion modelling studies were performed to simulate the dispersion of these emissions downwind (taking into account the local topography and meteorology) in order to estimate maximum ground level concentrations and deposition rates at nearby sensitive receptors and sensitive land uses. The results of the modelling studies were assessed against appropriate international air quality guidelines and standards.

Activities with a much lower potential for impacts on local air quality were assessed qualitatively, for example, ensuring that adequate separation distances exist between the activity and the nearest sensitive receptors.

Table E1 presents a summary of the facilities and air emission sources which have been assessed for this Project, in addition to the method of assessment.

Executive Summary

Table E1 Summary of Air Quality Assessment Methodology

Project Site	Phase	Facilities/Air Emission Sources	Prediction/ Assessment Method	Scenario
Power Plant	Construction	Site preparation and ground works, general construction of the power plant and associated infrastructure.	Qualitative	-
	Operation	Operation of the power plant and associated infrastructure, including truck movements from plantations to the power plant.	3D CALPUFF modelling	Worst Case
Plantations/ Nursery	Construction	Upgrading or establishing road access and site preparation, ground works and construction of the 9.58 ha plant nursery	Qualitative	-
	Operation	Establishment of up to 4,500 ha/yr of plantation area and harvesting of timber.	Qualitative	-

Assessment Criteria

PNG does not currently have any statutory air quality standards. Therefore, a review of relevant air quality criteria and guidelines set by a number of international agencies has been performed, including:

- International Finance Corporation (IFC) EHS guidelines;
- World Health Organization (WHO) Air Quality Guidelines; and

The ambient air quality criteria adopted for use in this study are summarised below in **Table E2**.

Table E2 Ambient Air Quality Criteria Adopted for this Assessment

Pollutants	Averaging Period	Limit (µg/m^3)	Source	Notes
NO_2	1-hour	200	WHO, 2005	
	Annual	40	WHO, 2005	
SO_2	10-Minutes	500	WHO, 2005	
	24-hours	20	WHO, 2005	
CO	1-hour	30,000	WHO, 2000	
	24-hours	10,000	WHO, 2000	
PM_{10}	24-hours	50	WHO, 2005	
	Annual	20	WHO, 2005	
$PM_{2.5}$	24-hours	25	WHO, 2005	
	Annual	10	WHO, 2005	
Benzene	Annual	0.17	WHO, 2005	Excess lifetime risk level of 1:1,000,000.

Executive Summary

Sensitive Receptors

Villages located within 7 km of the major Project infrastructure and the main access roads have been identified. The largest villages (Chivasing and Tararan) will be surrounded by a buffer zone of at least 50 m within which plantation establishment will not occur. Near smaller hamlets (such as Ganef) and other infrastructure, the need for, and size of, buffer zones will be negotiated with the local landowners/residents.

Assessment of Potential Impacts

Construction Phase Potential Impacts

The construction activities with the greatest potential for PM_{10} and $PM_{2.5}$ impacts at sensitive receptors (i.e. village locations) are the construction of the power plant and nursery and upgrading and establishing access roads into the plantation areas. The nearest populated areas to the power plant site are currently located 800 m to the northwest in the Ganef hamlet. According to the Institute of Air Quality Management (IAQM) screening criteria, if the access roads into the plantation areas are located greater than 350 m from sensitive receptors, they would not require assessment of dust impacts from construction activities. Hence it is therefore recommended that access roads into the plantation areas be located greater than 350 m from existing villages wherever possible.

Operational Phase Potential Impacts

The operational phase will result in the generation of point source and fugitive emissions.

Potential air quality impacts associated with emissions from the power plant stacks and fugitive dust emissions from trucks transporting logs to the power plant and transporting ash off-site have been assessed using dispersion modelling. Emissions from the power plant stacks were conservatively estimated based on IFC emission limits and USEPA emission factors for wood-fired boilers, and the modelling was performed assuming both 15 MW boilers were operating at full capacity 8,760 hours per year (24 hours per day, 365 days per year).

The results indicated:

- The incremental PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO and total VOC ground level concentrations predicted at all sensitive receptors are below the relevant air quality criteria.
- The cumulative maximum 24-hour average and annual average PM_{10} ground level concentrations predicted at the northern boundary of the site exceed the air quality criteria; however, currently this location is not populated.

Fugitive dust emissions from planting and harvesting activities may impact nearby sensitive receptors. It is therefore recommended that plantation areas be located greater than 350 m from existing villages where possible to minimise the risk of air quality impacts associated with ongoing plantation activities.

All other construction and operational activities associated with the Project would occur in locations remote from sensitive receptors and given the scale of the activities would not be expected to result in any adverse health or nuisance impacts at sensitive receptors.

Monitoring

Based on the key findings of the air quality impact assessment, an ambient air quality monitoring program should be performed throughout the construction and operational phases of the Project as outlined below.

Executive Summary

- Construction of the plantation access roads and the power plant site are the only construction phase activities with the potential to impact air quality at sensitive receptors as they may occur in proximity to a few villages.
    - If plantation access road construction areas are not located greater than 350 m from an existing village, it may be necessary to monitor any potential dust impacts from construction activities. It is therefore proposed that PM_{10} baseline monitoring be performed using beta-attenuation monitors (BAMs) in villages close to proposed access roads prior to construction works starting. Should any complaints regarding dust be received during the road construction, monitoring would be performed downwind of the activities to assess whether concentrations are elevated above the previously recorded baseline levels. This information would then be used in managing the impacts while the works are occurring in close proximity to villages.
    - The monitoring equipment would also be used to investigate impacts from other activities associated with the Project should any complaints or concerns be raised, and to collect baseline monitoring away from the active work areas.

  It is noted that Ganef hamlet is unlikely to be significantly impacted by the construction of the power plant. No monitoring of particulate matter is therefore recommended at Ganef hamlet during construction of the power plant.
- No exceedances of ambient air quality criteria at sensitive receptors are predicted for the operational phase of the Project, hence no routine ambient air quality monitoring program is proposed. If required, the particulate monitors discussed above for the construction phase may be used to investigate any complaints that are received or if concerns are raised regarding particulate levels downwind of operational activities.
- A stack monitoring programme should be developed for the power plant boiler stacks to ensure all units are operating within supplier specifications and in compliance with any stack emission limits.
- If plantation areas are not located greater than 350 m from an existing village, it may be necessary to monitor any potential dust impacts from plantation establishment and harvesting activities.

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APPENDICES

1 INTRODUCTION

ERIAS Group commissioned SLR on behalf of Markham Valley Biomass Limited (MVB) to perform a detailed Air Quality Assessment study for the proposed PNG Biomass Markham Valley project ('the Project'), located approximately 50 kilometres (km) northwest of Lae in Morobe Province, Papua New Guinea (PNG). MVB requires an assessment to address the relevant PNG regulatory requirements and international standards related to air quality assessments.

This report forms part of an Environmental Assessment (EA) for the Project. It describes the methodology used in the assessment, summarises the results of the assessment and describes the management measures proposed to mitigate the potential air quality impacts of the Project.

1.1 Impact Assessment Approach

The air quality impact assessment has been performed using a mixture of quantitative and qualitative assessment techniques. Design data available for the Project were reviewed to identify the key Project activities that have the most significant potential for impacts on local air quality, which were then assessed quantitatively. The emissions to air from these activities were estimated and atmospheric dispersion modelling studies were performed to simulate the dispersion of these emissions downwind (taking into account the local topography and meteorology) in order to estimate maximum ground level concentrations at nearby sensitive receptors. The results of the modelling studies were assessed based on international air quality guidelines and standards. Activities with a much lower potential for impacts on local air quality were assessed qualitatively, ensuring that adequate separation distances exist between the activity and the nearest sensitive receptors.

1.1.1 Impact Assessment Framework

The approach adopted for the air quality impact assessment follows that used for the overarching EA, and involved the following:

- Description of existing relevant environmental conditions of the Project footprint and surrounds, including the sensitivity of receptors, which may be affected by changes in the existing conditions.
- Assessment of potential, credible air quality impacts associated with all phases of the Project. Identification of the potential impacts has been based on knowledge of the existing environment, the Project description, experience with similar operations in similar biophysical and social environments and issues of concern to stakeholders.
- Identification of appropriate management and mitigation measures, where the measures described are technically and economically feasible within the context of the Project.

1.2 Structure of this Report

The structure of this report is outlined below:

- **Section 2** provides a brief outline of the Project focussing on the activities that have the potential for emissions to air;
- **Section 3** describes the study area with respect to the topography, climate and existing air quality and also identifies the nearest sensitive receptors;
- **Section 4** identifies the potential emissions to air associated with the construction and operational phases of the Project;
- **Section 5** discusses the regulatory requirements (e.g. air quality criteria) upon which this assessment is based;
- **Section 6** describes the methodology used in the air dispersion modelling to quantify the potential impacts on local quality;

- **Section 7** presents estimated emission rates for those emissions identified as having the potential to give rise to local air quality impacts;
- **Section 8** presents the results of the modelling;
- **Section 9** presents the impact assessment based upon the results of the modelling;
- **Section 10** discusses the mitigation measures proposed to limit off-site impacts and recommends monitoring programs where appropriate; and
- **Section 11** summarises the key findings of the air quality assessment.

2 PROJECT DESCRIPTION

The project area is located in the Markham Valley near the confluence of the Watut and Markham rivers, 50 km northwest of the provincial capital Lae. The Project site is accessed from the Highlands Highway and is located approximately 10 km west of Lae Nadzab Airport.

The Project has two related major components:

- Construction and operation of a new 30 MW power plant consisting of two separate 15 MW biomass-fired units that will be constructed several years apart; and
- Establishment of up to 15,000 hectares (ha) of eucalypt plantations to provide biomass (wood) that will be used as fuel for the power plant.

Additional components include a plant nursery and ancillary infrastructure (e.g. log yard, roads, water pipeline corridor).

2.1 Biomass Power Plant

The power plant will be located approximately 50 m to the sourth of the existing 132 kV electricity transmission lines. Power generated from the plant will be conveyed directly to these lines via a short section of 132 kV transmission line from the onsite switchyard and transformer. The power plant site covers a total area of 30.83 ha, including the log yard (laydown areas for wood stockpiles). Harvested biomass will be stockpiled then chipped, dried and stored at the power plant.

2.1.1 Construction

Construction of the power plant and nursery will involve a number of sequential steps culminating in commissioning and power delivery to the Ramu Grid. These steps include:

- Site preparation: This includes providing site access and involves vegetation clearing, cut and/or fill if required, and site compacting, as well as establishing site drainage, roads/parking/fencing, temporary laydown areas, warehouses and construction site offices/cabins (including stores, toilets and workers' eating facility). Construction objectives are to:
  - Complete as much as possible of the earthworks and construction of the stormwater drainage system and roads located within the power island before the October to January rainy season.
  - Construct the sub-base of the roads and the stormwater drainage system as fast as possible to facilitate stormwater drainage during the rainy season.
- Civil works: These will focus on ground excavation, piling and backfilling, and will provide the foundations for plant components such as the boiler, steam turbine and cooling tower, as well as other equipment including fuel handling facilities, log and woodchip handling facilities, and general services. Points to note are:
  - At least two concrete batching plants will be established on site, one with higher capacity (minimum 30 m^3 concrete per hour) and one for medium to smaller concrete pours (12 to 15 m^3 concrete per hour).
  - Over 6,000 m^3 of surplus excavated material and a large amount of topsoil (around 50,000 m^3) will be placed in a temporary storage area until the site landscaping commences. An area of about 2,000 m^2 has been reserved to store excess excavation material that will be used again after concreting of foundations for backfilling.
- Building construction: Buildings that will be constructed during this stage include an administration building, weigh bridge building and truck scale, workshop and warehouse, control room and other facilities.
- Mechanical equipment, structures and pipework installation: This includes installation of pipe racks, piping, tanks, boiler, cooling water tower, water treatment plant and similar.

- Electrical and instrument installation: This includes installation of cables, cable trays, ducts, lighting, transformers, switchgear, lightning and earthing protection systems, plant lighting and fire detection and alarm systems, and similar.

2.1.2 Operation

The power plant comprises two 15 MW modules each of which consists of one biomass boiler and one steam turbine generator, fired with wood chips supplied from the dedicated plantations at a rate of 175,300 BDMt (bone dry metric tonnes) of dry wood annually by 2023. The maximum peak load for the power plant will occur when it is operating at full capacity, generating 30 MW. The process flow diagram is presented in **Figure 1**.

Boiler operation will involve transport of woodchips from the fuel bins to the furnace via conveyor, where the fuel will be spread evenly over the stoker to allow uniform combustion. Water in the fuel will evaporate during the combustion process, with pyrolysis (loss of volatile matter) occurring within the temperature range of 200 to 400°C. Gasification of the remaining fuel, mainly fixed carbon, will then occur.

During the combustion process, most of the ash (around 60 to 70%) will be carried through the boiler by the flue gas, with around 30 to 40% remaining on the stoker where it will be discharged to the bottom ash handling system. Part of the fly ash will be collected in the dust collector (multi-cyclone) and the remaining fly ash will be collected in the electrostatic precipitator (ESP).

The hot flue gas in the furnace will be cooled before entering the superheaters at the outlet of the furnace and then the steam generating banks. The flue gas will then exit pass through the fan and ESP prior to being discharged to atmosphere via a 40 m tall stack (for each of the two boilers).

The bottom ash will be managed using a wet system, with the ash being used for road construction and hardstanding in the log storage area. The fly ash collected from the flue gas cleaning equipment (cyclones and bag filters/precipitators) will be transferred to the fly ash silo and will be transported off-site in wet or dry condition from the power plant for further use.

Supporting systems will include a feedwater system (including a deaerator to remove oxygen and other gases from the condensate and make-up water to prevent corrosion) to provide water for steam generation, soot blowers to remove accumulated ash from the superheater, boiler generating bank and economizer, light fuel oil burner for boiler start-up and/or support firing, chemical dosing, water/steam sampling and burner management system.

2.1.2.1 Emission Control Strategies

As noted above, the particulate emissions from the boilers will be controlled using a single stage multi-cyclone dust collector (MDC) followed by a multi-field electrostatic precipitator (ESP) prior to the exhaust gases being discharged to atmosphere via the 40 m tall stacks.

The boilers will also be designed to reduce emissions of oxides of nitrogen (NOx) and carbon monoxide (CO) with staged combustion control that includes the following:

- Sectionalized under-grate air plenum for improved under grate air distribution and control.
- Multi-level over-fire air system to create turbulence in the upper furnace and improve combustion.
- Pre-heated combustion air to help combust high moisture content biomass fuel.
- Conservatively sized furnace resulting in a low furnace volume heat release in order to maximise furnace retention time and combustion of unburned carbon including CO.
- Operator control of fuel quality, fuel feed and combustion air based on monitoring oxygen levels and fuel quality to maintain optimum combustion conditions thereby minimizing conditions forming CO.

- Low-NOx boiler design including membrane wall watertube furnace which provides water cooling of the primary combustion chamber resulting in cooling the flame temperature prior to entering the superheater and convection sections of the boiler.
- Provisions for an SO_2 emission reduction unit have not been considered as the average sulfur content of the fuel is very low (0.02% - 0.05%).

A Continuous Emission Monitoring System (CEMS) will not be installed in the stack, but suitable sampling ports for stack testing equipment should be installed. If stack testing performed during commissioning shows higher emission rates than those used in this assessment, consideration should be given to installing a CEMS to investigate the variation in emissions with time.

2.2 Eucalypt Plantations

Establishment of 15,000 ha of eucalypt plantations within the Project area will occur over a seven-year period between 2017 and 2023, with the plantation area to be maintained indefinitely. The maximum plantation area established in any one year will be 4,500 ha in 2019, with an average of around 2,000 ha/year established during this initial phase. This scale of plantation estate is proposed regardless of whether one or two 15 MW power plant units are eventually constructed.

Where practicable, plantations will be established in a dispersed pattern across the landscape in order to reduce localised impacts on environmental and/or socio-cultural values. Plantations will be established progressively across the Project area in ‘compartments’ of approximately 20 ha each, ranging from 5 to 50 ha based on local constraints such as watercourses, existing gardens/crops, or areas of unsuitable soils. Within a given compartment, planting (and later maintenance and harvesting) will occur concurrently.

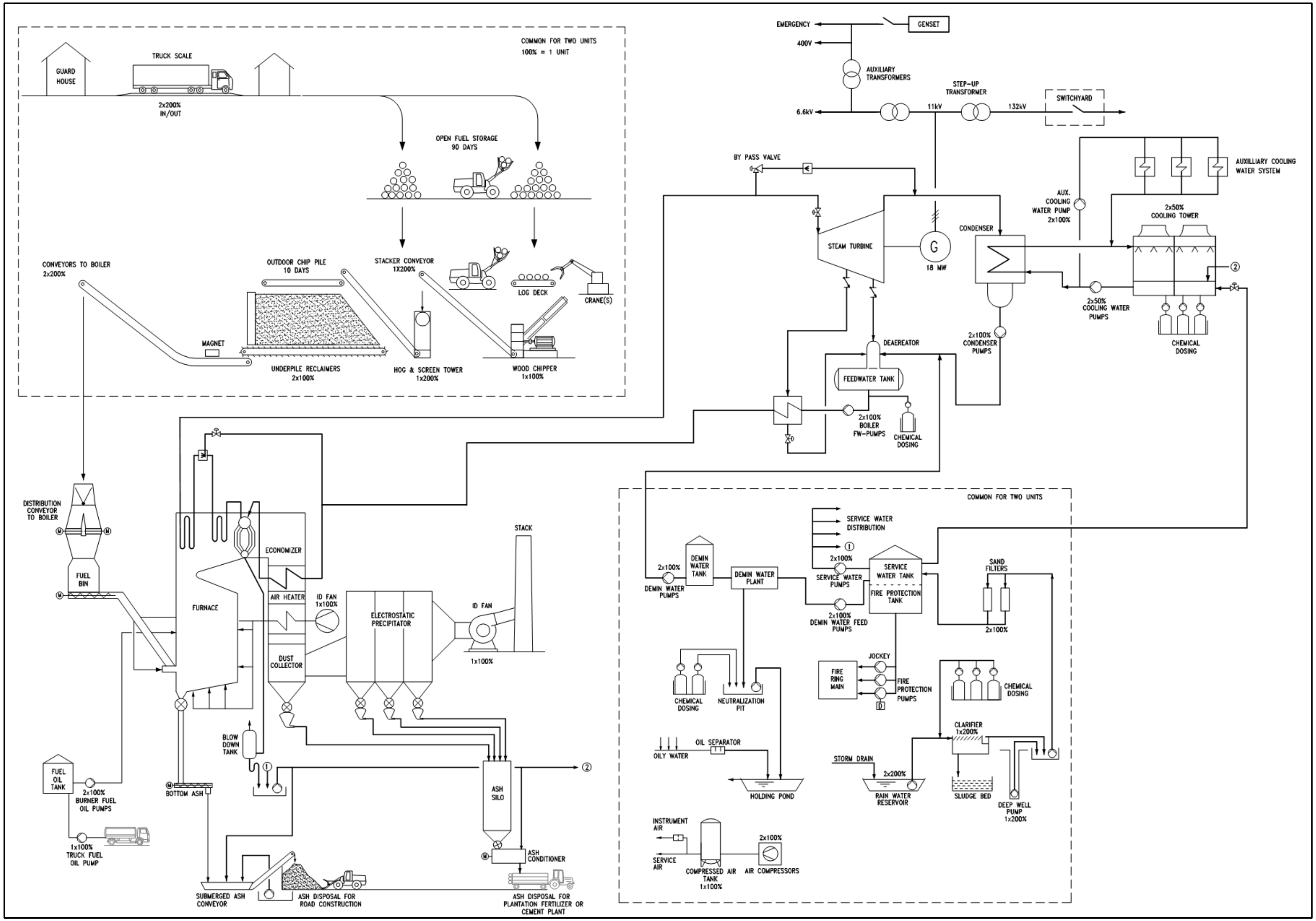
Plantation establishment will involve site clearing, soil preparation (cultivation and fertilisation) and if required, the application of Forest Stewardship Council (FSC) approved herbicides. Prior to site clearing and plantation establishment, road access to the proposed plantation areas will be established or upgraded. In areas to be planted, all existing vegetation including trees up to 30 cm in diameter will be removed to enable clear and unrestricted access to the site by manual or mechanical operations.

The Project will also develop plant nursery facilities capable of producing 8,000,000 plants per annum in order to establish plantations to produce sufficient biomass to sustainably meet fuel demand for the power plant.

The plantations will be managed on a rotation with up to two coppice[1] cycles. Harvested biomass will be transported to the power plant via trucks.

[1] In a coppiced plantation, young tree stems are repeatedly cut down to near ground level. In subsequent growth years, many new shoots will emerge, and, after a number of years the coppiced tree, or *stool*, is ready to be harvested, and the cycle begins again.

Figure 1 Overall Process Flow Diagram



3 SITE DESCRIPTION

The following section presents a description of the power plant site and surrounds with regards to topography, meteorology, the locations of nearby sensitive receptors and the existing air quality in the study area.

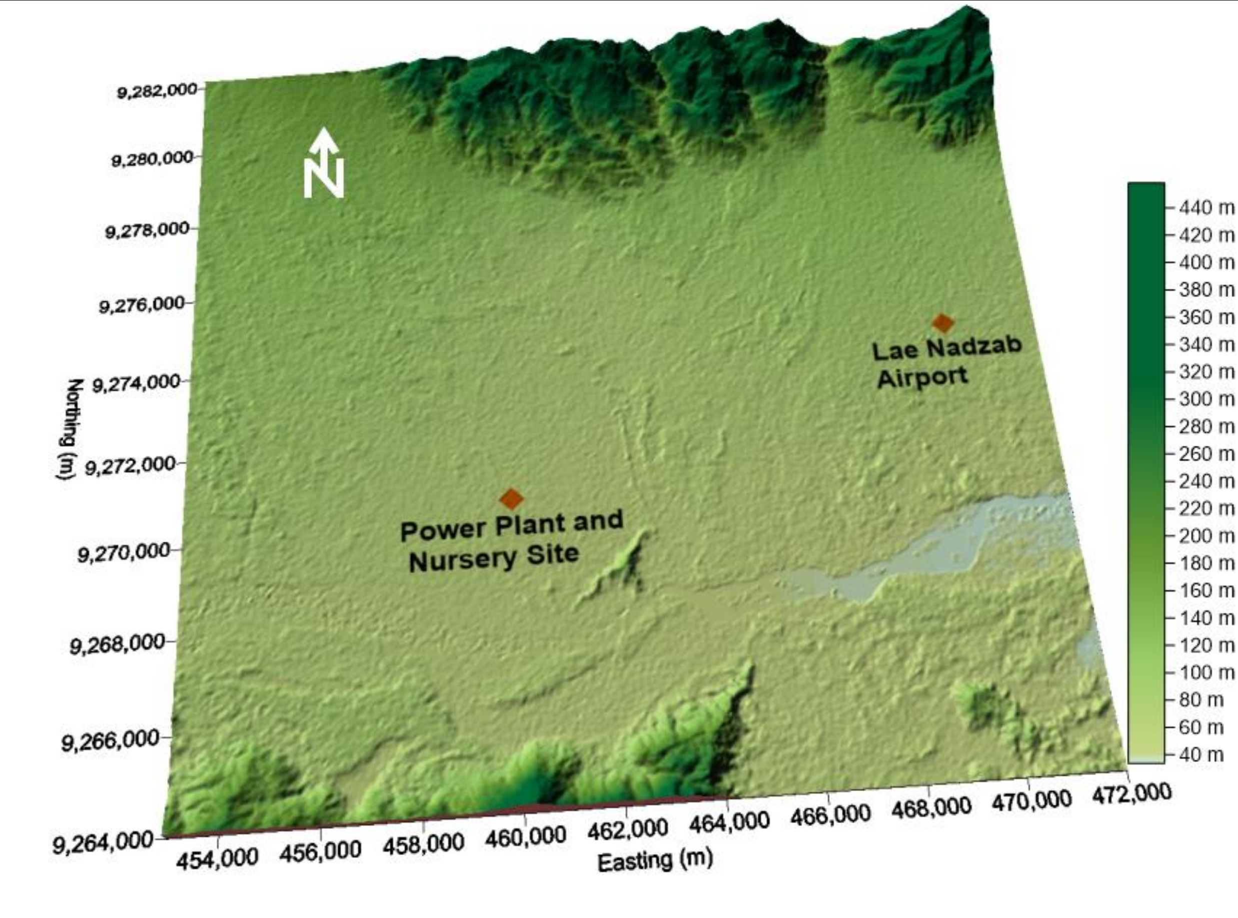
3.1 Local Topography and Land Use

Topography can influence wind patterns and plume dispersion. For example, in complex terrain, winds can be channelled along canyons and valleys, and areas of elevated terrain are more likely to experience elevated pollutant concentrations when emissions generated by a development impinge on these areas before being fully dispersed. The surface roughness of an area (a measure of the irregularity of the terrain and the presence of tall trees or buildings) influences the amount of mechanical turbulence in the air close to ground level, and thus how rapidly pollutants are dispersed.

The topography of the study area is illustrated in **Figure 2** based on topographical data sourced from the United States Geological Service's Shuttle Radar Topography Mission (SRTM) database that has recorded topography with a 3 arc second (~90 m) spacing. As shown in **Figure 2**, the topography surrounding the Project site is predominantly flat with low rolling hills. There are no significant topographical features close to the site that could significantly influence wind patterns, such as mountainous regions/peaks or coastlines. The nearest elevated terrain is located beyond the Markham River, approximately 5 km to the south.

The land use in the surrounding area is primarily subsistence agriculture and some cash cropping. The Project area is largely a modified environment, consisting of anthropogenic grassland or a mosaic with introduced rain trees. Grasslands are regularly burnt by local communities.

Figure 2 Topography Surrounding the Power Plant Site



3.2 Locations of Sensitive Receptors

The Project is situated in a relatively remote area with a number of villages located within the study area as shown in **Figure 3** and listed in **Table 1**.

Villages located within 7 km of the Project site have been identified. These sensitive receptors were identified based on the information provided by ERIAS/MVB and a review of aerial imagery within 7 km of the site by SLR. The air dispersion modelling results indicate that any impacts on air quality beyond these distances would be negligible, hence villages located outside these areas were not considered further.

The largest villages (Chivasing and Tararan) will be surrounded by a buffer zone of at least 50 m within which plantation establishment will not occur. Near smaller hamlets (such as Ganef) and other infrastructure, the need for, and size of, buffer zones will be negotiated with the local landowners/residents.

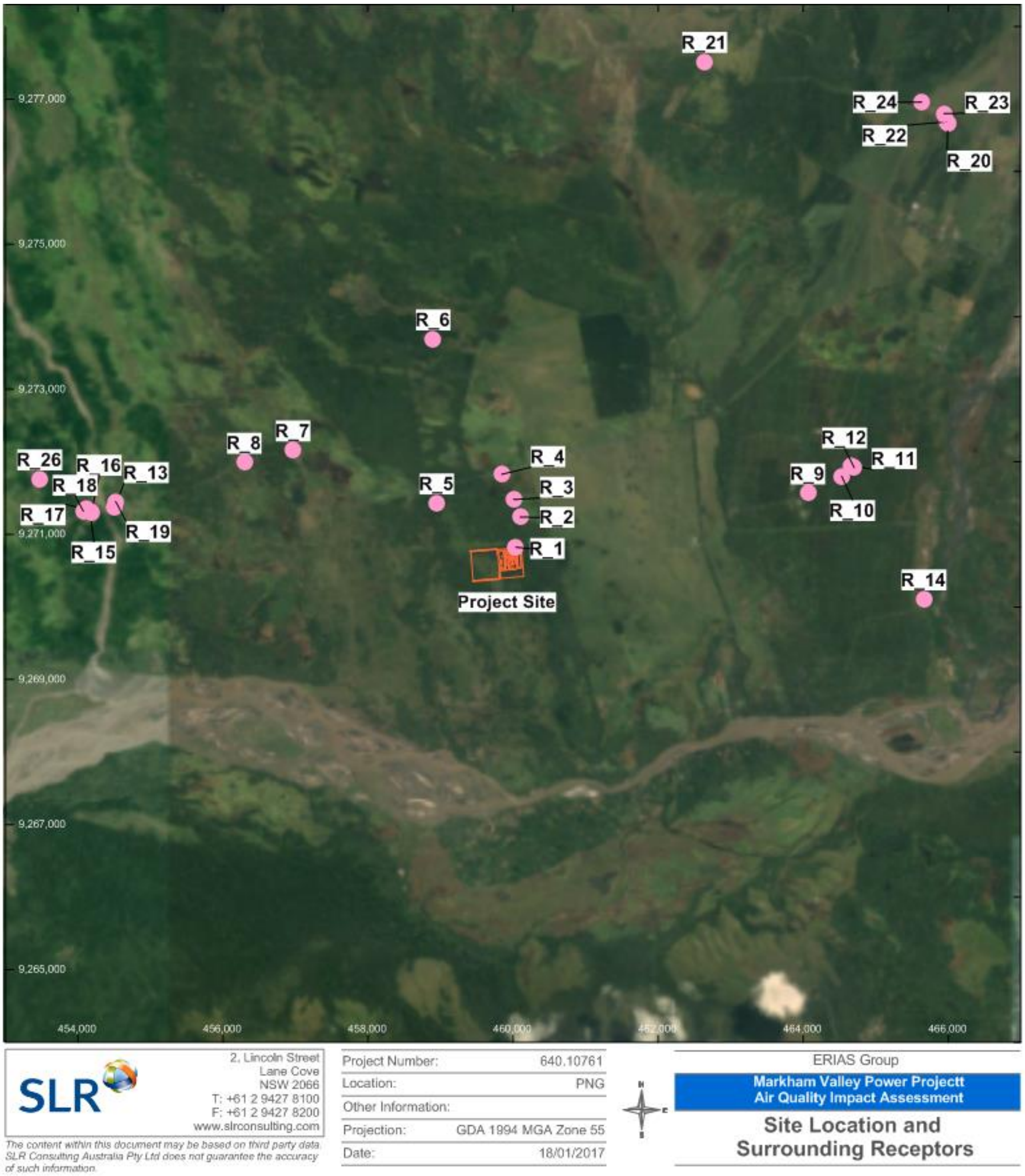
It is noted that receptor 1 (which is not a building or dwelling) is located to the immediate north of the power plant boundary fence line. While there are no settlements at this location currently, this receptor has been included to assess whether there is any potential for adverse impacts should in migration occur in this area after the project is operational. The maximum offsite predictions are predicted to occur along the northern boundary, hence these results represent the worst case offsite impacts.

Table 1 Sensitive Receptors

Site ID	Location	Approximate distance from site boundary	Coordinates (m, UTM Zone 55s)	
			X	Y
R_1[1]	Northern boundary	0 km N	460,039	9,270,823
R_2	Outbuilding (no road access)	0.40 km N	460,097	9,271,238
R_3	Outbuilding (no road access)	0.67 km N	460,005	9,271,480
R_4	Ganef Community Nursery	1.0 km N	459,842	9,271,828
R_5	Ganef (hamlet)	0.8 km NW	458,949	9,271,434
R_6	Mempangnaron	3.05 km NNW	458,899	9,273,694
R_7	Furif	2.8 km NW	456,966	9,272,162
R_8	40 Miles	3.4 km NW	456,294	9,271,995
R_9	Markham Farm Aidpost - west (hospital)	3.8 – 4.4 km ENE	464,065	9,271,573
R_10	Markham Farm Aidpost - east (hospital)	3.8 – 4.4 km ENE	464,530	9,271,803
R_11	Markham Farm Elementary School	3.8 – 4.4 km ENE	464,651	9,271,951
R_12	Markham Farm Primary School	3.8 – 4.4 km ENE	464,702	9,271,918
R_13	41 Mile Night Market	4.9 km WNW	454,510	9,271,380
R_14	Kaiapit	5.5 km E	465,666	9,270,109
R_15	Chivasing Police Station	5.3 km WNW	454,164	9,271,319
R_16	Chivasing Aid Post (hospital)	5.3 km WNW	454,181	9,271,294
R_17	Chivasing Elementary School	5.3 km WNW	454,122	9,271,347
R_18	Chivasing Primary School	5.3 km WNW	454,075	9,271,319
R_19	41 Mile Night Market-residences	4.9 km WNW	454,520	9,271,453
R_20	Erap	8.2 km NE	465,993	9,276,658
R_21	Arisisi	7.1 km NNE	462,643	9,277,518
R_22	Erap Primary School	8.3 km NE	465,974	9,276,686
R_23	Erap Station Elementary School	8.4 km NE	465,939	9,276,801
R_24	Nigassim	8.3 km NE	465,635	9,276,959
R_26	Chivasing Elementary School Crew Site	6.0 km WNW	453,474	9,271,765

[1] Represents the worst case impact at site boundary to assess impacts associated with potential in migration but currently is not inhabited.

Figure 3 Sensitive Receptors

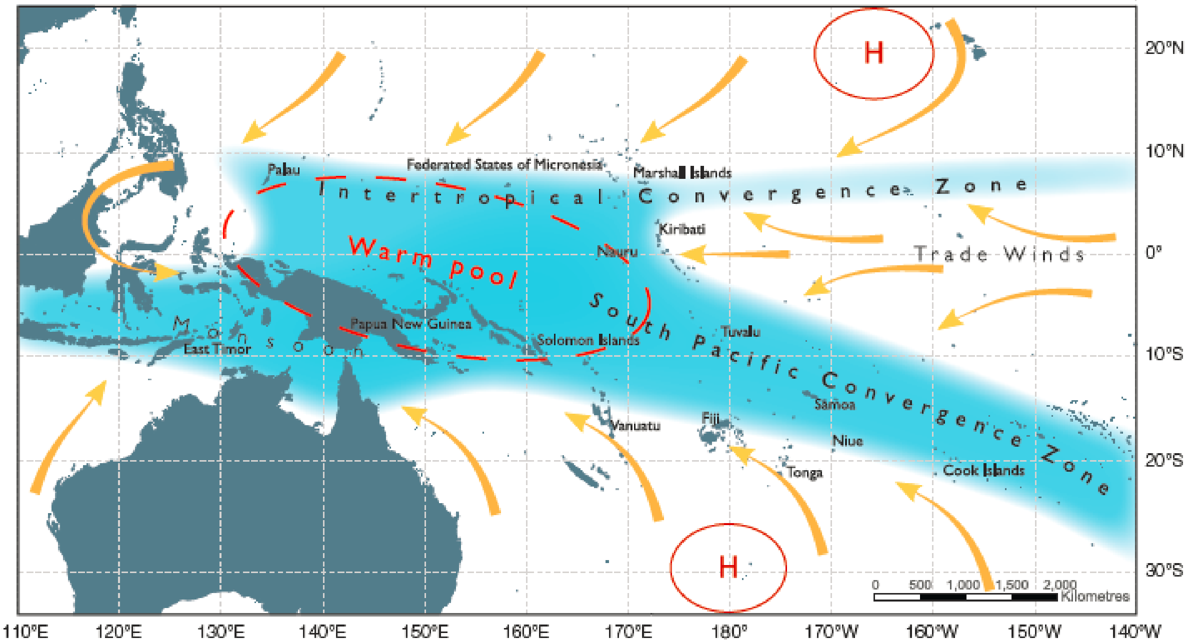


3.3 Climate and Meteorology

The meteorological characteristics of an area have significant impact on the dispersion of pollutants; the predominant wind directions determine the direction in which the majority of the pollutants are dispersed; the typical wind speeds influence (for example) how much dust may be generated through erosion of disturbed areas and how far air pollutants may travel downwind before being fully dispersed; and rainfall patterns influence soil moisture content and thus the potential for dust to be generated through the handling of soils and by traffic on haul roads.

PNG has a monsoon-type climate, with the rainfall and temperature influenced by three large-scale wind convergence and rainfall regimes: the Inter-Tropical Convergence Zone, the South Pacific Convergence Zone and the West Pacific Monsoon (see **Figure 4**).

Figure 4 Influence of West Pacific Monsoon, South Pacific Convergence Zone and Inter-Tropical Convergence Zone on PNG's Rainfall and Temperature



SOURCE: World Bank, 2013.

Due to its proximity to the equator, average daily temperatures in PNG are very stable throughout the year with no marked seasonality. Mean daily temperatures at Port Moresby (southern PNG) are 27˚C and show very little variation throughout the year: similarly average daily temperatures at Solano, Admiralty Islands (far north) are 27˚C (World Bank, 2013).

Western and northern parts of PNG experience the highest rates of precipitation, since the north- and westward-moving monsoon clouds are heavy with moisture by the time they reach these more distant regions. In addition, while rainfall at Momote weather station in the far north is more evenly distributed throughout the year with no dry season, the southern region of PNG experiences extreme variations in rainfall linked with the monsoons. The dry season typically runs from June to September, while the rainy season typically occurs during December to March. Rainfall patterns in PNG are also strongly influenced by the El Niño Southern Oscillation (ENSO) Cycle with droughts in El Niño years and excess rain/flooding in La Niña years (World Bank, 2013).

Typhoons can occur during the rainy season from December to mid-March, and can cause heavy damage, flooding and erosion.

Further details of meteorological conditions at the Project site are provided below. This analysis is largely based on data from the Lae Nadzab airport automatic weather station (AWS). The Lae Nadzab Airport AWS is located approximately 10 km northeast of the power plant site (see **Figure 2**), and would be reflective of the meteorology at the power plant site. A summary of the data recorded from 2012 – 2015 by this AWS is presented in **Section 3.3.1** to **Section 3.3.3**.

3.3.1 Temperature

Temperature data recorded from September 2012 to December 2015 at Lae Nadzab Airport AWS were reviewed. As shown in **Table 2**, the Lae Nadzab Airport AWS experienced a consistent annual average temperature of 26°C over the three years from 2013 to 2015. Monthly average temperatures ranged from 20°C and maximums of 34-36°C recorded between late-2012 and 2015.

The coolest months fall between June and September during the dry season, however the temperatures in the Project area remain reasonably constant throughout the year.

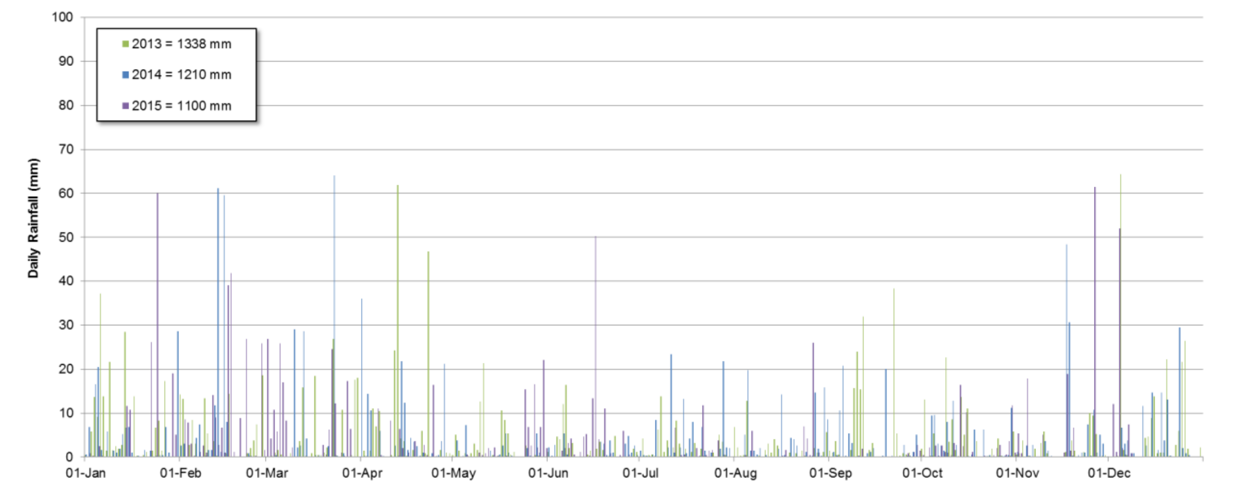
Table 2 Average Monthly Temperature Data for Lae Nadzab Airport

Month	**Lae Nadzab Airport AWS Temperature (°C)**			
	2012	**2013**	**2014**	**2015**
Monthly Average Temperatures				
January		27	27	28
February		27	27	27
March		28	27	27
April		27	27	27
May		26	26	27
June		26	26	25
July		25	24	26
August		25	26	25
September	26	25	26	26
October	26	26	26	26
November	27	27	27	27
December	28	27	28	27
Annual Average Temperature	27	26	26	26
Minimum Temperature	20	20	20	20
Maximum Temperature	34	36	36	36

3.3.2 Rainfall

The annual rainfall in the Project area typically ranges between approximately 1,200 mm to 1,400 mm. The wettest months are October to April, while the driest months are June to August. Daily rainfall records for 2013 – 2015 are shown in **Figure 5**.

Figure 5 Daily Rainfall Data for Lae Nadzab Airport



Note: Annual rainfall shown in legend

3.3.3 Wind Speed and Direction

Table 3 presents the average and maximum wind speeds recorded by the Lae Nadzab Airport AWS in 2012-2015. There is little inter-annual variation in the wind speeds recorded. While winds appear to be slightly higher during 2012, this is likely to be due to only September to December data being available.

Table 3 Average and Maximum Wind Speed Data for Lae Nadzab Airport

	Lae Nadzab Airport AWS Wind Speed (m/s)			
	2012	**2013**	**2014**	**2015**
Average	3.4	2.4	2.3	2.9
Maximum	9.9	8.4	8.2	9.8

Figure 6 shows that the wind speed frequency distribution at Lae Nadzab Airport AWS during 2014 and 2015 was reasonably consistent over these two years.

Figure 7 presents annual wind roses compiled based on the wind speed and wind direction data from Lae Nadzab Airport AWS for 2014 and 2015. The wind roses show the frequency of occurrence of winds by direction and strength. The bars correspond to the 16 compass points – N, NNE, NE, ENE etc. The bar at the top of each wind rose diagram represents winds blowing from the north (i.e., northerly winds), and so on. The length of the bar represents the frequency of occurrence of winds from that direction, and the widths of the bar sections correspond to wind speed categories, the narrowest representing the lightest winds. Thus it is possible to visualise how often winds of a certain direction and strength occur over a long period, either for all hours of the day, or for particular periods during the day.

The annual wind roses compiled from data recorded during 2014 and 2015 indicate that winds blowing from the east-northeast are predominant in the area. The frequency of easterly winds slightly increased in 2015 compared to 2014, and east-southeasterly winds increased in intensity. The annual frequency of calm conditions was 8.6% in 2014 and decreased to 6.3% in 2015. These variations are minor and within expected inter-annual differences in wind speed and direction.

As there is little difference in the temperature and wind data reported for 2014 and 2015, the most recent year, 2015, was used to compile the site-representative 3-dimensional meteorological dataset used in the dispersion modelling study (refer **Section 6.3**).

Figure 6 Wind Speed Frequency Distribution – Lae Nadzab Airport AWS, 2014 and 2015

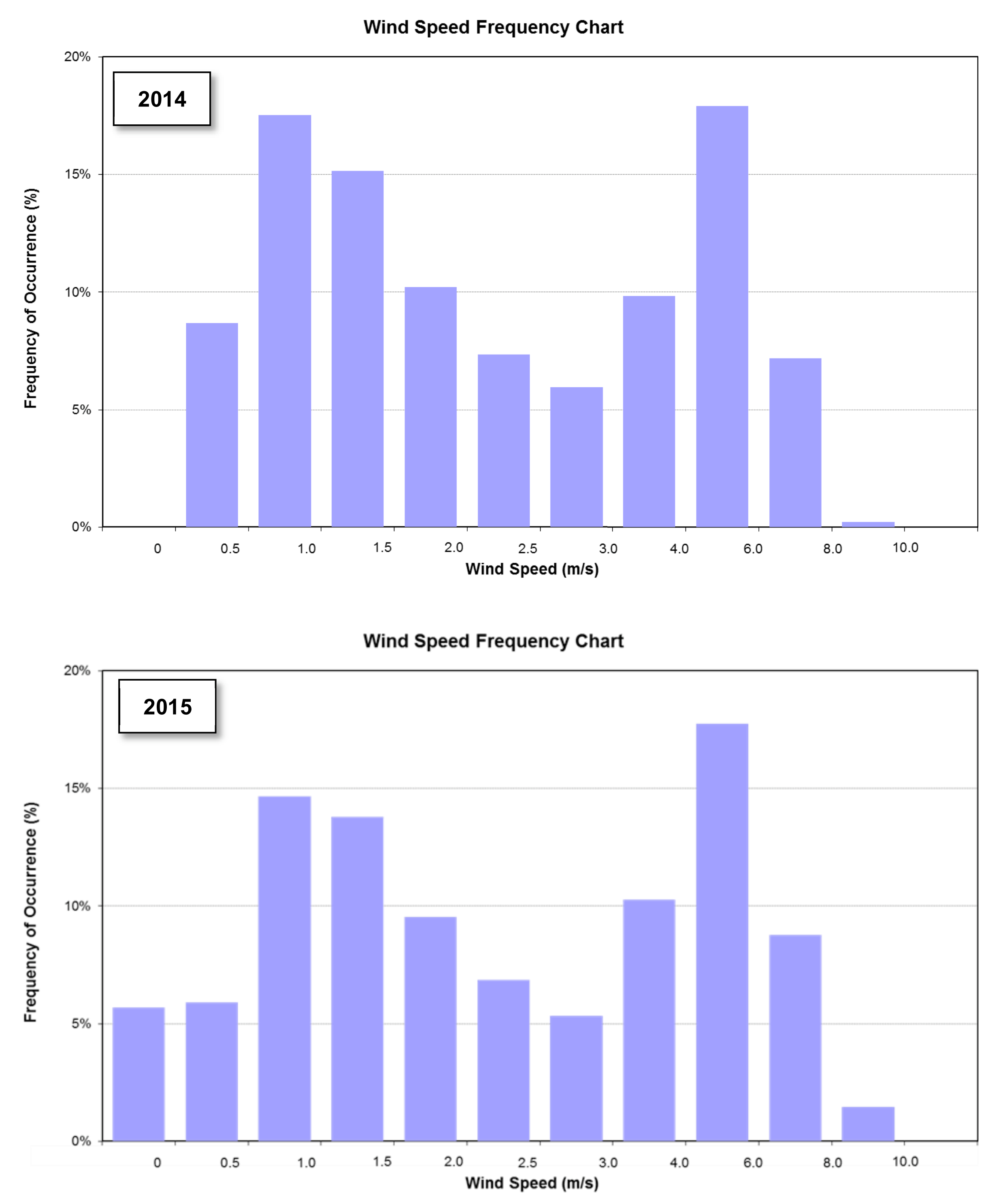
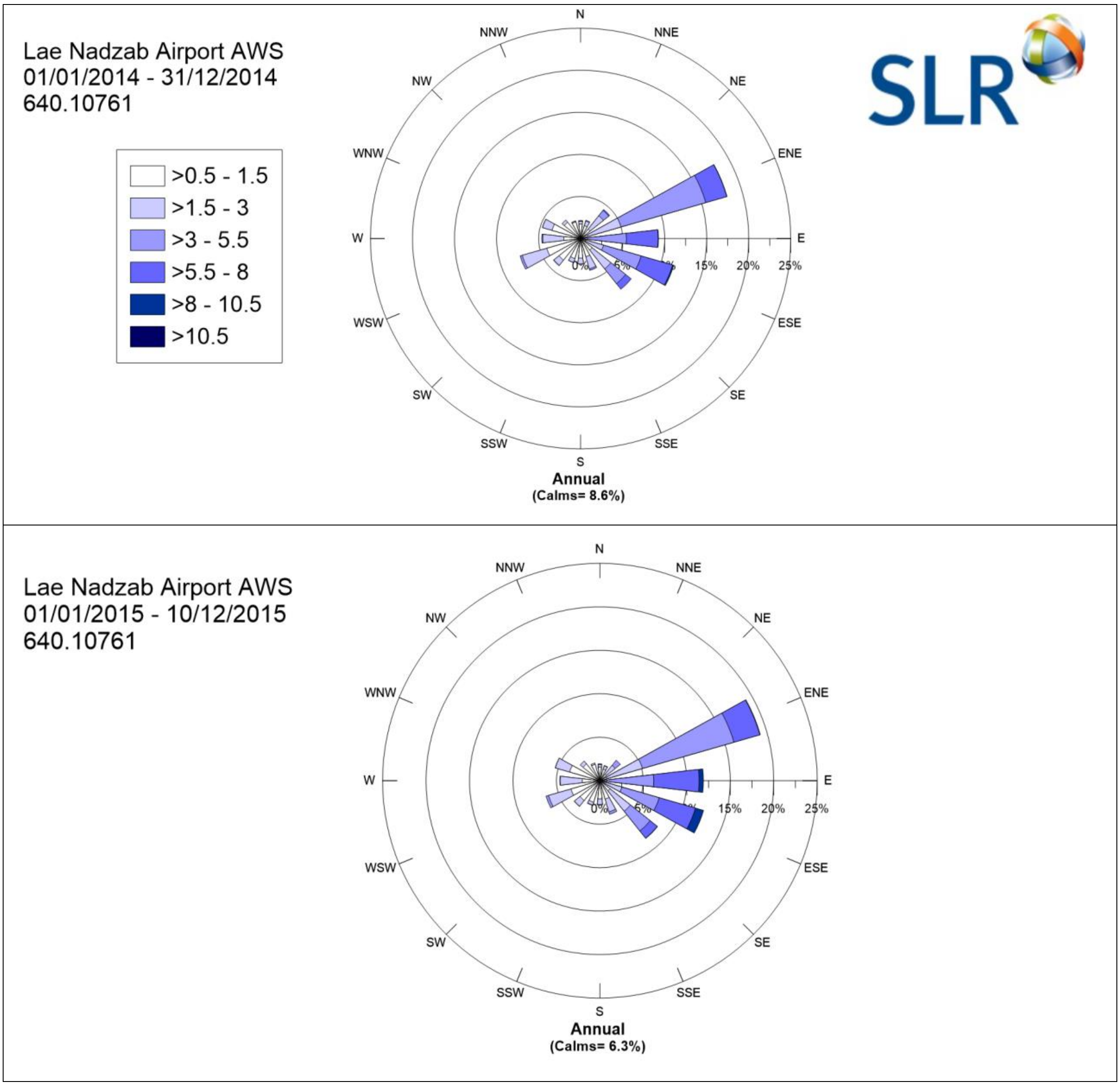


Figure 7 Annual Wind Rose – Lae Nadzab Airport, 2014 and 2015



3.4 Existing Air Quality

A baseline ambient air quality monitoring program has not been conducted for the Project.

As the site is remote from existing industrial pollution sources, the existing ambient air quality can be assumed to be generally good with negligible concentrations of gaseous pollutants. Background levels of particulate matter are also expected to be low given the relatively high rainfall however they would not be negligible. Potentially significant sources of background particulate matter include both natural sources (e.g. wind erosion, pollens) and anthropogenic activities (e.g. cooking fires, unsealed roads used for forestry operations, generators (if used), and agricultural activities). In particular, the use of firewood for cooking fires and local grass burning are potentially significant sources of exposure to air pollutants for the local population. During peak flowering times for surrounding vegetation, pollen levels could be elevated. There is also potential for significant events, such as a volcanic eruption, to affect air quality across large areas of the Asia-Pacific region, including the Project site, however this would be very rare. Wildfires are also rare, but have occurred in the past during dry El Niño years, caused by agricultural fires for land clearing burning out of control (NASA, 2009).

The air quality impact assessment has used a computer-based dispersion model to estimate the ground-level concentrations of air emissions associated with the operation of the power plant. These emissions can reasonably be assumed to be released into a pristine environment, with the existing concentrations of gaseous pollutants associated with wood combustion (i.e., nitrogen dioxide (NO_2), sulfur dioxide (SO_2) and carbon monoxide (CO)) assumed to be negligible.

Data are not available regarding background concentration of volatile organic compounds (VOCs), which will also be emitted by the power plant. There will be natural sources of VOCs present in the region surrounding the Project site, in particular emissions of isoprene, monoterpenes and the short-chained carbonyls formaldehyde, acetaldehyde and acetone from vegetation. This assessment has assessed the potential VOC emissions from the power plant based on the worst case assumption that all VOC emissions are in the form of benzene, as this compound has the most stringent ambient air quality criteria. Background concentrations of benzene at the Project site can be assumed to be negligible given the absence of local industrial sources or significant levels of traffic emissions.

The air quality impact assessment prepared by Holmes Air Sciences (HAS) in 2009 for the upstream components of the Papua New Guinea Liquefied Natural Gas Project (PNG LNG Project) has been reviewed (HAS, 2009). The upstream development components of this project included the construction and recompletion of wells, and construction of a gas gathering system and gas conditioning plant in the Hides Gas Field, some 430 km west-northwest of the proposed power plant site.

The HAS air quality impact assessment states:

> *"There are no ambient air quality monitoring data to establish existing levels of air pollutants. The project areas are remote from existing industrial pollution sources except those that are part of the existing facilities or those very closely related to these, for example the existing power station at the Hides Gas Plant that supplies power to the Porgera Project. The approach used in the current assessment uses a computer-based dispersion model to estimate the ground-level concentrations of emissions including those from the existing sources as well as the new sources. These are collectively assumed to be released into a pristine environment where the existing concentrations of gaseous pollutants are taken to be negligible."*

For the assessment of potential cumulative impacts on ambient particulate concentrations during the construction period, the HAS air quality impact assessment noted the following:

> *"Background PM_{10} levels have not been measured in this area, but based on local land use are estimated to be less than 20 µg/m^3 (annual average) and less than 30 to 40 µg/m^3 (24-hour average) except when affected by smoke from fires."*

The air quality impact assessment prepared for the Hidden Valley Gold Mine in 2004, which is located approximately 100 km south of the proposed power plant site, was also reviewed (RHA, 2004). This study also did not include a baseline air quality monitoring program. Instead the background concentrations of particulate levels were conservatively estimated based on ambient monitoring data from rural areas in Western Australia. A 24-hour average background PM_{10} concentration of 20 µg/m^3 was used and background concentrations of NO_2 and SO_2 were assumed to be negligible due to the absence of any industry or other anthropogenic sources in the area.

Consistent with other air quality impact assessments performed in the region, background concentrations of particulate matter have been estimated by SLR as shown in **Table 4** based our experience in the collection and review of PM_{10} and $PM_{2.5}$ monitoring data and with consideration given to the local land use and rainfall in the Project area.

Table 4 Estimated Background Particulate Concentrations

Pollutant	Averaging Period	Assessment Criterion (µg/m³)	Expected Range (µg/m³)	Background Concentration Assumed (µg/m³)
PM_{10}	24-hours	50	5 – 35	25
	Annual	20	10 – 20	15
$PM_{2.5}$	24-hours	25	2 – 20	15
	Annual	10	5 – 10	8

4 IDENTIFICATION OF AIR EMISSION SOURCES

4.1 Construction Phase

The main emissions to air from the construction phase of the Project are expected to include:

- Particulate matter from site preparation and ground works such as those associated with clearing and grading the power plant, log yard and nursery sites and clearing the plantation area, the construction of the power plant and the establishment of access roads, services and temporary structures, construction of the transmission lines and preparation of the plantation area; and
- Products of combustion (including NO_X, CO, carbon dioxide (CO_2), SO_2, VOCs and particulate matter) from diesel-powered construction equipment such as trucks, excavators, bulldozers, and stationary plant/machinery etc.

Emissions from the construction of roads would be transient in nature as the works progress and any localised impacts would be short term. The other emission sources would be more static, however the emission rates would vary significantly with time, depending upon the construction stage and the associated activity levels.

In addition to the main emission sources identified above, there would also be:

- Products of combustion (NO_X, CO, CO_2, SO_2, VOCs and particulate) from the transport of workers (aircraft, passenger buses and light vehicles); and
- VOCs from the storage and transfer of diesel, fertilisers and other bulk chemical storage.

4.2 Operational Phase

The main emissions to air during the operational phase of the Project would be:

- Particulate matter from fuel preparation (chipping, grading, etc.) and the operation of the biomass-fuelled power plant;
- Products of combustion from the operation of the biomass-fuelled power plant; and
- Products of combustion from diesel-powered equipment such as trucks etc. operating at the power plant.

In addition to the main operational-phase emission sources identified above, there would also be:

- Particulate matter and products of combustion from vehicles travelling along the unsealed access roads (including trucks transporting wood to the power plant);
- Fugitive particulate matter and products of combustion from the establishment of up to 4,500 ha/year of plantation area and harvesting of timber;
- Products of combustion from the transport of workers (passenger buses and light vehicles); and
- VOCs from stored biomass fuel, supplementary support fuels (if present) and diesel/petrol required for other fixed and mobile plant.

4.3 Assessment Methodology

As noted in **Section 1.1**, this air quality impact assessment has been performed using a mixture of quantitative and qualitative assessment techniques. Key Project activities that have the greatest potential for impacts on local air quality have been assessed quantitatively through the estimation of emission loads and an atmospheric dispersion modelling study. Activities with a much lower potential for impacts on local air quality were assessed qualitatively, ensuring that adequate separation distances exist between the activity and the nearest sensitive receptors based on recommended guidelines set by Australian regulatory agencies for specific types of activities, and by using the Institute of Air Quality Management's (IAQM) screening criteria.

Table 5 presents a summary of the facilities and air emission sources which have been assessed for this Project, in addition to the method of assessment.

Table 5 Summary of Air Quality Assessment Methodology

Project Site	Phase	Facilities/ Air Emission Sources	Prediction/ Assessment Method	Scenario
Power Plant	Construction	Site preparation and ground works, general construction of the power plant and associated infrastructure.	Qualitative	-
	Operation	Operation of the power plant and associated infrastructure, including truck movements from plantations to power plant.	3D CALPUFF modelling	Worst Case
Plantation / Nursery	Construction	Upgrading or establishing road access and site preparation, ground works and construction of the 9.58 ha plant nursery	Qualitative	-
	Operation	Establishment (clearing, planting) of up to 4,500 ha/year of plantation area and harvesting of timber.	Qualitative	-

5 IMPACT ASSESSMENT CRITERIA

Regulatory authorities manage air quality through a range of mechanisms, including ambient air quality guidelines and source emission limits.

5.1 Defining Biophysical Environmental Values

A biophysical environmental value is generally defined as a quality or physical characteristic of the environment that is important to ecological health or public amenity. Based on this definition, the key environmental values relating to air emissions are those relating to public health and amenity and include:

- Health of humans;
- Health of other forms of life, including the protection of ecosystems and biodiversity;
- Local amenity and aesthetic enjoyment;
- Visibility; and
- The useful life and aesthetic appearance of buildings, structures, property and materials.

The following impact assessment criteria have been identified for use in this air quality impact assessment to assess the Project's potential impacts on the above biophysical environmental values.

5.2 Overview of Relevant Guidelines

Ambient air quality guidelines or standards relate to the maximum downwind, ground level concentrations that may occur as a result of the emissions and are the recommended maximum concentrations to which the public may be exposed. These criteria are normally based on the results of epidemiological or other health-based studies and are generally designed to protect sensitive populations from adverse health effects, or to prevent damage to sensitive vegetation and crops. When assessing compliance with ambient air quality criteria it is necessary to account for other sources in the area so that the total cumulative impact of all sources is considered.

Source emissions limits are maximum allowable emission concentrations or emission rates which relate to in-stack concentrations at the point of discharge. Emission limits are normally specified for particular source types, such as SO_2 emission rates for sulfuric acid plants, metals emission concentrations for waste incinerators or NO_X emission concentrations for diesel-fired combustion sources, and are generally based on the current best available technology for the relevant equipment.

5.2.1 PNG Environmental Legislation

The *Environment Act 2000* is the primary legislation in PNG which regulates the environmental impact of development activities and how adverse effects of such activities should be avoided, mitigated or remedied. The Environment Act caters for the sustainable management of the biological and physical components of the land, air and water resources of the country.

Several guidelines have also been published by the PNG Conservation and Environment Protection Authority (CEPA, formerly known as the Department of Environment and Conservation), including:

- *Guideline for submission of an application for an environmental permit to discharge waste*. GL-Env/03/2004. These include:
    - Noise discharges. IB-ENV/03/2004;
    - Air discharges. IB-ENV/02/2004; and
    - Water and Land Discharges. IB-ENV/04/2004.

The Technical Guideline (Additional Information) for air discharges sets out the information that should be provided as part of an application for an Environment (Waste Discharge) Permit where air emissions may be generated. This includes:

- Details of the source, nature, composition and rate of air emissions;
- Information on emissions control equipment and proposed methods to limit air discharges (specific information for fabric filters, afterburners and wet scrubbers is requested);
- Maintenance procedures and contingency procedures to avoid air discharges from process failure and shut down;
- Stack emission details;
- Calculated ground level concentrations of pollutants proposed to be discharged to air under normal and maximum operating conditions and start up and shutdown conditions; and
- An assessment of the impact of the proposal on the environment.

PNG does not currently have any statutory air quality standards. A review of relevant air quality criteria and guidelines set by a number of agencies has therefore been performed in the following sections, including:

- International Finance Corporation (IFC) EHS guidelines; and
- World Health Organization (WHO) Air Quality Guidelines.

The objective of this review was to identify appropriate criteria to use in the assessment in the absence of PNG-specific guidelines or similar. The guidelines used are presented in **Section 5.3**, while details of the review performed are provided in **Sections 5.2.2** and **5.2.3**.

5.2.2 IFC Assessment Requirements

Environmental, Health and Safety General Guidelines: Environmental – Air Emissions and Ambient Air Quality

The International Finance Corporation (IFC) *Environmental, Health and Safety Guidelines: Environmental – Air Emissions and Ambient Air Quality* (IFC, 2007) provides an approach to the management of significant sources of air emissions, including specific guidance for assessment and monitoring of impacts. This guideline states that:

> *"Where possible, facilities and projects should avoid, minimize, and control adverse impacts to human health, safety, and the environment from emissions to air. Where this is not possible, the generation and release of emissions of any type should be managed through a combination of:*
>
> - *Energy use efficiency*
> - *Process modification*
> - *Selection of fuels or other materials, the processing of which may result in less polluting emissions*
> - *Application of emissions control techniques"*

The IFC EHS General Guidelines – Air Emissions and Ambient Air Quality (IFC, 2007) require that impacts on air quality of a proposed development be estimated through qualitative or quantitative assessments by the use of baseline air quality assessments and atmospheric dispersion models to assess potential ground level concentrations. Local atmospheric, climatic, and air quality data should be applied when modelling plume dispersion, taking into account atmospheric downwash, wakes, or eddy effects of the source, nearby structures and terrain features.

In addition, projects with significant sources of air emissions, and potential for significant impacts to ambient air quality, should prevent or minimise impacts by ensuring that:

- Emissions do not result in pollutant concentrations that reach or exceed relevant ambient quality guidelines and standards by applying national legislated standards or, in their absence, the current World Health Organization (WHO) Air Quality Guidelines, or other internationally recognized sources; and
- Emissions do not contribute a significant portion to the attainment of relevant ambient air quality guidelines or standards (as a general rule, the guideline suggests 25% of the applicable air quality standards to allow additional, future sustainable development in the same airshed).

Environmental, Health and Safety Guidelines for Thermal Power Plants

The IFC industry sector EHS Guideline Document for Thermal Power Plants (IFC, 2008) is designed to be used together with the General EHS Guidelines document and provide general and industry-specific examples of Good International Industry Practice. This document notes that principal air emissions sources from thermal power plants includes combustion processes fueled by gaseous, liquid and solid fossil fuels and biomass, designed to deliver electrical or mechanical power, steam, heat, or any combination of these, regardless of the fuel type.

The EHS Guideline Document for Thermal Power Plants (IFC, 2008) specifies emissions guidelines applicable to facilities with a total heat input capacity of greater than 50 MWth. For facilities with a total heat input capacity of less than 50 MWth, which would apply to this Project, reference is made to the emission limits set out in the General EHS Guidelines document. However, MVB have committed to meeting the more stringent emission guidelines for solid fuel boilers specified in the Guideline Document for Thermal Power Plants for facilities between 50 and 600 MWth in capacity. Both sets of emission limit values are presented in **Table 6**.

Table 6 IFC Emissions Guidelines for Solid Fuel Boilers

Pollutant	**Maximum In-Stack Concentration (mg/Nm^3 dry gas basis, 6% O_2)**	
	Thermal Power Plants (>50 <600 MW) (Non-degraded airshed)	**General EHS Guidelines (<50 MW)**
Particulate matter	50	50 or up to 150 if justified by assessment
Nitrogen oxides	510 [a]	650
Sulfur dioxide	900 – 1,500 [b]	2,000

Notes:
a. Stoker boilers may require different emissions values which should be evaluated on a case-by-case basis through the EA process.
b. Targeting the lower guidelines values and recognizing issues related to quality of available fuel, cost effectiveness of controls on smaller units, and the potential for higher energy conversion efficiencies (Fuel Gas Desulfurization (FGD) may consume between 0.5% and 1.6% of electricity generated by the plant).

5.2.3 World Health Organization

The first edition of the WHO air quality guidelines was issued in 1987 and was intended for European countries. By 2000, research concerning health effects of air pollution had significantly advanced to enable the WHO to update its guideline resulting in the publication of *Air Quality Guidelines for Europe, Second Edition* (WHO, 2000). In this edition the guidelines were no longer presented as European-specific, but applied to all countries.

In 2005, WHO issued the *Air Quality Guideline - Global Update – Particulate Matter, Ozone, Nitrogen Dioxide and Sulphur Dioxide* (WHO, 2005), which updated their recommended ambient air quality guidelines for PM_{10} and SO_2 based on current research. Interim targets were also provided by the WHO in recognition of the need for a staged approach to achieving the new recommended guidelines. The updated guidelines and interim targets are presented in **Table 7**.

Table 7 WHO Air Quality Guidelines, Global Update 2005

Pollutant	Averaging Time	Interim Target 1 (µg/Nm^3)	Interim Target 2 (µg/Nm^3)	Interim Target 3 (µg/Nm^3)	Guideline Value (µg/Nm^3)
Nitrogen dioxide	1-hour	-	-	-	200
	1-Year	-	-	-	40
Sulfur dioxide	10-minutes	-	-	-	500
	24-hours	125	50	-	20
PM_{10}	24-hours	150	100	75	50
	1-Year	70	50	30	20
$PM_{2.5}$	24-hours	75	50	37.5	25
	1-Year	35	25	15	10

Guidelines for other substances relevant to this Project from the WHO's *Air Quality Guidelines for Europe, Second Edition* (WHO, 2000) are presented in **Table 8**.

Table 8 WHO Air Quality Guidelines for Europe, 2000

Pollutant	Averaging Time	Guideline (µg/m^3)	Notes
Benzene	Annual	0.17	Excess lifetime risk level of 1:1,000,000.
		1.7	Excess lifetime risk level of 1:100,000.
		17	Excess lifetime risk level of 1:10,000.
Carbon Monoxide	1-hour	30,000	
	24-hours	10,000	

5.2.4 Forest Stewardship Council

As the Project involves forest management, this air quality assessment has also been performed with reference to Principle 6 of the National Forest Management Standards for Papua New Guinea, v1.1 2010 (Forest Stewardship Council , 2010) which refers to management of Environmental Impact:

> *Forest management shall conserve biological diversity and its associated values, water resources, soils and unique and fragile ecosystems and landscapes and, by so doing, maintain the ecological functions and the integrity of the forest.*

Reference is made to associated FSC 'International Generic Indicators' guidelines (Forest Stewardship Council, 2015) which provide further detail in regards to this principle as follows:

> *6.2 Prior to the start of site-disturbing activities, the [proponent] shall identify and assess the scale, intensity and risk of potential impacts of management activities on the identified environmental values;*
>
> *[..]*
>
> *6.3 The [proponent] shall identify and implement effective actions to prevent negative impacts of management activities on the environmental values, and to mitigate and repair those that occur, proportionate to the scale, intensity and risk of these impacts.*
>
> *[..]*

6.4 The [proponent] shall protect rare species and threatened species and their habitats [in the study area[2]] through conservation zones, protection areas, connectivity and/or (where necessary) other direct measures for their survival and viability. These measures shall be proportionate to the scale, intensity and risk of management activities and to the conservation status and ecological requirements of the rare and threatened species.

The [proponent] shall take into account the geographic range and ecological requirements of rare and threatened species beyond the boundary of the [study area], when determining the measures to be taken inside the [study area].

Principle 6 refers to both human residents as well as local fauna, and both can be adversely impacted by excessive air emissions. It is important to note that this principle is not objective but requires application of the best available information. Accordingly, the standard for assessment is here considered to be in line with other international guidelines for air quality impact assessments, such as those listed in the above subsections.

5.3 Air Quality Criteria Adopted for this Assessment

The ambient air quality criteria adopted for use in this study are summarised below in **Table 9**.

Table 9 Ambient Air Quality Criteria Adopted for this Assessment

Pollutants	Averaging Period	Limit (µg/m^3)	Source
NO_2	1-hour	200	(WHO, 2005)
	Annual	40	(WHO, 2005)
SO_2	10-Minutes	500	(WHO, 2005)
	24-hours	20	WHO, 2005
CO	1-hour	30,000	(WHO, 2000)
	24-hours	10,000	(WHO, 2000)
PM_{10}	24-hours	50	(WHO, 2005)
	Annual	20	(WHO, 2005)
$PM_{2.5}$	24-hours	25	(WHO, 2005)
	Annual	10	(WHO, 2005)
Benzene	Annual	0.17	(WHO, 2005)

[2] Defined by the FSC as the spatial area or areas submitted for FSC certification with clearly defined boundaries managed to a set of explicit long term management objectives which are expressed in a management plan. This area or areas include(s): all facilities and area(s) within or adjacent to this spatial area or areas under legal title or management control of, or operated by or on behalf of the proponent, for the purpose of contributing to the management objectives; and all facilities and area(s) outside, and not adjacent to this spatial area or areas and operated by or on behalf of the proponent, solely for the purpose of contributing to the management objectives.

6 ATMOSPHERIC DISPERSION MODELING METHODOLOGY

6.1 Scenarios Modelled

As outlined in **Section 4** and **Table 5**, emissions to air from operation of the power plant have been assessed quantitatively using air dispersion modelling. As discussed in **Section 2.1.2**, the biomass power plant includes two 15 MW power plant modules each of which consist of one biomass boiler and one steam turbine generator. One emissions scenario has been modelled, which is defined as the maximum peak load for the power plant of 30 MW.

In addition, fugitive particulate matter emissions associated with the operation of the power plant have been included in this modelling scenario. These emission sources include on-site (within the boundary of the power plant site) movement of trucks transporting logs to the power plant and carting fly ash off-site for re-use.

6.2 Modelling Methodology

6.2.1 CALPUFF

Emissions from the Project have been modelled using the USEPA's CALPUFF (Version 6.267) modelling system.

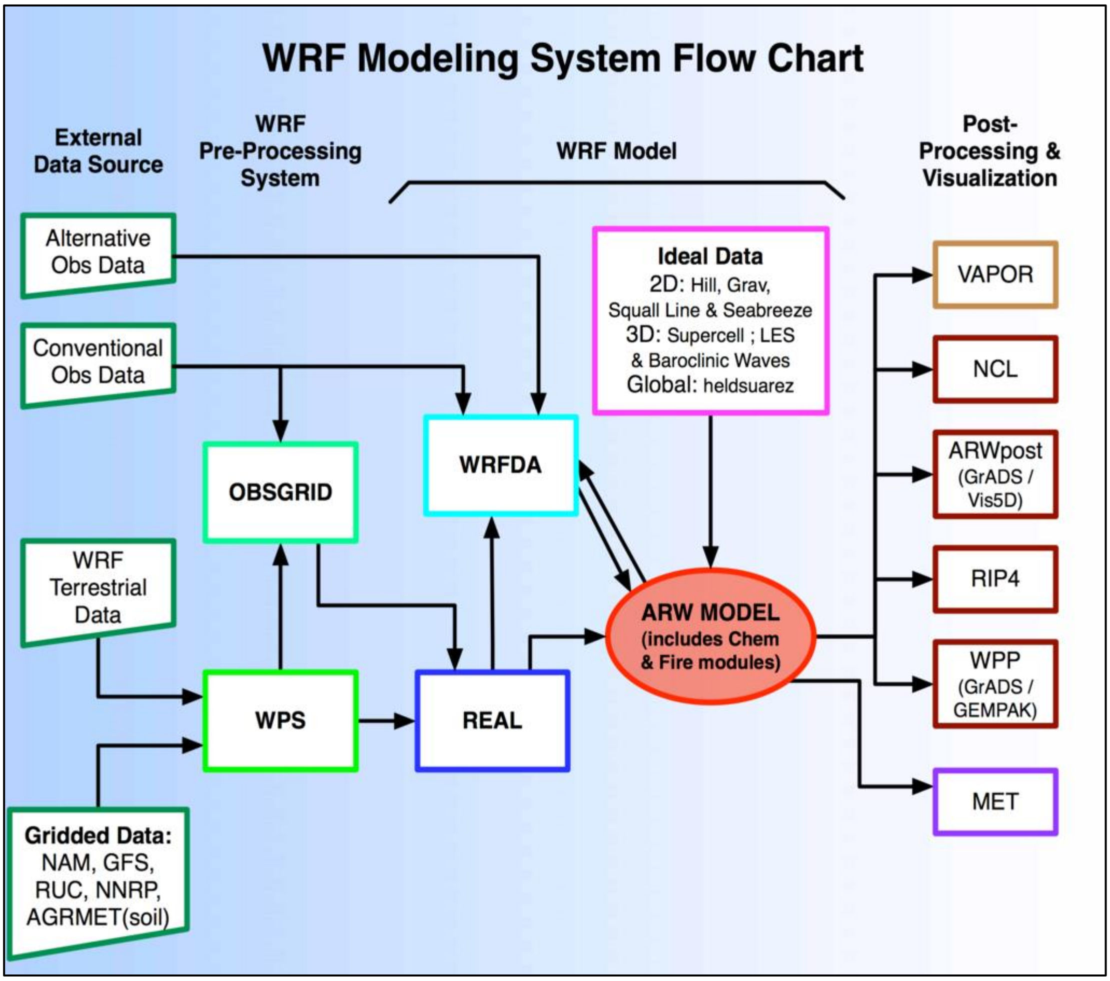
CALPUFF is a transport and dispersion model that advects "puffs" of material emitted from modelled sources, simulating dispersion and transformation processes along the way. In doing so it typically uses the fields generated by a meteorological pre-processor CALMET, discussed further below. Temporal and spatial variations in the meteorological fields selected are explicitly incorporated in the resulting distribution of puffs throughout a simulation period. The primary output files from CALPUFF contain either hourly concentration or hourly deposition fluxes evaluated at selected receptor locations. The CALPOST post-processor is then used to process these files, producing tabulations that summarize results of the simulation for user-selected averaging periods.

The CALPUFF model requires hourly temperature, wind and other meteorological data on a three-dimensional gridded modelling domain that are required as inputs. For this study the meteorological data inputs have been compiled using the Weather Research and Forecast (WRF) and CALMET meteorological models as described below.

6.2.2 Weather Research and Forecast Model (WRF)

The WRF model is a mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting needs. The model serves a wide range of meteorological applications, across scales from tens of meters to thousands of kilometres. A brief overview of the WRF modelling system is presented in **Figure 8**.

Figure 8 WRF Modelling System Flowchart



Source: (UCAR, 2016)

For this assessment, the WRF modelling system was used to produce the meteorological field required as an input to the CALMET meteorological model over the domains shown in **Figure 9**. Parameters used in the WRF model for this assessment are presented in **Table 10**. Modelling was performed for the 2015 calendar year as discussed in **Section 3.3.3**).

Figure 9 WRF Modelling Domains

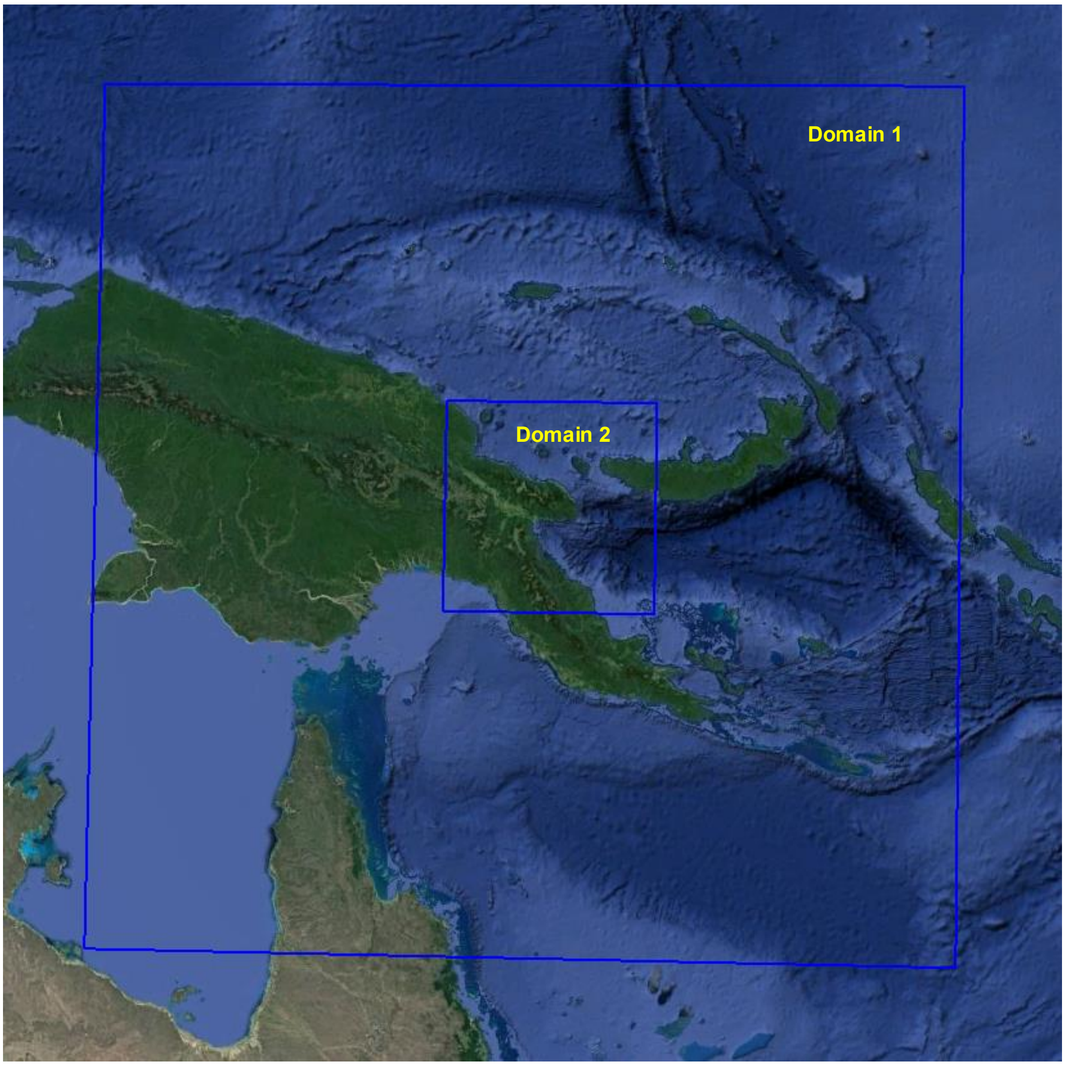


Table 10 Meteorological Parameters used for this Study (WRF)

Parameter	Domain 1	Domain 2
Modelling domain	2,100 km × 2,100 km	490 km × 490 km
Grid resolution	30 km	10 km
Number of vertical levels	30	30
Microphysics	WSM6	WSM6
Cumulus parametrisation	Kain-Fritsch	Kain-Fritsch
Shortwave radiation physics	Dudhia	Dudhia
Longwave radiation physics	RRTM	RRTM
Planetary boundary layer	YSU	YSU

6.2.3 CALMET

In the simplest terms, CALMET is a meteorological model that develops hourly wind and other meteorological fields on a three-dimensional gridded modelling domain that are required as inputs to the CALPUFF dispersion model. Associated two-dimensional fields such as mixing height, surface characteristics and dispersion properties are also included in the file produced by CALMET. The interpolated wind field is then modified within the model to account for the influences of topography, sea breeze (where relevant), as well as differential heating and surface roughness associated with different land uses across the modelling domain. These modifications are applied to the winds at each grid point to develop a final wind field. The final hourly varying wind field thus reflects the influences of local topography and land uses.

CALMET modelling was conducted using the nested CALMET approach, where the final results from a coarse-grid run were used as the initial guess of a fine-grid run to generate three dimensional meteorological data for the power plant and its surrounding areas. This has the advantage that off-domain terrain features including slope flows and blocking effects can be allowed to take effect and the larger-scale wind flow provides a better start in the fine-grid run.

The outer domain was modelled with a resolution of 3 km. WRF-generated three-dimensional meteorological data were used as the initial-guess wind field and local topographical and land use information were used to refine the wind field predetermined by the WRF output. Available meteorological data recorded at the nearest meteorological station (Lae Nadzab Airport) were entered into the CALMET model as an observed dataset to refine the model prediction.

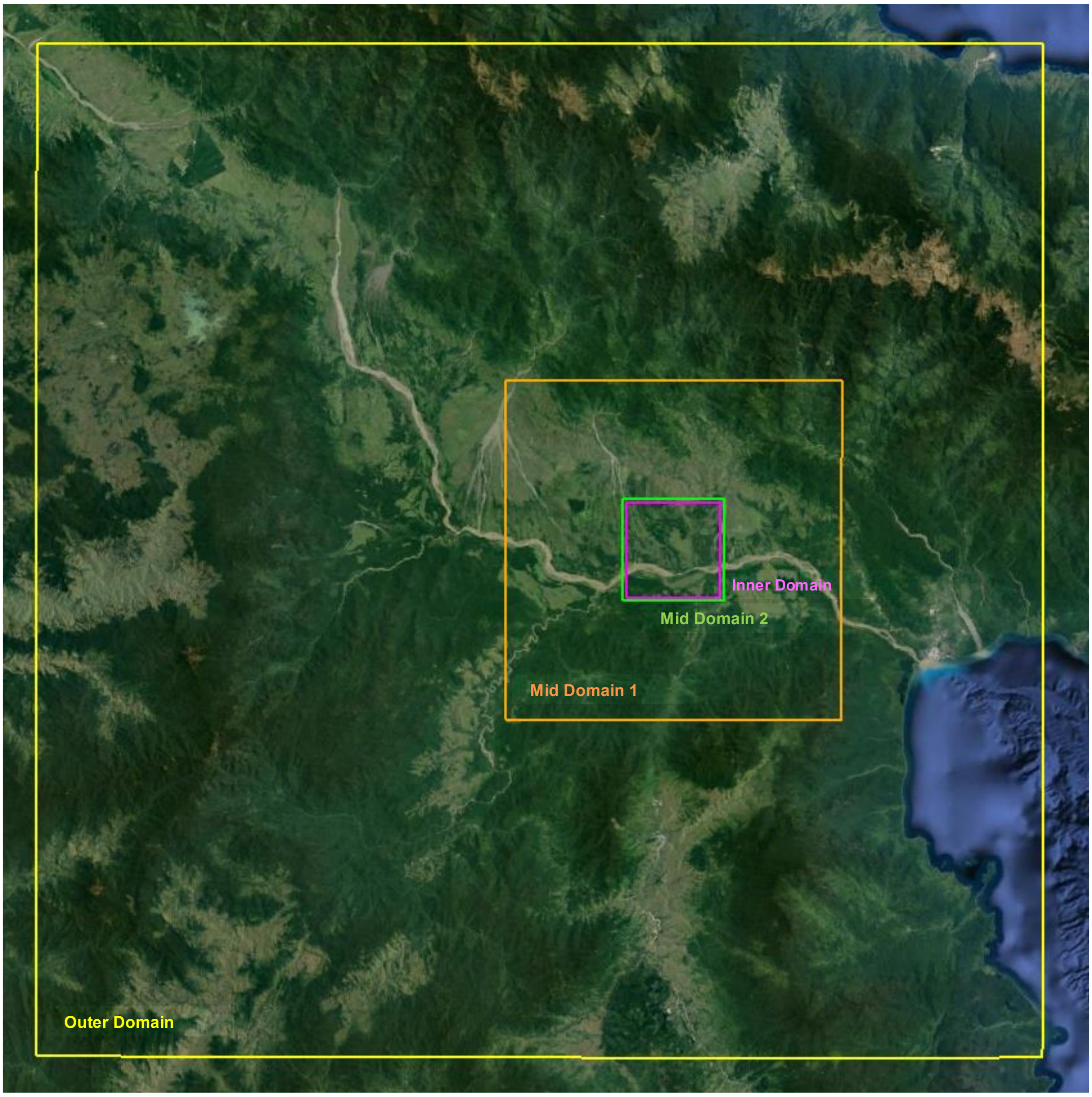
The output from the outer domain CALMET modelling was then used as the initial-guess field for the mid and inner domain CALMET modelling. A horizontal grid spacing of 1 km, 0.3 km and 0.1 km were used in the two mid and inner domains to adequately represent the important local terrain features and land use. Fine-scale local topographical and land use information were used in the inner domain run to refine the wind field parameters predetermined by the coarse CALMET runs.

Table 11 details the parameters used in the meteorological modelling to drive the CALMET model, while the extents of the model domains are illustrated in **Figure 10**.

Table 11 Meteorological Parameters used for this Study

Meteorological Modelling Parameters	Project Site
Outer Domain	
Meteorological grid	150 km × 150 km
Meteorological grid resolution	3 km
Initial guess filed	3D output from WRF model
Mid Domain 1	
Meteorological grid	50 km × 50 km
Meteorological grid resolution	1 km
Initial guess field	3D output from outer domain modelling
Mid Domain 2	
Meteorological grid	15 km × 15 km
Meteorological grid resolution	0.3 km
Initial guess field	3D output from mid domain 1 modelling
Inner Domain	
Meteorological grid	14 km × 14 km
Meteorological grid resolution	0.1 km
Initial guess field	3D output from mid domain 2 modelling

Figure 10 CALMET Modelling Domains



6.3 Meteorological Data Used in Modelling Study

A summary of the meteorological dataset derived using the methodology described in **Section 6.2** and used in CALPUFF for the air quality assessment is provided in the following sections.

6.3.1 Wind Speed and Direction - Power Plant Site

A summary of the annual wind behaviour predicted at the power plant site for 2015 is presented as a frequency distribution plot in **Figure 11** and as a wind rose plot in **Figure 12**. The annual wind rose indicates that the prevailing wind directions are from the east and west-southwest. Calm conditions were predicted to occur 12% of the time. Wind speeds are light to moderate in nature, ranging between 0.5 m/s and 8 m/s.

Figure 11 Frequency of Wind Speed as Predicted by CALMET (2015) – Power Plant Site

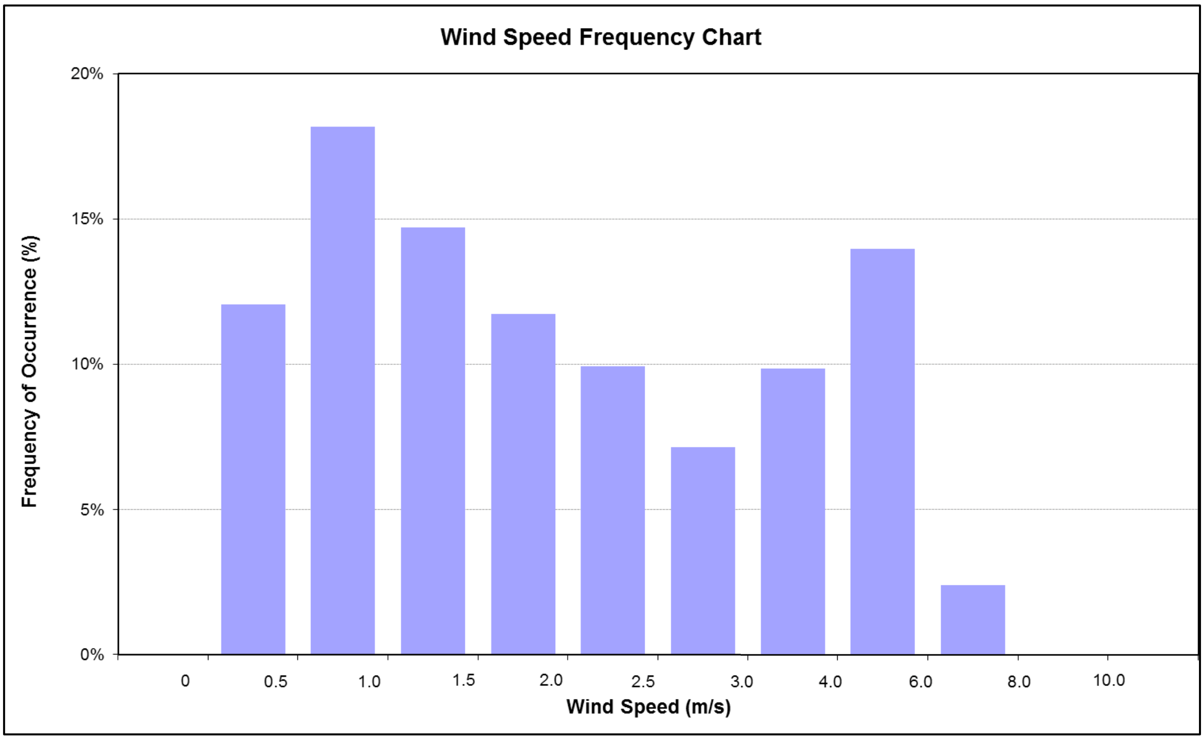
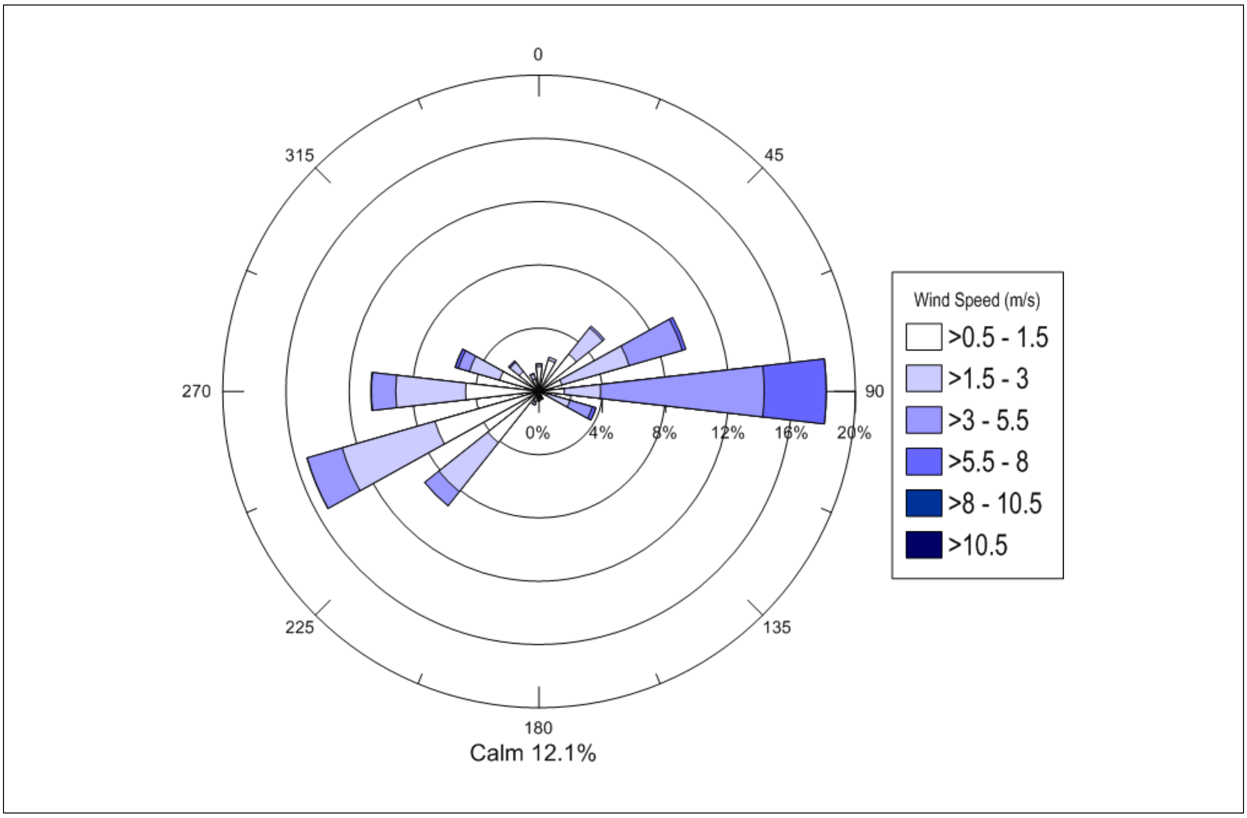


Figure 12 Annual Wind Rose as Predicted by CALMET (2015) – Power Plant Site

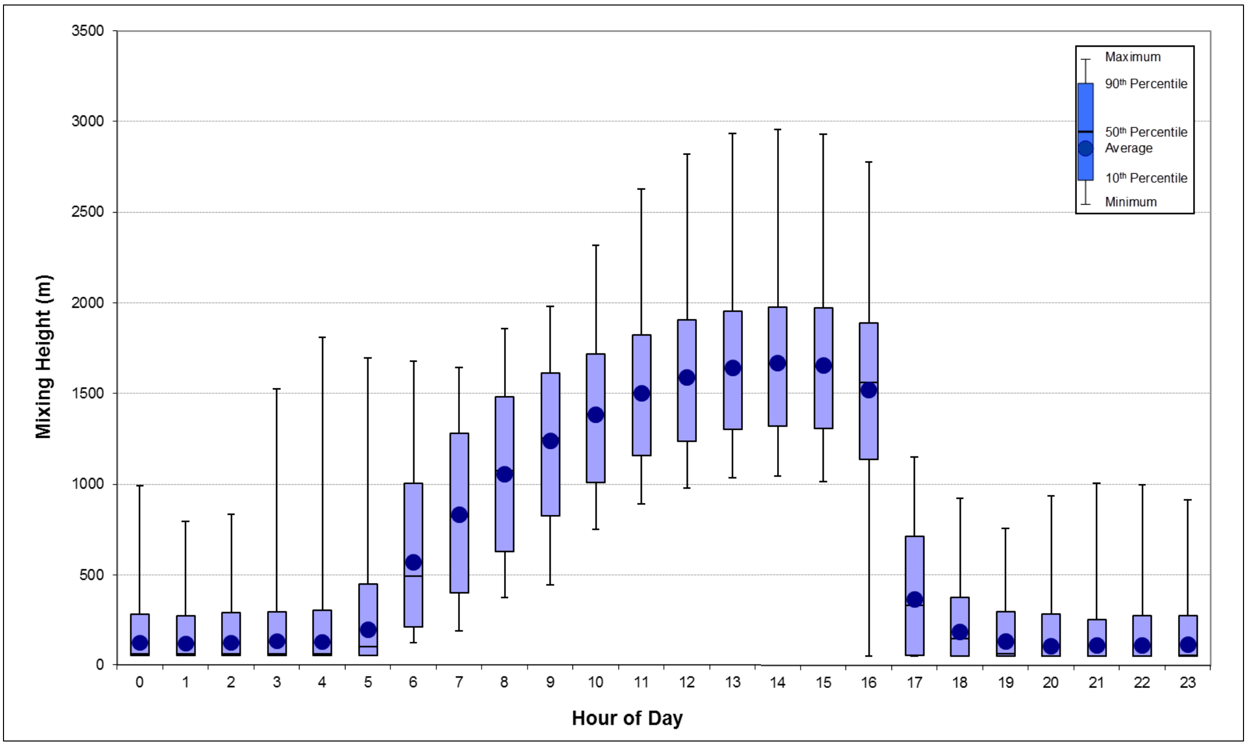


6.3.2 Mixing Height

A summary of the mixing height profiles predicted at the power plant site for 2015 is shown in **Figure 13**.

As would be expected, an increase in the mixing height during the morning is apparent, arising due to the onset of vertical mixing following sunrise. Maximum mixing heights occur in the mid to late afternoon, due to the dissipation of ground-based temperature inversions and the growth of the convective mixing layer.

Figure 13 Mixing Height Profiles as Predicted by CALMET (2015) – Power Plant Site



6.3.3 Atmospheric Stability

Atmospheric stability refers to the tendency of the atmosphere to resist or enhance vertical motion. The Pasquill-Turner assignment scheme identifies six Stability Classes, A to F, to categorize the degree of atmospheric stability as follows:

- A = Extremely unstable conditions
- B = Moderately unstable conditions
- C = Slightly unstable conditions
- D = Neutral conditions
- E = Slightly stable conditions
- F = Moderately stable conditions

The meteorological conditions defining each Pasquill stability class are shown in **Table 12**.

Table 12 Meteorological Conditions Defining Pasquill Stability Classes

Surface wind speed (m/s)	Daytime insolation			Night-time conditions	
	Strong	Moderate	Slight	Thin overcast or > 4/8 low cloud	<= 4/8 cloudiness
< 2	A	A - B	B	E	F
2 - 3	A – B	B	C	E	F
3 - 5	B	B - C	C	D	E
5 - 6	C	C - D	D	D	D
> 6	C	D	D	D	D

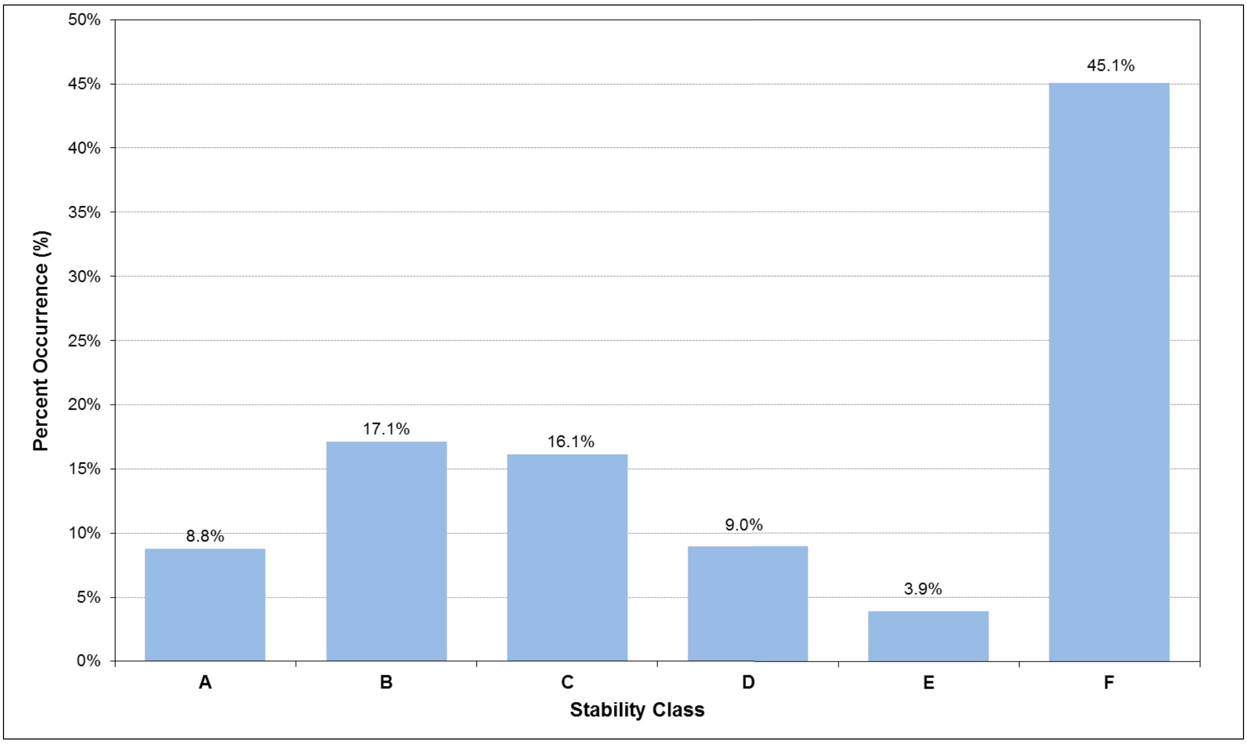
(Source: (Pasquill, 1961))

Notes:

1. Strong insolation corresponds to sunny midday in midsummer in England; slight insolation to similar conditions in midwinter.
2. Night refers to the period from 1 hour before sunset to 1 hour after sunrise.
3. The neutral category D should also be used, regardless of wind speed, for overcast conditions during day or night and for any sky conditions during the hour preceding or following night as defined above.

The frequency of each stability class predicted by CALMET during the modelling period, extracted at the Project site, is presented in **Figure 14**. The results indicate a high frequency of conditions typical to Stability Class F. These conditions represent a stable atmosphere and occur during night-time, when wind speeds are low.

Figure 14 Stability Class Distributions at the Project Site as Predicted by CALMET (2015)



6.4 Topographical and Land Use Data

Terrain information covering the model domains was sourced from the United States Geological Services Shuttle Radar Topography Mission data set (NASA, 2000) which has an approximate 90 m resolution. Land use data was estimated from aerial imagery using land use categories outlined by TRCs Atmospheric Study Group (TRC ASG, 2011).

6.5 Building Wake Effects

Building wake effects impact the dispersion of pollutants at near-field receptors. The emissions associated with the operation of the Project are point source emissions. These source types are subject to plume downwash effects associated with building wakes.

Given the nearest sensitive receptors are in close proximity to the point sources associated with the power plant, building wake effects have been included in the modelling.

6.6 Modelling of NO_X Chemistry

NO_X emissions from combustion processes are primarily NO, with only a few volume percent as NO_2. However, once the gases are discharged into the atmosphere, chemical reactions take place which result in the transformation of NO in the plume to NO_2.

There are various methods for estimating NO_2 concentrations from model predictions of NO_X as the plume is emitted from the emission point. For this assessment, maximum off-site ground level NO_2 concentrations were estimated from the downwind NO_X predictions given by CALPUFF using the USEPA's Ozone Limited Method (OLM). The OLM is based on the assumption that approximately 10% of the NO_X emissions are generated as NO_2 (Alberta Environment, 2003). If the ozone (O_3) concentration is greater than 90% of the predicted NO_X concentrations, all the NO_X is assumed to be converted to NO_2, otherwise $NO_2 = 0.1 * NO_X + Min(0.9*NO_X,(46/48)*O_3)$.

A background ozone concentration of 40 ppb (86 µg/m^3) was used in the calculations based on studies that have shown that ambient ozone concentrations in remote locations typically range from 20-40 ppb (CGER, 1991).

6.7 Accuracy of Modelling

Atmospheric dispersion models all represent a simplification of the many complex processes involved in the dispersion of pollutants in the atmosphere. To obtain good quality results it is important that the most appropriate model is used and the quality of the input data (meteorological, terrain, source characteristics) is adequate.

The main sources of uncertainty in dispersion models, and their effects, are discussed below.

- **Oversimplification of physics:** This can lead to both under-prediction and over-prediction of ground level pollutant concentrations. Errors are smaller in puff models such as CALPUFF, which include the effects of non-steady-state meteorology (i.e., spatially- and temporally-varying meteorology).
- **Errors in emission rates:** Ground level concentrations are proportional to the pollutant emission rate. In this study, the modelling is based on emission estimates derived from the use of published emission factors and estimated activity levels for worst case operational activities. In order to address the uncertainty associated with these estimates, conservative assumptions have been made so that the emissions are not under-predicted.
- **Errors in source parameters:** Plume rise is affected by source dimensions, temperature and exit velocity. Inaccuracies in these values will contribute to errors in the predicted height of the plume centreline and thus ground level pollutant concentrations.

- **Errors in wind direction and wind speed**: Wind direction affects the direction of plume travel, while wind speed affects plume rise and dilution of plume. Errors in these parameters can result in errors in the predicted distance from the source of the plume impact, and magnitude of that impact. In addition, aloft wind directions commonly differ from surface wind directions (referred to as "wind shear"). The preference to use rugged meteorological instruments to reduce maintenance requirements also means that light winds are often not well characterised.
- **Errors in mixing height:** If the plume elevation reaches 80% or more of the mixing height, more interaction will occur, and it becomes increasingly important to properly characterize the depth of the mixed layer as well as the strength of the upper air inversion.
- **Errors in temperature:** Ambient temperature affects plume buoyancy, so inaccuracies in the temperature data can result in potential errors in the predicted distance from the source of the plume impact, and magnitude of that impact.
- **Errors in stability estimates:** Gaussian plume models use estimates of stability class, and 3D models use explicit vertical profiles of temperature and wind (which are used directly or indirectly to estimate stability class for Gaussian models). In either case, errors in these parameters can cause either under-prediction or over-prediction of ground level concentrations. For example, if an error is made of one stability class, then the computed concentrations can be off by 50% or more.

USEPA makes the following statement in its Modelling Guideline (USEPA, 2005) on the relative accuracy of models:

> *"Models are more reliable for estimating longer time-averaged concentrations than for estimating short-term concentrations at specific locations; and the models are reasonably reliable in estimating the magnitude of highest concentrations occurring sometime, somewhere within an area. For example, errors in highest estimated concentrations of ±10 to 40% are found to be typical, i.e., certainly well within the often quoted factor-of-two accuracy that has long been recognized for these models. However estimates of concentrations that occur at a specific time and site, are poorly correlated with actually observed concentrations and are much less reliable."*

In summary, modelling of air emissions is subject to a number of sources of uncertainty. The main source of uncertainty for the air dispersion modelling study performed for this Project relates to the pollutant emission rates, which are based on published emission factors and/or manufacturers emission limits. Care has been taken to use conservative assumptions in estimating the emission rates where possible.

7 ESTIMATION OF EMISSIONS TO AIR – POWER PLANT

In order to provide source emissions data for use in the atmospheric dispersion modelling, emissions to air from the power plant have been estimated for the following activities:

- Stack emissions based on the maximum peak load for the power plant of 30 MW;
- Fugitive dust emissions from trucks transporting logs to the power plant and transporting ash off-site.

Based on available information and emission data from literature, the potential for significant dust emissions occurring at the power plant site from the wood chippers, handling and storage of wood chips and bottom ash and wind erosion from exposed areas during operations is minimal. Any emissions generated from these activities are therefore anticipated to be unlikely to result in any significant elevation of the existing particulate levels at offsite locations. Dust emissions from these activities have therefore not been assessed further in this report.

7.1 Boilers

7.1.1 Pollutant Emission Rates

Pollutant emission rates for the two 15 MW boilers have been calculated firstly using World Bank/IFC emission guidelines (refer **Section 5.2.2**) and, where IFC limits are unavailable, emission factors published by USEPA in AP-42 Chapter 1.6 *Wood Residue Combustion in Boilers* (USEPA, 2003). The calculations performed to derive the emission rates listed in **Table 13** are based on the following operational conditions (per boiler):

- Steam generation per boiler of 68 tonnes per hour
- Fuel consumption rate of 28,473 kg/hr
- Fuel moisture content of 50%
- Heat input of 257.8 MMBtu/hr (75.5 MW)

While the Project assumes that the average fuel moisture content will be 35% by weight, the boiler system is designed to fire biomass fuel with a maximum moisture content of 50% by weight. Therefore, the emission rates shown in **Table 13** have been calculated on the emissions generated when firing 50% moisture content biomass fuel to account for the lowest potential biomass fuel heating value (dry basis) and higher ash content. This provides a conservative estimate of the pollutant emissions from the boilers.

It is noted that as the particulate and NO_X emission rates are based on the IFC emission limits for Thermal Power Plants, the emission rates used in the modelling for these pollutants comply with the IFC limits. The IFC emission limit for SO_2 is given as a range of 900 – 1,500 mg/Nm^3 (dry gas basis, 6% O_2) depending upon the quality of available fuel, and the cost effectiveness and energy efficiency of emissions controls (see **Table 6**). The mass emission rate used in the modelling for SO_2 of 3.16 g/s per boiler is equivalent to 132 mg/Nm^3 (dry gas basis, 6% O_2). This is well below the lowest end of the range set by IFC for SO_2 emissions from thermal power plants.

Table 13 Boiler Emission Rates (per boiler)

Pollutant	Emission Factor	Emission Rate		Basis of Emission Factor Used
	(lb/MMBtu)	(kg/hr)	(g/s)	
Total Particulate	0.037	4.3	1.20	Equivalent to the adopted IFC Emission Limit of 50 mg/Nm^3 @ 6% O_2 [1]
PM_{10}	-	3.2	0.89	Calculated using a PM_{10}/TSP emission ratio of 0.74 based on AP-42 emission factors based on use of an ESP (Chapter 1.6, Table 1.6-1)
$PM_{2.5}$	-	2.8	0.77	Calculated using a $PM_{2.5}$/TSP emission ratio of 0.65 based on AP-42 emission factors based on use of an ESP (Chapter 1.6, Table 1.6-1)
NO_X	0.375	43.8	12.18	Equivalent to the adopted IFC Emission Limit of 510 mg/Nm^3 @ 6% O_2 [1]
SO_2	-	11.4	3.16	Calculated based on an average fuel sulfur content of 0.02% [1]
CO	0.600	70.2	19.49	USEPA AP-42 Emission Factor (Chapter 1.6, Table 1.6-2)
VOCs	0.017	2.0	0.55	USEPA AP-42 Emission Factor (Chapter 1.6, Table 1.6-3)

Notes:

1. Biomass Boiler Emissions, (MCB, 2017)

7.1.2 Stack Parameters

Stack parameters are provided for the power plant boilers in **Table 14**.

Table 14 Stack Parameters for the Boilers

Stack Information	Data	Unit
Stack Location[1] UTM Zone 55 coordinates	Stack 1- 460,046 E, 9,270,584 N Stack 2 - 460,067 E, 9,270,584 N	m
Base Elevation[2]	59	m
Stack Height	40	m
Stack Diameter	1.83	m
Exit Temperature[3]	160	°C
Flue Gas Flow Rate[3]	44.6	m³/s
Exit Velocity[3]	24.2	m/s

Notes:

1. Sourced from “Power plant layout with Stack location_MLC markup.pdf”.
2. Sourced from MCB Boiler Performance Data Sheets.
3. Sourced from MCB Boiler Performance Data Sheets. For conservatism, the exit temperature and exhaust gas flowrate associated with 35% fuel moisture content were used in the modelling.

7.1.3 Hours of Operation

The modelling has been performed based on both 15 MW boilers operating 24 hours per day, 365 days per year (8,760 hours per year).

7.2 Fugitive Emissions

Fugitive dust emissions have been estimated for inclusion in the air dispersion modelling, for trucks transporting logs to the power plant and transporting ash off-site. As discussed earlier in this report, the potential for dust emissions from materials handling, wood chipping, conveying woodchips to the boiler, bottom ash handling and wind erosion from exposed areas is likely to be minimal and therefore hasn't been included in the modelling.

Emission rates for fugitive emissions of PM_{10} and $PM_{2.5}$ from truck movements have been calculated using estimated activity rates (i.e., number of truck movements, on-site distance travelled) and USEPA emission factors from AP-42 Section 13.2.2 Unpaved Roads (USEPA, 2006). The estimated emissions are presented in **Table 15**. The fugitive dust emissions presented in **Table 17** were modelled as a series of volume sources spread evenly along the haul road.

It is noted that the latest Project information indicates that the average annual log truck movements from 2020 to 2054 would be 25,400 (each way), including loads to the power plant and loads to the port. The average number of loads to the power plant is forecasted to be approximately 21,000 per annum. This is equivalent to about 58 loads per day which is slightly higher than that assumed for estimating fugitive dust emission rates. Increasing the truck frequency from 50 to 58 movements per day would increase the fugitive PM_{10} and $PM_{2.5}$ emission rates from this source by approximately 16%. Based on a review of the modelling results, an increase in the emission rate from this source of this magnitude would not change the conclusions presented in this report.

Table 15 Estimated Fugitive Dust Emission Rates

Activity	USEPA AP-42 Emission Factor (kg/VKT)		Number of Truck Trips	On-site Distance Travelled	Truck Travel Distance	Estimated Emission Rate (g/s)	
	PM_{10}	**$PM_{2.5}$**	**Trips/day**	**km**	**VKT/day**	**PM_{10}**	**$PM_{2.5}$**
Transport truck - Logs	1.203	0.120	50	1.5	75	0.5	0.1
Transport truck - Ash	0.880	0.088	1	1.5	1.5	0.01	0.001

Notes:

1. VKT = Vehicle Kilometres Travelled
2. Assumes 50% control from level 1 watering (2 L/m^2/hour) of haul roads
3. The haul road silt content was conservatively assumed to be 10%. (USEPA, 2006) states that unpaved road silt contents at lumber sawmills range from 4.8 – 12% with a mean of 8.4%.
4. Average weight of log trucks is 40 tonnes; average weight of ash trucks has been assumed to be 20 tonnes.

8 ATMOSPHERIC DISPERSION MODELLING RESULTS

The results of the operational phase dispersion modelling scenario are presented in the following section.

8.1 Particulate Matter

Table 16 and **Table 17** presents the incremental and cumulative (i.e. including background levels shown in **Section 3.4**) maximum 24-hour average and annual average PM_{10} and $PM_{2.5}$ concentrations predicted at the nearest identified sensitive receptors, based on the stack and emission data detailed in **Section 7**. Contour plots showing the predicted incremental impacts across the modelling domain are included in **Appendix A**.

Table 16 Suspended PM_{10} Concentrations Predicted at Sensitive Receptors

Sensitive Receptor		PM_{10} Ground Level Concentration (µg/m^3)			
		Incremental		Cumulative	
ID	Description	Maximum 24-hour	Annual Average	Maximum 24-hour	Annual Average
R_1[1]	Northern boundary	27.4	9.8	**52.4**	**24.8**
R_2	Outbuilding (no road access)	7.2	1.8	32.2	16.8
R_3	Outbuilding (no road access)	3.9	0.7	28.9	15.7
R_4	Ganef Community Nursery	2.0	0.2	27.0	15.2
R_5	Ganef (hamlet)	1.3	0.2	26.3	15.2
R_6	Mempangnaron	0.2	<0.1	25.2	<16.1
R_7	Furif	0.2	<0.1	25.2	<16.1
R_8	40 Miles	0.2	<0.1	25.2	<16.1
R_9	Markham Farm Aidpost - west (hospital)	0.8	0.2	25.8	15.2
R_10	Markham Farm Aidpost - east (hospital)	0.6	0.2	25.6	15.2
R_11	Markham Farm Elementary School	0.5	0.2	25.5	15.2
R_12	Markham Farm Primary School	0.6	0.2	25.6	15.2
R_13	41 Mile Night Market	0.2	<0.1	25.2	<16.1
R_14	Kaiapit	0.5	0.1	25.5	15.1
R_15	Chivasing Police Station	0.2	<0.1	25.2	<16.1
R_16	Chivasing Aid Post (hospital)	0.2	<0.1	25.2	<16.1
R_17	Chivasing Elementary School	0.2	<0.1	25.2	<16.1
R_18	Chivasing Primary School	0.2	<0.1	25.2	<16.1
R_19	41 Mile Night Market-Residences	0.2	<0.1	25.2	<16.1
R_20	Erap	<0.1	<0.1	<25.1	<16.1
R_21	Arisisi	<0.1	<0.1	<25.1	<16.1
R_22	Erap Primary School	<0.1	<0.1	<25.1	<16.1
R_23	Erap Station Elementary School	<0.1	<0.1	<25.1	<16.1
R_24	Nigassim	<0.1	<0.1	<25.1	<16.1
R_26	Chivasing Elementary School Crew Site	0.1	<0.1	25.1	<16.1
Criteria				**50**	**20**

[1] Represents the worst case impact at site boundary to assess impacts associated with potential in migration but currently is not inhabited.

The incremental PM_{10} concentrations predicted at all sensitive receptors are below the relevant air quality criteria. The cumulative maximum 24-hour average and annual average PM_{10} ground level concentrations predicted at the northern boundary of the site exceed the air quality criteria in a localised area immediately adjacent to the site boundary. Ground level concentrations predicted at this location are up to 53 µg/m^3 as a 24-hour average compared to the criterion of 50 µg/m^3; however, this location is not currently populated.

Table 17 Suspended $PM_{2.5}$ Concentrations Predicted at Sensitive Receptors

Sensitive Receptor		$PM_{2.5}$ Ground Level Concentration (µg/m^3)			
		Incremental		Cumulative	
ID	Description	Maximum 24-hour	Annual Average	Maximum 24-hour	Annual Average
R_1[1]	Northern boundary	3.7	1.2	3.7	9.2
R_2	Outbuilding (no road access)	1.0	0.2	1.0	8.2
R_3	Outbuilding (no road access)	0.7	0.1	0.7	8.1
R_4	Ganef Community Nursery	0.5	<0.1	0.5	<8.1
R_5	Ganef (hamlet)	0.4	<0.1	0.4	<8.1
R_6	Mempangnaron	<0.1	<0.1	<15.1	<8.1
R_7	Furif	0.1	<0.1	0.1	<8.1
R_8	40 Miles	0.1	<0.1	0.1	<8.1
R_9	Markham Farm Aidpost - west (hospital)	0.3	<0.1	0.3	<8.1
R_10	Markham Farm Aidpost - east (hospital)	0.3	<0.1	0.3	<8.1
R_11	Markham Farm Elementary School	0.2	<0.1	0.2	<8.1
R_12	Markham Farm Primary School	0.2	<0.1	0.2	<8.1
R_13	41 Mile Night Market	0.2	<0.1	0.2	<8.1
R_14	Kaiapit	0.5	<0.1	0.5	<8.1
R_15	Chivasing Police Station	0.2	<0.1	0.2	<8.1
R_16	Chivasing Aid Post (hospital)	0.2	<0.1	0.2	<8.1
R_17	Chivasing Elementary School	0.2	<0.1	0.2	<8.1
R_18	Chivasing Primary School	0.2	<0.1	0.2	<8.1
R_19	41 Mile Night Market - Residences	0.1	<0.1	0.1	<8.1
R_20	Erap	<0.1	<0.1	<15.1	<8.1
R_21	Arisisi	<0.1	<0.1	<15.1	<8.1
R_22	Erap Primary School	<0.1	<0.1	<15.1	<8.1
R_23	Erap Station Elementary School	<0.1	<0.1	<15.1	<8.1
R_24	Nigassim	<0.1	<0.1	<15.1	<8.1
R_26	Chivasing Elementary School Crew Site	<0.1	<0.1	<15.1	<8.1
Criteria				**25**	**10**

[1] Represents the worst case impact at site boundary to assess impacts associated with potential in migration but currently is not inhabited.

The incremental $PM_{2.5}$ concentrations predicted at all sensitive receptors are below the relevant air quality criteria.

8.2 Nitrogen Dioxide

Table 18 presents the incremental maximum 1-hour and annual average NO_2 concentrations predicted at the nearest identified sensitive receptors, based on the stack and emission data detailed in **Section 7**. As discussed in **Section 3.4**, background concentrations of NO_2 have been assumed to be negligible. Contour plots showing the predicted incremental impacts across the modelling domain are included in **Appendix A**.

The ozone limiting method was used to calculate the conversion of nitrogen oxides (NO_X) to nitrogen dioxide (NO_2) (**Section 6.6**).

The NO_2 concentrations predicted at all sensitive receptors and at all locations off-site are below the relevant air quality criteria.

Table 18 Nitrogen Dioxide Concentrations Predicted at Sensitive Receptors

Sensitive Receptor		**NO_2 Ground Level Concentration (µg/m^3)**	
ID	**Description**	**Maximum 1-hour**	**Annual Average**
R_1[1]	Northern boundary	106.4	2.8
R_2	Outbuilding (no road access)	96.3	0.9
R_3	Outbuilding (no road access)	97.0	0.6
R_4	Ganef Community Nursery	92.5	0.4
R_5	Ganef (hamlet)	70.7	0.9
R_6	Mempangnaron	9.4	0.1
R_7	Furif	21.0	0.4
R_8	40 Miles	18.9	0.5
R_9	Markham Farm Aidpost - west (hospital)	37.8	0.6
R_10	Markham Farm Aidpost - east (hospital)	38.9	0.5
R_11	Markham Farm Elementary School	34.3	0.5
R_12	Markham Farm Primary School	36.1	0.5
R_13	41 Mile Night Market	16.2	0.7
R_14	Kaiapit	36.8	0.5
R_15	Chivasing Police Station	18.4	0.7
R_16	Chivasing Aid Post (hospital)	18.6	0.7
R_17	Chivasing Elementary School	18.0	0.7
R_18	Chivasing Primary School	19.2	0.7
R_19	41 Mile Night Market - Residences	18.1	0.7
R_20	Erap	5.1	<0.1
R_21	Arisisi	3.7	<0.1
R_22	Erap Primary School	5.0	<0.1
R_23	Erap Station Elementary School	4.8	<0.1
R_24	Nigassim	4.7	<0.1
R_26	Chivasing Elementary School Crew Site	14.7	0.4
Criteria		**200**	**40**

[1] Represents the worst case impact at site boundary to assess impacts associated with potential in migration but currently is not inhabited.

8.3 Sulfur Dioxide

Table 19 presents the incremental maximum 10-minute and 24-hour average SO_2 concentrations predicted at the nearest identified sensitive receptors, based on the stack and emission data detailed in **Section 7**. As discussed in **Section 3.4**, background concentrations of SO_2 have been assumed to be negligible. Contour plots showing the predicted incremental impacts across the modelling domain are included in **Appendix A**.

The SO_2 concentrations predicted at all sensitive receptors and at all locations off-site are below the relevant air quality criteria.

Table 19 Sulfur Dioxide Concentrations Predicted at Sensitive Receptors

Sensitive Receptor		**SO_2 Ground Level Concentration (µg/m^3)**	
ID	**Description**	**Maximum 10-minute**	**Maximum 24-hour**
R_1[1]	Northern boundary	90.2	7.3
R_2	Outbuilding (no road access)	52.0	2.4
R_3	Outbuilding (no road access)	54.8	1.9
R_4	Ganef Community Nursery	37.7	1.2
R_5	Ganef (hamlet)	26.5	1.1
R_6	Mempangnaron	3.5	0.2
R_7	Furif	7.9	0.4
R_8	40 Miles	7.1	0.5
R_9	Markham Farm Aidpost - west (hospital)	14.1	1.2
R_10	Markham Farm Aidpost - east (hospital)	14.6	1.0
R_11	Markham Farm Elementary School	12.9	0.8
R_12	Markham Farm Primary School	13.6	0.9
R_13	41 Mile Night Market	6.1	0.6
R_14	Kaiapit	13.8	1.8
R_15	Chivasing Police Station	6.9	0.6
R_16	Chivasing Aid Post (hospital)	7.0	0.6
R_17	Chivasing Elementary School	6.7	0.6
R_18	Chivasing Primary School	7.2	0.6
R_19	41 Mile Night Market - Residences	6.8	0.5
R_20	Erap	1.9	0.1
R_21	Arisisi	1.4	<0.1
R_22	Erap Primary School	1.9	0.1
R_23	Erap Station Elementary School	1.8	0.1
R_24	Nigassim	1.7	0.1
R_26	Chivasing Elementary School Crew Site	5.5	0.4
Criteria		**500**	**20**

[1] Represents the worst case impact at site boundary to assess impacts associated with potential in migration but currently is not inhabited.

It is noted that the results presented in this section are based on an average sulfur content in the fuel of 0.02%. However MVB have advised that the fuel sulfur content may vary up to 0.05% as a worst case. This increase would result in an equivalent increase in the maximum downwind concentrations predicted by the modelling (i.e. 2.5 times higher). Based on the modelling results presented in **Table 19**, no off-site exceedances of the relevant SO_2 criteria would be predicted even at the maximum expected sulfur content in the fuel of 0.05%. The worst case concentrations that would be predicted at the nearest sensitive receptors would be well below (30% or less of) the relevant criteria.

8.4 Carbon Monoxide

Table 20 presents the incremental maximum 1-hour and 24-hour average CO concentrations predicted at the nearest identified sensitive receptors, based on the stack and emission data detailed in **Section 7**. As discussed in **Section 3.4**, background concentrations of CO have been assumed to be negligible. Contour plots showing the predicted incremental impacts across the modelling domain are included in **Appendix A**.

Table 20 Carbon Monoxide Concentrations Predicted at Sensitive Receptors

Sensitive Receptor		CO Ground Level Concentrations (µg/m³)	
ID	**Description**	**Maximum 1-hour**	**Maximum 24-hour**
R_1[1]	Northern boundary	385.6	44.3
R_2	Outbuilding (no road access)	221.6	14.5
R_3	Outbuilding (no road access)	234.4	11.4
R_4	Ganef Community Nursery	161.8	7.3
R_5	Ganef (hamlet)	114.1	7.1
R_6	Mempangnaron	15.5	1.3
R_7	Furif	34.0	2.7
R_8	40 Miles	30.6	2.8
R_9	Markham Farm Aidpost - west (hospital)	63.4	7.3
R_10	Markham Farm Aidpost - east (hospital)	62.6	6.0
R_11	Markham Farm Elementary School	56.3	5.1
R_12	Markham Farm Primary School	58.2	5.3
R_13	41 Mile Night Market	26.4	3.6
R_14	Kaiapit	60.0	11.1
R_15	Chivasing Police Station	29.5	3.8
R_16	Chivasing Aid Post (hospital)	29.8	3.8
R_17	Chivasing Elementary School	28.8	3.7
R_18	Chivasing Primary School	30.8	3.8
R_19	41 Mile Night Market - Residences	29.0	3.5
R_20	Erap	8.3	0.7
R_21	Arisisi	6.2	0.6
R_22	Erap Primary School	8.2	0.7
R_23	Erap Station Elementary School	8.0	0.7
R_24	Nigassim	7.8	0.6
R_26	Chivasing Elementary School Crew Site	23.7	2.3
	Criterion	**30,000**	**10,000**

[1] Represents the worst case impact at site boundary to assess impacts associated with potential in migration but currently is not inhabited.

The CO concentrations predicted at all sensitive receptors and at all locations off-site are below the relevant air quality criteria.

8.5 Total VOCs (as benzene)

Table 21 presents the incremental annual average total VOC (as benzene) concentrations predicted at the nearest identified sensitive receptors, based on the stack and emission data detailed in **Section 7**. As no appropriate criteria is available for assessing total VOC ground level concentrations, the predicted concentrations of VOCs have been compared to the most stringent air quality criterion for an individual VOC, benzene. In reality, benzene would make up a small percentage of the total VOCs emitted from the plant. While natural sources of organic compounds will be present in the area, background concentrations of benzene can be assumed to be negligible.

Contour plots showing the predicted incremental impacts across the modelling domain are included in **Appendix A**.

Table 21 Total VOCs (as benzene) Concentrations Predicted at Sensitive Receptors

Sensitive Receptor		Total VOC (as benzene) Ground Level Concentrations (µg/m³)
ID	**Description**	**Annual Average**
R_1[1]	Northern boundary	0.14
R_2	Outbuilding (no road access)	0.05
R_3	Outbuilding (no road access)	0.03
R_4	Ganef Community Nursery	0.02
R_5	Ganef (hamlet)	0.04
R_6	Mempangnaron	<0.01
R_7	Furif	0.02
R_8	40 Miles	0.03
R_9	Markham Farm Aidpost - west (hospital)	0.03
R_10	Markham Farm Aidpost - east (hospital)	0.03
R_11	Markham Farm Elementary School	0.02
R_12	Markham Farm Primary School	0.02
R_13	41 Mile Night Market	0.04
R_14	Kaiapit	0.03
R_15	Chivasing Police Station	0.03
R_16	Chivasing Aid Post (hospital)	0.03
R_17	Chivasing Elementary School	0.03
R_18	Chivasing Primary School	0.03
R_19	41 Mile Night Market - Residences	0.03
R_20	Erap	<0.01
R_21	Arisisi	<0.01
R_22	Erap Primary School	<0.01
R_23	Erap Station Elementary School	<0.01
R_24	Nigassim	<0.01
R_26	Chivasing Elementary School Crew Site	0.02
	Criterion	**0.17**

[1] Represents the worst case impact at site boundary to assess impacts associated with potential in migration but currently is not inhabited.

The total VOC concentrations predicted at all sensitive receptors and at all locations off-site are below the air quality criterion for benzene.

9 ASSESSMENT OF AIR QUALITY IMPACTS

Sections 9.1 and **9.2** summarise the findings of the qualitative assessment and atmospheric dispersion modelling and identify the sensitive receptors that have the potential to be impacted by air emissions from the construction and operational phases of the Project. These sections focus on the potential for health-related or nuisance-based impacts at nearby human settlements.

In addition to human health and nuisance impacts, there is also potential for other environmental impacts as a result of air emissions from the Project, most notably the potential for damage to vegetation due to elevated concentrations of SO_2 or the settling of dust onto leaves. This is discussed in **Section 9.3**.

9.1 Construction Phase

Construction will result in the generation of fugitive particulate matter emissions. These emissions have the potential to result in elevated PM_{10} and $PM_{2.5}$ concentrations in the vicinity of the works. Elevations in ambient concentrations of combustion-related gaseous pollutants due to construction vehicle operations would also be anticipated, but air quality impacts from construction activities of the scale proposed, in this sparsely populated region, would generally be limited to dust-related impacts.

Emissions of VOCs from the storage and transfer of diesel, while minor, have also been discussed.

9.1.1 Fugitive Particulate Emissions

The construction activities with the greatest potential for PM_{10} and $PM_{2.5}$ impacts at sensitive receptors (i.e. village locations) are:

- Construction of the power plant site (i.e. clearing of vegetation, truck deliveries of construction materials, construction of buildings and associated infrastructure and wind erosion of disturbed areas);
- Upgrading and establishing access roads into the plantation areas; and
- Establishment (clearing and planting) of plantation areas.

The Institute of Air Quality Management's (IAQM) *Guidance on the Assessment of Dust from Demolition and Construction* (IAQM, 2014) uses a screening process based on distance to the nearest sensitive receptor to assess the potential risks of dust impacts from construction activities. The screening criteria provided by IAQM screen out assessment of impacts from construction activities where sensitive receptors are located more than 350 m from the boundary of the site, more than 50 m from the route used by construction vehicles on public roads and more than 500 m from the site entrance. This step is noted as having deliberately been chosen to be conservative, and is anticipated to require assessments for most projects.

For the power plant site, the nearest populated area is the Ganef hamlet, which is 800 m from the power plant site.[3] This settlement is therefore more than 350 m from the boundary of the site and more than 500 m from the site entrance, however it is adjacent to the Highlands Highway and as a result may be less than 50 m from the route used by construction vehicles. Construction traffic is anticipated to access the site along the Highlands Highway from Lae and will turn off to access the site just prior to reaching Ganef. As most of the construction traffic is not anticipated to pass directly by Ganef, and most vehicles will be travelling at low speeds to turn into the site, minimal dust-related impacts are expected. If required, mitigation measures to minimise trackout of dirt onto the Highlands Highway (sweeping/washing of the road, wheel washes, rumble bars etc.) should be implemented to minimise such impacts.

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3 Based on the expectation that R2 and R3, which represent outbuildings with no road access, would not be occupied for extended periods of time.

Based on the IAQM screening criteria, if construction activities in the plantation areas are located greater than 350 m from an existing village, they would not require a risk assessment of dust impacts from construction activities. The largest villages (Chivasing and Tararan) will be surrounded by a buffer zone of at least 50 m within which plantation establishment will not occur, however consideration should also be given to the planning of access roads to maximise the separation distance between these villages and the Project access roads. Where possible, access roads into plantation areas should be located more than 350 m from existing residential receptors. Where access roads are required to be less than 350 m from existing residential receptors, additional mitigation measures outlined in **Section 10** should be applied as appropriate to minimise the risk of impacts at the residential receptors during construction. This will also minimise impacts due to wheel-generated dust from vehicles using these roads during the operational phase.

9.1.2 Fugitive VOCs from Fuel Storage

Emissions of VOCs from the storage and handling of diesel would occur as a result of breathing losses (due to expansion and contraction of the gases in the head space of the storage tanks due to changes in ambient temperature) and working losses (due to displacement of vapour-laden gases from the head space of the storage tank as it is filled). There is also the potential for VOC emissions to occur as result of evaporation of minor spills during tank/vehicle filling activities.

These emissions would be minor in nature and would disperse rapidly, and would not be expected to have any measureable impacts on ambient concentrations beyond a few hundred metres from fuel storage areas. Published recommended buffer distances for the separation of sensitive land uses from fuel storage areas are as follows (EPAV, 1990):

Storage of petroleum products and crude oil in tanks exceeding 2,000 tonnes capacity:

(a) with fixed roofs 300 m;

(b) with floating roofs 100 m.

The identified sensitive receptors are located more than 800 m from the power plant site and therefore it may be reasonably concluded that no adverse air quality impacts at these locations would be expected as a result of fuel storage and handling activities.

9.2 Operational Phase

Potential air quality impacts associated with emissions from the power plant stacks and fugitive dust emissions from trucks transporting logs to the power plant and transporting ash off-site have been assessed using dispersion modelling (refer **Section 8**). The results indicated that maximum ground level PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO and total VOC ground level concentrations predicted at all existing sensitive receptor locations are well below the relevant air quality criteria. The cumulative maximum 24-hour average and annual average PM_{10} ground level concentrations predicted north of the site exceed the air quality criteria in a localised area immediately adjacent to the site boundary. Worst case ground level PM_{10} concentrations of up to 53 µg/m^3 as a 24-hour average are predicted at this location compared to the criterion of 50 µg/m^3; however, this location is not currently inhabited.

Other emissions to air that would occur during the operational phase that have not been quantitatively assessed include:

- Wheel-generated dust emissions from vehicle movements on the main access road (not including log and ash truck movements);
- Emissions of combustion-related pollutants due to on-site vehicle operations;
- Fugitive dust emissions from planting and harvesting activities occurring within the plantation areas; and
- Emissions of VOCs from the storage and transfer of diesel.

Vehicle movements on the main access road other than log and ash trucks are anticipated to be infrequent and the particulate emissions from these additional vehicles would be minimal compared to those generated by the log and ash trucks (which were included in the dispersion modelling study). It is considered unlikely therefore that these additional vehicle movements would contribute significantly to particulate levels in the surrounding area. In addition, appropriate road maintenance, logistics planning and implementation of speed limits would be used to reduce the potential for vehicle-generated emissions from the main access road to result in nuisance dust impacts at nearby villages during dry periods.

Any increase in ambient concentrations of combustion-related pollutants due to exhaust emissions from on-site vehicle operations would be minimal compared to the impact of emissions from the power plant stacks and have not been considered further.

As noted previously, it is recommended that access roads into plantation areas be located greater than 350 m from existing villages where possible.

As discussed in **Section 9.1.2**, emissions to air from fuel storage would not be expected to give rise to any significant impacts on air quality due to the scale of the activities and the distances to sensitive receptors.

9.3 Potential Impacts on Vegetation

In addition to human health and nuisance impacts addressed above, there is also potential for other environmental impacts as a result of air emissions from the Project. The most significant of these is the potential for damage to vegetation due to dust and SO_2 emissions.

High levels of dust deposition may cause damage to vegetation through mechanisms such as the blocking of leaf stomata (and the inhibition of gas exchange), or reduced photosynthesis due to smothered surfaces (or in extreme cases lower ambient light levels). The relatively high rainfall in the study area would minimise such impacts by washing away dust deposited on leaves. Deposition rates also generally decrease rapidly with distance from the source and any damage to vegetation due to dust emissions is expected to be very localised and limited to less than 100 m or so from the active work areas.

SO_2 injury in plants is classified as either acute or chronic. Acute injury is caused by absorption of high concentrations of SO_2 in a relatively short time. The symptoms of acute injury appear as two-sided lesions that usually occur between the veins and occasionally along the margins of the leaves. Chronic injury is caused by long-term absorption of SO_2 at sub-lethal concentrations. The symptoms appear as a yellowing or chlorosis of the leaf, and occasionally as a bronzing on the under surface of the leaves. Different plant species and varieties and even individuals of the same species may vary considerably in their sensitivity to SO_2. These variations occur because of the differences in geographical location, climate, stage of growth and maturation. Nevertheless, reasonably accurate values for “no-response thresholds” for adverse effects have been derived for broad categories of plants, and WHO has set an annual guideline for SO_2 of 20 µg/m^3 to protect forests and natural vegetation (WHO, 2000).

A worst case, annual average off-site SO_2 concentration of 0.7 µg/m^3 is predicted by the modelling at the northern site boundary of the power plant site based on the emission rates presented in **Section 7**. This is well below the WHO annual average guideline for vegetation impacts of 20 µg/m^3. It is therefore concluded that the potential for adverse impacts on vegetation due to SO_2 emissions from the power plant site would be negligible. Given the low annual average SO_2 concentrations predicted, a contour plot of the predicted annual average SO_2 concentrations is not included.

9.4 Cumulative Impacts

The IFC's *Good Practice Handbook: Cumulative Impact Assessment and Management: Guidance for the Private Sector in Emerging Markets* (IFC, 2013) defines cumulative impacts as

> *"those that result from the successive, incremental, and/or combined effects of an action, project, or activity (collectively referred to in this document as "developments") when added to other existing, planned, and/or reasonably anticipated future ones".*

With respect to air quality, potential cumulative impacts for the Project could occur in the event that:

- There are other major construction projects occurring at the same time and in close vicinity of the major Project construction sites, such as the power plant site, access roads and plantation areas;
- A major source of combustion-related air emissions is constructed in close vicinity of the power plant site;
- The access roads constructed for the project result in increased traffic movements on these and other connected roads by non-Project related traffic; or
- Other significant sources of particulate emissions are established in the vicinity of the plantations and access roads (eg, agricultural activities such as land clearing and burnoffs in previously uncultivated areas, possibly due to the establishment of new access roads or as a result of population growth due to in-migration associated with the Project).

The potential for cumulative air quality impacts during the construction phase is limited due to the temporary nature of the works and the very localised nature of fugitive dust impacts associated with construction projects. No other major proposed or approved construction projects have been identified in the area (i.e. within 1 km) that would have potential for any significant cumulative impacts.

In addition, this air quality impact assessment has identified that during the operational phase, even under worst case meteorological conditions, ground level concentrations of air pollutants due to the proposed emissions from the power plant site are well below the relevant air quality guidelines at identified sensitive receptor locations. It is noted that the IFC *Environmental, Health and Safety Guidelines: Environmental – Air Emissions and Ambient Air* (IFC, 2007) states that projects with significant sources of air emissions, and potential for significant impacts to ambient air quality, should prevent or minimise impacts by ensuring that

> *"Emissions do not contribute a significant portion to the attainment of relevant ambient air quality guidelines or standards (as a general rule, the guideline suggests 25% of the applicable air quality standards to allow additional, future sustainable development in the same airshed)"*

Excluding Receptor 1 (which is located on the site boundary and is currently uninhabited), the maximum ground level concentrations of PM_{10} and $PM_{2.5}$, SO_2 and CO predicted as a result of emissions from the Project are less than 14% of the relevant guideline. Maximum predicted 1-hour average concentrations of NO_2 range from 35% to 48% of the relevant guideline at Receptors 2 to 5, which are located within 1 km of the power plant site, however the annual average NO_2 concentrations predicted at these sensitive receptors are all less than 3% of the relevant guideline. Based on these results, and in the absence of any known proposed or approved major projects within 1 km of the power plant site, it is considered that the impacts associated with the proposed emissions from the power plant would not preclude additional, future sustainable development in the same airshed.

Similarly, fugitive dust emissions from the use of Project access roads and from planting and harvesting activities within the plantation areas are anticipated to be able to be managed such that any potential cumulative impacts from future additional dust emission sources in the area would not give rise to unacceptable cumulative impacts. Measures to achieve this include careful planning of access road locations, establishment of buffer areas around sensitive receptors, and good design and maintenance of access roads.

10 MITIGATION AND MONITORING

10.1 Mitigation

10.1.1 Construction Phase

Air emissions associated with construction activities will be managed through compliance with an Environmental Management Plan (EMP). This should include implementation of procedures designed to meet the air quality objectives adopted for the Project (**Table 9**) and other relevant guidelines/standards. The EMP should be implemented so that:

- The works are conducted in a manner that limits the generation of air emissions;
- The effectiveness of the controls being implemented is monitored;
- Additional measures are implemented where required, as determined by the monitoring program; and
- A complaints management system is implemented so that any identified incidents or substantiated complaints are dealt with through investigation and implementation of corrective treatments.

The following general mitigation measures should be implemented during the construction phase of the Project:

- Use of water to suppress dust emissions during periods of extended dry weather and when dust nuisance has the potential to occur as a result of construction activities (including vehicle movements on unpaved surfaces, clearing and grading, excavation and rehabilitation).
- Installation of fixed water sprays to control dust from key areas, as required.
- Limit open burning of vegetation or other waste materials.
- Limit the use of material stockpiles and locate them away from areas prone to elevated erosion or sensitive receptor locations.
- Maintain all vehicles and machinery used for the construction of the Project in accordance with the manufacturer's specifications to limit exhaust emissions.
- Limit truck queuing, unnecessary idling of trucks and unnecessary trips through logistical planning of materials delivery and work practices.
- Implement speed limits via posted speed limit signs on Project unsealed roads (when required).
- Cover vehicle loads when travelling on the access roads etc.
- Ensure vehicles keep to marked trafficable areas, which should be maintained in a damp and compacted condition (when required) to enhance safety and limit dust emissions.
- Limit cleared areas as far as practicable and retaining existing vegetation where possible.
- Strip areas progressively and only where it is necessary for works to occur.
- Employ stabilisation methods such as matting, grassing or mulch, where practicable.
- Ensure clean up and restoration proceeds as soon as is practicable after works are completed to limit the duration of exposure of disturbed areas.

When construction activities occur in close vicinity (i.e. within ~1 km) of sensitive receptors, the following additional mitigation measures should be implemented to limit these emissions:

- Locate fixed and mobile equipment (i.e., generators) sensitively with respect to local people.
- Use additional water sprays and water trucks to suppress dust emissions, when required.
- Postpone, limit or relocate dust-generating activities in windy conditions (where practicable).

- Notify each village of the times and duration of works and that they may be affected by emissions from the works as the construction works approach.
- Establish clear communication methods to ensure affected communities have access to effective communication links to the operational managers, and any substantiated complaints can be addressed appropriately and sensitively.

Further, the plantation access roads may have some flexibility in design to allow minor deviations to limit or avoid potential air quality impacts at sensitive receptor locations.

10.1.2 Operational Phase

The atmospheric dispersion modelling study performed as part of this assessment is based on good industry practice being adopted during operations to reduce discharges to air. Air emissions associated with operational activities should be managed through compliance with an EMP. This should include implementation of procedures designed to meet the air quality objectives adopted for the Project (**Table 9**) and other relevant guidelines/standards, so that:

- The operation is conducted in a manner that limits the generation of air emissions;
- The effectiveness of the controls being implemented is monitored;
- Additional measures are implemented where required, as determined by the monitoring program; and
- A complaints management system is implemented so that any identified incidents or substantiated complaints are dealt with through investigation and implementation of corrective treatments.

General mitigation measures listed in **Section 10.1.1** should also be implemented during the operational phase of the Project.

10.2 Monitoring

The vast majority of air emission sources associated with the construction of the Project are fugitive in nature and are not emitted via stacks, vents or chimney flues; hence a source emission monitoring program is not relevant. During the operational phase, a monitoring program should be implemented to monitor emissions to air from the power plant boiler stacks.

An ambient air quality monitoring program should be developed and implemented for both the construction and operational phases of the Project as outlined below.

10.2.1 Construction Phase

Construction of the plantation access roads and the power plant, nursery and plantation site are the only construction phase activities with potential to impact on ambient air quality at sensitive receptors, based on the scale of activities proposed and their proximity to sensitive receptors.

If the plantation access road construction areas are located within 350 m of an existing village, it is recommended that consideration be given to monitoring for dust impacts from these construction activities.

Activities associated with the construction of roads would move as the works progress, hence these impacts would only occur for a short duration at any given location. The use of fixed monitoring sites would therefore not be appropriate for this activity and as a result the use of standard monitoring equipment used for the measurement of suspended and deposited particulate, such as High Volume Air Samplers (HVAS), Tapered Element Oscillating Microbalance (TEOMs) and dust deposition gauges, is not practicable. In addition, road construction works performed in similar environments have shown that there is minimal dust generated from these activities.

It is therefore recommended that PM_{10} baseline monitoring be performed using beta-attenuation monitors (BAMs) or low volume air samplers (LVAS) in villages close to the proposed access road area prior to construction works starting. Should legitimate[4] complaints regarding dust be received during the road construction, monitoring should be performed downwind of the activities to assess whether concentrations are elevated above the previously recorded baseline levels. This information should then be used in managing the impacts while the works are occurring in close proximity to villages. This monitoring equipment should also be used to investigate impacts from other activities associated with the Project (e.g. plantation site preparation/cultivation) if any legitimate complaints or concerns are raised, and to collect baseline monitoring away from the active work areas.

As discussed in **Section 9.1**, the Ganef hamlet is located 800 m from the boundary of the power plant site, hence it is unlikely to be significantly impacted by construction activities within the power plant site. However it is located adjacent to the Highlands Highway and as a result may be less than 50 m from the route used by construction vehicles. If the majority of the construction traffic will be travelling to and from Lae and will therefore turn off the Highlands Highway prior to reaching Ganef, monitoring of dust impacts at Ganef is not anticipated to be warranted. However, if significant numbers of trucks carrying spoil and or equipment to or from site will be passing directly past Ganef then it is recommended that consideration be given to monitoring for dust impacts from these vehicles using a HVAS, BAM and/or a dust deposition gauge.

All air quality monitoring activities should be documented within the relevant EMPs, which will address:

- Responsibilities for the monitoring program;
- Sampling locations;
- Monitoring parameters;
- Instrumentation requirements, calibration and maintenance procedures, and operational methodology;
- Quality assurance requirements (including the maintenance of calibration records, data handling, manipulation and storage); and
- Reporting procedures.

In addition to the monitoring proposed above, the effectiveness of the mitigation measures implemented to limit emissions should also be monitored through liaison with affected residents, complaints records and a program of regular visual observations by site supervisors when the works are being carried out in close vicinity to the villages.

10.2.2 Operational Phase

No exceedances of ambient air quality criteria are predicted at sensitive receptor locations in the vicinity of the power plant site during the operational phase of the Project, hence no routine ambient air quality monitoring program is recommended in these areas. Where plantation areas are located within 350 m from an existing village, consideration should be given to monitoring for potential dust impacts during plantation establishment and harvesting activities. These monitoring requirements would be identical to those outlined in **Section 10.2.1**.

A stack emission sampling programme should be included in the EMP for the power plant boiler stacks. This monitoring should include the following as a minimum:

Upon commissioning of each boiler unit:

- Measurement of in-stack concentrations and emission rates (post ESP) of:
  - Particulate matter;
  - Oxides of nitrogen;

[4] i.e., Not obviously vexatious or malicious

    - Sulfur dioxide;
    - VOCs; and
    - Carbon monoxide.
- Determinations of gas temperature, stack gas velocity, moisture content, CO_2/O_2 content and exhaust gas flow rate.

Post-Commissioning:

- Monitoring of the above parameters should be performed on an ongoing basis (e.g. annually).

Each stack should be fitted with suitable stack testing ports to allow safe and suitable access for flow and concentration measurements.

11 CONCLUSIONS

The key findings of the air quality impact assessment are as follows:

- The construction activities with the greatest potential for PM_{10} and $PM_{2.5}$ impacts at sensitive receptors (i.e. village locations) are
  - Construction of the power plant, log yard and nursery site (i.e. clearing of vegetation, truck deliveries of construction materials, construction of buildings and associated infrastructure);
  - Upgrading and establishing access roads into the plantation areas; and
  - Establishment (clearing and planting) of plantation areas.
- The Ganef hamlet is located 800 m from the boundary of the power plant site, hence it is unlikely to be significantly impacted by construction activities within the power plant site. However it is located adjacent to the Highlands Highway and as a result may be less than 50 m from the route used by construction vehicles. If significant numbers of trucks carrying spoil and or equipment to or from site will be passing directly past Ganef, mitigation measures to minimise trackout of dirt onto the Highlands Highway (sweeping/washing of the road, wheel washes, rumble bars etc.) should be implemented to minimise such impacts.
- The largest villages (Chivasing and Tararan) will be surrounded by a buffer zone of at least 50 m within which plantation establishment will not occur, however consideration should also be given to the planning of access roads to maximise the separation distance between these villages and the Project access roads. Where possible, access roads into plantation areas should be located more than 350 m from existing residential receptors. Where access roads are required to be less than 350 m from existing residential receptors, additional mitigation measures should be applied as appropriate to minimise the risk of impacts at the residential receptors during construction. This will also minimise impacts due to wheel-generated dust from vehicles using these roads during the operational phase.
  - The operational phase will result in the generation of point and fugitive emissions. The emissions from the power plant stacks and fugitive dust emissions from trucks transporting logs to the power plant and transporting ash off-site were assessed using dispersion modelling, conservatively based on stack and emission data for both 15 MW units operating at full capacity 24 hours per day, 7 days per week. The results of the modelling indicated that Maximum off-site PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, total VOC ground level concentrations at all sensitive receptors are predicted to be well below the relevant air quality criteria.
  - Maximum 24-hour average and annual average PM_{10} ground level concentrations (including estimated background levels) predicted north of the site exceed the air quality criteria in a localised immediately adjacent to the site boundary. Worst case ground level PM_{10} concentrations of up to 53 µg/m^3 as a 24-hour average are predicted at this location compared to the criterion of 50 µg/m^3; however, this location is not currently inhabited.
- Fugitive dust emissions from planting and harvesting activities may impact nearby sensitive receptors. It is therefore recommended that plantation areas be located greater than 350 m from existing villages, where possible, to minimise the risk of air quality impacts associated with ongoing plantation activities.
- All other construction and operational activities assessed in this study would occur in locations remote from sensitive receptors and given the scale of the activities would not be expected to result in adverse health or nuisance impacts at sensitive receptors.

Based on the key findings of the air quality impact assessment, an ambient air quality monitoring program should be performed throughout the construction and operational phases of the Project as outlined below.

- Construction of the plantation access roads and the power plant, nursery and plantation site are the only construction phase activities with potential to impact on ambient air quality at sensitive receptors, based on the scale of activities proposed and their proximity to sensitive receptors.

- If the plantation access road construction areas are located within 350 m from an existing village, consideration should be given to monitoring for potential dust impacts from construction activities. It is recommended that PM_{10} baseline monitoring be performed using BAMs or LVASs in villages close to proposed access roads prior to construction works starting. Should any complaints regarding dust be received during the road construction, monitoring should be performed downwind of the activities to assess whether concentrations are elevated above the previously recorded baseline levels. This information should then be used in managing the impacts while the works are occurring in close proximity to villages.
- If significant numbers of trucks carrying spoil and or equipment to or from the power plant site will be passing directly past Ganef then it is recommended that consideration be given to monitoring for dust impacts from these vehicles using a BAM, LVAS and/or a dust deposition gauge.
- This monitoring equipment should also be used to investigate impacts from other activities associated with the Project should any complaints or concerns be raised, and to collect baseline monitoring away from the active work areas.

- No exceedances of ambient air quality criteria at sensitive receptors in the vicinity of the power plant are predicted for the operational phase of the Project, hence no routine ambient air quality monitoring program is recommended in these areas. Where plantation areas are located within 350 m from an existing village, consideration should be given to monitoring for potential dust impacts during plantation establishment and harvesting activities.
- A stack monitoring programme should be developed for the power plant boiler stacks to ensure all units are operating within supplier specifications and in compliance with any stack emission limits.

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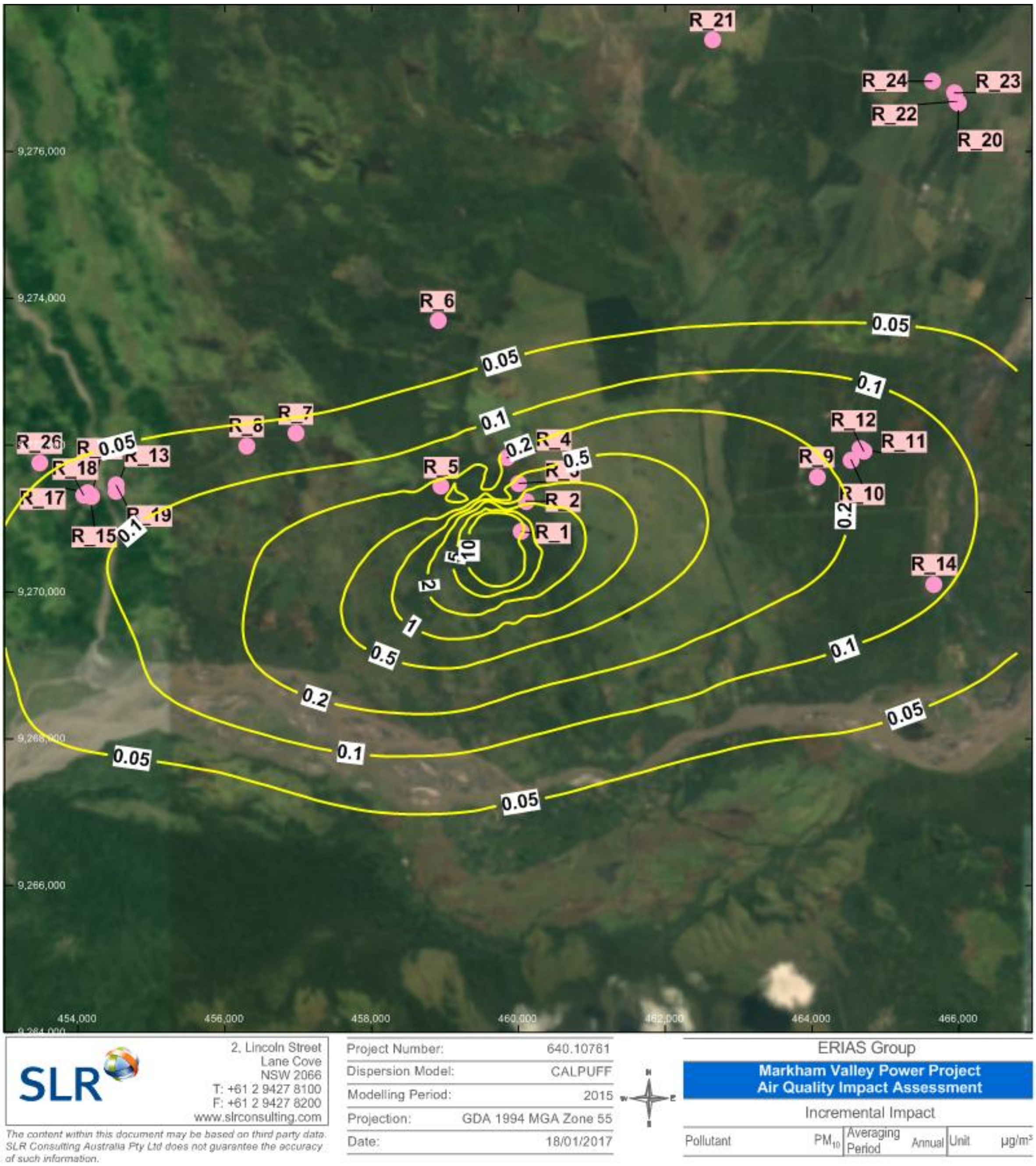

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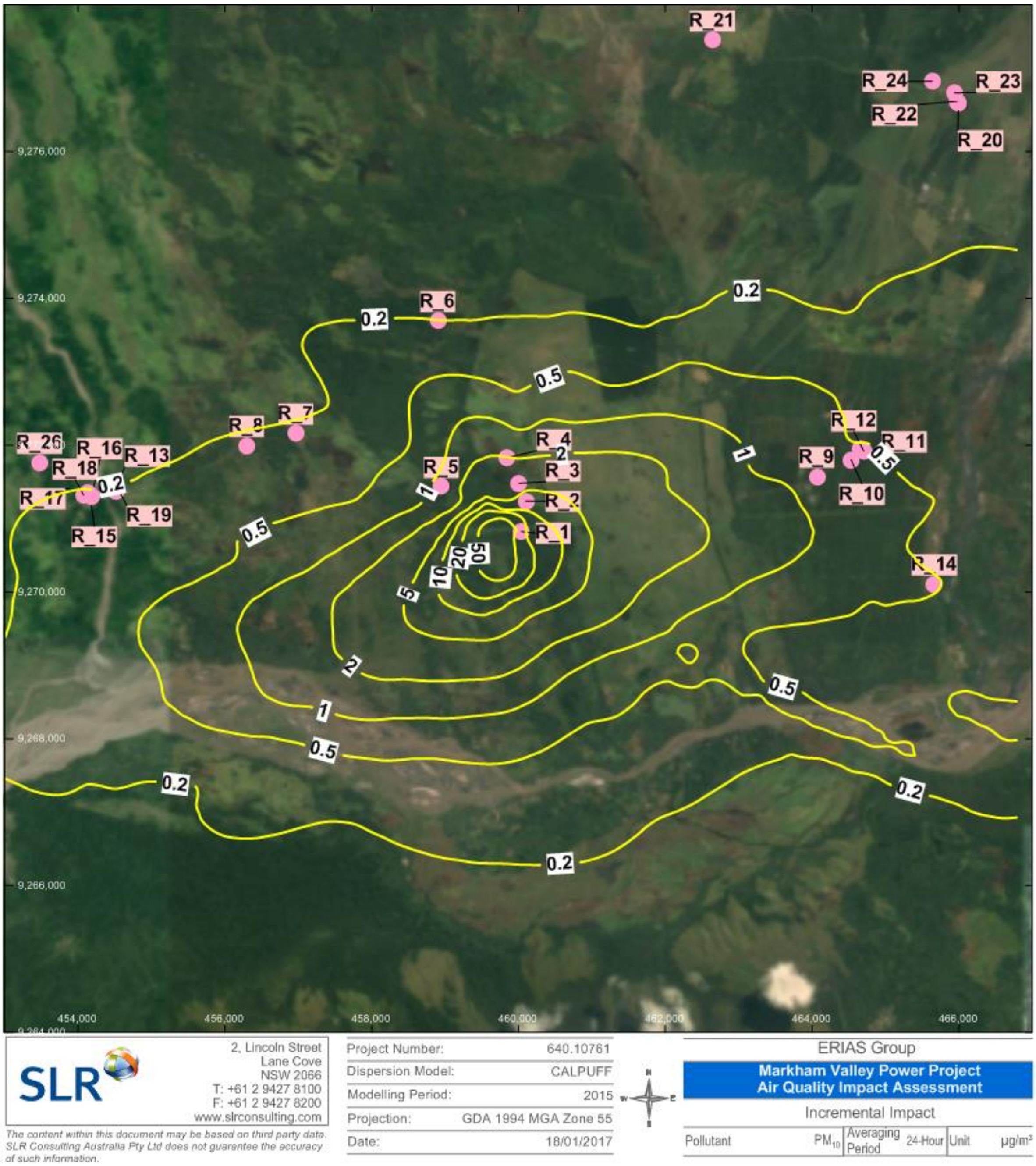

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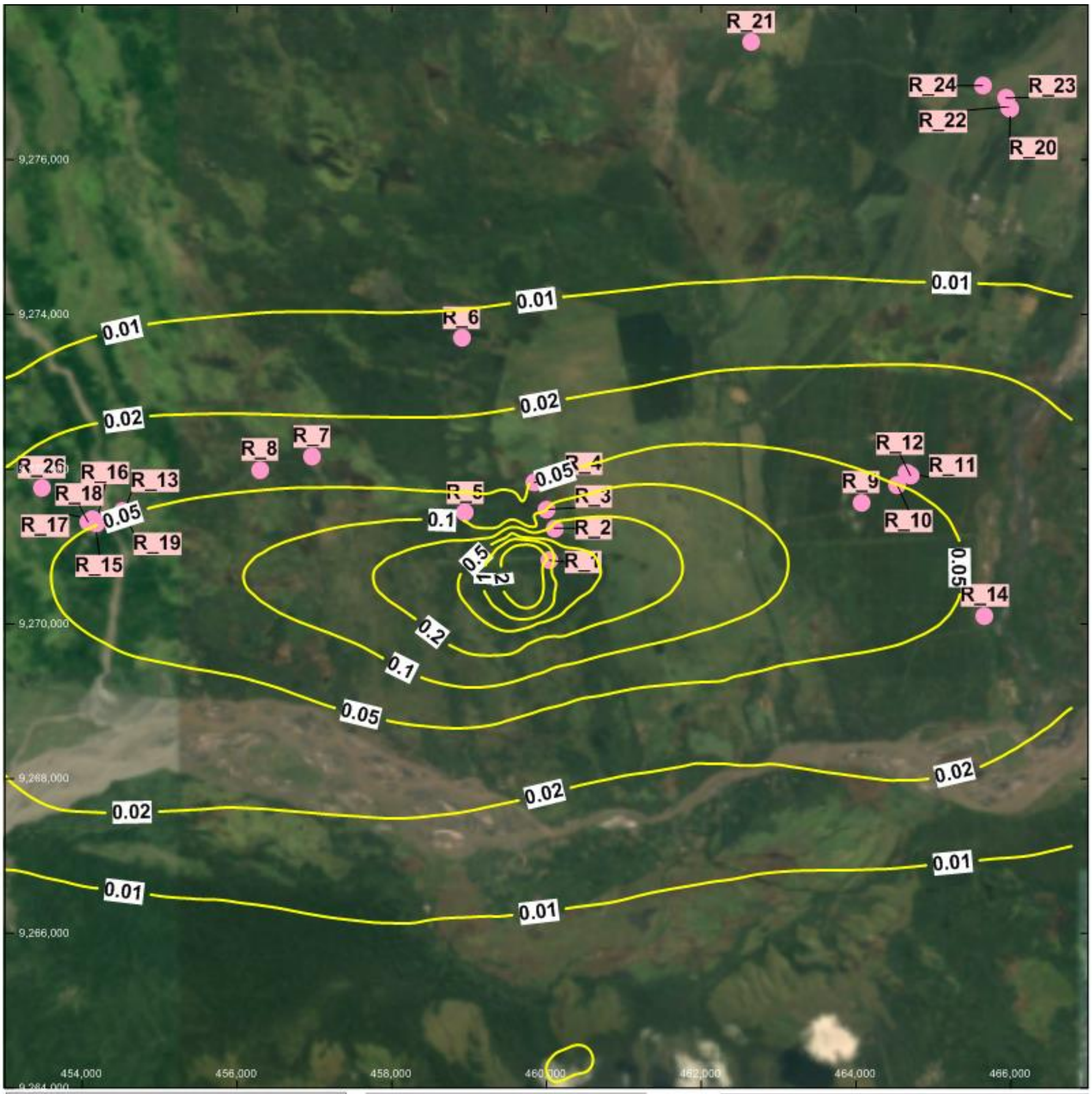

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Modelling Period:	2015
Projection:	GDA 1994 MGA Zone 55
Date:	18/01/2017

SLR
2, Lincoln Street
Lane Cove
NSW 2066
T: +61 2 9427 8100
F: +61 2 9427 8200
www.slrconsulting.com

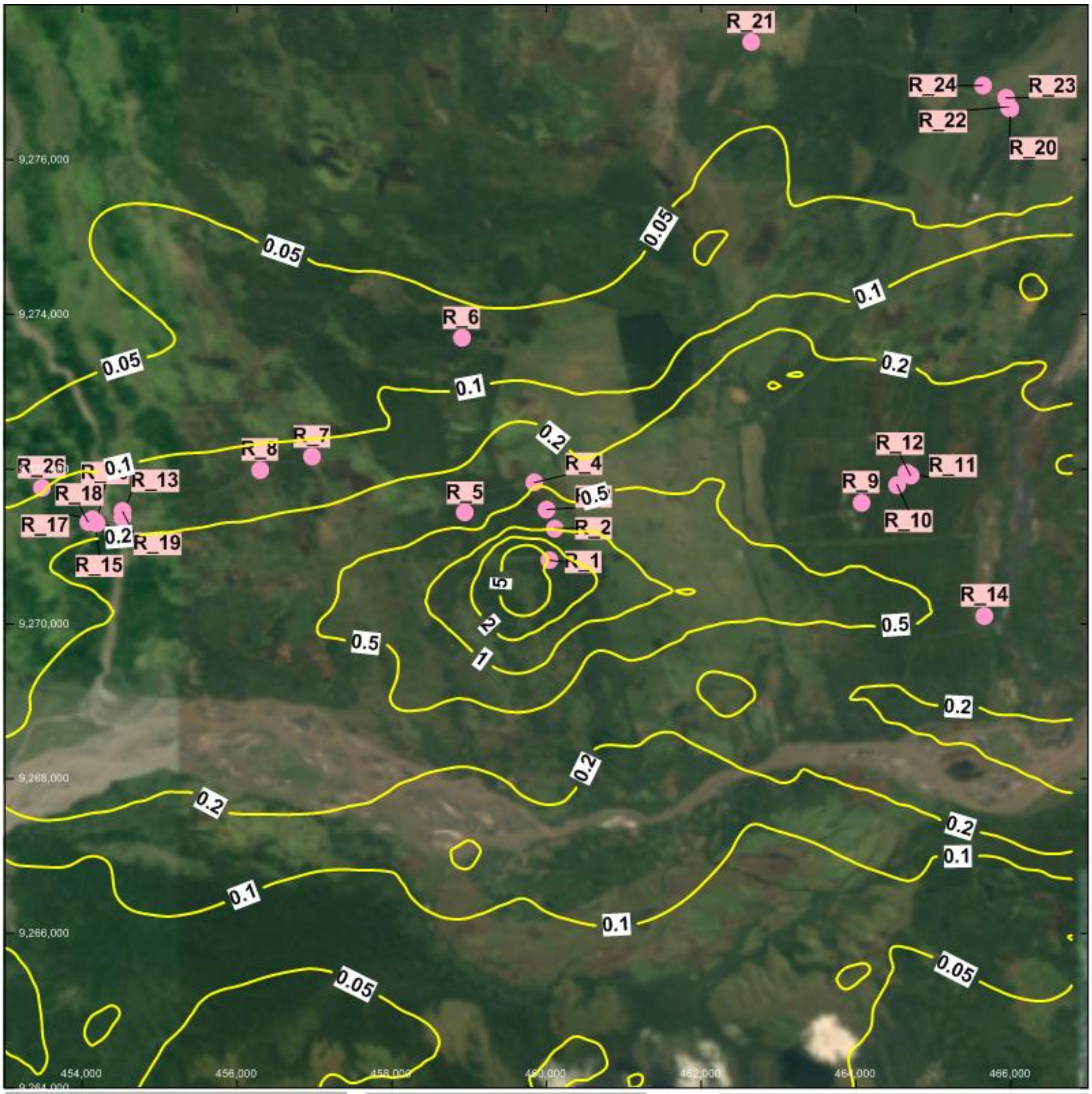
ERIAS Group

Markham Valley Power Project
Air Quality Impact Assessment

Incremental Impact

Pollutant	$PM_{2.5}$	Averaging Period	Annual	Unit	µg/m³

CONTOUR PLOTS



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F: +61 2 9427 8200
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Markham Valley Power Project
Air Quality Impact Assessment

Incremental Impact

Pollutant	$PM_{2.5}$	Averaging Period	24-Hour	Unit	µg/m³

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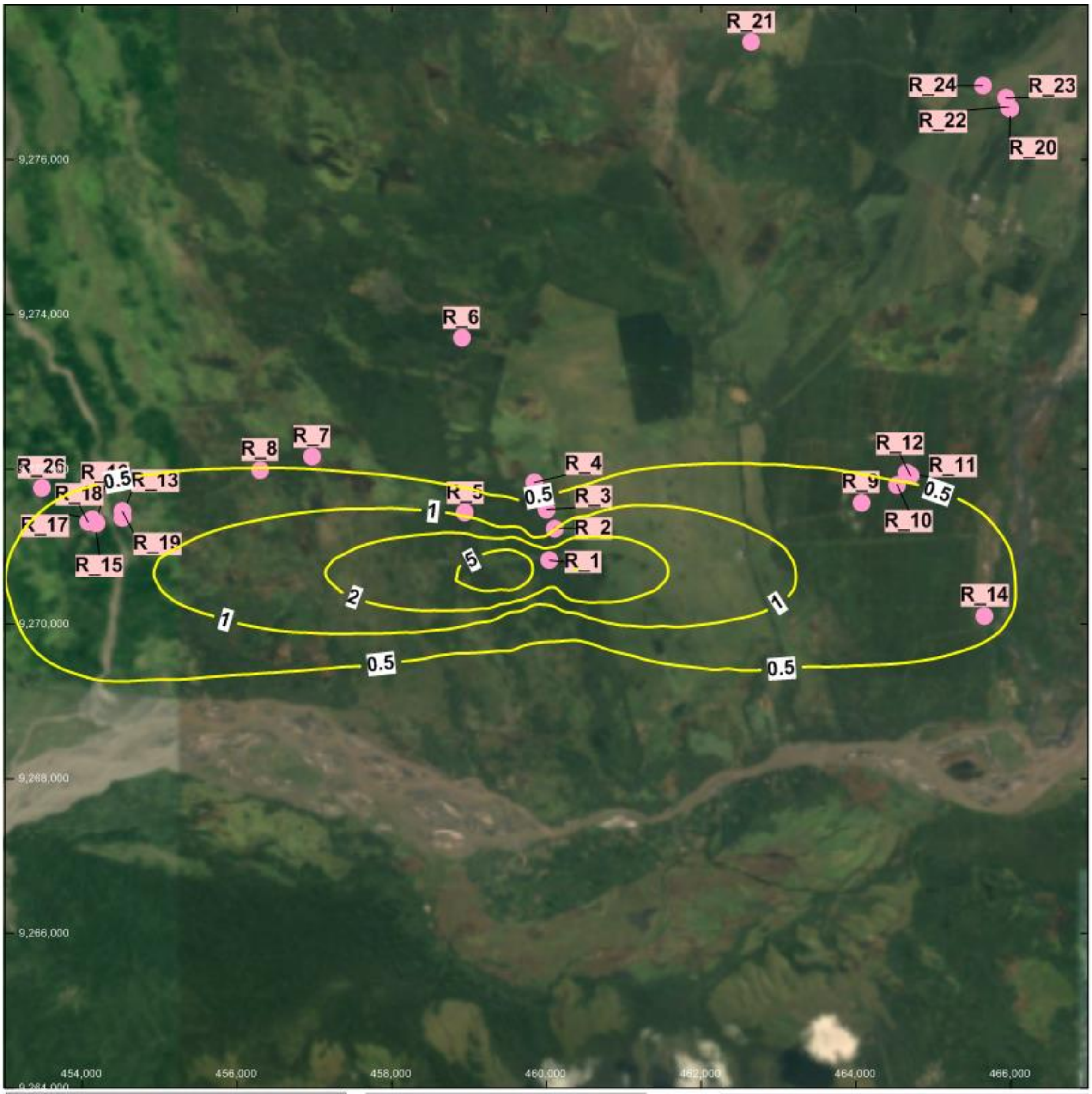

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Markham Valley Power Project
Air Quality Impact Assessment

Incremental Impact

Pollutant	NO_2	Averaging Period	Annual	Unit	µg/m³

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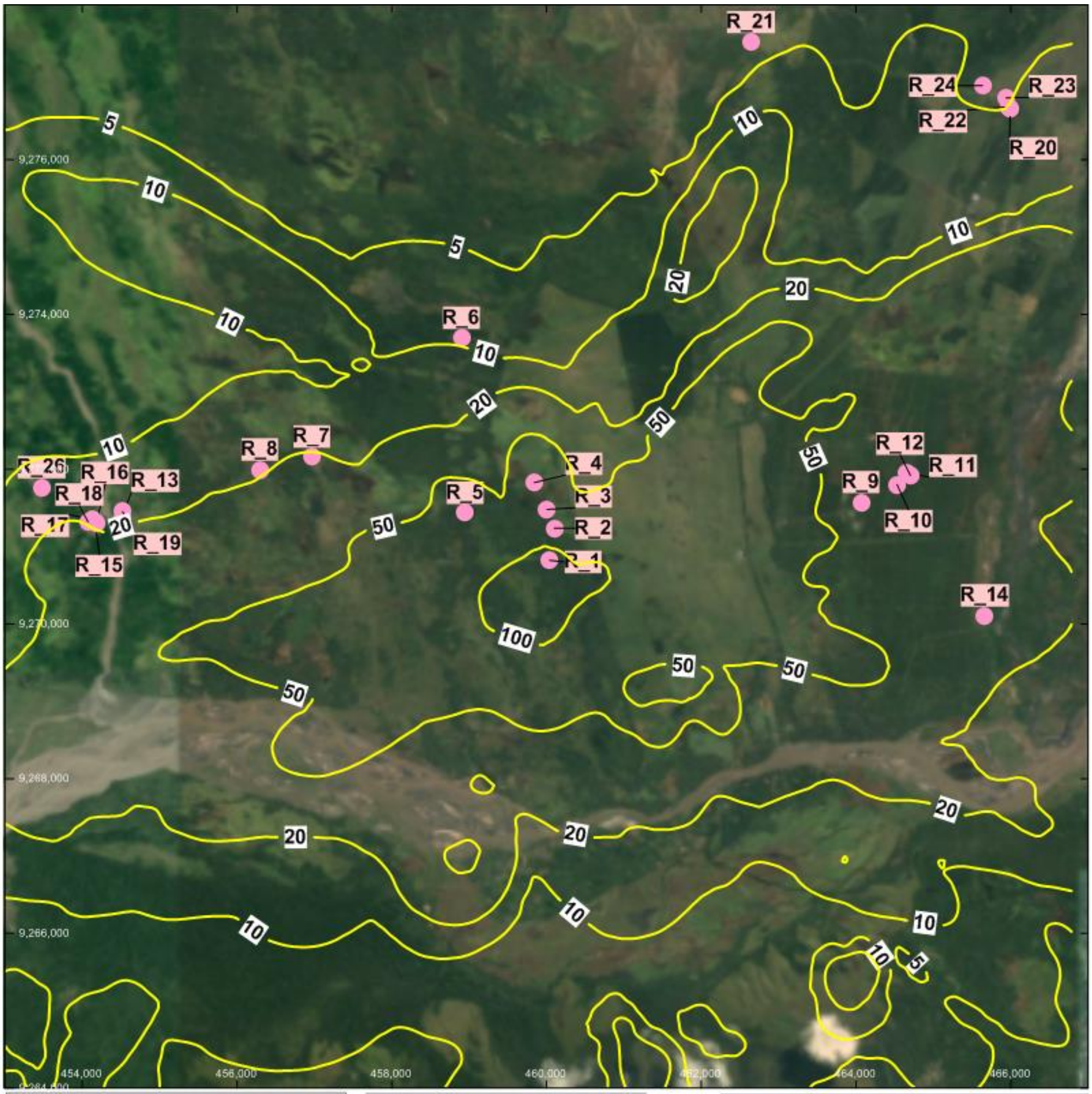

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Air Quality Impact Assessment

Incremental Impact

Pollutant	NO_2	Averaging Period	1-Hour	Unit	µg/m³

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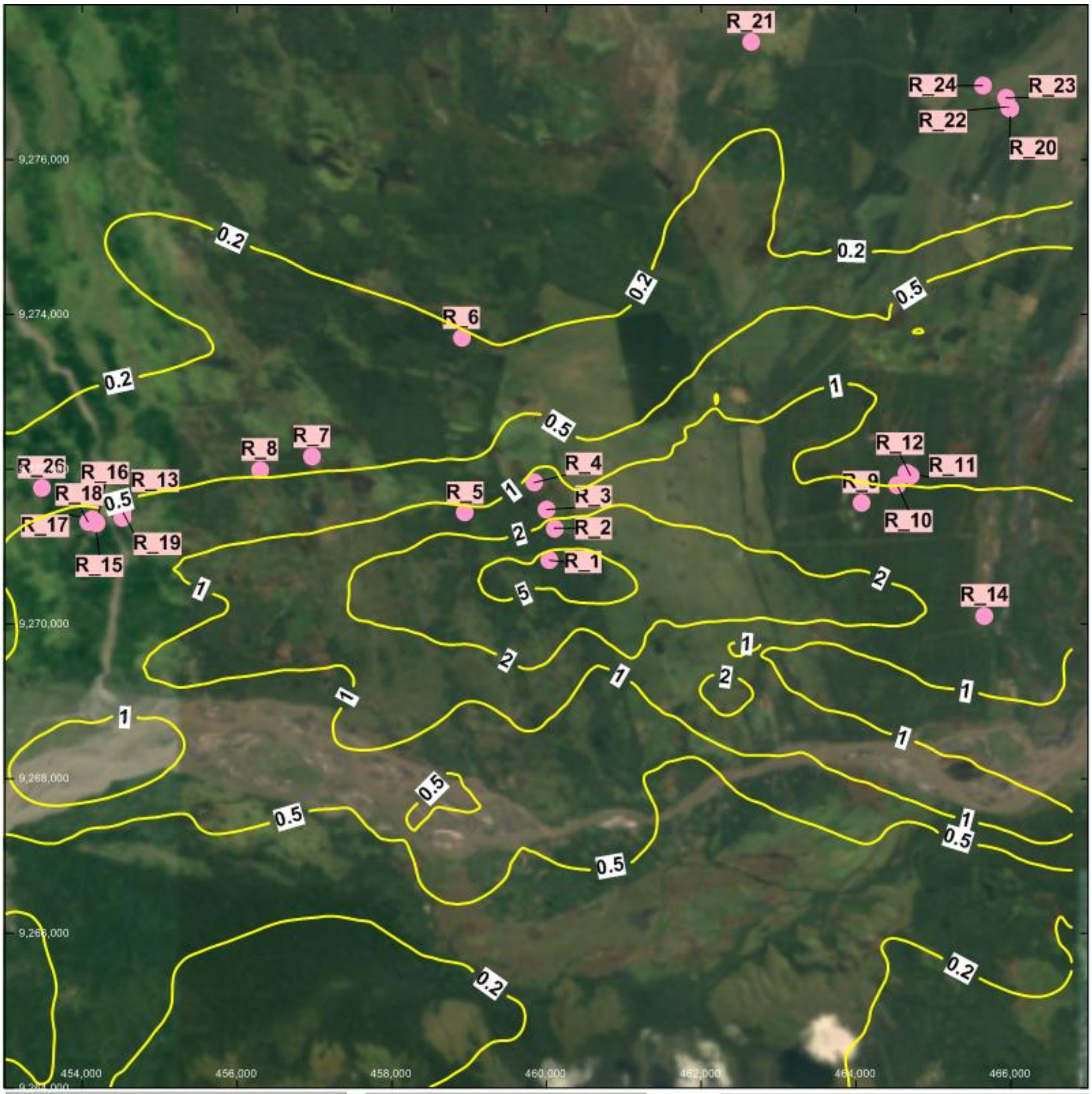

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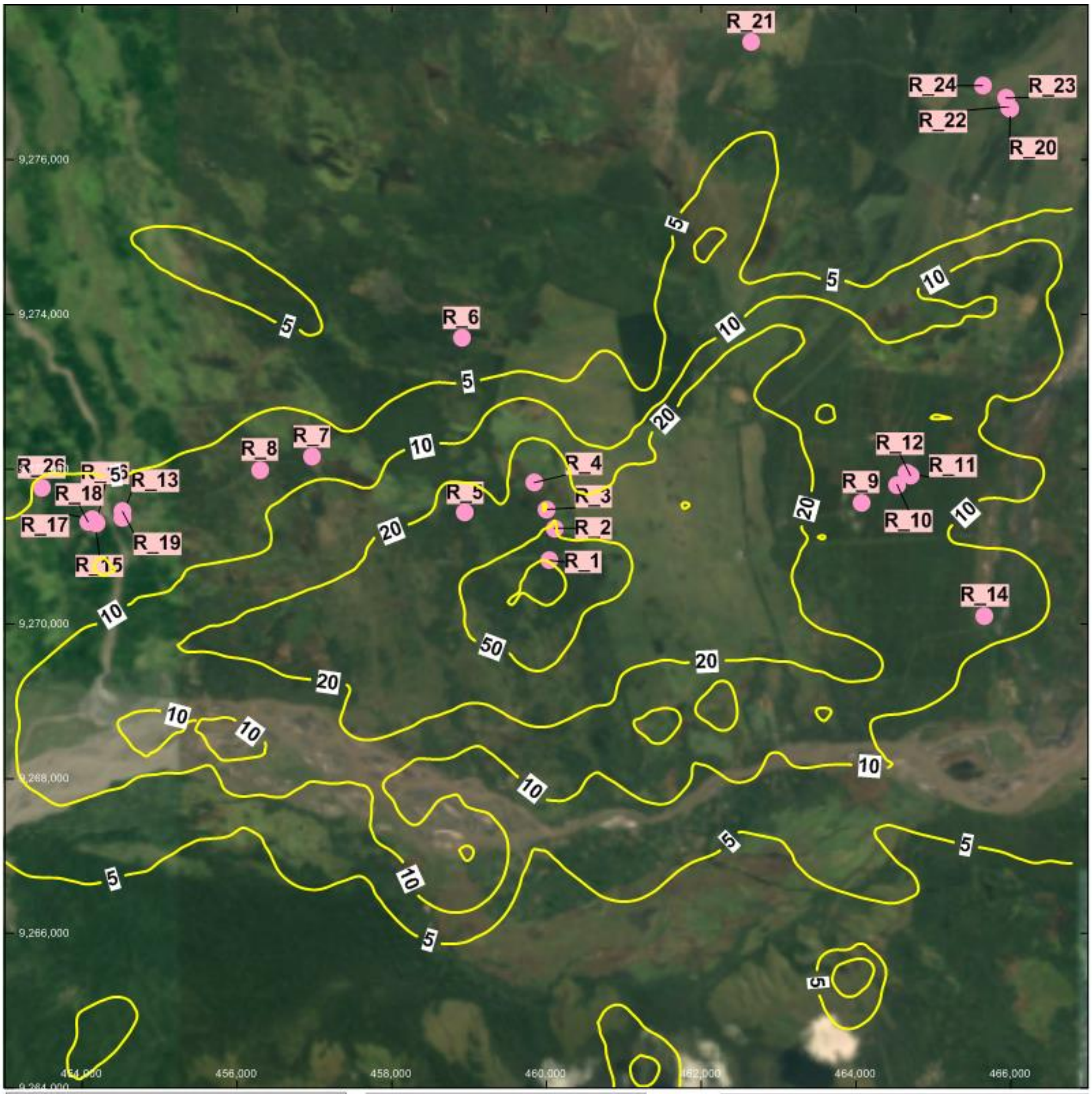
Markham Valley Power Project
Air Quality Impact Assessment

Incremental Impact

Pollutant	SO_2	Averaging Period	24-Hour	Unit	µg/m³

CONTOUR PLOTS



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F: +61 2 9427 8200
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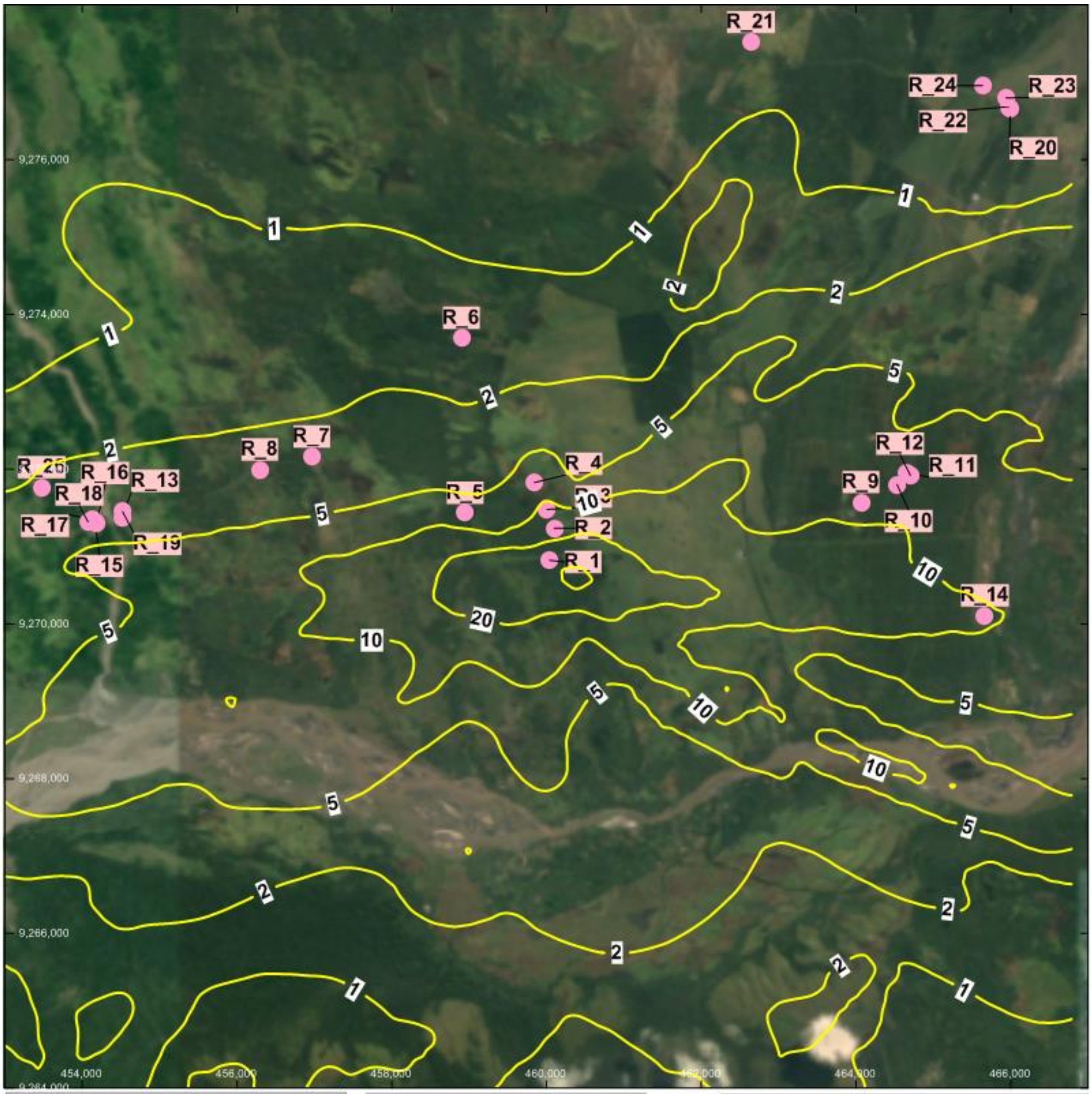
Markham Valley Power Project
Air Quality Impact Assessment

Incremental Impact

Pollutant	SO_2	Averaging Period	10 Minute	Unit	µg/m³

CONTOUR PLOTS



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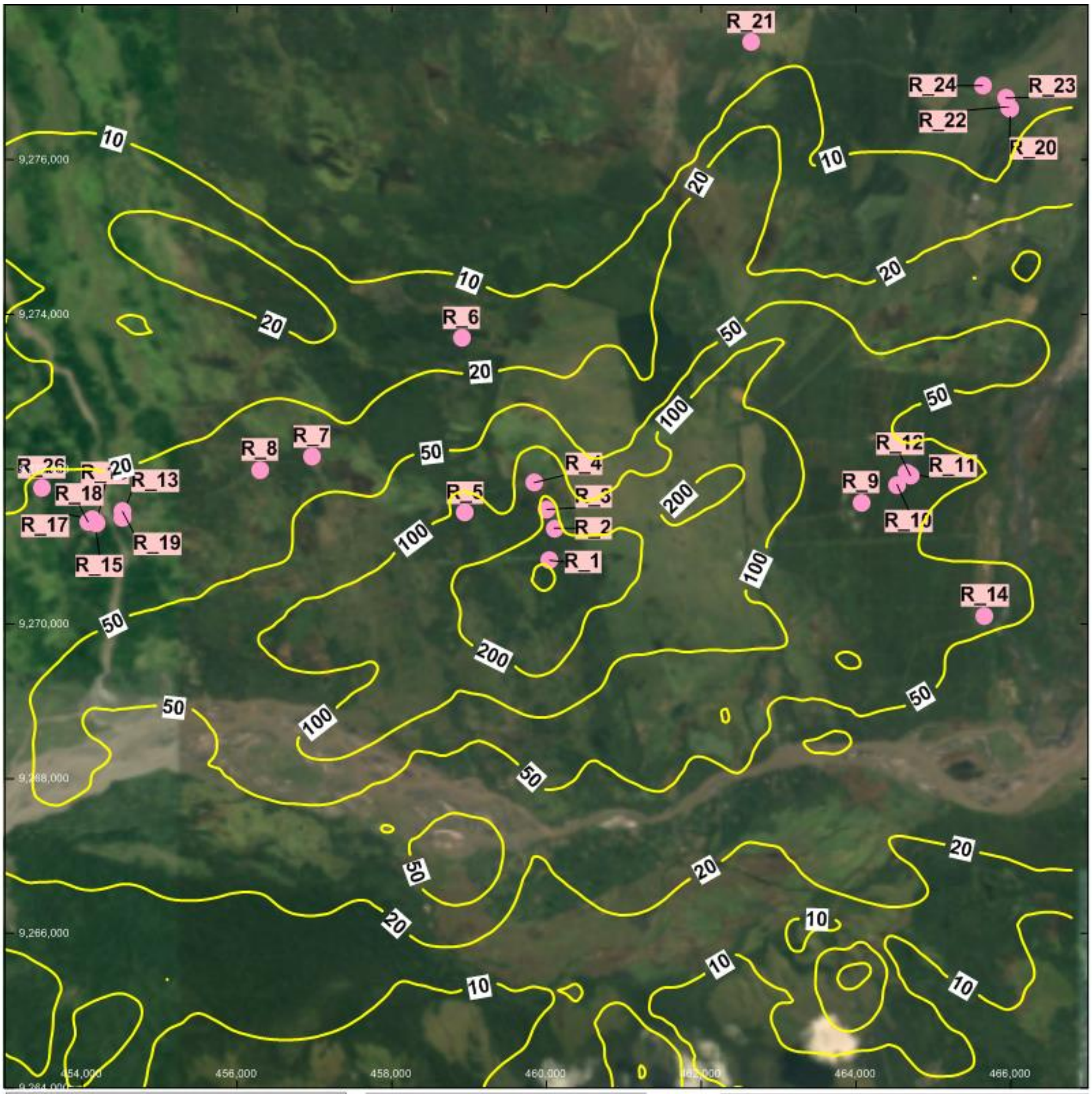
Air Quality Impact Assessment

Incremental Impact

Pollutant	CO	Averaging Period	24-Hour	Unit	µg/m³

CONTOUR PLOTS



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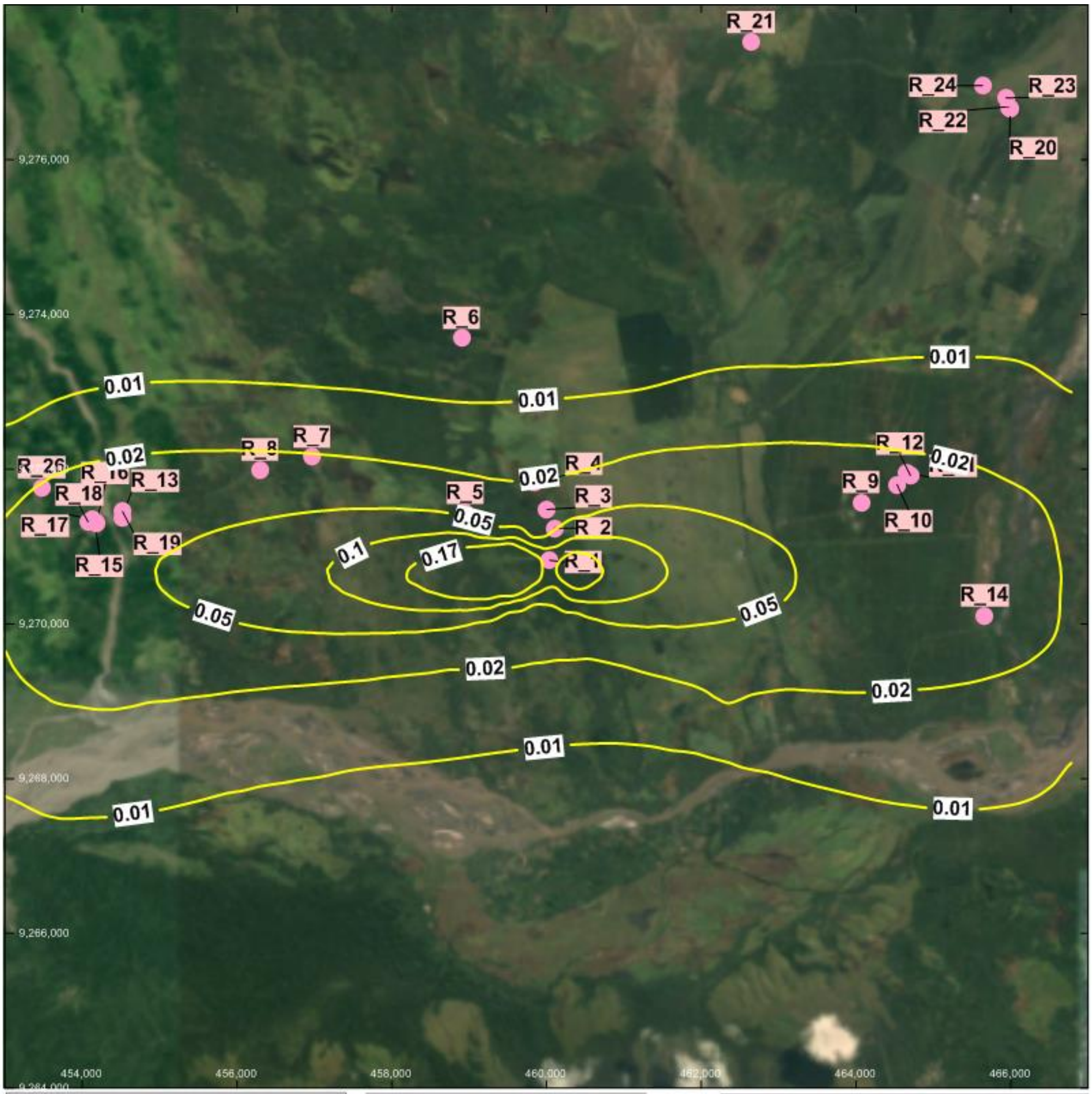
Markham Valley Power Project
Air Quality Impact Assessment

Incremental Impact

Pollutant	CO	Averaging Period	1-Hour	Unit	µg/m³

CONTOUR PLOTS



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2, Lincoln Street
Lane Cove
NSW 2066
T: +61 2 9427 8100
F: +61 2 9427 8200
www.slrconsulting.com

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Markham Valley Power Project
Air Quality Impact Assessment

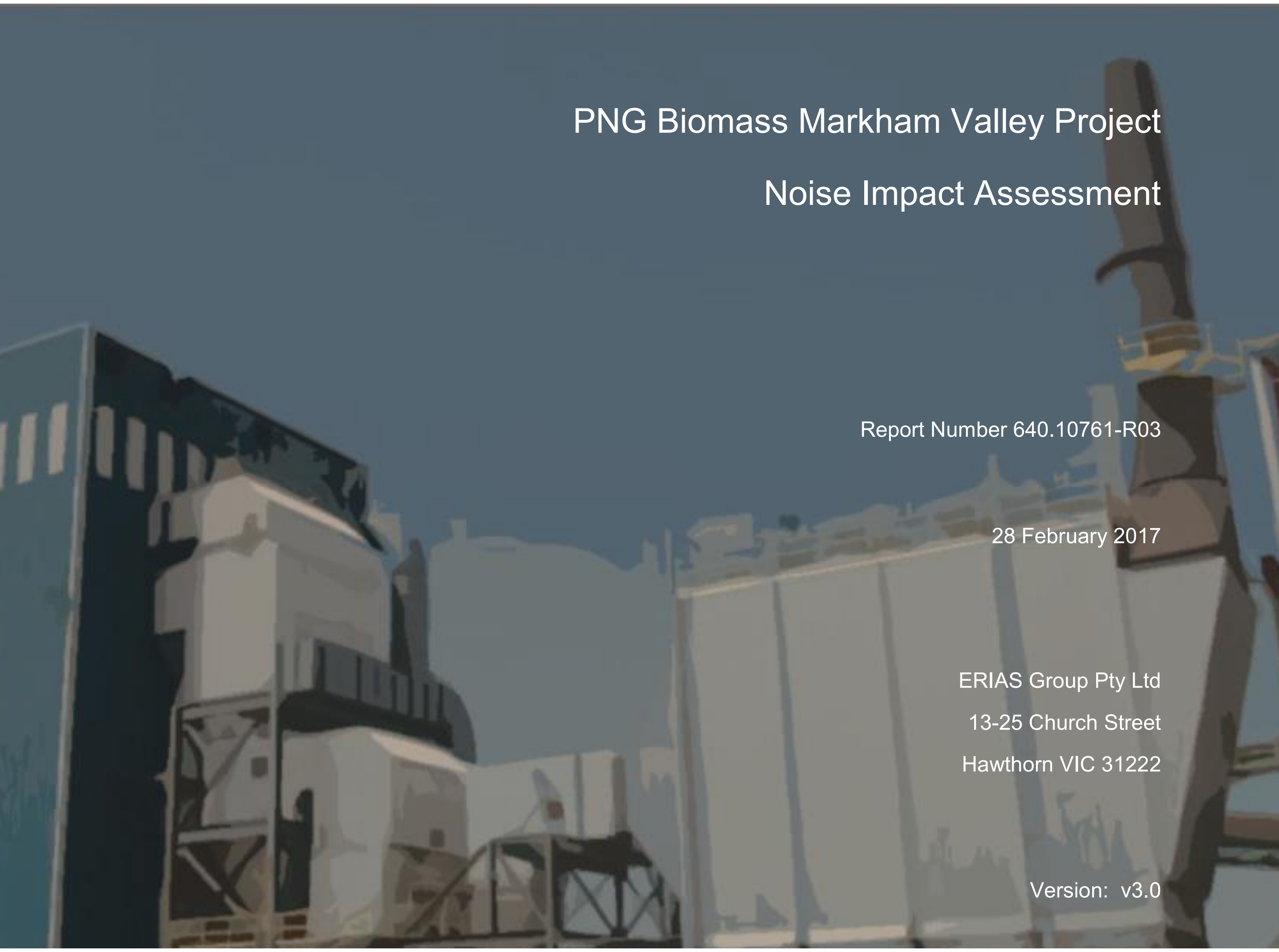
Incremental Impact

Pollutant	VOC (as benzene)	Averaging Period	Annual	Unit	µg/m³

Appendix 4
Noise Impact Assessment

SLR

global environmental solutions



PNG Biomass Markham Valley Project

Noise Impact Assessment

Report Number 640.10761-R03

28 February 2017

ERIAS Group Pty Ltd
13-25 Church Street
Hawthorn VIC 31222

Version: v3.0

PNG Biomass Markham Valley Project

Noise Impact Assessment

PREPARED BY:

SLR Consulting Australia Pty Ltd
ABN 29 001 584 612
Suite 2, 2 Domville Avenue
Hawthorn VIC 3122 Australia

T: +61 3 9249 9400   F: +61 3 9249 9499
melbourne@slrconsulting.com   www.slrconsulting.com

DOCUMENT CONTROL

Reference	Date	Prepared	Checked	Authorised
640.10761-R03-v3.0	28 February 2017	Luke Zoontjens	Miguel de la Mata	Luke Zoontjens
640.10761-R03-v2.0	20 February 2017	Luke Zoontjens	Gustaf Reutersward	Luke Zoontjens
640.10761-R03-v1.0	13 January 2017	Luke Zoontjens	Miguel de la Mata	

Executive Summary

The PNG Biomass Markham Valley project will involve construction and operation of a new 30 MW power plant (constructed in two 15 MW phases). In line with the project environmental approval requirements, this report presents an assessment of the likely noise emissions from the power plant, and details mitigation measures in order to achieve compliance with recommended criteria.

The noise assessment considered construction and operation of the power plant, in neutral and enhanced 'worst case' weather conditions, using industry standard prediction models and source data.

The recommended noise criteria for this project were derived from relevant documents including the World Health Organization (WHO) *'Guidelines for Community Noise 1999'* and the International Finance Corporation (IFC)/World Bank *Noise Management Guidelines 2007*.

Construction

It is expected that construction noise emissions will comply with recommended criteria on advice that construction is limited to the day period.

In regard to the day time limits, the analysis indicates that the predicted noise will be:

- typically below the $L_{Aeq,1hour}$ 75 dB criterion at the site boundary, and
- below the 3+ month construction noise limit of $L_{Aeq,1hour}$ 55 dB at distances in excess of 300 m from the site boundary.

During the night period, a construction noise goal of L_{Aeq} 37 dB is recommended as applicable. On this basis, noise from modelled construction activities at the nearest settlements 400 to 700 m north of the power plant are expected to be (with the exception of the power generators) above recommended levels during the night period and likely to be occasionally audible. Further away at Ganef, the concrete batching plant, trucks, tractors, graders and cranes are expected to be above recommended levels but similar to ambient noise levels, so unlikely to result in significant complaint.

In addition, it is noted that any night period operations involving truck pass-bys near villages may not be appropriate, and alternative routes or timings should be considered to reduce the potential for noise impacts.

It is recommended that any fixed construction plant (e.g. generators, concrete batching plant etc.) be located as far as possible from the northern boundary of the power plant site to minimise noise impacts during the day.

Operation

Operational noise emissions are considered to be generally acceptable on the basis that:

- For the day period, project noise criteria are forecast to be met at all known residences under all scenarios and under all meteorological conditions;
- At the nearest residential landowner locations, night time levels are below the criterion of L_{Aeq} 45 dB;
- Under neutral conditions, the noise levels meet the recommended target; and
- Under both neutral and worst case conditions, these levels are similar to and less than ambient noise levels expected in the local area (L_{Aeq} values ranging from approximately 40 to 50 dB during evening and night periods).

Executive Summary

However, noise levels at ultimate (full) capacity are forecast to be above recommended (non-mandatory) levels for two settlements within 700 m of the northern boundary. At these locations, noise levels during the night period are forecast to be above WHO goals but typically similar to background noise levels.

Long distance noise emissions from the power plant site are estimated to be most influenced by noise from the wood chipper, stack exhaust, turbine buildings and cooling towers, and there are various controls which can be applied to these elements to improve outcomes from that currently forecast, as discussed below.

Corona discharge noise from transmission lines are estimated to be compliant with project noise limits (and/or less than or equal to ambient noise levels) on the basis of a spatial buffer distance of at least 120 m (increasing to 300 m in regards to recommended targets). As such noise is highly variable and subject to ongoing condition and prevailing weather, it is recommended that field measurements are undertaken to confirm actual noise emission levels before implementing specific buffer controls of this order.

Recommendations

It is recommended that:

1. Alternative routes or timings are considered to reduce the potential for noise impacts from truck pass-bys near villages, particularly in the evening and night.
2. It is recommended that any fixed construction plant (e.g. generators, concrete batching plant etc.) be located as far as possible from the northern boundary of the power plant site to minimise noise impacts during the day.
3. The following controls be implemented in conjunction with recommendations in Section 5:

- **Cooling towers:** Fit a straight lined ducting cowl or suitable attenuator to the vertical discharge fans and implement variable fan speed controls. Consider lower speed, larger diameter fans.
- **Turbine buildings:** The model considers the turbine prior to being acoustically treated, so a suitable acoustic enclosure and ducting can be installed to effectively reduce noise emissions.
- **Wood chippers:** Orientate the feed chute openings away from the direction of nearest residential areas and/or fit acoustically-lined shrouds that absorb and screen noise. Select suitable wood chippers with lowest noise emissions (L_{WA} values).

Table of Contents

1 INTRODUCTION

The PNG Biomass Markham Valley Project is described as follows:

> *The Project has two components – the establishment of up to 16,000 ha of sustainably managed eucalypt plantations, and a biomass-fuelled power plant consisting of two 15 MW units, with the preferred power plant site being located in the southeast of the Project area. Construction of the power plant and related infrastructure, and development of the plantations, will take place over several years. Plantation development will be supported by road upgrades and/or construction, and a development of a large plant nursery. Plantations will be harvested every 7 to 9 years to provide about 175,000 BDMt/yr (bone dry metric tonnes of biomass (wood) per year).*
>
> *The combustion of dry biomass will generate steam from water sourced from bores or the Markham River. This steam will drive steam turbine generators, thereby generating electricity that will be transferred directly to the nearby high voltage Ramu Grid transmission system, which runs from Lae and Madang in the east to Mt Hagen and Mendi in the west. The power will be distributed to supply energy to major industries, households and rural communities.*

In line with the project approval requirements, this report presents an assessment of the likely noise emissions from the power plant, and details mitigation measures in order to achieve compliance with recommended criteria.

A summary of the acoustic terminology used throughout this report is provided in **Appendix A.**

1.1 Scope

This report presents the outcomes of the following desktop noise impact assessment, which:

- Characterises the existing noise environment (background ambient noise conditions) within the vicinity of the power plant site and provide context at the local and national scale (**Section 2.2**).
- Develops appropriate Project noise level targets aligned to relevant national/international criteria as required (**Section 2.1**).
- Predicts and models noise emissions likely to be generated during both the construction and operation phases of the Project (**Section 3**), including:
    - Temporary construction noise related to building the power station and transmission lines and establishing the plantations.
    - Noise related to power plant operations and in particular wood chipping activities, Corona discharge noise from transmission lines, and plantation activities including routine/rotational earthworks, harvesting and trucking.
- Conduct the study to satisfy relevant assessment requirements of PNG legislation and IFC Environmental and Social Performance Standards (2012), particularly Performance Standard 3: Resource Efficiency and Pollution Prevention.
- Assesses the potential impacts of noise on nearby sensitive receptors both during construction and operations (**Section 4**).
- Advises on appropriate and feasible mitigation to allow the Project to comply with noise targets (**Section 5**).
- Assesses residual impacts on the noise environment as a result of the proposed Project (**Section 5.2**).

Noise sources excluded in the assessment include:

- Regenerated noise from vibration.
- Vehicle movements outside the power plant site boundary during operations.

2 CRITERIA

2.1 Summary

A summary of Project noise criteria is provided in **Table 1**.

Table 1 Project Noise Criteria / Goals

Activity	Source	Noise Receiver	Time period	Noise Criteria / Goals (measured externally)	Reference (Note [1])
Normal operations and construction periods longer than three months	Continuous	Site boundary	All hours	$L_{Aeq,1hour}$ 70 dB	EIR
	Continuous	Residential	Night	$L_{Aeq,1hour}$ 45 dB (internal noise goal: $L_{Aeq,1hour}$ 37 dB (Note [2])	WHO / IFC
			Day	$L_{Aeq,1hour}$ 55 dB	IFC
	Single events	Residential	Night	L_{Amax} 60 dB (internal noise goal: L_{Amax} 52 dB) (Note [2])	WHO
Construction periods less than three months	Continuous	Residential	Night	$L_{Aeq,1hour}$ 45 dB (internal noise goal: $L_{Aeq,1hour}$ 37 dB) (Note [2])	WHO / IFC
			Day	$L_{Aeq,1hour}$ 75 dB	WHO
	Single events	Residential	Night	L_{Amax} 60 dB (internal noise goal: L_{Amax} 52 dB) (Note [2])	WHO
Vehicle movements on existing main roads	Intermittent	Residential	Day	No numerical limit	-
			Night	L_{Amax} 60 dB (internal noise goal: L_{Amax} 52 dB) (Note [2])	WHO

Note 1: EIR refers to the draft Project Environmental Inception Report. Reference is also made to the World Health Organization (WHO) *Guidelines for Community Noise* (1999) and IFC Health and Safety Guidelines (International Finance Corporation and World Bank Group, 2007). Refer **Section 2.4** below for further information.

Note 2: A noise level 8 dB lower than that indicated in the WHO/IFC Guidelines is recommended as an internal (non-mandatory) goal to reflect the low level of sound attenuation provided by most village accommodation in PNG.

In regards to general continuous operational noise, a criterion of L_{Aeq} 45 dB at night for residential receivers, in accordance with the IFC Noise Management Guidelines, is to be adopted for the Project.

A best practice design goal of L_{Aeq} 37 dB has been recommended as an internal (non-mandatory) goal for night time continuous noise to reflect the lower level of sound attenuation provided by most village accommodation in Papua New Guinea (PNG) and further minimise potential impacts to local villages at night.

From the ERIAS Group (2016) draft Environmental Inception Report:

> *Excluding start up and shut down periods, blowdown and operation of the bypass vent valve, the power plant will be designed and operated such that near field noise emissions (within 1 m of equipment) will be limited to 85 dB(A). Far field noise levels of the overall facility (including start up and shutdown) will be limited to 70 dB(A) at the site boundary (assuming that this is at least 150 m from the highest noise emitter).*

The basis for the above criteria is presented in the following subsections.

2.2 Existing Acoustic Environment

Background noise monitoring can be used as a guide for determining Project noise goals, since the ambient noise environment influences the potential for intrusion. For example, high ambient background sound levels can mask industrial noise levels, reducing the potential for impact.

SLR has previously undertaken noise monitoring in PNG locations that are similar to the Project area. Whilst distances between these locations and the Project area vary and the locations are spread across various regions within PNG, the terrain and character of the environment are anticipated to be comparable and it is therefore reasonable to expect the ambient noise environment to be similar. The range of ambient background noise levels at similar remote receivers (i.e. villages) measured in 2009 are as follows:

- Day (7am to 6pm) - L_{A90} 30 to 43 dB.
- Evening (6pm to 10pm) - L_{A90} 40 to 49 dB.
- Night (10pm to 7am) - L_{A90} 34 to 46 dB.

These previous noise surveys indicate that the local acoustic environment is usually dominated by insects, wind noise in foliage, birds, periods of heavy rain, domestic animals, and noise due to typical village domestic activities. The previous noise surveys concluded that high insect noise levels are a common feature of the ambient environment throughout the year.

The baseline ambient and background noise levels cited in this section were used in the assessment for reference and subjective analysis; however, due to the limited amount of monitoring data available for the Project area, a more conservative approach of applying absolute limits based on the internationally recognised noise criteria (**Section 2.1**) has been adopted.

2.3 Biophysical Environmental Values

The Project noise impact assessment criteria are used to assess the Project's potential impacts on biophysical environmental values. A biophysical environmental value is generally defined as a quality or physical characteristic of the environment that is important to ecological health or public amenity. Based on this definition, the key environmental values relating to noise and vibration are those relating to public health and amenity and include:

- Health of humans including sleep disturbance.
- Speech communication.
- Health of other forms of life, including the protection of ecosystems and biodiversity.
- Local amenity and aesthetic enjoyment.

2.4 Overview of Relevant Guidelines

The Project will include both operational and construction components. Operational criteria are applicable to noise sources which will operate throughout the life of the Project and to noise from long term construction activities. The latter include works that take more than three months to complete.

The primary objective of any environmental noise policy is to protect people from the adverse effects of noise. Excessive noise has the potential to cause nuisance, including sleep deprivation, stress and increased blood pressure, as well as other physical, physiological and psychological effects.

In addition, any noise policy must allow for business and industry to operate without needing to comply with unnecessarily stringent requirements.

PNG does not currently have specific domestic noise policies. In the absence of a local noise policy, it is appropriate to consider internationally recognised guidelines. Many countries around the world have developed their own noise policies to protect the health and amenity of residents. The policies are typically based on: previous studies and experience within those countries; statistical analysis of community reaction to various levels of noise; and/or studies undertaken elsewhere around the world.

The two environmental noise guideline documents most commonly used in PNG are World Health Organization (WHO) *Guidelines for Community Noise* (World Health Organization, 1999) and the International Finance Corporation (IFC) and World Bank *General Environmental, Health and Safety (EHS) Guidelines: Environmental Noise Management* (International Finance Corporation and World Bank Group, 2007). The criteria presented in these documents are based on historical studies and, ultimately, are similar to criteria developed in Australia and other developed countries.

In addition to the WHO and IFC Guidelines, a number of Australian guideline documents and standards are also used to address noise sources and activities that are not covered by the WHO or IFC Guidelines. The Australian criteria are often derived from, or are based on, other international standards (British, European and American).

Standards and guidelines considered relevant to this Project are provided below.

2.4.1 WHO Guidelines for Community Noise – 1999

The WHO guidelines provide detailed background information and cover various noise related issues such as hearing impairment (occupational noise), sleep disturbance, cardiovascular and physiological effects.

Recommendations from the WHO guidelines relevant to the Project are provided below.

2.4.1.1 Day Period

The WHO guidelines recommend the following day period noise levels, measured externally:

- L_{Aeq} 50 dB to ‘protect the majority of people from being moderately annoyed’.
- L_{Aeq} 55 dB to ‘protect the majority of people from being seriously annoyed’.
- L_{Aeq} 70 dB at industrial and commercial areas to prevent hearing impairment.

In addition, the WHO guidelines nominate an internal noise level inside dwellings of L_{Aeq} 35 dB for the purpose of allowing good speech communication.

Assessment periods are not defined in WHO (1999). For the purpose of this assessment it is assumed that the levels are to be measured over one hour.

2.4.1.2 Night Period – Sleep Disturbance

The WHO guidelines generally prescribe two noise levels at residential locations to ensure that sleep is not adversely affected, these being:

- L_{Aeq} 30 dB for continuous noise.
- L_{Amax} 45 dB for single events (maxima).

The above levels are applicable at the receptor’s ear position, which would typically be indoors during the night time, and the WHO (1999) guidelines suggest that a correction of 15 dB can be applied to determine the equivalent external criteria for a typical house with the windows slightly open. The 15 dB correction is consistent with typical western/European building construction. Typical dwellings in villages in and around the Project area are of lightweight construction with a significant number of gaps and openings in the façades. For this reason a lesser correction of 8 dB has been adopted.

Consequently, appropriate external noise limits are:

- L_{Aeq} 37 dB for continuous noise.
- L_{Amax} 52 dB for single events.

The WHO guidelines also note that special attention should be given to the following conditions when investigating sleep disturbance:

- Noise sources in an environment with a low background noise level. For example, night traffic in suburban residential areas.
- Environments where a combination of noise and vibrations are produced such as heavy duty road vehicles.
- Sources with low-frequency components. Disturbances may occur even though the sound pressure level during exposure is below L_{Aeq} 30 dB.

2.4.2 IFC/World Bank Guidelines

2.4.2.1 Noise Management Guidelines – 2007

The 2007 IFC guidelines for the management of environmental noise prescribe limits for the day and night periods. The following is an extract:

> *"Noise impacts should not exceed the levels presented in Table 1.7.1, or result in a maximum increase in background levels of 3 dB at the nearest receptor location off-site.*
>
> ***Table 1.7.1 Noise Level Guidelines***

Receptor	*One Hour LAeq (dBA)*	
	Day (7:00 am -10:00 pm)	*Night (10:00 pm -7:00 am)*
Residential / Institutional /educational	*55*	*45*
Industrial / Commercial	*70*	*70*

> *Highly intrusive noises, such as noise from aircraft flyovers and passing trains, should not be included when establishing background noise level."*

The noise levels presented in the table above are derived from the WHO (1999) guidelines discussed in **Section 2.4.1** of this report. Note that the values in the table correspond to the outdoor noise levels for continuous noise. The IFC guidelines do not provide recommendations for single noise events, such as blasting.

The IFC guidelines also provide a requirement that background noise levels not be increased by more than 3 dB. However, this criterion is not satisfactorily defined in the IFC (2007) document:

- The acoustical descriptors used for the assessment of background noise level are not specified.
- It is unclear whether the criterion is meant to apply when background noise levels are very low (resulting in a greater level of acoustical amenity at quiet locations) or when background levels are very high (thereby avoiding the imposition of unnecessarily low noise limits in already noisy locations). The former definition would potentially result in more stringent noise limits than in most other parts of the world such as Australia.
- It is unclear whether the background based criterion should be incurred at all times, or during the night time only.

Given this ambiguity, further reference to background based limits will not be included in this report.

2.4.2.2 IFC/World Bank Performance Standards on Environmental and Social Sustainability

Item 11 of Performance Standard 3 - Resource Efficiency and Pollution Prevention within the IFC Performance Standards on Environmental and Social Sustainability (International Finance Corporation (IFC), 2012) states that

> *To address potential adverse project impacts on existing ambient conditions,12 the client will consider relevant factors, including, for example (i) existing ambient conditions; (ii) the finite assimilative capacity of the environment; (iii) existing and future land use; (iv) the project's proximity to areas of importance to biodiversity; and (v) the potential for cumulative impacts with uncertain and/or irreversible consequences. In addition to applying resource efficiency and pollution control measures as required in this Performance Standard, when the project has the potential to constitute a significant source of emissions in an already degraded area, the client will consider additional strategies and adopt measures that avoid or reduce negative effects. These strategies include, but are not limited to, evaluation of project location alternatives and emissions offsets.*

In lieu of specific objective requirements, achieving the criteria set out in **Section 2.1** above as per the IFC Noise Management Guidelines (**Section 2.4.2.1**) is considered to meet this performance standard in regards to environmental noise emissions.

2.4.3 Forest Stewardship Council

As the project involves forest management, this noise assessment is designed in response to Principle 6 of the National Forest Management Standards for Papua New Guinea, v1.1 2010 (Forest Stewardship Council , 2010) which refers to management of Environmental Impact:

> *Forest management shall conserve biological diversity and its associated values, water resources, soils and unique and fragile ecosystems and landscapes and, by so doing, maintain the ecological functions and the integrity of the forest.*

Reference is made to associated FSC 'International Generic Indicators' guidelines (Forest Stewardship Council, 2015) which provide further detail in regards to this principle as follows:

> *6.2 Prior to the start of site-disturbing activities, The [proponent] shall identify and assess the scale, intensity and risk of potential impacts of management activities on the identified environmental values;*
>
> *[..]*
>
> *6.3 The [proponent] shall identify and implement effective actions to prevent negative impacts of management activities on the environmental values, and to mitigate and repair those that occur, proportionate to the scale, intensity and risk of these impacts.*
>
> *[..]*
>
> *6.4 The [proponent] shall protect rare species and threatened species and their habitats [in the study area[3]] through conservation zones, protection areas, connectivity and/or (where necessary) other direct measures for their survival and viability. These measures shall be proportionate to the scale, intensity and risk of management activities and to the conservation status and ecological requirements of the rare and threatened species.*

[3] Defined by the FSC as the spatial area or areas submitted for FSC certification with clearly defined boundaries managed to a set of explicit long term management objectives which are expressed in a management plan. This area or areas include(s): all facilities and area(s) within or adjacent to this spatial area or areas under legal title or management control of, or operated by or on behalf of the proponent, for the purpose of contributing to the management objectives; and all facilities and area(s) outside, and not adjacent to this spatial area or areas and operated by or on behalf of the proponent, solely for the purpose of contributing to the management objectives

The [proponent] shall take into account the geographic range and ecological requirements of rare and threatened species beyond the boundary of the [study area], when determining the measures to be taken inside the [study area].

Principle 6 refers to both human residents as well as local fauna, and both can be adversely impacted by excessive noise. It is important to note that this principle is not objective but requires application of the best available information. Accordingly, the standard for assessment is here considered to be in line with other international guidelines on environmental noise such as that listed in the above subsections.

3 METHODOLOGY

This section presents the noise prediction method and assumptions, the investigated modelling scenarios, and main modelling inputs and procedures.

3.1 Approach

Noise prediction and assessment for the Project reflects two broad approaches:

- Where site locations and defined layouts are available (e.g. power plant site), noise predictions have been made to discrete receptors and the surrounding area using SoundPLAN (SoundPLAN GmbH), a detailed industry noise model as per **Section 3.2**.
- For construction works which are geographically linear with anticipated short term associated impacts, or where detailed information regarding construction equipment or technique is lacking due to the preliminary stage of the Project, a more generalised buffer distance approach has been followed where the levels have been predicted by either a simplified SoundPLAN noise model or calculation spreadsheets depending upon available information as per **Section 3.4**.

Both approaches are consistent with industry standards applicable in Australasia and enable assessment against the criteria outlined in **Section 2.1**. The analysis and reporting has been completed by a qualified acoustics engineer with 14 years' experience and membership to the Australian Acoustical Society (AAS). SLR is an accredited Member Firm of the Association of Australasian Acoustical Consultants (AAAC).

3.2 Noise Sources

3.2.1 Construction

The mobile (and fixed) plant and equipment and associated sound power levels (SWL) for each modelling scenario are presented in **Table 2**, based on information provided as of the date of the first version of this report.

The SWLs have been sourced from SLR's noise source database.

Table 2 Construction of the Power Plant and Associated Civil Works and Infrastructure

Equipment	Duty %	Total Qty. Of Noise Sources	Individual continuous Sound Power Level (L_{WA}, dB)	Location
Construction Of Civil Works / Support Facilities / Fuel Storage Area				
20T Excavator	75	2	105	Nearest to each receiver within extent of proposed fuel storage, administration, workshop and office areas
45T Excavator	100	1	108	
D7 Dozer	100	1	110	
Tipper Truck	100	1	106	
Water Truck	100	1	115	
Cat 14 Grader	100	1	110	
50T All Terrain Crane	100	1	112	
Construction of main buildings				
Cat 40T ADT	100	2	106	Nearest to each receiver within extent of main furnace, turbine, cooling tower and silos
20T Excavator	75	2	105	
45T Excavator	75	2	108	
Cat 966 Loader	100	1	113	

Equipment	Duty %	Total Qty. Of Noise Sources	Individual continuous Sound Power Level (L_{wA}, dB)	Location
Water Truck	100	1	112	
Tipper Truck	75	4	114	
50T All Terrain Crane	100	2	109	
Portable Refrigeration - (L_{Aeq} 85dB @1m)	100	4	102	
Standby Diesel Generators	100	4	124	
Concrete Truck	75	1	104	
Batch Plant	100	1	118	
Onsite power, accommodation camp				
Air Conditioners - Small	100	10	84	Nearest to each receiver within extent of administration buildings and carpark
Diesel Generators	100	2	108	

Construction timing is modelled as follows:

- 10 hour days Monday to Friday between 07:00 and 17:00, 5 hours during the day on Saturdays.
- If there is a need to accelerate works, this is likely to be by extending Saturday hours up to 10hrs between 07:00 and 17:00.

We have since the first issue of this report been advised that machinery that may also be used by the civil subcontractor during construction include:

- Two piling rigs for driven piles (or bore piling machines in case of bore piles).
- One pile hammer for driven piles.
- Two concrete pumps.
- Four concrete truck mixers.
- Four concrete vibrators.

The mechanical erection contractor will typically use one large crawler crane (approx capacity of 230 t) for boiler erection and one medium sized hydraulic crane for all the remaining mechanical lifting works. Some small mobile cranes (25 to 35 t) might be used as required.

3.2.2 Operations

In order to provide representative noise impacts across the life of the Project, mobile and fixed plant and equipment associated with the Project has been modelled for the following scenarios:

Table 3 Key noise sources

Item	Quantity	Noise level definition	Comments, rationale
Biomass furnace and supporting plant building	2	Continuous noise level L_{Aeq} 85 dB at 1 m from any intake/enclosure Noise spectrum will be that of typical boiler with insulated steel panels and acoustic louvres	From existing specification. The main boiler building is not clad, but the steam turbine will be placed in a noise enclosure.
Wood chippers and conveyors	2	Intermittent noise level L_{wA} 116 dB; L_{Aeq} 85 dB at operator head position	30 tonnes / hour, Wood fuel PTO, 550 rpm 2 operate for 30 MW capacities. Modelled as having unshrouded feed chutes
Steam turbine buildings	2	Continuous noise level L_{Aeq} 85 dB at 1 m from opening	15 MW each
Cooling towers	2	Continuous noise level L_{wA} 110 dB; L_{Aeq} 85 dB at 1 m from enclosure at head height	2 x 6 m fans each Estimated as 3 MW fan capacity 50% duty
Electrical transformer station	1	L_{wA} 86 dB	Estimated from AS 60076.10:2009, Standard Transformer - No Fan 18 MVA, 132kV, 50 Hz
Workshop		L_{Amax} 85 dB at 1 m from any opening / enclosure	Non-specialised air and bench tools
Air compressor	2	L_{Aeq} 85 dB at 1 m from any intake / enclosure	Containerised. Spectrum based on 100 kW centrifugal unit.
ID Stack fan	2	L_{Aeq} 85 dB at 1 m from any intake / enclosure	Containerised Single fan each (not multiple / paired), 25 m^3/s
Generator set	1	L_{Aeq} 85 dB at 1 m from any intake / enclosure	Containerised, 3 MW, 1,500 rpm Used only for emergency operation and periodic maintenance
Truck	3 movements per hour day period (up to 2 per hour at night)	L_{wA} 106 dB along defined track route within compound	57 trucks each way per day (~175,300 tonnes / year) at ultimate capacity Mobile plant, worst case positions
Crane	1	L_{wA} 102 (continuous) Operates 50% of the time	Fixed position, for loading logs into chipper
Reach forklifts	1	L_{wA} 109 dB (continuous) Operates 50% of the time	Mobile plant, 30 t capacity for moving logs from open fuel storage
Front end loaders	1	L_{wA} 113 dB (continuous) Operates 50% of the time	Rubber tired Caterpillar 966 or equal for moving chip pile
Electrical corona discharge [4]	-	L_{wA} 61 dB	Highly variable. Based on 132 kV, adjusted from SLR measurements of similar during high humidity conditions

The noise model of these operations assumes that:

[4] Noise from corona discharge associated with a high-voltage transmission line has a crackling or hissing component which commonly occurs at high humidity levels, e.g. above 80 percent relative humidity.

- Apart from the wood chippers, the steam turbines are the only pieces of equipment with a noise level above L_{Aeq} 85dB at 1 m prior to treatment – regardless they have been modelled as having an enclosure, resulting in L_{Aeq} 85 dB at 1 m at each standing head position (1.5 m height) above any ground / floor level.
- As per the draft EIR (ERIAS Group, 2016):

  Excluding start up and shut down periods, blowdown and operation of the bypass vent valve, the power plant will be designed and operated such that near field noise emissions (within 1 m of equipment) will be limited to 85 dB(A). Far field noise levels of the overall facility (including start up and shutdown) will be limited to 70 dB(A) at the site boundary (assuming that this is at least 150 m from the highest noise emitter).
- All plant and equipment operates concurrently in order to simulate the overall maximum potential noise emission for each scenario.
- The power plant itself (including steam turbine) will be operated 24 hours per day, 7 days per week.
- Log handling, wood processing and wood chipping are proposed to be 12 hours per day, 6 days per week. Current information is 7am to 7pm, Monday to Saturday. However, log handling, chipping and fuel operations will be capable of operating 24 hours/during night time hours, and information indicates that longer hours (>12) or extra days (>6; I.e., Sundays) could occur if deemed necessary.

The volume of Project-related traffic, which would primarily be the transportation of logs and supplies (inward), waste ash (outward) and staff, is estimated to be 57 trucks each way per day. The traffic volumes are below those required to accurately predict noise levels using normal road prediction models[5]. For infrequent pass-by events associated with the Project, it is more appropriate to conduct an assessment of individual pass-by noise levels. In particular, consideration of night period individual pass-by levels is the most critical and can be assessed with respect to WHO sleep disturbance criteria.

3.2.3 Duration Adjustment, De-rating Factors and Emergency Operating Conditions

A noise model typically assumes that all noise sources are operating simultaneously at full power. For complex noise models with a large number of noise sources (especially mobile equipment typical for civil works) the predictions can overestimate a real world measured noise level as many of the noise sources do not operate continuously at full power and their operation may be intermittent or cyclical.

Recognition that all equipment will not operate 100% of the time allows for the predicted results to be refined to represent a more realistic scenario. A de-rating factor has been applied to all equipment associated with the operation of the Project to represent realistic noise operations. The de-rating factor is based on the anticipated duty of a source. The duty of a source is the assumed percentage of time that a source is likely to operate and has been estimated based on previous experience and our current understanding of the Project. **Table 2** and **Table 3** provide details of the duty applied to each source.

Safety reversing beepers, if required to be fitted, they may be audible during the construction or operation of the Project support infrastructure (roads and tracks) when in proximity to villages; however as a mandatory safety requirement would not usually come under assessment for short-term construction activities. During operations, given the typical offset distances of the villages to the Project components (greater than 3 km), reversing alarms and other emergency operating conditions would generally not be audible at the surrounding villages and have therefore not been included under the noise assessment of the Project.

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[5] For example, under the UK's Department of Transport *Calculation of Road Traffic Noise (1988)* (CoRTN), the minimum traffic flow required for calculation is 1000 vehicles in an 18-hour period. CoRTN is one of the most widely used traffic noise prediction algorithms accepted by authorities internationally.

3.3 Plant compound area

3.3.1 Numerical Code

In order to calculate the noise emission levels at the nearest noise sensitive receptor locations, the CONCAWE (1981) environmental noise attenuation model was implemented within the SoundPLAN (SoundPLAN GmbH) (Version 7.4) numerical platform. This involved compilation of the digital ground map (containing ground contours), the location and sound power levels (L_w) of each key noise source, and the location of sensitive receivers.

The CONCAWE method was developed for large open air industrial facilities and incorporates the influence of wind and atmospheric stability on propagation. The CONCAWE method has been used successfully on other projects in PNG and is routinely used to predict noise from mining and industrial facilities.

SoundPLAN has been used successfully on other projects in PNG and Australasia, and is routinely used to predict noise from mining and industrial facilities by taking into account factors such as distance attenuation, ground hardness, air absorption and barrier shielding effects, as well as meteorological conditions.

3.3.2 Environment and Terrain Effects

Although the study area is relatively flat, the local topography can still affect the propagation of noise. The extent of change in noise levels due to topographical effects depends on the level of shielding or reflection provided (which is very site specific). These factors have been modelled as follows:

- The effect of topographical shielding is taken into account in the 3D modelling and noise predictions for the modelling scenarios described in **Section 4.**
- Fuel (biomass/log) stockpiles are conservatively considered to have no shielding benefit (conservative).
- Ground absorption is detailed in **Table 4.** The hardness of intervening ground between noise sources and receptors also affects the propagation of noise whereby the acoustic impedance (ground absorption coefficient) determines how the direct and reflected acoustic ray paths interact.

Table 4 Ground Absorption

Where: G= 0 for reflective hard ground G= 1 absorptive soft ground	G = 1 for natural ground vegetation areas. This is considered in lieu of specific foliage attenuation.
	G = 0.25 in project site areas. This is considered appropriate for partially compacted ground and dirt with no vegetation.
	G = 0 for water bodies.

3.3.3 Weather Effects

The noise propagation predictions require careful consideration of meteorological conditions (wind, temperature, humidity and temperature inversions) within the Project area.

Selected temperature and humidity conditions are based on indicative average values for the night period at the Project area (SLR Consulting Australia Pty Ltd, 2017).

Table 5 Modelled Meteorological Parameters

Weather Conditions	'Neutral'	'Enhanced' ('Worst Case')
Temperature	24°C	24°C
Humidity	86%	86%
Air absorption rate	ISO 3891	ISO 3891
Pasquill Atmospheric Stability Class	D (Note [1])	F (Note [2])
Wind Speed	0 m/s	2.5 m/s
Wind Direction	N/A	Downwind
Temperature Inversion	No	Yes

Note 1 Class D represents neutral conditions, where temperature inversions are unlikely to occur.

Note 2 Temperature inversions occur during stable atmospheric conditions (low winds and clear skies) and typically between dusk and dawn. Atmospheric Stability Class F represents the conditions in which temperature inversion are likely to occur. Class F was predicted to occur for a significant period of the time and as such this would be considered to occur sufficiently often to be considered a prevailing condition and, therefore, it has been modelled in addition to 'neutral' conditions.

3.3.4 Receiver and Assessment Locations

Receivers were modelled based on the information provided as at the date of this report and review of aerial imagery within 6 km of the power plant site. A full list of receivers is provided in the associated Air Quality report authored by SLR (2017).

Note that the variation in prediction results increases significantly over large distances and the recommended 'reliable range' of the model is approximately 2,000 m. With consideration of such standard limitations, and likely ratio between source noise levels and criteria, the study is limited to 6 km from the power plant site boundary.

Noise emission levels have been predicted at the nearest noise sensitive receptor(s) surrounding the power plant. All receivers have been positioned 1.5 m above ground and assessed under free-field conditions (no façade reflection).

Noise contour plots have been produced for the nominated modelling scenarios in the area surrounding the power plant site. The noise contour plots are located in **Appendix B**.

3.4 Traffic and plantation activities

The below table provides recommended separation distances for major plantation works, noting that the extent and alignment have not yet been confirmed.

Table 6 Traffic and plantation activities

Equipment	Noise level, dB	Recommended separation distance, m			
		Day period	Night period		
		$L_{Aeq,1hour}$ 55 dB	$L_{Aeq,1hour}$ 45 dB	$L_{Aeq,1hour}$ 37 dB	L_{Amax} 60 dB (Note[1])
Plantation activities					
Excavator with timber processing head	L_{wA} 115	400	1,000	> 1,500	-
D7 Dozer	L_{wA} 110	220	600	> 1,200	-
Cat 14 Grader	L_{wA} 110				
50T All Terrain Crane	L_{wA} 112	300			-

Equipment	Noise level, dB	Recommended separation distance, m			
		Day period	Night period		
		$L_{Aeq,1hour}$ 55 dB	$L_{Aeq,1hour}$ 45 dB	$L_{Aeq,1hour}$ 37 dB	L_{Amax} 60 dB (Note[1])
Truck movements on roads					
Haul truck (Note[2])	L_{AE} 122 (passby) L_{wAmax} 113	-	70	120	200

Note 1 Applicable to vehicle movements on existing main roads only.
Note 2: $L_{Aeq,1hour}$ based on 3 trucks an hour.

From this table it can be seen that

- Separation distances of the order of 400 m or less is appropriate to the day period, assuming constant operation;
- the excavator with timber processing head is considered the highest risk in regards to meeting night time requirements, with the likely separation distance being at least 1 km. In practice at these distances, received noise levels will vary substantially according to prevailing weather conditions and may not be perceptible from ambient levels; and
- if trucks are to be used during the night period, the route should be more than 200 m from a nearby residence where practicable.

3.5 Uncertainty of Prediction

The statistical accuracy of environmental noise predictions using CONCAWE has been comprehensively tested (Marsh, 1982). In models replicating scenarios with well-defined parameters the CONCAWE predictions were accurate to ±2 dB in any one octave band between 63 Hz and 4 kHz and ±1 dB overall under the same conditions.

However, noise predictions inherently require that a large number of parameters are defined, many of which can only initially be based upon preliminary assumptions (e.g. plant and equipment assumed in each modelled scenario, sound power levels of plant and equipment, duty and durations of operation, precise locations of sources, receptors and vegetation attenuation), some of which have already been discussed in this report.

In considering the combined uncertainties of these assumptions, of which many are conservative, the authors believe that the values predicted by the model would be within ±5 dB of actual with 90 percent certainty as per international guidelines (ISO, 2008), should the Project proceed as currently described. This shall be taken into consideration when evaluating and assessing impacts with respect to the margin of compliance or exceedance.

4 RESULTS AND DISCUSSION

4.1 Construction

Predicted noise levels associated with construction stages of the Project are presented for enhanced (worst case) meteorological propagation conditions.

Indicative offset distance calculations have been conducted to assist with planning of the construction stage of the Project. The sound power levels (SWL) have been sourced from SLR Consulting's noise source database.

Table 7 provides a list of the main items of plant associated with construction and indicative noise levels at an offset distance for each item of plant (i.e. single source of noise). The closest offset distance shown is 50 m, which would be representative of worst case construction activities conducted near the boundary of the power plant site.

Table 7 Construction Noise Sources – Offset Distance Noise Levels

Source	Noise Level at Offset Distance, L_{Aeq} dB					Project Goals
	50 m	100 m	200 m	400 m	800 m	
Concrete Batching Plant	68	62	56	49	42	**75 dB** for 3 month construction period or less (day). **55 dB** if construction activities for more than 3 month period (day). **37 dB** during the night.
Generators (55 kW)	50	44	38	31	<30	
Water Trucks, Tractors, Graders, Crane	68	62	56	49	42	
Compressors, Bobcat, Rollers, Excavator	63	57	51	44	37	

It should be considered that many activities would occur simultaneously on the site, and as such the noise would be cumulative from all above sources. While there are no strict guidelines for day period construction activities, noise levels above L_{Aeq} 75 dB should be avoided.

In regards to the day time limits, the above analysis indicates that predicted noise will be:

- typically below L_{Aeq} 75 dB at the site boundary, and
- below the 3+ month construction noise limit of L_{Aeq} 55 dB at distances in excess of 300 m from the site boundary.

During the night period, the normal operational noise goals of L_{Aeq} 37 dB would be applicable. On this basis, noise from modelled construction activities at the nearest settlements 400 to 700 m north of the power plant are expected to be:

- during the day compliant with the project goals for either short or long-term construction; and
- with the exception of the power generators, above recommended levels during the night period;

Considering ambient conditions as discussed in **Section 2.2**, cumulative construction noise levels at the nearest residential receivers are forecast to increase between 7 and 19 dB above ambient during the day but remain within project goals. The cumulative noise increase during the evening and night is forecast as between 5 and 15 dB above ambient should all plant be operating at that time.

At the nearest township (Ganef) approximately 0.8 to 1.1 km distant, noise from modelled construction activities are expected to be approximately 3 to 4 dB less than that at the nearest settlements, and therefore similarly compliant during the day. At night, the concrete batching plant, trucks, tractors, graders and cranes are expected to be above recommended levels but similar to ambient noise levels.

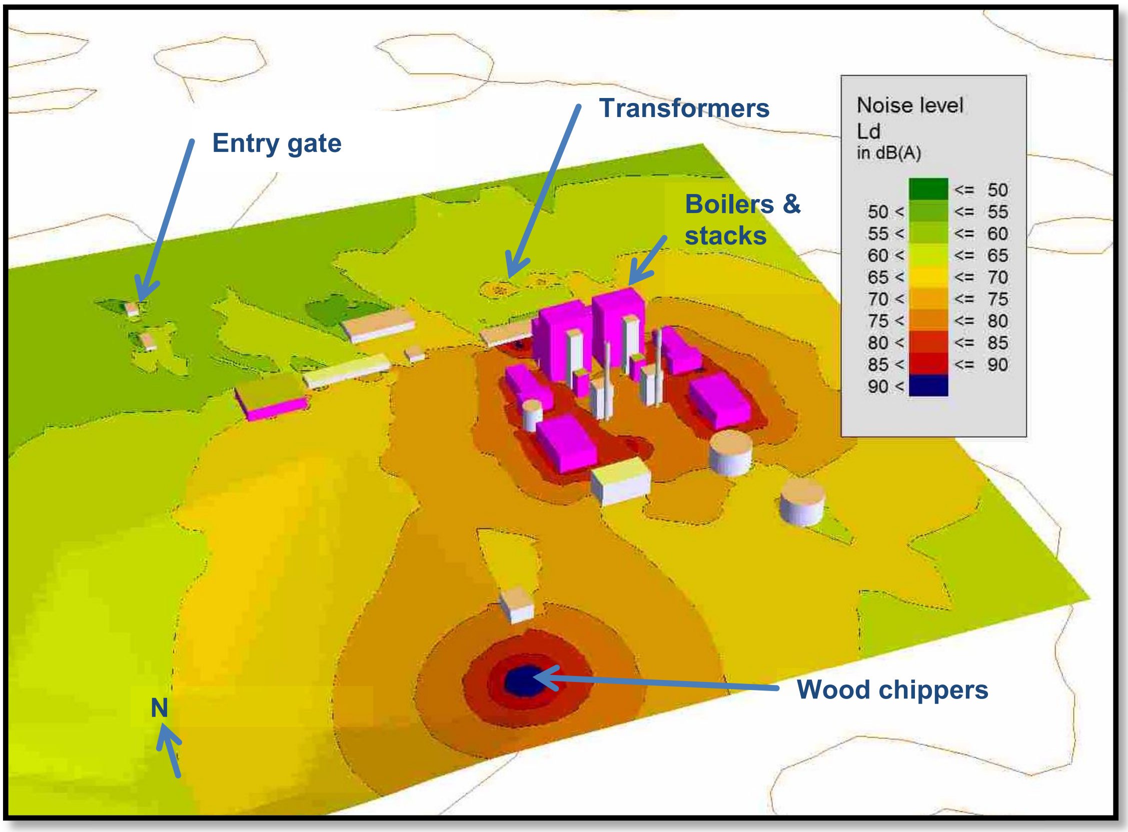
It is noted that night period operations involving truck pass-bys near villages may not be appropriate, and alternative routes or timings should be considered to reduce the potential for noise impacts.

It is recommended that any fixed construction plant (e.g. generators, concrete batching plant etc.) be located as far as possible from the northern boundary of the power plant site to minimise noise impacts during the day.

4.2 Operation

Noise emission levels within the power plant area have been checked within the modelling software to ensure they are generally below L_{Aeq} 85 dB at 1 m in line with advice provided by the proponent, as per the following figure.

Figure 1 Indicative Noise Levels Within Power Plant Compound (View Towards North and Northeast)



Note that noise levels higher than L_{Aeq} 85 dB are anticipated near the wood chippers on the presumption that with constantly open feed chutes, noise cannot be practicably controlled to the same noise target as for other plant (L_{Aeq} 85 dB at 1 m). Note that the wood chippers are modelled as having unshrouded feed chutes, and will be more directional in their noise emissions than that indicated. This means that if future noise levels from the wood chippers are considered excessive, there remain options to reduce noise impacts by orientating the feed chutes and/or fitting acoustically-lined shrouds which absorb and direct noise away from the direction of residential areas.

A summary of the predicted noise levels under both neutral and enhanced (worst case) meteorological conditions is provided in **Table 8** for the nearest affected locations. Both neutral and enhanced meteorological propagation conditions are presented.

Generally these results are considered acceptable on the basis that:

- The day period Project noise criterion of L_{Aeq} 55 dB is met at all residences under all scenarios and under all meteorological conditions;

- At the nearest residential landowner locations, night time levels are below or equal to the criterion of L_{Aeq} 45 dB;
- Under neutral conditions, the noise levels meet the recommended (non-mandatory) target; and
- Under both neutral and worst case conditions, these levels are similar to and less than ambient noise levels expected in the area (L_{Aeq} values ranging from 40 to 50 dB during evening and night periods).

However, noise levels above recommended (non-mandatory) target levels are forecast for the two settlements here referred to as Locations ‘Q’ and ‘R’ (i.e., settler residences south of Ganef Community Nursery). At these locations, noise levels during the night period are forecast to be above WHO goals but typically similar to background noise levels.

Table 8 Operational Noise Predictions, L_{Aeq} dB

Site ID	Location	Approx. distance from site boundary	Noise goal / criteria		Weather conditions		Expected result
			Day	Night (Note [1])	Neutral	Enhanced (Worst case)	
R_1	Site boundary	0 m	70	70	Up to 62	Up to 64	Not a noise sensitive receiver. Compliant with L_{Aeq} 70 dB requirement. Result controlled by cooling towers and turbine buildings
R_2	Q – Settlement outbuilding	0.40 km N	55	37 / 45	**45**	**49**	Compliant during day period. At night, marginally compliant with IFC criteria under neutral conditions but up to +4 dB exceedance under worst case weather conditions At night, typically 1 to 12 dB above internal WHO goals assuming poor acoustic insulation. Outdoors at night, likely to be occasionally audible above background noise levels. Result primarily controlled by cooling tower emissions, then turbine buildings and wood chippers.
R_3	R – Settlement outbuilding	0.67 km N			**38**	**42**	
R_5	D – Ganef Community Nursery	1.0 km N			37	**41**	Meets recommended (non-mandatory) target under neutral conditions. Exceeds night time internal WHO goals under enhanced weather conditions, if wood chippers are used outside 7am to 10 pm.
R_4	O – Ganef hamlet	0.8 km NW			36	**42**	
-	E, F, G, H – Markham Farm	3.8 – 4.4 km ENE			<30	<30	Compliant, less than ambient noise level. Meets recommended targets
-	A – 41 Mile Market	4.9 km WNW					
-	L, N, K, M - Chivasing	5.3 km WNW					

1. The Project night time noise goal (non-mandatory) is L_{Aeq} 37 dB, whilst the night time criterion is 45 dB.

It should be noted that:

- The predicted levels are based on worst case peak operational conditions (30 MW operation) with enhanced meteorological conditions, and there is scope to manage this issue via reduced activities during the night and treatments to plant upon confirmation of actual plant noise data; and
- Occupiers of Locations 'Q' and 'R' are 'settlers', as opposed to landowners (although they are still considered residential in usage).

Current estimates put a suitable setback distance of around 650 m from the power plant site boundary to reliably meet L_{Aeq} 45 dB or less, prior to any further noise controls. Meeting the non-mandatory WHO criteria is forecast to be challenging at distances substantially less than this, such as the settlement at Location 'Q' which is approximately 400 metres from the northern boundary.

Long distance noise emissions from the power plant site are estimated to be most influenced by noise from the wood chipper, stack exhaust, turbine buildings and cooling towers, and there are various controls which can be applied to these elements to improve outcomes from that currently forecasted above, as discussed in the **Section 5**.

Corona discharge noise from transmission lines are estimated to be compliant with project noise limits (and/or less than or equal to ambient noise levels) on the basis of a spatial buffer distance of at least 120 m (increasing to 300 m in regards to recommended targets). As such noise is highly variable and subject to ongoing condition and prevailing weather, it is recommended that field measurements are undertaken to confirm actual noise emission levels before implementing specific buffer controls of this order.

4.3 Likely impacts on fauna

The potential effects of noise on wildlife include physical damage to hearing organs, increased energy expenditure or physical injury while responding to noise, interference with normal animal activities, and impaired communication. The ongoing impacts of these effects can include habitat loss through avoidance, reduced reproductive success and increased mortality.

There are no current government policies or other widely accepted guidelines as to noise levels or thresholds of relevance for wildlife, partly because the effects of noise on most wildlife species are poorly understood (Larkin, Margoliash, & Kogan, 1996) (Brown, 2001) (Ocean Studies Board (OSB), 2003).

PNG fauna species relevant to this study (biota) include a large range of species including

- Mammals such as rodents, bats, echidnas and tree kangaroos;
- A large variety of native invertebrates / insects;
- Birds such as cassowaries, pigeons, parrots and passerines;
- Amphibians such as tree frogs and Asiatic toads; and
- Reptiles such as snakes, lizards and saltwater crocodiles.

On this basis, the following presents a discussion on likely impacts on fauna given the current literature state of the art.

4.3.1 Generally

This limited understanding of the effects of noise on wildlife is understandable when the following points are considered:

- responses to noise disturbance cannot be generalised across species or genera;
- studies of one species cannot be extended to other species;

- responses even of individuals within a single species may vary;
- hearing characteristics are species-specific – for example, noise impacts on humans are determined using a frequency weighting filter (A-weighting) which corresponds to human hearing characteristics, determined through laboratory testing. The frequency-dependent hearing characteristics of other mammals cannot be determined in this way;
- when studying the effects of noise on animals, it can be difficult to separate noise effects from other sensory disturbing effects (for example, visual or olfactory cues); and
- experimental research in a laboratory is not always applicable in a natural setting.

As with humans, an animal's response to noise can depend on a variety of factors including noise level, frequency distribution, duration, number of events, variation over time, rate of onset, noise type, existence and level of ambient noise, time of year and time of day. The animal's location, age, sex, and past experience may also affect their response to noise.

Despite the difficulties associated with assessing noise impacts on animals, there are a few studies that have been referenced to draw some general conclusions and inform the noise mitigation treatments recommended in **Section 5** below.

4.3.2 Typical effects of noise on fauna

There are several relevant elements to the responses of native biota to noise events:

- 'Masking' – where noise affects communication between individuals of a species.
- Individual reactions – ranging from a mild 'Alert' response through to 'Avoidance' (or abandonment) of habitat, including the possibility of nests being abandoned due to novel noise impacts.
- Impacts to food sources such as invertebrates.

The effects of 'Masking' are likely to be extremely varied. Generally speaking, it can reasonably be assumed that small forest or grassland songbirds and smaller wetland bird species, as well as many amphibians, will be adversely affected by 'Masking' to a greater degree than larger and/or more solitary species. For many of these species, vocal communications are vital, and the smaller species at least would have difficulty calling at sufficient volumes to overcome 'Masking' when the noise stimuli are at high levels and/or are of long duration.

Individual responses to noise events, as noted above, will vary from a mild 'Alert' response (to relatively low noise events) through to 'Avoidance' or the abandonment of otherwise suitable habitat. The individual responses, summarised in **Table 9**, will vary between species and groups, as well as between individuals within a single species.

Table 9 Likely responses of bird wildlife to noise stimuli

Response	Actions
Alert	Looks briefly at source Turns head
Alarm	Looks intently at source Changes position Shows intent to flee
Flight	Moves a short distance from source Ceases feeding of young and/or foraging
Avoidance	Permanently vacates area or abandons nests

With respect to the impacts of noise on native wildlife, it is to be noted that notwithstanding a substantial body of research and observations, there are no clear or well-defined thresholds for species' tolerance, even on an individual species basis.

Whilst there are many observations with respect to the responses of breeding and non-breeding birds to aircraft overflights (for example), as well as a number of studies relating to bird densities in proximity to roads, there are little data to indicate specific thresholds at which different responses are elicited in different species.

Furthermore, many of those observations and studies have been unable to differentiate between the impacts of noise itself and the other associated impacts of the movement of vehicles, aircrafts or people.

4.3.3 Sensitivities

Measures of absolute auditory sensitivity in a wide variety of bird species show a region of maximum sensitivity between 1 kHz to 5 kHz, with a rapid decrease in sensitivity at higher frequencies. The data suggest that in this frequency range, birds show a level of hearing sensitivity that is similar in most respects to that found for the most sensitive mammals, with avian performance clearly inferior above and below this range of frequencies (Manci, Gladwin, Villella, & Cavendish, 1988). For this project these higher frequencies are attenuated relatively quickly over large distances (consider that distant thunder is low frequency noise), resulting in a reduced area of effect on birds compared to humans and other mammals which can hear lower frequency sound more easily.

An investigation by the US Fish & Wildlife Service (Manci, Gladwin, Villella, & Cavendish, 1988) provides some relevant data for the effects of noise on the Marbled Murrelet and the Northern Spotted Owl. The former is an oceanic feeder and nests in old-growth forests, and the latter strictly occupies forests. As there is very little information specific to birds native to PNG, the noise thresholds from the US Fish & Wildlife Service have been used to provide the basis for comment here.

Table 10 Noise thresholds for responses by North American birds (Modified from USFWS guidance)

Effect threshold	Defined as	Noise level
Detectability	Where the noise is detectable but a Murrelet or Spotted Owl does not show any reaction	4 dB above baseline noise level
Alert	Where the Murrelet or Spotted Owl shows apparent interest by turning its head or extending its neck.	‘could not be documented with any precision’ therefore ‘subjectively placed between the detectability and harassment/injury threshold’ Alert – L_{Amax} 57dB
Disturbance	Where the Murrelet or Spotted Owl shows avoidance of the noise by hiding, defending itself, moving the wings or body, or postponing a feeding.	‘could not be documented with any precision’ therefore ‘subjectively placed between the detectability and harassment/injury threshold’ Disturbance – L_{Amax} 70dB
Harassment/injury	Where the Murrelet or Spotted Owl is injured, defined as an adult flushed from the nest or the young missing a feeding.	L_{Amax} 92dB

The general conclusion of a review undertaken by the US Department of Transportation Federal Highway Administration (2004) is that some (although not all) bird species are sensitive to road traffic noise (at least during breeding), and that the distances over which this effect is observed can vary considerably (from a few metres to more than 3 km away). Observations also include reduced bird diversity and density of bird life near roads, and in some cases this is associated with average noise levels above L_{Aeq} 50 dB.

Dawe & Goosem (2008) noted that:

> *“Anthropogenic noise can also trigger flight and alert responses in birds and altered behaviour after the noise disturbance, which can lead to reduced breeding success, at noise levels ranging from 65–85 dB(A). Complete habituation to such disturbance does not always occur, even in less noise-sensitive species”*

An earlier study (Awbrey, Hunsaker, & Church, 1995) determined that Californian Gnat-catchers (with a call of approximately L_{Aeq} 50 dB) had a masking distance of 15.2 m from the edge of the road, and did not occur where the road noise was greater than L_{Aeq} 69 dB. However, this species also successfully bred near an airport with noise levels in excess of L_{Aeq} 70 dB.

A study of road noise in Victoria (Parris & Schneider, 2009) revealed reductions in populations of the Grey Shrike-thrush and Grey Fantail adjacent to busy roads, with those species becoming undetectable at sites with road noise levels of L_{Aeq} 67 and 72 dB respectively.

There are many reports regarding the effects of aircraft noise on birds. It has been reported that jet fighter over-flights had no significant effect on egrets in Florida (Black, Collopy, Percivial, A., Tiller, & Bohall, 1984), and that aircraft noise levels of L_{Aeq} 85 dB were required to elicit escape behaviour in the Crested Tern (Brown, 2001).

4.3.4 Likely impacts

The majority of activities associated with fixed plant are anticipated to be generally continuous in nature and move at a rate considered too low to induce startle reactions in nearby fauna. For transient events, such impacts are unlikely to be anything other than highly localised in space and not for more than a few hours at a time.

If the food source is permanently negatively affected by localised construction and operations, then it is reasonable to consider that fauna would migrate to areas further away and therefore less likely to be startled over the long term. Inspection of the previous sections, **Table 7** and **Appendix B** suggests this area of effect would be up to around 400 m from the plant boundary.

The responses of native biota to noise disturbances will vary depending upon the type of noise. Generally speaking, ‘continuous’ noises (such as those generated by major plant items) are more readily tolerated by native biota (particularly birds) than are ‘episodic’ noise disturbances (such as truck passbys). For example, where a bird has become habituated to the ‘continuous’ (background) noise of operations, the ‘episodic’ alarm noise may still elicit an adverse response.

For example, it is likely that groups of ground feeding birds standing at up to 100 m from a construction site may respond to the initiation of activities (involving both any alarms and the start-up noise) by alarm and/or flight. On the basis of the above, such birds could reasonably be expected to move away from the noise source either by walking or flying, whereas a foraging bird may well move towards a continuous noise source such as a generator, even closer than 100 m, because the noise will be perceived as a ‘continuous’ and on-going source of (background) noise.

It is also relevant to note that wildlife is not adapted solely to a ‘quiet’ environment. As discussed in **Section 2.2**, the existing natural environment produces noise stimuli on an ongoing basis and often with higher peak levels during short term events.

5 RECOMMENDED NOISE MITIGATION AND IMPACT MINIMISATION MEASURES

Noise mitigation options are recommended below in terms of general good practice and also specific controls applicable to address any potential exceedances of criteria.

5.1 Generally

Whilst the noise model represents anticipated typical scenarios for the Project, it could be expected that actual operational scenarios may be different at times to those assumed in the model. It is therefore recommended that the following good practice impact management strategies be considered in order to reduce the likelihood of any noise impacts:

- Where practicable, the offset distance between noisy plant items and nearby noise sensitive receptors should be as great as possible.
- With respect to activities located in the vicinity of sensitive receptors, advanced notice of high noise activities should be provided and respite periods employed.
- As far as possible, maintenance work on all construction plant should be carried out away from noise sensitive receptors and confined to standard daytime construction hours.
- Select plant with consideration of lowest noise emission level ("buy quiet").
- All plant and machinery used for the Project should be regularly maintained to minimise noise emissions.
- Site access roads should be kept well maintained so as to mitigate the potential for vibration from trucks which induces noise.
- Minimise the number of individual vehicle pass-bys through villages by grouping vehicles into a convoy.
- Minimise the use of the access roads during the night period.

5.2 Operational Treatments

On the basis of the equipment noise data presented in **Section 3.2.2**, the results at the nearest residential areas (Receivers 'Q' and 'R' in Appendix B, Maps 1 and 2) are forecast to be controlled by the cooling tower fan discharges, the turbine buildings and wood chippers.

To meet the Project night time noise criteria of $L_{Aeq,1hour}$ 45 dB, a noise reduction of at least 5 dB at the nearest residences is practicable as follows:

- **Cooling towers:** Fit a straight lined ducting cowl or suitable attenuator to the vertical discharge fans and implement variable fan speed controls. Consider lower speed, larger diameter fans.
- **Turbine building:** The model considers the turbine prior to being acoustically treated, so a suitable acoustic enclosure and ducting can be installed to effectively reduce noise emissions.
- **Wood chippers:** Orientate the feed chute openings away from the direction of nearest residential areas and/or fit acoustically lined shrouds which absorb and screen noise. Select suitable wood chippers with lowest noise emissions (L_{WA} values).

On the basis of the above, these improvements if implemented are expected to result in noise levels at the nearest receivers (Receivers 'Q' and 'R' in Appendix B, Maps 1 and 2) which are consistent with existing ambient noise levels and comply with the IFC criteria.

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Glossary of terms

1 Sound Level or Noise Level

The terms “sound” and “noise” are almost interchangeable, except that in common usage “noise” is often used to refer to unwanted sound.

Sound (or noise) consists of minute fluctuations in atmospheric pressure capable of evoking the sense of hearing. The human ear responds to changes in sound pressure over a very wide range. The loudest sound pressure to which the human ear responds is ten million times greater than the softest. The decibel (abbreviated as dB) scale reduces this ratio to a more manageable size by the use of logarithms.

The symbols SPL, L or L_P are commonly used to represent Sound Pressure Level. The symbol L_A represents A-weighted Sound Pressure Level. The standard reference unit for Sound Pressure Levels expressed in decibels is 2 x 10^{-5} Pa.

2 “A” Weighted Sound Pressure Level

The overall level of a sound is usually expressed in terms of dB(A), which is measured using a sound level meter with an “A-weighting” filter. This is an electronic filter having a frequency response corresponding approximately to that of human hearing.

People’s hearing is most sensitive to sounds at mid frequencies (500 Hz to 4000 Hz), and less sensitive at lower and higher frequencies. Thus, the level of a sound in dB(A) is a good measure of the loudness of that sound. Different sources having the same dB(A) level generally sound about equally loud.

A change of 1 dB(A) or 2 dB(A) in the level of a sound is difficult for most people to detect, whilst a 3 dB(A) to 5 dB(A) change corresponds to a small but noticeable change in loudness. A 10 dB(A) change corresponds to an approximate doubling or halving in loudness. The table below lists examples of typical noise levels

Sound Pressure Level (dB(A))	Typical Source	Subjective Evaluation
130	Threshold of pain	Intolerable
120	Heavy rock concert	Extremely noisy
110	Grinding on steel	
100	Loud car horn at 3 m	Very noisy
90	Construction site with pneumatic hammering	
80	Kerbside of busy street	Loud
70	Loud radio or television	
60	Department store	Moderate to quiet
50	General Office	
40	Inside private office	Quiet to very quiet
30	Inside bedroom	
20	Recording studio	Almost silent

Other weightings (e.g. B, C and D) are less commonly used than A-weighting. Sound Levels measured without any weighting are referred to as “linear”, and the units are expressed as dB(lin) or dB.

3 Sound Power Level

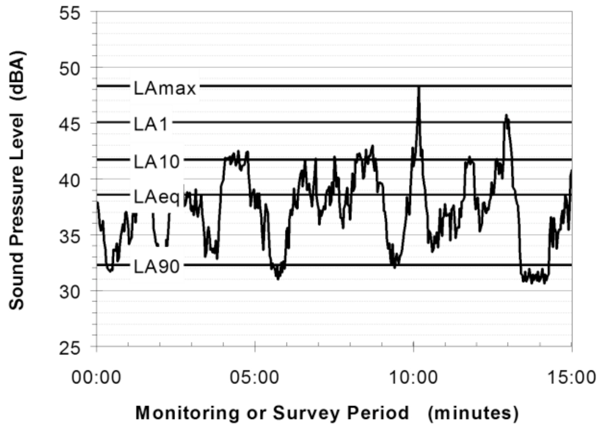
The Sound Power of a source is the rate at which it emits acoustic energy. As with Sound Pressure Levels, Sound Power Levels are expressed in decibel units (dB or dB(A)), but may be identified by the symbols SWL or LW, or by the reference unit 10^{-12} W.

The relationship between Sound Power and Sound Pressure may be likened to an electric radiator, which is characterised by a power rating, but has an effect on the surrounding environment that can be measured in terms of a different parameter, temperature.

4 Statistical Noise Levels

Sounds that vary in level over time, such as road traffic noise and most community noise, are commonly described in terms of the statistical exceedance levels LAN, where LAN is the A-weighted sound pressure level exceeded for N% of a given measurement period. For example, the LA1 is the noise level exceeded for 1% of the time, LA10 the noise exceeded for 10% of the time, and so on.

The following figure presents a hypothetical 15 minute noise survey, illustrating various common statistical indices of interest.



Of particular relevance, are:

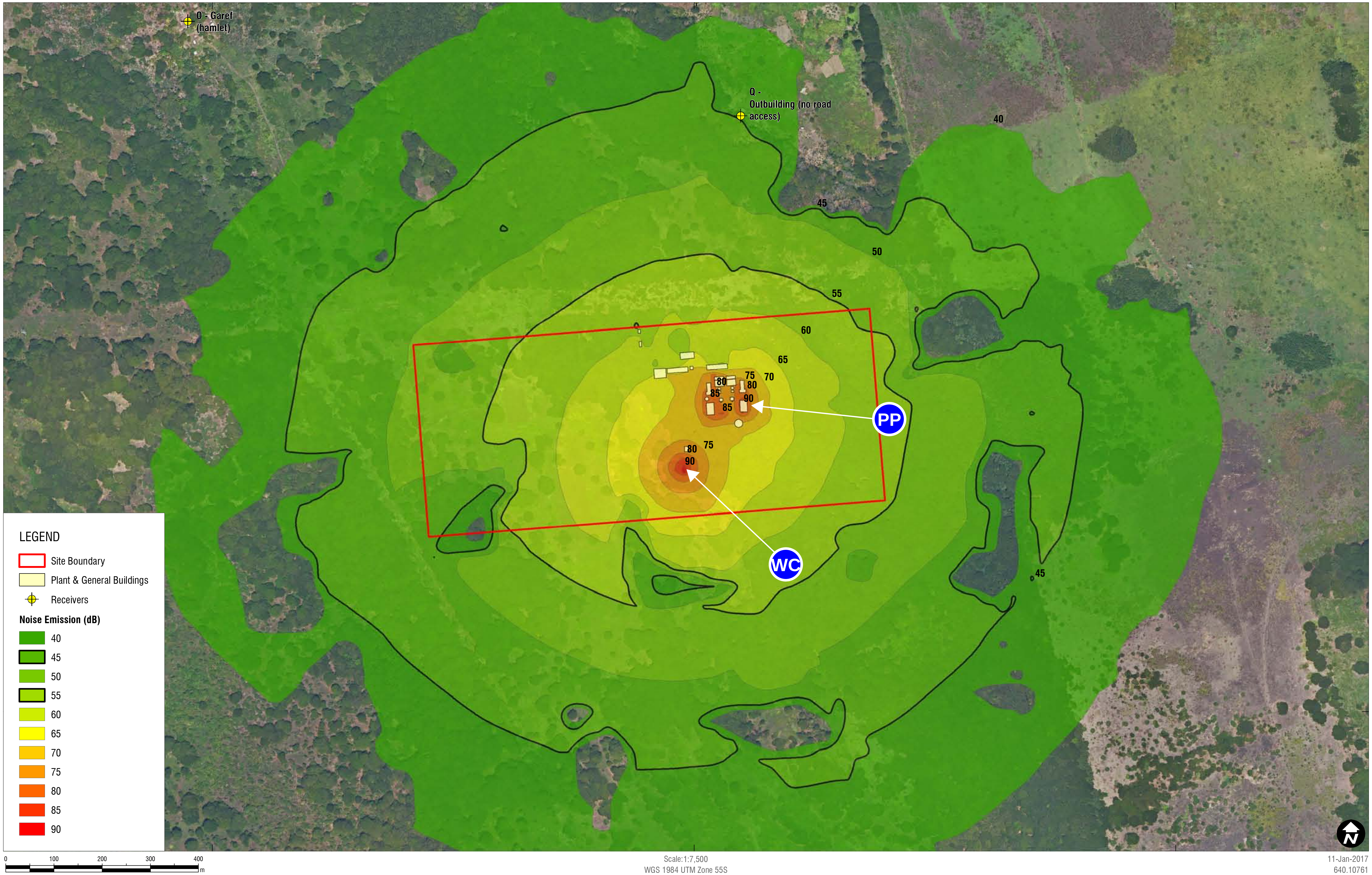
- LA1 The noise level exceeded for 1% of the 15 minute interval.
- LA10 The noise level exceeded for 10% of the 15 minute interval. This is commonly referred to as the average maximum noise level.
- LA90 The noise level exceeded for 90% of the sample period. This noise level is described as the average minimum background sound level (in the absence of the source under consideration), or simply the background level.
- LAeq The A-weighted equivalent noise level (basically the average noise level). It is defined as the steady sound level that contains the same amount of acoustical energy as the corresponding time-varying sound.

When dealing with numerous days of statistical noise data, it is sometimes necessary to define the typical noise levels at a given monitoring location for a particular time of day. A standardised method is available for determining these representative levels.

This method produces a level representing the “repeatable minimum” LA90 noise level over the daytime and night-time measurement periods, as required by the EPA. In addition the method produces mean or “average” levels representative of the other descriptors (LAeq, LA10, etc).

NOISE CONTOURS

SLR64010761_Map01	Forecast Operational Noise Emissions, Neutral Conditions, Enlarged view
SLR64010761_Map02	Forecast Operational Noise Emissions, Worst Case (Enhanced) Conditions, Enlarged view
SLR64010761_Map03	Forecast Operational Noise Emissions, Neutral Conditions, Enlarged view, Site zoomed view
SLR64010761_Map04	Forecast Operational Noise Emissions, Worst Case (Enhanced) Conditions, Site zoomed view



WC Wood chippers

PP Boilers / Turbine area

Forecast Operational Noise Emissions
Neutral Conditions

MAP 01

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SLR

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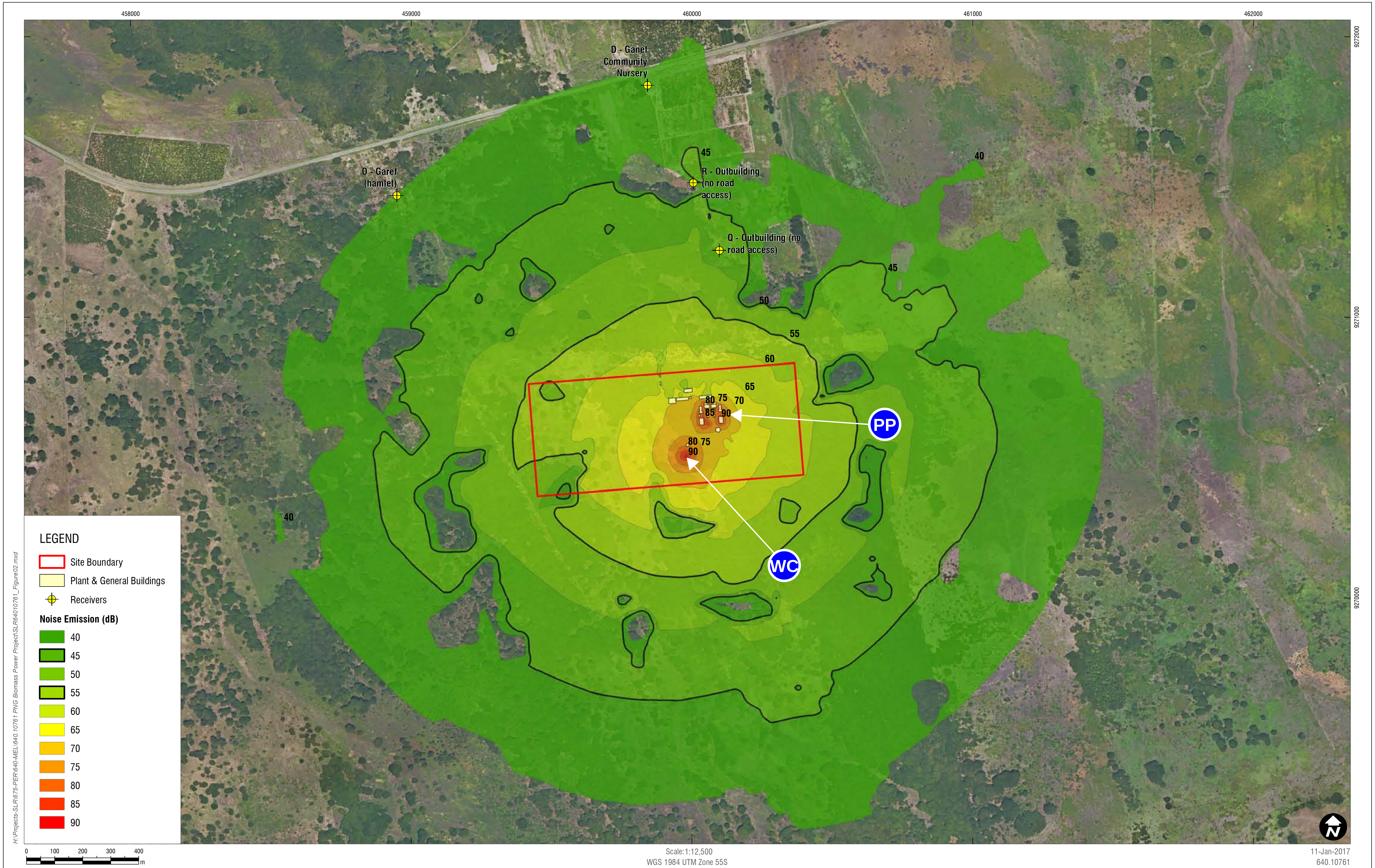

WC Wood chippers

PP Boilers / Turbine area

Sheet Size : A3

SLR

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Forecast Operational Noise Emissions Enhanced Conditions

MAP 02

WC Wood chippers

PP Boilers / Turbine area

Sheet Size : A3

SLR

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Operations
Forecast Site Noise Levels
Neutral Conditions

MAP 03

Sheet Size : A3

SLR

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WC Wood chippers

PP Boilers / Turbine area

Operations
Forecast Site Noise Levels
Enhanced Conditions

MAP 04

Appendix 5
Surface Water and Sediment Quality Report

Markham Valley Biomass Limited

PNG Biomass Markham Valley

Surface Water and Sediment Quality Report

March 2017

(Report No. 01183B_4_v2)

Markham Valley Biomass Limited

PNG Biomass Markham Valley

Surface Water and Sediment Quality Report

March 2017
(Report No.01183B_4_v2)

Prepared by ERIAS Group Pty Ltd
(ACN: 155 087 362)

13–25 Church Street
Hawthorn, Victoria, 3122
Australia
P +61 3 9023 9281
E info@eriasgroup.com
W eriasgroup.com

Client Contact:	Michael Henson michael.henson@alignedenergy.net

ERIAS Group Contact:	Michael Jones michael.jones@eriasgroup.com
ERIAS Group Alternative Contact:	Michelle Clark michelle.clark@eriasgroup.com

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1. Introduction

1.1 Background

Oil Search Limited (Oil Search or OSL), through its wholly-owned subsidiary Markham Valley Biomass Limited (MVB)[1], proposes to develop the PNG Biomass Markham Valley project (the Project) in Morobe Province, Papua New Guinea (PNG). The Project area is located the Markham Valley, about 50 km west-northwest of the provincial capital Lae (Figure 1.1).

The Project has two components – the establishment of up to 15,000 ha of sustainably managed eucalypt plantation, and a biomass-fuelled power plant consisting of two 15 MW units, with the preferred power plant site being located in the southeast of the Project area (see Figure 1.1). Construction of the power plant and related infrastructure, and development of the plantations, will take place over several years. Plantation development will be supported by road upgrades and a large plant nursery. Plantations will be harvested every 7 to 9 years to provide 175,300 BDMt (bone dry metric tonnes) of biomass (wood) per year.

The combustion of dry biomass will generate steam from water sourced from bores or the Markham River. This steam will drive steam turbine generators, thereby generating electricity that will be transferred directly to the nearby high voltage Ramu Grid transmission system, which runs from Lae and Madang in the east to Mt Hagen and Mendi in the west. The power will be distributed to supply energy to major industries, households and rural communities.

1.2 Study Area

Figure 1.1 shows the preferred power plant site and the indicative area within which plantation development is proposed, subject to the findings of the environmental assessment (EA) report, government approvals and land negotiations. From a surface water perspective, the study area is defined by the Erap River in the east, the Leron River in the west, and the Markham River in the south. The other main watercourses within the study area are the Rumu River and, to a lesser extent, Maralumi River.

1.3 Objectives and Tasks

The specific objectives of the water and sediment sampling program were to provide:

- A 'snapshot' of background water and sediment quality of the rivers within the study area, focusing in particular on surface waters that are representative of the drainages within the study area.
- Initial data that will be supplemented by further sampling as Project development proceeds.
- Information to support the aquatic ecology study that has also been undertaken as part of the Project's environmental assessment.

[1] At the time of preparing this report, Markham Valley Biomass Limited was in the process of a name change to PNG Biomass Limited. However, for the purposes of this report, the former will be used.

These objectives were achieved by taking samples of river/stream water and bed or bank sediment at a number of locations, with the samples subsequently being analysed for a range of water and sediment quality parameters. A number of parameters were also recorded in situ.

1.4 Report Structure

The report is structured as follows:

- Chapter 1: Provides background information.
- Chapter 2: Describes the sampling methods employed and location of the water and sediment sampling sites.
- Chapter 3: Presents the results of the water and sediment quality data analysis.
- Chapter 4: Provides a summary of results and conclusions.
- Chapter 5: References.

Results are presented both in tables and, for selected data, in figures, all of which follow Chapter 5. Two appendices are also attached.

2. Methods

2.1 Sampling Design and Rationale

The 2016 water and sediment sampling program took into account the following general environmental factors:

- The accessibility of suitable sampling sites.
- The size of the study area.
- Potential delays in transporting samples to laboratories.

Specific environmental factors that were considered included:

- The need for samples to be representative of both the particular watercourses being sampled and general surface drainage in the study area.
- Potentially strong currents (particularly in the major rivers) and the heavily braided nature of some of these rivers.
- The nature of the local geology and catchment land use, and the consequent potential implications concerning surface water quality.
- Potential influences of river hydrology on water quality at the time of sampling, e.g., total suspended solids (TSS) concentrations may vary with river discharge.

Given these objectives and taking into account the environmental factors and information that is readily available, the sampling program was designed as a descriptive study. In other words, the focus is to characterise watercourses within the study area to provide information to support the EA, rather than being a statistically rigorous program that can be used to assess change or determine cause-and-effect relationships (although data from relevant sites will support future monitoring). Specific aspects of the design of the sampling program include:

- Spatial extent:
  - Sampling sites were located in sub-catchments within the study area on the northern side of the Markham River, and the Markham River itself. Additional details about the sampling sites are provided in Section 2.2.
- Scale – sampling site determination included consideration of factors such as:
  - Obvious changes in watercourse type, e.g., turbid versus clear-water streams.
  - Inputs of major tributaries.
  - Anthropogenic influences and other sources that may affect water and sediment quality.
  - Proposed Project activities and location of Project components, e.g., the power plant.

- Sampling patterns – the program involved targeted sampling that was aimed at characterising representative watercourses draining the Project area, taking into account known or potentially sensitive locations and the potential locations of Project components. Variation within a sampling site was examined to some degree by scheduling sampling events over a 9-month period.

2.2 Sampling Sites

Water and sediment sampling sites and the dates and times sampled during the sampling program are summarised in Table 2.1. Site locations are shown in Figure 2.1.

Table 2.1 – Water Sampling Sites

Site Name	Site ID	Description	Latitude	Longitude	Sample Type	Date & Time
Markham River (Downstream)	Mark-1	Downstream of potential Project impacts	-006° 37' 05.27"	146° 39' 58.54"	W W W/S	30/03/16 30/09/16 14/12/16
Markham River (Upstream)	Mark-2 (JC)	Upstream of most potential Project impacts but downstream of confluence of Markham/Watut Rivers	-006° 37' 44.22"	146° 34' 28.79"	W	30/03/16
Markham River (Upstream)	Mark-2	Upstream of most potential Project impacts	-006° 38' 12.16"	146° 32' 14.10"	W/S W	29/09/16 14/12/16
Rumu River	Rumu-2	Rumu River	-006° 35' 30.70"	146° 35' 14.21"	W W/S W	31/03/16 29/09/16 14/12/16
Maralumi River	Trib C-2 (JC)	Fed from multiple streams from the north; connects to Markham River	-006° 29' 53.14"	146° 36' 26.48"	W	31/03/16
Maralumi River	Trib C-2	Fed from multiple streams from the north; connects to Markham River; located >10 km downstream from Trib C-2 (JC)	-006° 34' 46.60"	146° 39' 48.82"	W W/S	30/09/16 14/12/16*
Klin Wara	Trib G-1	Drains western part of Project area; connects to Markham River	-006° 35' 0.28"	146° 31' 03.40"	W W/S W	31/03/16 29/09/16 14/12/16

W = water sample; S = bed sediment sample. * Coordinates unverified for this sample.

Although samples were generally taken at the same locations for all three sampling events, exceptions were:

- Mark-2, where sampling in the first event occurred downstream of the confluence of the Markham and Watut rivers whereas the remaining two events involved sampling upstream of the confluence.

- Trib C-2, where sampling occurred at two separate locations in the Maralumi River catchment.

Efforts were made to sample the man-made drainage line running from the nursery site at the power plant location, southwards to the Markham River. However, this drain was dry when inspected and no samples could be obtained.

2.3 Parameters

2.3.1 Surface Water

Identification of the specific water quality parameters to be determined was based on the need to generally characterise existing water quality, taking into account natural ambient conditions, current catchment activities, activities likely to be associated with the Project, and the requirements of relevant water quality standards and guidelines.

In situ water quality parameters that were recorded varied between sampling events, although pH was determined on all occasions. Temperature, conductivity (EC), total dissolved solids (TDS), oxidation-reduction potential (ORP), dissolved oxygen (DO) and turbidity were recorded when possible. In addition, samples were taken to allow the following parameters to be determined by laboratory analysis:

- General water quality: major ions (Na, K, Ca, Mg, Cl, SO_4), fluoride, total alkalinity and total suspended solids (TSS).
- Nutrients: total nitrogen (TN), total kjeldahl nitrogen (TKN), nitrite, nitrate, nitrate/nitrite (NO_x), ammonia (NH_3), total phosphorus (TP) and reactive phosphorus.
- Filtered (<0.45 μm) metals: Ag, Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Fe, Pb, Mo, Mn, Hg, Ni, Sb, Se, Sn, V and Zn.
- Unfiltered (total) metals: Ag, Al, As, B, Ba, Be, Cd, Co, Cr, Cu, Fe, Pb, Mo, Mn, Hg, Ni, Sb, Se, Sn, V and Zn.
- Total petroleum hydrocarbons (TPH), total recoverable hydrocarbons (TRH).
- Phenols.
- Benzene, toluene, ethylbenzene, xylenes and naphthalene (BTEXN).
- Polynuclear aromatic hydrocarbons (PAH).
- Total sulfur.
- Total organic carbon (TOC).
- Oil and grease.
- Chemical oxygen demand (COD).
- Biochemical oxygen demand (BOD).

- Colour (true).
- Faecal coliforms.
- Chlorophyll a.

Samples for phenols, BTEXN and PAH were not taken in the third sampling event due to results for all samples in the first two sampling events being less than the reporting limits.

Due to the short holding times that are recommended to maintain sample integrity, results for faecal coliforms, BOD, nitrate, nitrite and reactive phosphorus should be regarded as being indicative only.

2.3.2 Bed Sediment

As for the surface water quality parameters, sediment quality parameters were determined based on the need to generally characterise existing sediments, taking into account natural ambient conditions, current catchment activities, activities likely to be associated with the Project, and the requirements of relevant sediment quality guidelines.

Samples were taken to allow the following parameters to be determined by laboratory analysis:

- General sediment characteristics: particle size distribution, moisture content, total carbon (TC), total organic carbon (TOC), total inorganic carbon (TIC).
- Nutrients: total nitrogen (TN), total kjeldahl nitrogen (TKN), nitrite, nitrate, nitrate/nitrite (NO_x), ammonia (NH_3), total phosphorus (TP) and reactive P.
- <2000 μm metals[2]: Ag, Al, As, B, Ba, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Sb, Se, Sn, V, Zn (total and 1M hydrochloric acid extractable).
- <63 μm metals: Ag, Al, As, B, Ba, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Sb, Se, Sn, V, Zn (total).
- Total petroleum hydrocarbons (TPH), total recoverable hydrocarbons (TRH).
- Phenols.
- Benzene, toluene, ethylbenzene, xylenes and naphthalene (BTEXN).
- Polynuclear aromatic hydrocarbons (PAH).
- Glyphosate/aminomethylphosphonic acid (AMPA).

Organochlorine pesticides, PCBs, tributyltin and radionuclides were excluded from the analytical program as Project activities will not materially involve these variables.

[2] This is the particle size fraction recommended in Simpson et al. (2013).

2.4 Sample Collection

Sample bottles were provided by the laboratory that undertook sample analysis, i.e., ALS Environmental (or other laboratories used by ALS for specialist analyses, e.g., faecal coliforms). Details of water sample bottles, and sampling and preservation requirements, are provided in Appendix 1. Samples were taken either by MVB personnel (March 2016, December 2016) or as part of the aquatic ecology field program (September 2016). Water quality sampling involved the following tasks:

- Suitable sampling sites were identified.
- In situ water quality parameters were recorded at each site.
- Water samples were collected at each site and prepared for storage prior to their dispatch to the laboratory.
- Sampling information and measured data were recorded.

Bed sediment sampling involved the following tasks:

- Suitable sampling sites were identified (at the same locations as the water sampling sites).
- Bed sediment samples were collected at each site and prepared for storage prior to their dispatch to the laboratory.
- Sampling information and measured data were recorded.

Procedures for both water and bed sediment sampling and sample handling for the December 2016 sampling event are provided in Appendix 1. Similar procedures were followed for the previous two events.

2.5 Laboratories, Analytical Methods and Reporting Limits

2.5.1 Water Samples

Water samples were analysed by ALS Environmental, a NATA[3]-accredited laboratory with proven relevant experience in their Australian laboratories. Samples were analysed using standard (accredited) methods. Reporting limits are shown in Table 2.2 to allow comparison with relevant guidelines and standards for most variables of interest (see Section 3.1).

Table 2.2 – Reporting Limits for Analysis of Water Samples

Parameter	Limit of Reporting
Ca, Mg, Na, K, Cl, SO_4, alkalinity	1 mg/L
F	0.1 mg/L
Al, Ag, As, B, Ba, Cd, Co, Cu, Cr, Fe, Hg, Pb, Mn, Mo, Ni, Sb, Se, Sn, Zn	0.1 to 50 μg/L
NH_3, TN, TKN, NOx, TP	10 to 100 μg/L
Oil and grease	5 mg/L

[3] National Association of Testing Authorities, Australia.

Parameter	Limit of Reporting
Sulfur, TOC	1 mg/L
Phenols	1 to 2 µg/L
TSS	5 mg/L
COD	10 mg/L
BOD	2 mg/L
Chlorophyll a	1 µg/L
Colour (true)	1 PCU
TRH (C6-C40)/TPH (C6-C36)	20 to 100 µg/L
PAH	0.5 to 1 µg/L
BTEXN	1 to 5 µg/L

2.5.2 Bed Sediment Samples

Sediment samples were analysed by ALS Environmental using standard (accredited) methods. Reporting limits (Table 2.3) allow comparison with relevant sediment quality guidelines, such as those in Simpson et al. (2013).

Table 2.3 – Reporting Limits for Analysis of Sediment Samples

Parameter	Limit of Reporting (Dry Weight)
Moisture content, particle sizing	1%
TC/TOC/TIC	0.02%
TRH (C6-C40)/TPH (C6-C36)	3 to 5 mg/kg
Phenols	0.5 to 2 mg/kg
PAHs	4 to 5 µg/kg
BTEXN	0.2 to 0.5 mg/kg
Al, Ag, As, B, Ba, Cd, Co, Cu, Cr, Fe, Hg, Pb, Mn, Mo, Ni, Sb, Se, Sn, V, Zn	0.01 to 1 mg/kg
NH_3, TN, TKN, NOx, TP	0.1 to 20 mg/kg

2.6 Quality Assurance and Quality Control

Quality assurance and quality control samples were included in the sampling and analytical program. Specific aspects included (i) field blanks, (ii) appropriate records concerning sampling details, calibration and maintenance of sampling equipment and meters, and sample storage and transport (including chain-of-custody procedures), and (iii) a laboratory quality control program that involved analysis of:

- Laboratory control samples.
- Spiked samples.
- Laboratory duplicates.
- Laboratory method blanks.

3. Results and Discussion

3.1 Assessment Framework

Assessment of water quality and bed sediment quality data requires consideration of the relevant beneficial values of the water, such as its use as a drinking water source or for the maintenance or protection of the existing aquatic ecosystem. Different beneficial values may have varying water quality requirements, with the protection of aquatic ecosystems generally requiring the highest water quality of all beneficial values. Relevant beneficial values assumed for this assessment focus on (i) protection of aquatic ecosystems (which includes protection of fish and similar organisms), and (ii) use of watercourses as drinking water sources. Consideration was also given to other beneficial values such as recreation, where appropriate. Potentially applicable guidelines/standards are discussed below.

3.1.1 Water Quality

3.1.1.1 Drinking Water

Relevant drinking water quality guidelines/standards include:

- Papua New Guinea Public Health (Drinking Water) Regulation 1984, Schedule 2 (Drinking Water).
- World Health Organization guidelines for drinking water quality, 4th edition (WHO, 2011).

3.1.1.2 Freshwater Aquatic Ecosystem Protection

Relevant water quality guidelines/standards to protect freshwater aquatic ecosystems include:

- Papua New Guinea Environment (Water Quality Criteria) Regulation 2002, Schedule 1.
- Australia and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC/ ARMCANZ, 2000).

The most pertinent of the above are the requirements specified in the Papua New Guinea Environment (Water Quality Criteria) Regulation 2002, Schedule 1, which provides PNG statutory obligations. The ANZECC/ARMCANZ (2000) guidelines have been used in a number of water quality assessments in Papua New Guinea to supplement the PNG statutory requirements and provide a more conservative assessment framework.

Assessment against guidelines has considered both unfiltered (total) and filtered (dissolved) metal concentrations. Guidelines or criteria for aquatic ecosystem protection generally acknowledge the higher bioavailability of dissolved toxicants, and hence focus on dissolved concentrations rather than total toxicant concentrations. Drinking water guidelines are generally based on total metal concentrations and are usually applicable ‘at tap’, i.e., after treatment to remove suspended sediment.

3.1.2 Sediment Quality

In the absence of PNG statutory requirements, sediment quality in streams has been assessed against the updated ANZECC/ARMCANZ sediment quality guidelines (Simpson et al., 2013). Analytical data are compared with two sets of values:

- Sediment quality guideline values (SQGV) – biological effects are likely to be negligible if the contaminant concentration is less than the SQGV.
- Upper guideline (SQG-High) values – biological effects are expected where the contaminant concentration exceeds the SQG-high values.

Contaminant concentrations between the SQGV and SQG-high represent a range where effects are possible.

Other assessment procedures described in Simpson et al. (2013) and Simpson and Batley (2016), such as toxicity testing, examining pore water and elutriates, measuring biomarkers and assessing benthic community structure, have not been used in this assessment due to the relatively low risk associated with the Project in terms of potential impacts on aquatic ecosystems.

3.2 Surface Water Quality

The following discussion presents the findings of the Project sampling program for surface water samples. An example of a laboratory report is provided in Appendix 2; all reports are available on request.

3.2.1 Quality Control Results

Results for field blanks, together with the large number of results less than reporting limits, indicate that sample handling is not likely to have resulted in material sample contamination.

Interpretive quality control reports provided by the laboratory are included in the laboratory reports (Appendix 2). Results for laboratory duplicates, blanks, control samples, matrix spikes and sample surrogates were generally within acceptable limits as defined by the laboratory. Although laboratory matrix spikes showed occasional recoveries marginally outside the data quality objectives, and some quality control sample frequency outliers were noted, these outliers are not considered to be material with respect to using the data within the context of this report.

Some analysis holding time breaches occurred for some parameters; however, this was unavoidable given the remote location of the survey area and the requirement to transport samples to Australia for analysis. The holding time breaches do not materially affect the results in terms of providing water and sediment quality data for general characterisation.

3.2.2 General Parameters

Results for general water quality parameters are summarised in Table 3.1, as derived from instantaneous in situ measurements (temperature, pH, EC/TDS, DO, turbidity) and laboratory analysis of samples (suspended solids (TSS), pH, EC). These data show generally slightly alkaline[4], well-oxygenated waters[5] (although Trib C-2 on Maralumi River shows quite low DO), with EC values that are representative of fresh (as opposed to brackish or saline) streams and show trends that reflect the major ion concentrations. Temperatures are relatively elevated compared with those in highland streams, as would be expected in a lowland environment. The pH values are typical of PNG streams containing significant limestone or similar geologies in their catchments. The greatest variability, both within and between sites, is evident with TSS (and turbidity between sites), and this is likely to be related to differences in stream flow (i.e., increased stream flow often generates elevated TSS levels), and the nature of the various watercourses being sampled and their sub-catchments. Total suspended solids concentrations at some sites, particularly in the Markham and Rumu rivers, were high (2,000 to 5,000 mg/L), as was noted by ECO Care (2013) for surface water samples obtained from the general Project area in late 2012. In contrast, TSS levels in the smaller tributaries (Trib G-1 and Trib C-2) were considerably lower (generally <50 mg/L), and consistent with Trib G-1 being known by local communities as 'Klin Wara' (clean water).

In terms of water quality guidelines and similar, the Papua New Guinea Environment (Water Quality Criteria) Regulation 2002 criteria for temperature is ‘no alteration greater than 2°C’. All results for pH were within the range specified in the Papua New Guinea Public Health (Drinking Water) Regulation 1984 (Schedule 2) (i.e., 6.5 – 9.2) (apart from the single anomalous result for Trib G-1 (Klin Wara)); the corresponding requirement in the Papua New Guinea Environment (Water Quality Criteria) Regulation 2002 is ‘no change to natural pH'. No criteria are available against which to assess conductivity, TDS or TSS. Dissolved oxygen results were generally above the minimum required by the Papua New Guinea Environment (Water Quality Criteria) Regulation 2002 (i.e., >6 mg/L), apart from the low value noted at Trib C-2 noted above.

3.2.3 Major Ions

Results for major ions are summarised in Table 3.2 and shown in Figure 3.1[6]. All results are well below relevant criteria listed in the table.

Calcium is generally the dominant cation in the Markham and Rumu rivers (which is consistent with the catchment geology containing substantial amounts of limestone or similar), with Na having the next highest concentrations, and Mg and K levels being considerably lower. The order of cation dominance at these sites in descending order of concentration is Ca > Na >> Mg > K, while that for anions[7] is HCO_3 >> SO_4 > Cl (with F concentrations being generally comparable to, or less than, Cl levels). The lower Na and HCO_3 results at Mark-2 (JC) compared with the other Mark-2 results may reflect the influence of the Watut River. Major ions results for Trib G-1 and Trib C-2 show Na being dominant with respect to Ca, particularly at Trib C-2, with Mg and K again being somewhat lower. Anion dominance remains as for the other sites. Major ion concentrations at the same sites between sampling events are generally relatively similar, although it should be noted that lower Ca, Mg and Na concentrations in March 2016 at the site labelled Trib C-2 (JC) reflect the location of this site somewhat upstream of the site where Trib C-2 samples were

[4] The pH value of 11.8 for Trib G-1 in September 2016 is regarded as anomalous.
[5] The DO value (mg/L) of 1.37 for Mark-1 in September 2016 is regarded as anomalous.
[6] For major ion concentrations that are below the limits of reporting, the concentration has been plotted in Figure 3.1 as half of the limit of reporting.
[7] Alkalinity values reported in Table 3.2 are primarily due to HCO_3.

subsequently taken. The major ion results are largely consistent with those reported by ECO Care (2013) for surface waters in the general Project area, the main difference being considerably higher Cl levels reported by the latter.

Elevated alkalinity values are consistent with the high Ca concentrations and limestone or similar rock types in the catchment, and are typical of other rivers in Papua New Guinea that are near-neutral to mildly alkaline and dominated by Ca and bicarbonate ions. The tributary streams (Trib G-1 and, in particular, Trib C-2) show the highest alkalinity, higher Na and, to a lesser extent, higher Mg than the other sites, and this is most likely due to different geological characteristics of these sub-catchments.

Water hardness ranges from moderate (e.g., Mark-1) through to very hard (e.g., Trib C-2).

3.2.4 Nutrients

Results for nutrients are summarised in Table 3.3.

Total nitrogen (total N) concentrations range from 0.2 to 1.7 mg/L. No criterion for total N is currently specified for Papua New Guinea. Although not directly comparable in terms of physical settings, it is worth noting that the default 'trigger level'[8] for lowland rivers in tropical Australia for slightly disturbed ecosystems is 0.2 to 0.3 mg/L (ANZECC/ARMCANZ, 2000) (although it is noted that higher values apply to rivers draining forest catchments).

Total Kjeldahl nitrogen (TKN) concentrations are marginally less than, or the same as, total N, reflecting the low level of inorganic nitrogen in the water samples. Concerning the latter, NO_x concentrations range between <0.01 and 0.13 mg/L at all sites, with the highest concentrations found in Trib G-1. To provide some comparison, the default trigger level for lowland rivers in tropical Australia for slightly disturbed ecosystems is 0.01 mg/L (ANZECC/ARMCANZ, 2000).

Ammonia (NH_3) concentrations are generally below or close to the reporting limit (generally <0.01 mg/L) and below water quality criteria at all sites. The default 'trigger level' for ammonia in slightly to moderately disturbed rivers in Australia (based on toxicological concerns) is 0.9 mg/L (ANZECC/ ARMCANZ, 2000).

Total P concentrations in Trib G-1 and Trib C-2 range from 0.02 to 0.20 mg/L, while results for the Markham and Rumu rivers range from 0.41 to 3.82 mg/L. These results most likely reflect the different TSS values, with total P data reflecting particulate-associated P. As for total N, no criteria are currently specified for total P in Papua New Guinea. Again, while not directly comparable, the default trigger level for lowland rivers in tropical Australia for slightly disturbed ecosystems is 0.01 mg/L total P (ANZECC/ARMCANZ, 2000).

3.2.5 Metals

Results for filtered (<0.45 μm) and unfiltered metals are shown in Tables 3.4 and 3.5, respectively.

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[8] Trigger values are concentrations that, if exceeded, would indicate a potential environmental problem, and so trigger a management response, e.g., further investigation and subsequent refinement of the guidelines according to local conditions (ANZECC/ARMCANZ, 2000).

It should be noted that the ANZECC/ARMCANZ (2000) guidelines provide algorithms to account for the effects of water hardness on Cd, Cu, Ni, Pb, and Zn toxicity. Water hardness results for the samples ranged from 89 to 257 mg/L $CaCO_3$, which represents moderately hard to extremely hard water. However, a conservative approach has been adopted and the ANZECC/ARMCANZ trigger value representing water of 'soft' hardness (30 mg/L $CaCO_3$) has been included for these metals in Tables 3.4 and 3.5 (see table notes for further details).

3.3.5.1 Filtered Metals

Filtered As, B, Ba, Cd, Co, Cr, Fe, Mn, Ni, Pb, Sb, Sn and Zn concentrations are below or close to limits of reporting at all sites in all sampling events and hence below all criteria shown in Table 3.4. Filtered Al concentrations at all sites are less than drinking water and aquatic ecosystem protection guidelines and frequently below the limits of reporting. Copper results are either below or a little above Australian guideline levels (<0.001 to 0.005 mg/L compared with an Australian guideline value of 0.0014 mg/L for soft waters; the corresponding value for moderately hard waters is 0.0035 mg/L). All filtered Mo, V and Be values are less than, equal to or slightly greater than the respective reporting limits; there are no applicable drinking water or aquatic ecosystem protection guidelines for these metals.

Filtered Ag values are less than or slightly above[9] the reporting limit and, therefore, less than the drinking water and aquatic ecosystem protection guidelines other than the ANZECC/ARMCANZ (2000) value. Concerning the latter, the reporting limit does not allow direct comparison. However, while Ag is particularly toxic to aquatic life in laboratory experiments, it is generally found to occur in natural waters in less bioavailable complexes with chloride, dissolved organic carbon and sulfur-containing ligands and hence laboratory analytical data may over-estimate its toxicity (ANZECC/ARMCANZ, 2000). Experience with resource development projects in Papua New Guinea suggests that Ag toxicity is not a material concern in PNG river systems.

Filtered Hg and Se values are all less than or equal to their reporting limits of 0.0001 and 0.01 mg/L, respectively, and are therefore also less than the drinking water and aquatic ecosystem protection guidelines other than the ANZECC/ARMCANZ (2000) values. Assigning a value of 0.5 x reporting limit, i.e., 0.00005 and 0.005 mg/L respectively, to these results allows comparison with ANZECC/ARMCANZ (2000) and indicates that the guideline values are generally not exceeded. The exception is Hg at Trib G-1 in September 2016, where the reported value of 0.0001 mg/L exceeds the guideline of 0.00006 mg/L. However, the corresponding unfiltered Hg value is less than the reporting limit, hence this filtered value is questionable.

The low filtered metal concentrations reported herein are consistent with studies elsewhere in Papua New Guinea. ECO Care (2013) reported that surface water samples in the general Project area had 'low heavy metal concentrations (that) pose no risk to aquatic fauna or communities'.

3.3.5.2 Unfiltered Metals

Unfiltered B, Ba and Se concentrations are below all criteria shown in Table 3.5. Unfiltered Cd, Sb, Se and Sn concentrations at all sites are less than drinking water and, generally, aquatic

[9] The single value that was not reported as less than the reporting limit is suspect since the corresponding unfiltered Ag value is less that the reporting limit.

ecosystem protection guidelines and frequently or entirely below the limits of reporting. As for filtered results, Mo does not have guideline values for unfiltered concentrations, however no results are above 0.002 mg/L.

Unfiltered Ag values are less than the reporting limit and, therefore, less than the applicable guidelines other than the ANZECC/ARMCANZ (2000) criterion (refer to discussion of Ag in previous subsection).

Unfiltered Co was detected at all sites other than Trib G-1 (all sampling events) and Trib C-2 (September 2016). As the PNG criteria for Co in aquatic ecosystems is set at the limit of detectability (in this case, 0.001 mg/L), these detections would qualify as exceedances if the PNG criteria were to apply to total concentrations (which they do not).

Unfiltered Hg values are less than the reporting limit of 0.0001 mg/L and hence are also less than the drinking water and aquatic ecosystem protection guidelines other than the ANZECC/ ARMCANZ (2000) values. Assigning a value of 0.5 x reporting limit, i.e., 0.00005 and 0.005 mg/L respectively, to these results (as was done for the filtered Hg values) indicates that the guideline values are not exceeded.

Results from a number of sites, particularly those with high TSS concentrations, approach or exceed ANZECC/ARMCANZ (2000) trigger values for unfiltered Al, As, Mn, Cr, Cu, Ni, Pb and Zn, as well as unfiltered Fe limits for both drinking water guidelines and the PNG criterion for aquatic ecosystems (if the latter were to apply to total metal concentrations). Results for unfiltered Be are either at or very close to the reporting limit, while those for unfiltered V appear to generally reflect TSS concentrations.

Unfiltered metal concentrations are generally lowest in Trib G-1 and Trib C-2, particularly in terms of Al, Fe and Mn, and to a lesser extent Ba, Co, Cr, Cu, Ni, Pb, V and Zn. These metal concentrations are closely correlated with suspended sediment concentrations (see Figure 3.2 for an example of unfiltered (total) Fe and Mn correlated with suspended sediments) and indicate a major contribution of particulate-associated metals. This is consistent with findings from other sampling programs in Papua New Guinea and reflects natural biogeochemical processes within the river system. This correlation is likely to at least partially explain the differences in concentrations of metals such as Al and Fe in samples from the same sites taken at different dates.

3.2.6 Hydrocarbons

Water samples from the first two sampling events were analysed for hydrocarbons including:

- Polynuclear aromatic hydrocarbons (PAH).
- Total petroleum hydrocarbons (TPH).
- Total recoverable hydrocarbons (TRH).
- Benzene, toluene, ethylbenzene, xylenes and naphthalene (BTEXN).

Concentrations are below reporting limits in all samples and at all sites, hence only TPH/TRH and BTEXN were determined in the third sampling event. Again, concentrations are below reporting limits in all samples. The current dataset has therefore not been tabulated. Full laboratory analysis results are included in Appendix 2.

Table 3.6 presents hydrocarbon reporting limits together with ‘trigger value’ criteria where available.

3.2.7 Phenols

Water samples from the first two sampling events were analysed for phenolic compounds, with the results being shown in Table 3.7. All concentrations are below the reporting limits at all sampling sites and also below relevant criteria for drinking water and ecosystem protection. Given these findings, samples from the third sampling event were not analysed for phenolic compounds.

3.2.8 Faecal Coliforms

Due to the short holding times that are recommended to maintain sample integrity, faecal coliforms shown in Table 3.8 are only indicative of the conditions at the time of sampling. It should also be noted that both criteria for aquatic ecosystems apply to at least five samples collected within a month, and as such the results presented herein are not directly comparable.

Faecal coliform results exceed the PNG drinking water regulations and WHO (2011) guidelines for all sites, part from Trib G-1 in September 2016. A number of results from all sites apart from Trib G-1 also exceed both PNG regulations (for drinking water and aquatic ecosystems) and the ANZECC/ARMCANZ (2000) guideline value for other beneficial values such as fishing. Poor water quality from a microbiological perspective can be attributed to human settlements near the rivers, and the results reported herein are consistent with those reported in ECO Care (2013), where it was noted that 'presence of coliform bacteria is consistent with findings of other river within the Watut, Markham and the general Lae area'.

3.2.9 Other Parameters

The results for other water quality parameters, including colour, sulfur, total organic carbon (TOC), oil and grease, chemical oxygen demand (COD), biochemical oxygen demand (BOD) and chlorophyll a, are shown in Table 3.9.

Concentrations of BOD and chlorophyll a are below the reporting limit at all sampling sites, with the low BOD values indicating a low biodegradable organic content, and the chlorophyll a concentrations being indicative of low primary productivity (ANZECC/ARMCANZ (2000) default value for lowland rivers in tropical Australia is 5 mg/m^3). Oil and grease concentrations are also below the reporting limits at all sampling sites, with the corresponding requirement in the Papua New Guinea Environment (Water Quality Criteria) Regulation 2002 being ‘none'.

The total S values are consistent with the SO_4 concentrations and indicate that other sulfur species, e.g., sulfide, are present only at low levels, which is consistent with the generally well-oxygenated nature of the rivers (see Table 3.1).

Total organic carbon concentrations are variable between sites and range from below the limits of reporting (<1 mg/L) to 10 mg/L, with little correlation with suspended solids results. Colour is also variable (but low), ranging from 3 to 20 PCU with the higher values occurring in at Trib G-1 and Trib C-2.

A final point to note is that concentrations of these other water quality parameters show relatively little variation over time, the greatest changes being evident in COD at Mark-1 and Rumu-2 sites.

3.3 Sediment Quality

3.3.1 Quality Control Results

The following discussion presents the findings of the Project sampling program for bed sediment samples. Laboratory reports are provided in Appendix 2.

3.3.2 Particle Size

Results from the laboratory determinations of particle size distribution (PSD) are summarised in Table 3.10, with the full particle size distributions included in Appendix 2. The various fractions included in Table 3.10 are defined as follows:

- Clay (<0.002 mm).
- Silt (0.002 mm to 0.06 mm).
- Sand (0.06 mm to 2 mm).
- Gravel (2 mm to 6 cm).

Sediment samples are generally dominated by sand-sized (Trib G-1, Rumu-2, Mark-1, Trib C-2) or gravel-sized (Mark-2) particles. Clay-size material is only a very small proportion (no more than 6%) at all sites, which is indicative of the generally fast-flowing nature of these streams and the absence of depositional environments.

3.3.3 General Parameters and Glyphosate

Results for general sediment quality parameters are presented in Table 3.11.

Total organic carbon (TOC) was <0.5% in all sediment samples. The highest result was in Trib G-1 (0.23%) and lowest in Rumu-2 (0.04%). All samples also had relatively low levels of total inorganic carbon (TIC) (0.42 to 0.77%), which reflects a range of geological characteristics in the catchments rather than dominance by limestone or similar material.

Also shown in Table 3.11 are results for glyphosate and aminomethylphosphonic acid (AMPA) for two sediment samples taken in December 2016. Glyphosate is a broad-spectrum herbicide that is used in sectors such as agriculture and forestry, and will be used by MVB for weed control. Anecdotal evidence also suggests that local communities in the Project area use this chemical, although the extent of current use is not known. Aminomethylphosphonic acid is glyphosate's principal degradation product, and determination of both glyphosate and AMPA in environmental samples is recommended by authorities such as the Australian Government's National Measurement Institute (NMI, 2017).

All results for glyphosate and AMPA were <0.05 mg/kg. As noted in Schuette (1998), glyphosate is strongly adsorbed to soil and is rapidly removed from water by adsorption onto sediment and suspended particulate matter, with sediment being the major sink in aquatic systems. Once in the sediments, the chemical continues to degrade at a 'moderate rate', with a reported half-life for a number of studies averaging from 30 to 40 days (Monsanto, 2014). Although the recommended sample storage time prior to analysis was exceeded for these samples, the fact that no glyphosate or its degradation product were detected suggests that background levels in bed sediments in the Markham River (Mark-1) and one of its tributaries (Trib C-2) are low. In comparison, 90th percentile values for glyphosate concentrations in sediments from wetlands in the intensively cultivated Great Plains of North America ranged from 0.066 mg/kg and 0.072 mg/kg in conservation reserves and native prairies, respectively, to 0.370 mg/kg where the dominant land use was active cropland (McMurry et al., 2016). However, this preliminary finding requires validation by further sampling and analysis.

3.3.4 Nutrients

Results for nutrients in sediments are summarised in Table 3.12.

Total nitrogen (total N) concentrations show some variability across sites, ranging from 40 to 220 mg/kg (dry weight). Total Kjeldahl nitrogen concentrations are equivalent to total N. Nitrate plus nitrite (NO_x) concentrations are below or close to the reporting limit (<0.1 mg/kg) at all sites other than Trib G-1 (2.1 mg/kg). This site also has elevated ammonia levels relative to the other sites.

Total phosphorous (total P) concentrations are relatively consistent between sites, ranging from 513 to 722 mg/kg at all sites. Reactive P is very low at all sites (0.2 to 0.4 mg/kg).

Nutrient concentrations are similar to, or lower than, those obtained for similar watercourses elsewhere in Papua New Guinea.

3.3.5 Metals

Where possible[10], total metals analyses were undertaken on sediment samples after separation into the <2,000 μm (i.e., <2 mm: sands, silts and clays) and <63 μm (i.e., silts and clays) fractions. The <2,000 μm fraction is considered to represent the whole sediment, with larger objects such as shells and plant matter being removed, and is the size fraction recommended in Simpson et al. (2013).

Metal concentrations are often higher in silts and clays due to the increased surface areas available for binding of metals (Simpson et al., 2005). Analysis of the <63 μm fraction allows the comparison of metals concentrations from different sampling occasions and sites to be based on equivalent sediment grain sizes (i.e., the effect of variable particle size distributions in samples is minimised).

Concentrations of metals extracted by a cold, dilute acid (1M HCl) digestion were also analysed, as this is considered to more closely represent the bioavailable fraction of metals in sediment than total metal levels.

Results for total and dilute acid extractable metals in sediments are summarised in Table 3.13.

[10] Insufficient sample was available for samples from Mark-1 and Trib C-2 to allow sieving, hence analyses were undertaken on the total sample. However, <1% of the Mark-1 sample was >2,000 μm, with the corresponding value for the Trib C-2 sample being 26%.

Total concentrations of Ag[11], As, Cd, Cr, Cu, Hg, Pb, Sb and Zn in the <2,000 μm fraction are less than or (for Cu) equal to the SQGVs at all sampling sites, with Ag and Hg being consistently below reporting limits. Total metal concentrations in the <63 μm fraction (for those three samples for which it was possible to obtain these fraction) were generally higher than, or the same as, those in the <2,000 μm fraction, as expected. Where reporting limits allow comparison, dilute acid extractable concentrations are generally considerably lower than the total concentrations.

Total Cu concentrations in the <63 μm fraction exceed the SQGV (65 mg/kg) in all sediment samples for which this fraction was available.

Total Ni concentrations in the <2,000 μm fraction and the <63 μm fraction exceed the SQGV (21 mg/kg) in all sediment samples, and this probably reflects natural geological sources. Dilute acid extractable Ni concentrations in most samples are, however, below the guideline values, the exception being Trib G-1. Dilute acid extractable concentrations of other metals in both fractions are less than the guideline values.

There are no applicable guideline screening levels for concentrations of Al, B, Ba, Co, Fe, Mn, Mo, Se or Sn in sediments. Total concentrations of these metals in the <63 μm fractions are generally higher than, or the same as, those in the <2,000 μm fractions, as expected. Notable exceptions to this include concentrations of Ba, which are higher in the <2,000 μm fraction.

As noted above, all metal concentrations in the <2,000 μm fractions are less than or equal to relevant criteria (where available) apart from Ni which was elevated compared with the SQGV at all sites. For those metals present at relatively elevated concentrations in the <2,000 μm fractions and for which criteria are not available, all are either less than or similar to:

- Mean crustal abundances (Salomons & Förstner, 1984) – Al (a mean crustal abundance of 82,000 mg/kg), Co (a mean crustal abundance of 20 mg/kg), Fe (a mean crustal abundance of 41,000 mg/kg), Mn (a mean crustal abundance of 950 mg/kg).
- Ranges in the earth's crust (WHO, 1990) – Ba (400 to 500 mg/kg in the earth's crust).

3.3.6 Phenols

Concentrations of all phenolic compounds are below the reporting limits at all sampling sites. Reporting limits range between 0.5 and 2.0 mg/kg.

Due to the results for all samples being less than the detection limits, these parameters have not been tabulated within this report (although relevant criteria and reporting limits are provided in Table 3.14). Full laboratory analysis results are included in Appendix 2.

3.3.7 Total Petroleum Hydrocarbons and BTEXN

The results for all total petroleum hydrocarbon (TPH) fractions, all total recoverable hydrocarbon (TRH) fractions, and BTEXN (benzene, toluene, ethylbenzene, xylenes and naphthalene) are below the limits of reporting at all sites (Table 3.14) and, where available, sediment quality guidelines (SQGV).

[11] Assuming that, where the reporting limit exceeds the SQGV, 0.5 x reporting limit is used for this comparison.

These parameters have therefore not been tabulated within this report. Full laboratory analysis results are included in Appendix 2.

3.3.8 Polycyclic Aromatic Hydrocarbons

The results for polycyclic aromatic hydrocarbons (PAHs) in sediments are shown in Table 3.15. Concentrations of PAHs are below detection limits in most samples, with the exception of occasional individual PAHs.

The sum of PAHs was normalised to 1% TOC to allow comparison with the sediment quality guidelines (Simpson et al., 2013)[12]. Normalised concentrations are highest in Trib G-1, but are reasonably similar between all sites. All concentrations are well below the SQGV for total PAHs of 10,000 μg/kg.

[12] Where the sample's TOC concentration was less than 0.2%, 0.2% was used as the default value for normalisation (Simpson et al., 2013; DEWHA, 2009).

4. Summary and Conclusions

Sampling and analysis of water and bed sediment samples from the Markham River and several tributaries has provided data that allows a characterisation of water and sediment quality in these rivers that will support an environmental assessment. Particularly relevant findings are summarised below.

4.1 Water Quality

Water quality results at all sites are generally consistent with data for other similar watercourses in Papua New Guinea. The results indicate generally good quality water in terms of maintaining aquatic ecosystems and potentially providing drinking water for local communities, albeit with some elevated suspended solids and faecal coliform results (which is also commonly found throughout Papua New Guinea). Particular points to note include:

- Water at all sites is alkaline and dominated by calcium (and/or sodium at some sites) and bicarbonate ions, consistent with the catchment geology containing substantial amounts of limestone or similar.
- Suspended solids levels are significantly higher in the Markham and Rumu Rivers as opposed to the other tributaries, and are particularly low in Trib G-1 (as reflected in its local name of 'Klin Wara').
- Filtered metal concentrations are low at all sampling sites, and generally meet drinking water and aquatic ecosystem protection guidelines. The exception is filtered Cu which slightly exceeds Australian guideline value for ecosystem protection, but is well below the PNG standard and is not likely to be toxicologically significant.
- Unfiltered metal concentrations are more variable, with significantly higher concentrations of unfiltered Al and Fe recorded in the Markham and Rumu rivers compared to other tributaries. These metal concentrations are closely correlated with suspended sediment concentrations and reflect a major contribution of particulate-associated metals.
- Phenols, PAHs, BTEXN, TPH/TRH, oil and grease, and BOD are below the reporting limits at all sites.
- Although some nutrient levels are elevated compared with guidelines for lowland rivers in tropical Australia, chlorophyll a levels are all below the reporting limits at all sites, which suggests that primary productivity may not be correlated with nutrient levels and may be controlled by other factors such as turbidity.
- Faecal coliform are significantly elevated at almost all sites (although the sampling regime does not allow direct comparison with a number of guidelines).

4.2 Sediment Quality

As with the water quality data, sediment quality results at all sites are consistent with data for other similar watercourses in Papua New Guinea, and indicate generally good sediment quality in terms of maintaining aquatic ecosystems. Particular points to note include:

- The river sediment samples are dominated by sand-sized and/or gravel-sized particles, which is consistent with a high-energy environment.
- Total organic carbon (TOC) was low <0.5% in all sediment samples. All samples also had relatively low levels of total inorganic carbon (TIC) (0.42 to 0.77%), which reflects a range of geological characteristics in the catchments rather than dominance by limestone or similar material.
- Nutrient concentrations are similar to, or lower than, those obtained for similar watercourses elsewhere in Papua New Guinea.
- All metal concentrations in the <2,000 μm fractions are less than or equal to relevant criteria (where available) apart from Ni which is elevated compared with the SQGV at all sites. For those metals present at relatively elevated concentrations in the <2,000 μm fractions and for which criteria are not available, all are either less than or similar to mean crustal abundances or ranges in the earth's crust. Dilute acid extractable Ni concentrations in most samples (which provide an indication of the potentially bioavailable metal) are, however, below the guideline values, the exception being Trib G-1 (22.9 mg/kg in the <63 μm fraction compared with the SQGV of 21 mg/kg). Dilute acid extractable concentrations of other metals in both fractions are less than the guideline values.
- Low concentrations of phenols, TPH/TRH, BTEXN and PAHs are evident in all sediment samples.
- Glyphosate and AMPA concentrations are less than the limit of reporting. This suggests that background levels in bed sediments are low, but this preliminary finding requires validation by further sampling and analysis.

5. References

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Regulations

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Independent State of Papua New Guinea. Environment (Water Quality Criteria) Regulation 2002, Schedule 1.

Tabulated Results

Table 3.1 – Water Quality – General Parameters

Sampling Location Name	Sample ID	Date	Temp. (°C)	pH		EC (μS/cm)		ORP (mV)	TDS (mg/L)	DO		Turbidity (NTU)	Suspended Solids (mg/L)
										(%)	(mg/L)		
Trib G-1	001[a]	31/03/16	-	8.52	8.18	-	465	-	-	-	-	-	14
	002[b]	29/09/16	28.9	11.80	8.35	519	450	50.6	331	117	8.87	0	14
	007[c]	14/12/16	-	8.56	7.94	-	456	-	-	-	-	-	<5
Trib C-2 (JC)	002[a]	31/03/16	-	8.67	8.20	-	415	-	-	-	-	-	298
Trib C-2	004[b]	30/09/16	27.1	8.59	8.23	982	935	170.4	637	39.7	3.05	11.3	68
	005[c]	14/12/16	-	8.37	7.77	-	773	-	-	-	-	-	49
Mark-1	003[a]	30/03/16	-	8.67	8.03	-	242	-	-	-	-	-	2,820
	005[b]	30/09/16	28.0	9.10	7.95	296	242	126.6	192	108.5	1.37	1494	2,650
	001[c]	14/12/16	-	7.96	6.37	-	252	-	-	-	-	-	3,990
Mark-2 (JC)	004[a]	30/03/16	-	8.67	8.00	-	350	-	-	-	-	-	1,910
Mark-2	001[b]	29/09/16	28.5	9.07	8.29	471	401	162.5	306	110.5	8.46	393	544
	003[c]	14/12/16	-	8.05	7.02	-	299	-	-	-	-	-	3,590
Rumu-2	005[a]	31/03/16	-	8.67	8.01	-	232	-	-	-	-	-	5,430
	003[b]	29/09/16	33.0	9.13	8.14	362	293	175.5	235	110.1	7.75	640	1,320
	004[c]	14/12/16	-	8.64	7.37	-	342	-	-	-	-	-	1,500
Field blank		31/03/16	-	-	6.08	-	<1	-	-	-	-	-	<5
Drinking Water Criteria													
PNG Public Health (Drinking Water) Regulation 1984 (Schedule 2) (maximum permissible levels)				6.5 – 9.2								25 (JTU)	
WHO (2011) (health-based guideline values)												<5	
Aquatic Ecosystem Protection Criteria													
PNG Environment (Water Quality Criteria) Regulation 2002			No change > 2°C	No change to natural pH							Not < 6 mg/L	No change > 25 NTU	
ANZECC/ARMCANZ (2000)				[d]		[d]		[d]	[d]	[d]		[d]	

Sample IDs: [a] EB1608860-00(x), [b] EB1624198-11(x), [c] EB1629782-00(x).
[d] Trigger values vary depending on ecosystem type and geographic location. Refer to source document.

Key:
In situ results collected in the field
Laboratory analysed results
Value exceeds PNG drinking water criteria
Value exceeds WHO drinking water criteria
Value exceeds all drinking water criteria
Value exceeds PNG aquatic ecosystem protection criteria
Value exceeds ANZECC/ARMCANZ aquatic ecosystem protection criteria
Value exceeds all aquatic ecosystem protection criteria
Value exceeds drinking water and aquatic ecosystem protection criteria

Table 3.2 – Water Quality – Major Ions

Sampling Location Name	Sample ID	Date	Hardness (mg $CaCO_3$/L)	Major Ions (mg/L)							Alkalinity (mg $CaCO_3$/L)
				Ca	Mg	Na	K	Cl	SO_4	F	
Trib G-1	001[a] 002[b] 007[c]	31/03/16 29/09/16 14/12/16	163 Hard 141 Hard 154 Hard	47 40 45	11 10 10	48 46 51	<1 <1 <1	<1 <1 1	18 17 16	0.4 0.4 0.4	255 228 255
Trib C-2 (JC)	002[a]	30/03/16	112 Mod.	30	9	64	1	1	20	0.3	226
Trib C-2 Trib C-2	004[b] 005[c]	30/09/16 14/12/16	257 Very Hard 215 Very Hard	52 50	31 22	125 111	3 2	2 2	12 14	0.2 0.2	502 461
Mark-1	003[a] 005[b] 001[c]	30/03/16 30/09/16 14/12/16	98.0 Mod. 88.9 Mod. 91.4 Mod.	31 29 30	5 4 4	15 18 17	<1 <1 <1	1 <1 <1	15 13 11	0.2 0.1 0.2	122 122 169
Mark-2 (JC)	004[a]	30/03/16	93.9 Mod.	31	4	15	<1	1	14	0.2	118
Mark-2	001[b] 003[c]	29/09/16 14/12/16	132 Hard 93.9 Mod.	38 34	9 5	41 29	<1 <1	1 1	16 13	0.3 0.2	202 159
Rumu-2	005[a] 003[b] 004[c]	31/03/16 29/09/16 14/12/16	129 Hard 101 Mod. 129 Hard	37 29 36	9 7 8	31 21 31	1 <1 1	1 <1 1	34 20 24	0.2 0.1 0.2	169 138 122
Field blank		31/03/16 29/09/16 14/12/16	-- -- --	<1 <1 <1	<1 <1 <1	<1 <1 <1	<1 <1 <1	-- -- --	<1 <1 <1	<0.1 <0.1 <0.1	-- -- --
Drinking Water Criteria											
PNG Public Health (Drinking Water) Regulation 1984 (Schedule 2) (maximum permissible levels)			600	200	150			1000	400	1.5	
WHO (2011) (health-based guideline values)						200		250[d]	250[d]	1.5	
Aquatic Ecosystem Protection Criteria											
PNG Environment (Water Quality Criteria) Regulation 2002							5		400	1.5	

ANZECC/ARMCANZ (2000) (trigger values for slightly-moderately disturbed systems)									

Sample IDs: [a] EB1608860-00(x), [b] EB1624198-11(x), [c] EB1629782-00(x).
[d] This is not a health-based value, however concentrations of chloride or sulfate in excess of 250 mg/L and sodium in excess of 200 mg/L can give rise to detectable taste in water.

Key:
Value exceeds PNG drinking water criteria; *Value exceeds WHO drinking water criteria*; **Value exceeds all drinking water criteria**.
Value exceeds PNG aquatic ecosystem protection criteria; *Exceeds ANZECC/ARMCANZ aquatic ecosystem protection criteria*; **Exceeds all aquatic ecosystem protection criteria**.
Value exceeds drinking water and aquatic ecosystem protection criteria.

Table 3.3 – Water Quality – Nutrients

Sampling Location Name	Sample ID	Date	Nutrients (mg/L)							
			NH_3	NO_x	Total Kjeldahl N	Nitrite	Nitrate	Total N	Total P	Reactive P
Trib G-1	001[a] 002[b] 007[c]	31/03/16 29/09/16 14/12/16	<0.01 <0.01 0.08	0.04 0.12 0.13	0.3 0.2 0.1	<0.01 <0.01 <0.01	0.04 0.12 0.13	0.3 0.3 0.2	0.02 0.02 0.02	<0.01 <0.01 <0.01
Trib C-2 (JC)	002[a]	30/03/16	<0.01	<0.01	0.2	<0.01	<0.01	0.2	0.20	0.01
Trib C-2 Trib C-2	004[b] 005[c]	30/09/16 14/12/16	0.03 0.08	0.06 0.02	0.4 0.3	0.01 <0.01	0.05 0.02	0.5 0.3	0.11 0.06	0.07 0.02
Mark-1	003[a] 005[b] 001[c]	30/03/16 30/09/16 14/12/16	0.03 <0.05 0.04	<0.01 0.06 0.08	1.3 0.8 1.5	<0.01 <0.01 <0.01	<0.01 0.06 0.08	1.3 0.9 1.6	2.14 1.72 2.47	0.02 0.02 0.02
Mark-2 (JC)	004[a]	30/03/16	<0.01	<0.01	1.1	<0.01	<0.01	1.1	1.35	0.02
Mark-2	001[b] 003[c]	29/09/16 14/12/16	<0.01 <0.01	0.08 0.07	0.4 1.6	<0.01 <0.01	0.08 0.07	0.5 1.7	0.41 2.90	0.01 0.01
Rumu-2	005[a] 003[b] 004[c]	31/03/16 29/09/16 14/12/16	<0.01 <0.01 0.02	<0.01 0.09 0.08	1.2 0.3 0.4	<0.01 <0.01 <0.01	<0.01 0.09 0.08	1.2 0.4 0.5	3.82 1.29 1.19	<0.01 0.01 <0.01
Field blank		31/03/16 29/09/16 14/12/16	<0.01 <0.01 <0.01	<0.01 <0.01 <0.01	<0.01 <0.01 <0.01	<0.01 <0.01 <0.01	<0.01 <0.01 <0.01	<0.01 <0.01 <0.01	<0.01 <0.01 <0.01	<0.01 <0.01 <0.01
Drinking Water Criteria										
PNG Public Health (Drinking Water) Regulation 1984 (Schedule 2) (maximum permissible levels)				45[d]			45			
WHO (2011) (health-based guideline values)			35[e]	50[d]		3	50			
Aquatic Ecosystem Protection Criteria										
PNG Environment (Water Quality Criteria) Regulation 2002			0.5	45[f]			45			

ANZECC/ARMCANZ (2000) (trigger values for slightly-moderately disturbed systems; 95% species protection level)	0.9	0.7[e]				[g]	[g]	

Sample IDs: [a] EB1608860-00(x), [b] EB1624198-11(x), [c] EB1629782-00(x).
[d] As nitrate. [e] This is not a health-based value, however 35 mg/L of ammonia is considered to be a taste threshold. [f] As nitrate + nitrite.
[g] Trigger values vary depending on ecosystem type and geographic location. Refer to source document.

Key:
Value exceeds PNG drinking water criteria
Value exceeds WHO drinking water criteria
Value exceeds all drinking water criteria
Value exceeds PNG aquatic ecosystem protection criteria
Value exceeds ANZECC/ARMCANZ aquatic ecosystem protection criteria
Value exceeds all aquatic ecosystem protection criteria
Value exceeds drinking water and aquatic ecosystem protection criteria

Table 3.4 – Water Quality – Filtered Metals (Ag to Fe)

Sampling Location Name	Sample ID	Date	Metals (dissolved/filtered, mg/L)										
			Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe
Trib G-1	001[a]	31/03/16	<0.001	<0.01	<0.001	0.10	<0.001	<0.001	<0.0001	<0.001	<0.001	0.001	<0.05
	002[b]	29/09/16	<0.001	<0.01	<0.001	0.09	<0.001	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.05
	007[c]	14/12/16	<0.001	0.02	<0.001	0.10	<0.001	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.05
Trib C-2 (JC)	002[a]	31/03/16	<0.001	<0.001	<0.001	0.09	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.05
Trib C-2	004[b]	30/09/16	<0.001	<0.001	0.002	0.01	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.05
Trib C-2	005[c]	14/12/16	<0.001	<0.001	0.001	0.11	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.05
Mark-1	003[a]	30/03/16	*0.002*	0.05	0.002	<0.05	0.003	<0.001	<0.0001	<0.001	<0.001	0.002	<0.05
	005[b]	30/09/16	<0.001	0.04	0.002	<0.05	0.002	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.05
	001[c]	14/12/16	<0.001	*0.07*	0.002	<0.05	0.002	<0.001	<0.0001	<0.001	<0.001	0.001	<0.05
Mark-2 (JC)	004[a]	30/03/16	<0.001	0.03	0.002	<0.05	0.003	<0.001	<0.0001	<0.001	<0.001	0.002	<0.05
Mark-2	001[b]	29/09/16	<0.001	0.03	<0.001	0.09	0.001	<0.001	<0.0001	<0.001	<0.001	0.002	<0.05
	003[c]	14/12/16	<0.001	*0.06*	<0.001	0.07	0.001	<0.001	<0.0001	<0.001	<0.001	0.002	<0.05
Rumu-2	005[a]	31/03/16	<0.001	0.04	<0.001	0.08	0.001	<0.001	<0.0001	<0.001	<0.001	0.005	<0.05
	003[b]	29/09/16	*0.001*	0.05	<0.001	0.06	<0.001	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.05
	004[c]	14/12/16	*0.002*	*0.08*	<0.001	0.08	<0.001	<0.001	<0.0001	<0.001	<0.001	0.001	<0.05
Field blank		31/03/16	<0.001	<0.01	<0.001	<0.05	<0.001	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.05
		29/09/16	<0.001	<0.01	<0.001	<0.05	<0.001	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.05
		14/12/16	<0.001	<0.01	<0.001	<0.05	<0.001	<0.001	<0.0001	<0.001	<0.001	<0.001	<0.05
Drinking Water Criteria													
PNG Public Health (Drinking Water) Regulation 1984 (Schedule 2) (maximum permissible levels – except Fe [d])			0.05		0.05				0.01			1.5	1.0[d]
WHO (2011) (maximum permissible levels)					0.01	2.4	0.7		0.003		0.05[f]	2	0.3

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Aquatic Ecosystem Protection Criteria											
PNG Environment (Water Quality Criteria) Regulation 2002	0.05		0.05	1.0	1.0		0.01	[e]	0.05[f]	1.0	1.0
ANZECC/ARMCANZ (2000) (trigger values for slightly-moderately disturbed systems)	0.00005[i]	0.055[g]	0.024[h]	0.37			0.0002[i]		0.001[i]	0.0014[i]	

Sample IDs: [a] EB1608860-00(x), [b] EB1624198-11(x), [c] EB1629782-00(x).
[d] This is not a health-based value, however at levels above 0.3 mg/L, iron stains laundry and plumbing fixtures and can give rise to detectable taste in water.
[e] Limit of detectability.
[f] Chromium (Cr) as hexavalent form.
[g] At pH >6.5.
[h] As(III). 0.013 mg/L for As(V).
[i] Based on 'soft' water hardness of 30 mg/L $CaCO_3$.

Key:
Value exceeds PNG drinking water criteria
Value exceeds WHO drinking water criteria
Value exceeds all drinking water criteria
Value exceeds PNG aquatic ecosystem protection criteria
Value exceeds ANZECC/ARMCANZ aquatic ecosystem protection criteria
Value exceeds all aquatic ecosystem protection criteria
Value exceeds drinking water and aquatic ecosystem protection criteria

Table 3.4 – Water Quality – Filtered Metals (cont'd) (Hg to Zn)

Sampling Location Name	Sample ID	Date	Metals (dissolved/filtered, mg/L)									
			Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	V	Zn
Trib G-1	001[a] 002[b] 007[c]	31/03/16 29/09/16 14/12/16	<0.0001 0.0001 <0.0001	0.005 0.004 0.005	<0.001 <0.001 <0.001	<0.001 <0.001 <0.001	<0.001 <0.001 <0.001	<0.001 <0.001 <0.001	<0.01 <0.01 <0.01	<0.001 <0.001 <0.001	0.02 0.03 0.03	<0.005 <0.005 <0.005
Trib C-2 (JC)	002[a]	31/03/16	<0.0001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.001	0.03	<0.005
Trib C-2 Trib C-2	004[b] 005[c]	30/09/16 14/12/16	<0.0001 <0.0001	0.002 0.018	<0.001 <0.001	<0.001 <0.001	<0.001 <0.001	<0.001 <0.001	<0.01 <0.01	<0.001 <0.001	<0.01 0.01	<0.005 <0.005
Mark-1	003[a] 005[b] 001[c]	30/03/16 30/09/16 14/12/16	<0.0001 <0.0001 <0.0001	0.002 0.001 0.002	<0.001 <0.001 <0.001	<0.001 <0.001 <0.001	<0.001 <0.001 <0.001	<0.001 <0.001 <0.001	<0.01 <0.01 <0.01	<0.001 <0.001 <0.001	0.01 0.01 0.01	<0.005 <0.005 <0.005
Mark-2 (JC)	004[a]	30/03/16	<0.0001	0.002	<0.001	<0.001	<0.001	<0.001	<0.01	<0.001	<0.01	<0.005
Mark-2	001[b] 003[c]	29/09/16 14/12/16	<0.0001 <0.0001	0.003 0.003	<0.001 <0.001	<0.001 <0.001	<0.001 <0.001	<0.001 <0.001	<0.01 <0.01	<0.001 <0.001	0.02 0.02	<0.005 <0.005
Rumu-2	005[a] 003[b] 004[c]	31/03/16 29/09/16 14/12/16	<0.0001 <0.0001 <0.0001	0.005 0.004 0.004	0.001 <0.001 <0.001	<0.001 <0.001 <0.001	<0.001 <0.001 <0.001	<0.001 <0.001 <0.001	<0.01 <0.01 <0.01	<0.001 <0.001 <0.001	0.01 0.01 0.02	<0.005 <0.005 <0.005
Drinking Water Criteria												
PNG Public Health (Drinking Water) Regulation 1984 (Schedule 2) (maximum permissible levels)			0.001	0.5			0.1		0.01			15
WHO (2011) (maximum permissible levels)			0.006	0.4		0.07	0.01	0.02	0.04			4[d]
Aquatic Ecosystem Protection Criteria												
PNG Environment (Water Quality Criteria) Regulation 2002			0.0002	0.5		1.0	0.005		0.01	0.5		5.0
ANZECC/ARMCANZ (2000) (trigger values for slightly-moderately disturbed systems)			0.00006[e]	1.9		0.011[e]	0.0034[e]		0.005			0.008[e]

Sample IDs: [a] EB1608860-00(x), [b] EB1624198-11(x), [c] EB1629782-00(x).
[d] This is not a health-based value, however at levels above 4 mg/L zinc can give rise to a detectable taste in water.

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[e] Based on 'soft' water hardness of 30 mg/L $CaCO_3$.

Key:
Value exceeds PNG drinking water criteria
Value exceeds WHO drinking water criteria
Value exceeds all drinking water criteria
Value exceeds PNG aquatic ecosystem protection criteria
Value exceeds ANZECC/ARMCANZ aquatic ecosystem protection criteria
Value exceeds all aquatic ecosystem protection criteria
Value exceeds drinking water and aquatic ecosystem protection criteria

Table 3.5 – Water Quality – Unfiltered Metals (Ag to Fe)

Sampling Location Name	Sample ID	Date	Metals (total/unfiltered, mg/L)										
			Ag	Al	As	B	Ba	Be	Cd	Co	Cr	Cu	Fe
Trib G-1	001[a] 002[b] 007[c]	31/03/16 29/09/16 14/12/16	<0.001 <0.001 <0.001	*0.32* *0.22* *0.18*	<0.001 <0.001 <0.001	0.12 0.10 0.10	<0.001 <0.001 <0.001	<0.001 <0.001 <0.001	<0.0001 0.0001 <0.0001	<0.001 <0.001 <0.001	<0.001 <0.001 <0.001	0.001 *0.002* 0.001	*0.32* 0.23 0.18
Trib C-2 (JC)	002[a]	31/03/16	<0.001	*7.54*	0.001	0.10	0.017	<0.001	*0.0003*	0.004	*0.008*	*0.014*	**7.01**
Trib C-2 Trib C-2	004[b] 005[c]	30/09/16 14/12/16	<0.001 <0.001	*1.30* *2.16*	0.002 0.002	0.12 0.11	0.002 0.004	<0.001 <0.001	<0.0001 <0.0001	<0.001 0.001	*0.002* *0.003*	*0.005* *0.006*	**1.60** **2.16**
Mark-1	003[a] 005[b] 001[c]	30/03/16 30/09/16 14/12/16	<0.001 <0.001 <0.001	*101* *92.3* *108*	*0.014* 0.01 *0.023*	0.08 0.08 <0.05	0.220 0.197 0.280	<0.001 <0.001 <0.001	0.0002 *0.0003* *0.0004*	0.065 0.059 0.061	**0.100** **0.082** **0.087**	*0.216* *0.217* *0.220*	**111** **109** **108**
Mark-2 (JC)	004[a]	30/03/16	<0.001	*49.6*	*0.014*	<0.05	0.137	0.002	*0.0005*	0.031	*0.049*	*0.105*	**59.0**
Mark-2	001[b] 003[c]	29/09/16 14/12/16	<0.001 <0.001	*25.3* *96.5*	0.002 0.005	0.11 0.06	0.058 0.186	<0.001 <0.001	<0.0001 0.0002	0.015 0.057	*0.024* **0.080**	*0.054* *0.205*	**29.7** **96.5**
Rumu-2	005[a] 003[b] 004[c]	31/03/16 29/09/16 14/12/16	<0.001 <0.001 <0.001	*156* *55.8* *59.1*	0.010 0.003 0.004	0.12 0.09 0.06	0.187 0.06 0.060	<0.001 <0.001 <0.001	<0.0001 0.0002 0.0002	0.114 0.035 0.034	**0.168** *0.039* *0.042*	*0.411* *0.114* *0.114*	**190** **61.0** **59.1**
Field blank		31/03/16 29/09/16 14/12/16	<0.001 <0.001 <0.001	<0.01 <0.01 <0.01	<0.001 <0.001 <0.001	<0.05 <0.05 <0.05	<0.001 <0.001 <0.001	<0.001 <0.001 <0.001	<0.0001 <0.0001 <0.0001	<0.001 <0.001 <0.001	<0.001 <0.001 <0.001	<0.001 <0.001 <0.001	<0.05 <0.05 <0.05
Drinking Water Criteria													
PNG Public Health (Drinking Water) Regulation 1984 (Schedule 2) (maximum permissible levels)			0.05		0.05				0.01			5	1.0
WHO (2011) (maximum permissible levels)					0.01	2.4	0.7		0.003		0.05[f]	2	0.3[d]
Aquatic Ecosystem Protection Criteria													
PNG Environment (Water Quality Criteria) Regulation 2002			0.05		0.05	1.0	1.0		0.01	[e]	0.05[f]	1.0	1.0

ANZECC/ARMCANZ (2000) (trigger values for slightly-moderately disturbed systems)	0.00005[i]	0.055[g]	0.024[h]	0.37			0.0002[i]		0.001[i]	0.0014[i]	

Sample IDs: [a] EB1608860-00(x), [b] EB1624198-11(x), [c] EB1629782-00(x).
[d] This is not a health-based value, however at levels above 0.3 mg/L, iron stains laundry and plumbing fixtures and can give rise to detectable taste in water.
[e] Limit of detectability.
[f] Chromium (Cr) as hexavalent form.
[g] At pH >6.5.
[h] As(III). 0.013 mg/L for As(V).
[i] Based on 'soft' water hardness of 30 mg/L $CaCO_3$.

Key:
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Value exceeds WHO drinking water criteria
Value exceeds all drinking water criteria
Value exceeds PNG aquatic ecosystem protection criteria
Value exceeds ANZECC/ARMCANZ aquatic ecosystem protection criteria
Value exceeds all aquatic ecosystem protection criteria
Value exceeds drinking water and aquatic ecosystem protection criteria

Table 3.5 – Water Quality – Unfiltered Metals (cont'd) (Hg to Zn)

Sampling Location Name	Sample ID	Date	Metals (total/unfiltered, mg/L)									
			Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	V	Zn
Trib G-1	001[a] 002[b] 007[c]	31/03/16 29/09/16 14/12/16	<0.0001 <0.0001 <0.0001	0.027 0.018 0.016	<0.001 <0.001 <0.001	<0.001 0.002 <0.001	<0.001 <0.001 <0.001	<0.001 <0.001 <0.001	<0.01 <0.01 <0.01	<0.001 <0.001 <0.001	0.02 0.03 0.03	<0.005 <0.005 <0.005
Trib C-2 (JC)	002[a]	31/03/16	<0.0001	**0.163**	<0.001	0.009	<0.001	<0.001	<0.001	<0.001	0.05	<0.005
Trib C-2 Trib C-2	004[b] 005[c]	30/09/16 14/12/16	<0.0001 <0.0001	**0.155** 0.083	<0.001 <0.001	0.002 0.003	<0.001 <0.001	<0.001 <0.001	<0.001 <0.001	<0.001 <0.001	0.01 0.02	<0.005 <0.005
Mark-1	003[a] 005[b] 001[c]	30/03/16 30/09/16 14/12/16	<0.0001 <0.0001 <0.0001	**2.67** **2.83** **2.95**	<0.001 <0.001 <0.001	*0.149* *0.132* *0.126*	**0.017** **0.014** **0.023**	<0.001 <0.001 <0.001	<0.01 <0.01 <0.01	<0.001 <0.001 <0.001	0.29 0.26 0.26	*0.181* *0.163* *0.200*
Mark-2 (JC)	004[a]	30/03/16	<0.0001	**1.53**	<0.001	*0.063*	**0.015**	<0.001	<0.01	<0.001	0.14	*0.099*
Mark-2	001[b] 003[c]	29/09/16 14/12/16	<0.0001 <0.0001	**0.769** **2.41**	<0.001 <0.001	*0.032* *0.126*	0.003 0.010	<0.001 <0.001	<0.01 <0.01	<0.001 <0.001	0.09 0.24	*0.036* *0.153*
Rumu-2	005[a] 003[b] 004[c]	31/03/16 29/09/16 14/12/16	<0.0001 <0.0001 <0.0001	**4.15** **1.27** **1.30**	0.002 0.001 0.001	*0.273* *0.077* *0.073*	**0.017** 0.004 0.004	<0.001 <0.001 <0.001	<0.01 <0.01 <0.01	<0.001 <0.001 <0.001	0.49 0.17 0.17	*0.273* *0.072* *0.086*
Field blank		31/03/16 29/09/16	<0.0001 <0.0001	<0.001 <0.001	<0.001 <0.001	<0.001 <0.001	<0.001 <0.001	<0.001 <0.001	<0.01 <0.01	<0.001 <0.001	<0.01 <0.01	<0.005 <0.005
Drinking Water Criteria												
PNG Public Health (Drinking Water) Regulation 1984 (Schedule 2) (maximum permissible levels)			0.001	0.5			0.1		0.01			15
WHO (2011) (maximum permissible levels)			0.006	0.4		0.07	0.01[d]	0.02	0.04[d]			4[e]
Aquatic Ecosystem Protection Criteria												
PNG Environment (Water Quality Criteria) Regulation 2002			0.0002	0.5		1.0	0.005		0.01	0.5		5

ANZECC/ARMCANZ (2000) (trigger values for slightly-moderately disturbed systems)	0.00006[f]	1.9		0.011[f]	0.0034[f]		0.005			0.008[f]

Sample IDs: [a] EB1608860-00(x), [b] EB1624198-11(x), [c] EB1629782-00(x).
[d] Provisional guideline value.
[e] This is not a health-based value, however at levels above 4 mg/L zinc can give rise to a detectable taste in water.
[f] Based on 'soft' water hardness of 30 mg/L $CaCO_3$.

Key:
Value exceeds PNG drinking water criteria
Value exceeds WHO drinking water criteria
Value exceeds all drinking water criteria
Value exceeds PNG aquatic ecosystem protection criteria
Value exceeds ANZECC/ARMCANZ aquatic ecosystem protection criteria
Value exceeds all aquatic ecosystem protection criteria
Value exceeds drinking water and aquatic ecosystem protection criteria

Table 3.6 – Water Quality – Hydrocarbon Criteria and Reporting Limits

	Trigger Value [a] (µg/L)	Reporting Limit (µg/L)
Benzene	950	1.0
Toluene, Ethylbenzene	[b]	2.0
o-xylene	350	2.0
p-xylene	200	2.0
m-xylene, m+p-xylene	[b]	2.0
Naphthalene	16	5.0
PAH	[c]	<0.5 – <1.0
TPH	[c]	<20 – <100
TRH	[c]	<20 – <100

Note: No hydrocarbon results from the three sampling events exceeded applicable reporting limits.

[a] ANZECC/ARMCANZ (2000) trigger value for freshwater, level of protection: 95% of species.
[b] Insufficient data to derive a reliable trigger value.
[c] No criteria currently available.

Table 3.7 – Water Quality – Phenols

Sampling Location Name	Sample ID	Date	Phenolic Compounds (µg/L)											
			Phenol	2-Chloro phenol	2-Methyl phenol	3- & 4-Methyl phenol	2-Nitro phenol	2.4-Di methyl phenol	2.4-Di chloro phenol	2.6-Di chloro phenol	4-Chloro-3-Methyl phenol	2.4.6-Tri chloro phenol	2.4.5-Tri chloro phenol	Penta-chloro phenol
Trib G-1	001[a] 002[b]	31/03/16 29/09/16	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.02 <0.02	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.02 <0.02
Trib C-2 (JC)	002[a]	31/03/16	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.02
Trib C-2	004[b]	30/09/16	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.02
Mark-1	003[a] 005[b]	30/03/16 30/09/16	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.02 <0.02	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.02 <0.02
Mark-2 (JC)	004[a]	30/03/16	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.02
Mark-2	001[b]	29/09/16	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.02
Rumu-2	005[a] 003[b]	31/03/16 29/09/16	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.02 <0.02	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.02 <0.02
Field blank		31/03/16 29/09/16	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.02 <0.02	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.01 <0.01	<0.02 <0.02
Drinking Water Criteria														
PNG Public Health (Drinking Water) Regulation 1984 (Schedule 2) (maximum permissible levels)														
WHO (2011) (health-based guideline values)												200[d]		9[e]

Aquatic Ecosystem Protection Criteria												
PNG Environment (Water Quality Criteria) Regulation 2002	2											
ANZECC/ARMCANZ (2000) (trigger values for slightly-moderately disturbed systems)	320	340			[f]	[f]	120	[f]			[f]	

Sample IDs: [a] EB1608860-00(x), [b] EB1624198-11(x), [c]EB1629782-00(x).
[d] Concentrations of 2.4.6-Trichlorophenol at or below the health-based guideline value may affect the appearance, taste or odour of the water, leading to consumer complaints.
[e] Provisional guideline value.
[f] Insufficient data to derive a reliable trigger value.

Key:
Value exceeds PNG drinking water criteria
Value exceeds WHO drinking water criteria
Value exceeds all drinking water criteria
Value exceeds PNG aquatic ecosystem protection criteria
Value exceeds ANZECC/ARMCANZ aquatic ecosystem protection criteria
Value exceeds all aquatic ecosystem protection criteria
Value exceeds drinking water and aquatic ecosystem protection criteria

Table 3.8 – Water Quality – Faecal Coliforms

Sampling Location Name	Sample ID	Date	Faecal Coliforms per 100 mL
Trib G-1	#1 TRIB G-1 #2 TRIB G-1 EB1629782007	31/03/16 29/09/16 14/12/16	>80 cfu/100mL [a] 2 MPN/100mL 130 MPN/100mL
Trib C-2 (JC)	#2 TRIB C-2	31/03/16	>80 cfu/100mL [a]
Trib C-2 Trib C-2	#4 TRIB C-2 EB1629782005	30/09/16 14/12/16	**5,400 MPN/100mL** **16,000 MPN/100mL**
Mark-1	#3 MARK-1 #5 MARK-1 EB1629782001	30/03/16 30/09/16 14/12/16	**1,600 MPN/100mL** **2,400 MPN/100mL** **3,500 MPN/100mL**
Mark-2 (JC)	#4 MARK-2	30/03/16	**2,400 MPN/100mL**
Mark-2	#1 MARK-2 EB1629782003	29/09/16 14/12/16	**920 MPN/ 100mL** **1,600 MPN/100mL**
Rumu-2	#5 RUMU-2 #3 RUMU-2 EB1629782004	31/03/16 29/09/16 14/12/16	350 MPN/100mL 540 MPN/100mL **9,200 MPN/100mL**
Drinking Water Criteria			
PNG Public Health (Drinking Water) Regulation 1984 (Schedule 2) (maximum permissible levels)			3[b]
WHO (2011) (health-based guideline values)			Not detectable in any 100 mL sample [c]
Aquatic Ecosystem Protection Criteria			
PNG Environment (Water Quality Criteria) Regulation 2002			200[d]
ANZECC/ARMCANZ (2000) (for selected beneficial values other than protection of aquatic ecosystems)			150[e] 1000[e]

[a] Samples were analysed using membrane filtration method. Subsequent samples were analysed with an alternative method to account for higher levels of faecal coliforms.
[b] Criterion is for non-disinfected water supplies for individuals or small communities.
[c] Water directly intended for drinking/treated water in distribution systems.
[d] Criterion is based on not fewer than 5 samples taken over a period of not more than 30 days, in which the median value of faecal coliforms shall not exceed 200 per 100 mL.

[e] 150/100 mL for primary contact in recreational waters, 1000/100 mL for fishing (minimum of 5 samples taken at regular intervals not exceeding 1 month, with 4 of 5 samples containing <600/100 mL (for primary contact), or <4000/100 mL (for fishing)).

Key:
Value exceeds PNG drinking water criteria
Value exceeds WHO drinking water criteria
Value exceeds all drinking water criteria
Value exceeds PNG aquatic ecosystem protection criteria
Value exceeds ANZECC/ARMCANZ aquatic ecosystem protection criteria
Value exceeds all aquatic ecosystem protection criteria
Value exceeds drinking water and aquatic ecosystem protection criteria

Table 3.9 – Water Quality – Other Parameters

Sampling Location Name	Sample ID	Date	Colour true (PCU)	Sulfur (mg/L)	TOC (mg/L)	Oil and grease (mg/L)	COD (mg/L)	BOD (mg/L)	Chlorophyll a (mg/m^3)
Trib G-1	001[a] 002[b] 007[c]	31/03/16 29/09/16 14/12/16	15 10 15	6 5 6	1 1 3	-- <5 <5	<10 <10 <10	<2 <2 <2	<1 <1 <1
Trib C-2 (JC)	002[a]	31/03/16	5	7	<1	--	<10	<2	<1
Trib C-2 Trib C-2	004[b] 005[c]	30/09/16 14/12/16	16 20	4 5	10 6	<5 <5	<10 <10	<2 <2	<1 <1
Mark-1	003[a] 005[b] 001[c]	30/03/16 30/09/16 14/12/16	6 3 6	6 4 5	1 6 2	-- <5 <5	<10 322 190	<2 <2 <2	<2 <3 <3
Mark-2 (JC)	004[a]	30/03/16	10	6	1	--	<10	<2	<1
Mark-2	001[b] 003[c]	29/09/16 14/12/16	6 8	5 6	5 2	<5 <5	<10 170	<2	<2 <3
Rumu-2	005[a] 003[b] 004[c]	31/03/16 29/09/16 14/12/16	6 3 5	13 6 9	<1 2 2	-- <5 <5	16 152 104	<2 <2 <2	<1 <2 <3
Field Blank		31/03/16 29/09/16 14/12/16	--	<1 <1 <1	<1 <1 <1	<5 <5 <5	<10 <10 <10	<2 <2 <2	<1 <1 <1
Drinking Water Criteria									
PNG Public Health (Drinking Water) Regulation 1984 (Schedule 2) (maximum permissible levels)			50 units				10[d]	6[d]	
WHO (2011) (health-based guideline values)									
Aquatic Ecosystem Protection Criteria									
PNG Environment (Water Quality Criteria) Regulation 2002			[e]			None			

ANZECC/ARMCANZ (2000) (trigger values for slightly-moderately disturbed systems)							

Sample IDs: [a] EB1608860-00(x). [b] EB1624198-11(x). [c]EB1629782-00(x).
[d] Data obtained from PNG Public Health (Drinking Water) Regulation 1984 (Schedule 1).
[e] No alteration to natural colouration (*for both fresh and seawater*).

Key:
Value exceeds PNG drinking water criteria
Value exceeds WHO drinking water criteria
Value exceeds all drinking water criteria
Value exceeds PNG aquatic ecosystem protection criteria
Value exceeds ANZECC/ARMCANZ aquatic ecosystem protection criteria
Value exceeds all aquatic ecosystem protection criteria
Value exceeds drinking water and aquatic ecosystem protection criteria

Table 3.10 – Sediment Quality – Size Classification

Sampling Location	Sample ID	Date	Clay (<2 μm)	Silt (<2 – 60 μm)	Sand (0.06 – 2mm)	Gravel (<2mm)	Cobbles (>6cm)
Trib G-1	EB1624198008	29/09/16	3	3	58	36	<1
Mark-2	EB1624198007	29/09/16	6	12	21	61	<1
Rumu-2	EB1624198009	29/09/16	5	8	86	1	<1
Mark-1 [a]	EB1629782002	14/12/16	2	5	93	<1	<1
Trib C-2 [b]	EB1629782006	14/12/16	0.1	4.9	69	ND [c]	ND

[a] Mark_1 is an unfractionated sample. Less than 1% of the sample is <2000 µm.
[b] TribC_2 is an unfractionated sample. 26% of the sample is <2000 µm. No further size breakdown was analysed therefore gravel and cobble cannot be determined.
[c] ND = Not Determined.

Table 3.11 – Sediment Quality – General Parameters

Sampling Location	Sample ID	Date	Moisture Content (%) [a]	TOC	TC	TIC	Glyphosate	AMPA
				(% dry weight) [a]				
Trib G-1	EB1624198008	29/09/16	16.9	0.23	0.65	0.42	ND [b]	ND
Mark-2	EB1624198007	29/09/16	21.2	0.11	0.57	0.46	ND	ND
Rumu-2	EB1624198009	29/09/16	26.3	0.04	0.38	0.34	ND	ND
Mark-1	EB1629782002	14/12/16	25.5	0.14	0.61	0.47	<0.05	<0.05
Trib C-2	EB1629782006	14/12/16	22.0	0.09	0.86	0.77	<0.05	<0.05

[a] Dried at 103°C.
[b] ND = Not Determined.

Table 3.12 – Sediment Quality – Nutrients

Sampling Location Name	Sample ID	Date	NH_3	NO_x (Nitrite + Nitrate as N)	Total Kjeldahl N	Nitrite	Nitrate	Total N	Total P	Reactive P
			(mg/kg, dry weight)							
Trib G-1	EB1624198008	29/09/16	3.3	2.1	160	<0.1	2.1	160	592	0.2
Mark-2	EB1624198007	29/09/16	1.2	0.2	100	<0.1	0.2	100	561	0.2
Rumu-2	EB1624198009	29/09/16	0.4	<0.1	140	<0.1	<0.1	140	513	0.2
Mark-1	EB1629782002	14/12/16	0.8	<0.1	220	<0.1	<0.1	220	722	0.1
Trib C-2	EB1629782006	14/12/16	1.1	<0.1	40	<0.1	<0.1	40	660	0.4

Table 3.13 – Sediment Quality – Metals (Ag to Fe)

Sampling Location Name	Sample ID	Date	Metals (mg/kg, dry weight)									
			Ag	Al	As	B	Ba	Cd	Co	Cr	Cu	Fe
<2000 µm Fraction (Total Metals)												
Trib G-1	EB1624198011	29/09/16	<0.1	38,600	1.9	<50	70.3	<0.1	16.9	25.9	55.9	39,000
Mark-2	EB1624198010	29/09/16	<0.1	37,300	2.5	<50	81.7	<0.1	18	28.6	**65.2**	43,700
Rumu-2	EB1624198012	29/09/16	<0.1	29,200	2.3	<50	34.7	<0.1	17.2	45.9	63.3	46,700
Mark-1 [a]	EB1629782002	14/12/16	<2	43,400	<5	<50	100	<1	19	33	**67.0**	42,300
Trib C-2 [b]	EB1629782006	14/12/16	<2	56,000	<5	<50	120	<1	15	19	**66.0**	37,700
<63 µm Fraction (Total Metals)												
Trib G-1	EB1624198014	29/09/16	<0.1	39,300	1.9	<50	65.6	0.1	24	54.8	**96.1**	52,700
Mark-2	EB1624198013	29/09/16	<0.1	38,700	3.4	<50	80.5	0.1	21	43.4	**76.8**	51,500
Rumu-2	EB1624198015	29/09/16	<0.1	25,900	2.5	<50	28	<0.1	20.4	77.4	**84.3**	66,200
SQG-high (Simpson et al., 2013)			4.0		70			10		370	270	
SQGV (Simpson et al., 2013)			1.0		20			1.5		80	65	

[a] Mark-1 is an unfractionated sample. Less than 1% of the sample is <2000 µm.
[b] Trib C-2 is an unfractionated sample. 26% of the sample is above <2000 µm.

Key:
Value exceeds SQGV.
Value exceeds SQG-high.

Table 3.13 – Sediment Quality – Metals (Ag to Fe) (cont'd)

Sampling Location Name	Sample ID	Date	Metals (mg/kg, dry weight)									
			Ag	Al	As	Ba	B	Cd	Co	Cr	Cu	Fe
<2000 µm Fraction (1M HCl Extractable Metals)												
Trib G-1	EB1624198011	29/09/16	<0.05	19,800	0.75	22.0	8	<0.05	5.64	4.02	24.6	8,130
Mark-2	EB1624198010	29/09/16	<0.05	17,500	0.82	28.8	9	<0.05	5.90	4.29	24.6	8,390
Rumu-2	EB1624198012	29/09/16	<0.05	14,700	0.61	12.3	9	<0.05	5.08	5.75	21.6	7,140
Mark-1 [a]	EB1629782002	14/12/16	<1	24,800	2.0	46.0	<1	<1	10.00	7.00	41.0	14,300
Trib C-2 [b]	EB1629782006	14/12/16	<1	26,600	1.0	75.0	<1	<1	6.00	3.00	22.0	9,390
<63 µm Fraction (1M HCl Extractable Metals)												
Trib G-1	EB1624198014	29/09/16	<0.05	22,800	0.71	32.3	18	0.09	11.30	11.8	60.2	14,500
Mark-2	EB1624198013	29/09/16	<0.05	18,800	1.0	33.5	18	0.07	7.95	7.68	32.2	13,900
Rumu-2	EB1624198015	29/09/16	<0.05	12,500	0.63	10.7	14	<0.05	5.23	6.06	22.8	8,420
SQG-high (Simpson et al., 2013)			4.0		70			10		370	270	
SQGV (Simpson et al., 2013)			1.0		20			1.5		80	65	

[a] Mark-1 is an unfractionated sample. Less than 1% of the sample is <2000 µm.
[b] Trib C-2 is an unfractionated sample. 26% of the sample is above <2000 µm.

Key:
Value exceeds SQGV.
Value exceeds SQG-high.

Table 3.13 – Sediment Quality – Metals (Hg to Zn) (cont'd)

Sampling Location Name	Sample ID	Date	Metals (mg/kg, dry weight)									
			Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	V	Zn
<2000 µm Fraction (Total Metals)												
Trib G-1	EB1624198011	29/09/16	<0.01	757	0.4	**35.1**	2.0	<0.1	<1	0.7	134	54.1
Mark-2	EB1624198010	29/09/16	<0.01	873	0.4	**37.4**	2.7	<0.1	<1	0.8	137	61.4
Rumu-2	EB1624198012	29/09/16	<0.01	647	0.5	**41.1**	2.2	<0.1	<1	0.8	166	56.5
Mark-1 [a]	EB1629782002	14/12/16	<0.01	810	<2	**48.0**	<5	6	14	5.0	139	62.0
Trib C-2 [b]	EB1629782006	14/12/16	<0.01	667	<2	**22.0**	6	5	9	5.0	157	53.0
<63 µm Fraction (Total Metals)												
Trib G-1	EB1624198014	29/09/16	0.02	1,050	0.3	**56.7**	3.7	<0.1	<1	1.1	173	70.2
Mark-2	EB1624198013	29/09/16	0.02	967	0.5	**47.3**	4.0	<0.1	<1	1.0	154	69.7
Rumu-2	EB1624198015	29/09/16	0.01	760	0.5	**45.1**	2.6	<0.1	<1	0.9	261	74.0
SQG-high (Simpson et al., 2013)			1.0			52	220	25				410
SQGV (Simpson et al., 2013)			0.15			21	50	2.0				200

[a] Mark-1 is an unfractionated sample. Less than 1% of the sample is <2000 µm.
[b] Trib C-2 is an unfractionated sample. 26% of the sample is <2000 µm.

Key:
Value exceeds SQGV.
Value exceeds SQG-high.

Table 3.13 – Sediment Quality – Metals (Hg to Zn) (cont'd)

Sampling Location Name	Sample ID	Date	Metals (mg/kg, dry weight)									
			Hg	Mn	Mo	Ni	Pb	Sb	Se	Sn	V	Zn
<2000 µm Fraction (1M HCl Extractable Metals)												
Trib G-1	EB1624198011	29/09/16	<0.10	277	0.14	11	0.86	<0.05	0.1	<0.05	14.1	13.3
Mark-2	EB1624198010	29/09/16	<0.10	254	0.14	10.3	1.15	<0.05	0.1	<0.05	14.2	14.2
Rumu-2	EB1624198012	29/09/16	<0.10	192	0.14	13.3	0.98	<0.05	<0.1	<0.05	12.8	11.6
Mark-1 [a]	EB1629782002	14/12/16	<0.10	373	<1	18	2	<1	<1	<1	27	20
Trib C-2 [b]	EB1629782006	14/12/16	<0.10	281	<1	8	<1	<1	2	<1	21	14
<63 µm Fraction (1M HCl Extractable Metals)												
Trib G-1	EB1624198014	29/09/16	<0.01	604	0.07	**22.9**	2.52	<0.05	0.2	0.08	44.5	27.9
Mark-2	EB1624198013	29/09/16	<0.01	379	0.15	14.5	1.84	<0.05	0.1	0.07	22.2	19.6
Rumu-2	EB1624198015	29/09/16	<0.01	200	0.14	12.6	1.42	<0.05	<0.1	<0.05	13.9	12.2
SQG-high (Simpson et al., 2013)			1.0			52	220	25				410
SQGV (Simpson et al. 2013)			0.15			21	50	2.0				200

[a] Mark-1 is an unfractionated sample. Less than 1% of the sample is <2000 µm.
[b] Trib C-2 is an unfractionated sample. 26% of the sample is <2000 µm.

Key:
Value exceeds SQGV.
Value exceeds SQG-high.

Table 3.14 – Sediment Quality – Hydrocarbon and Phenol Criteria and Reporting Limits

Parameter	SQGV (mg/kg)	Reporting Limit (mg/kg)
Benzene	[a]	0.2
Toluene, Ethylbenzene	[a]	0.5
o-xylene	[a]	0.5
m+p-xylene	[a]	0.5
Naphthalene	[a]	1.0
TPH	280	<10 – <100
TRH	[a]	<10 – <100
Phenol	320	0.5
2-Chlorophenol	340	0.5
2-Methylphenol	[a]	0.5
2-Nitrophenol	[a]	1
2.4-Dimethylphenol	[a]	0.5
2.4-Dichlorophenol	120	0.5
2.6-Dichlorophenol	[a]	0.5
4-Chloro-3-methylphenol	[a]	0.5
2.4.6-Trichlorophenol	3	0.5
2.4.5-Trichlorophenol	[a]	0.5
Pentachlorophenol	3.6	2

[a] No criteria currently available.

Table 3.15 – Sediment Quality – PAHs

Sampling Location Name	Sample ID	Date	2-Methylnaphthalene [a]	Acenaphthylene [a]	Anthracene [a]	Chrysene [a]	Benzo(g.h.i)perylene [a]	Dibenz(a.h)anthracene [a]	Indeno(1.2.3.cd)pyrene [a]	Perylene [a]	Sum of PAHs [b]	Sum of PAHs (normalised to 1% TOC) [c]
			(µg/kg)									
Trib G-1	EB1624198008	29/09/16	<5	8	6	4	7	7	7	<4	39	170
Mark-2	EB1624198007	29/09/16	6	<4	<4	<4	<4	<4	<4	8	14	128
Rumu-2	EB1624198009	29/09/16	<5	<4	<4	<4	<4	<4	<4	<4	<4	100
Mark-1	EB1629782002	14/12/16	<5	<4	<4	<4	<4	<4	<4	5	5	36
Trib C-2	EB1629782006	14/12/16	<5	<4	<4	<4	<4	<4	<4	<4	<4	44
SQG-high (Simpson et al. 2013)												50,000
SQGV (Simpson et al. 2013)												10,000

[a] All other PAH results were below their respective reporting limits, which ranged between 4 and 5 mg/kg.
[b] This result is computed from individual analyte detections at or above the level of reporting.
[c] Where the sample's TOC concentration was less than 0.2%, 0.2% was used as the default value for normalisation.

Figures

PROJECT AREA LOCATION

PNG Biomass Markham Valley I Surface Water and Sediment Quality Report

FIGURE 1.1

Image Source: Google Earth.

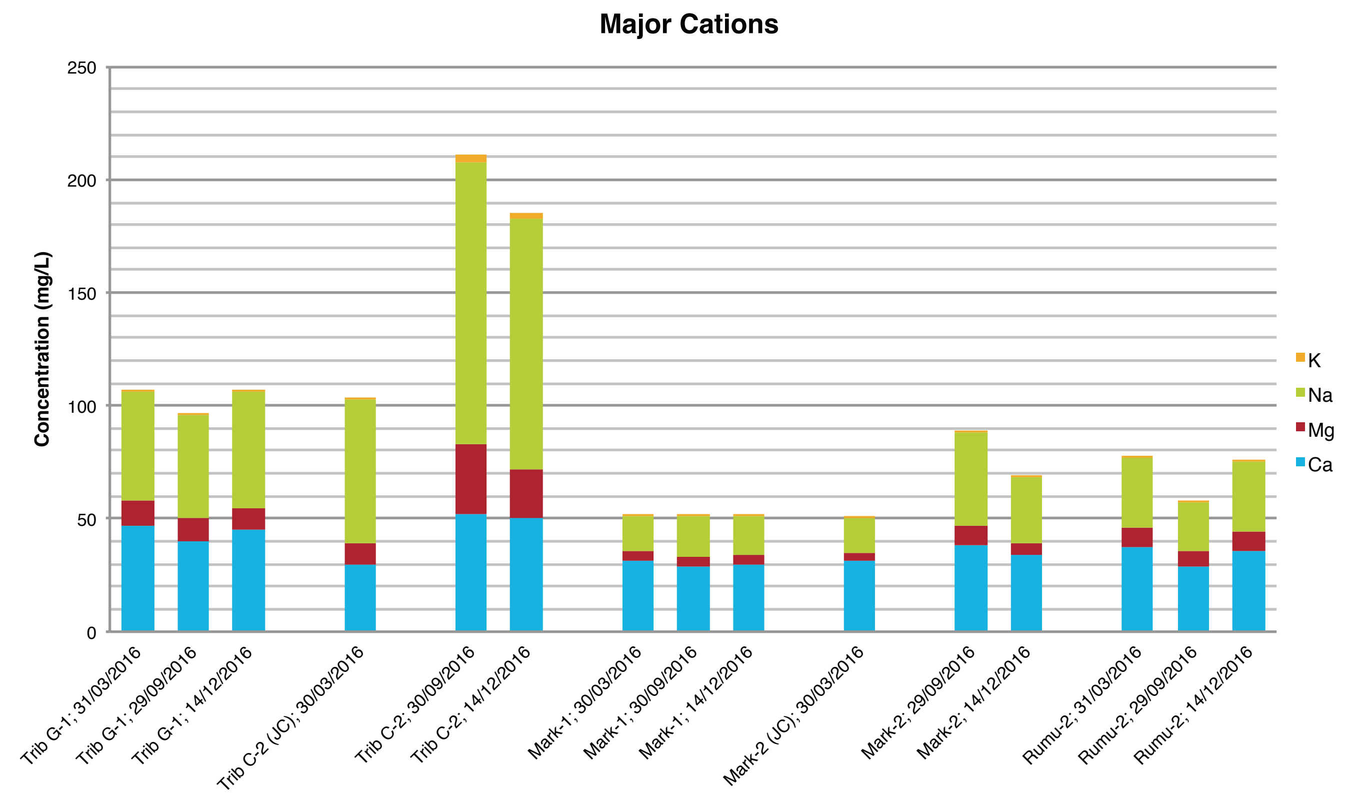
ERIAS Group I 01183B_4_F1-1_v2

WATER AND SEDIMENT SAMPLING SITES

PNG Biomass Markham Valley I Surface Water and Sediment Quality Report

FIGURE 2.1

FIGURE 3.1


Major Cations
Concentration (mg/L)
250
200
150
100
50
0
K
Na
Mg
Ca
Trib G-1; 31/03/2016
Trib G-1; 29/09/2016
Trib G-1; 14/12/2016
Trib C-2 (JC); 30/03/2016
Trib C-2; 30/09/2016
Trib C-2; 14/12/2016
Mark-1; 30/03/2016
Mark-1; 30/09/2016
Mark-1; 14/12/2016
Mark-2 (JC); 30/03/2016
Mark-2; 29/09/2016
Mark-2; 14/12/2016
Rumu-2; 31/03/2016
Rumu-2; 29/09/2016
Rumu-2; 14/12/2016

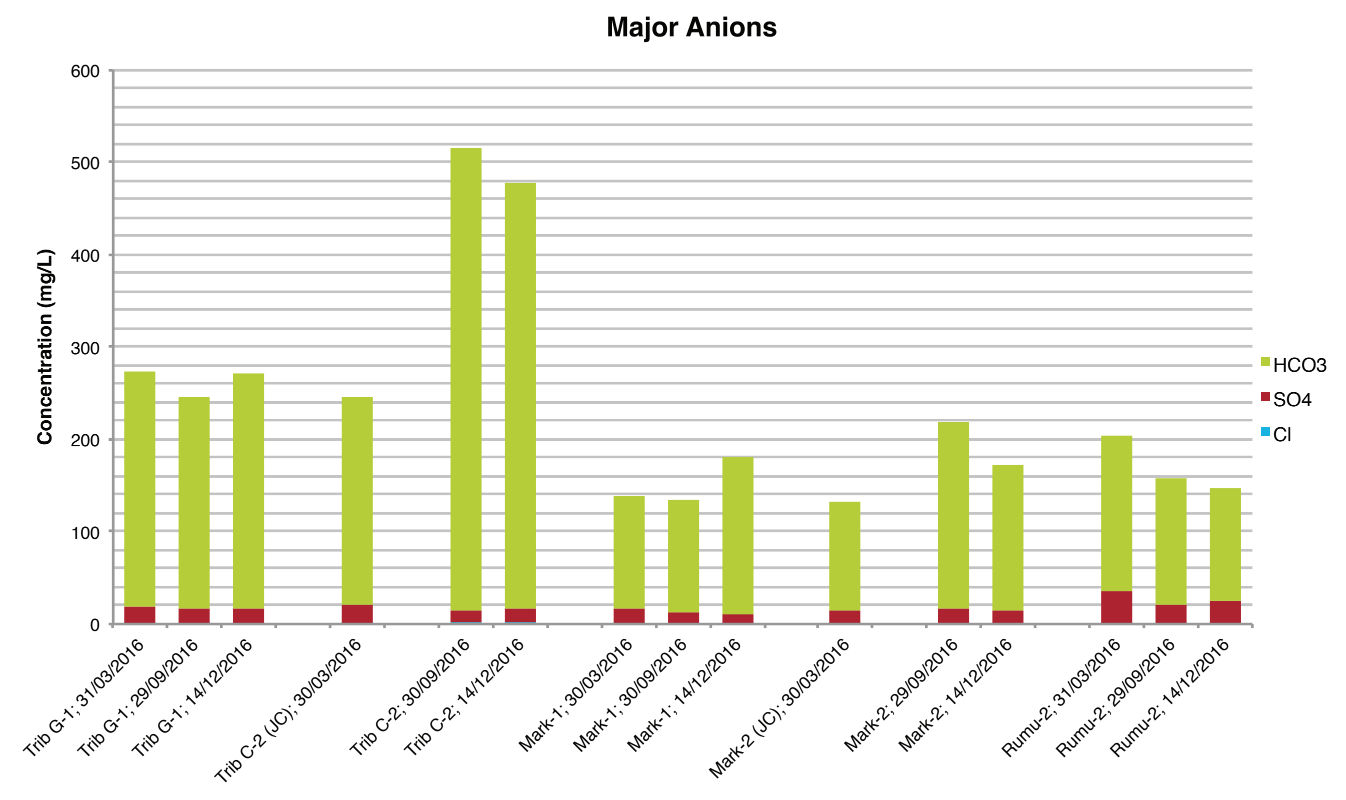
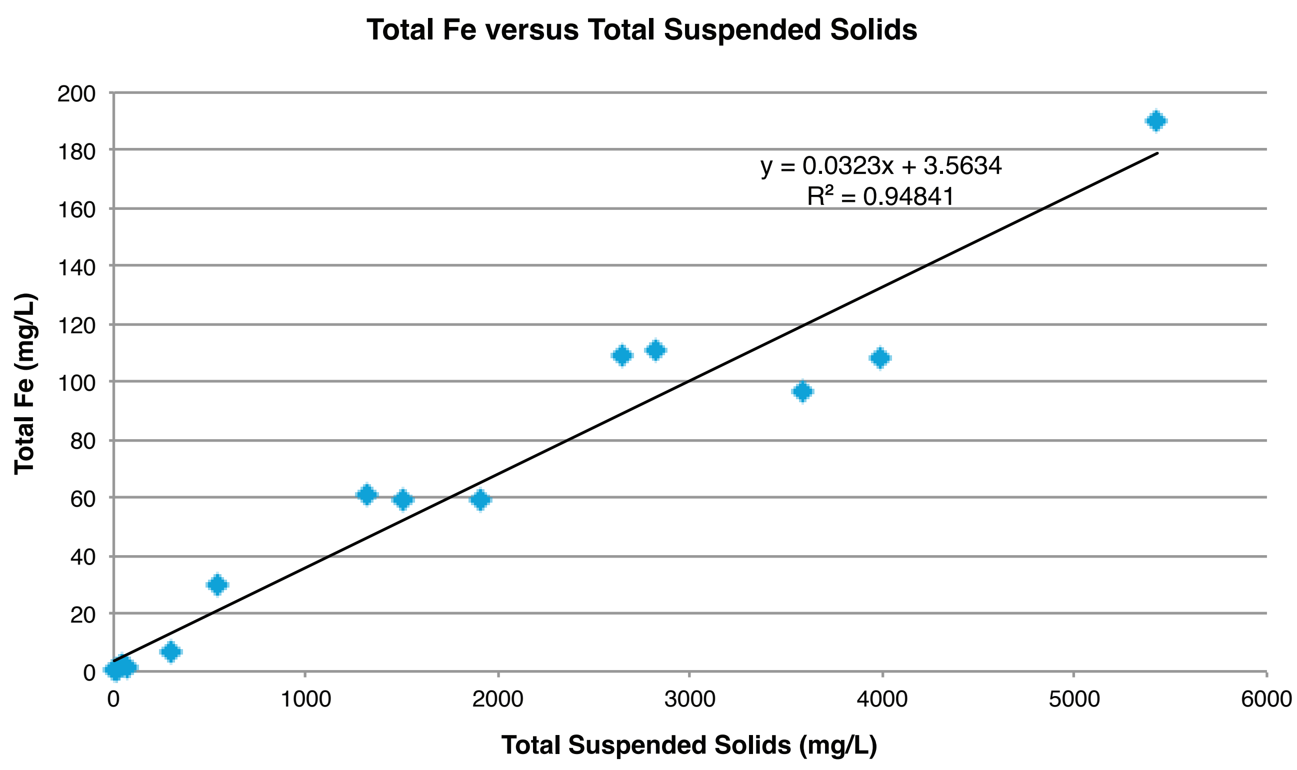
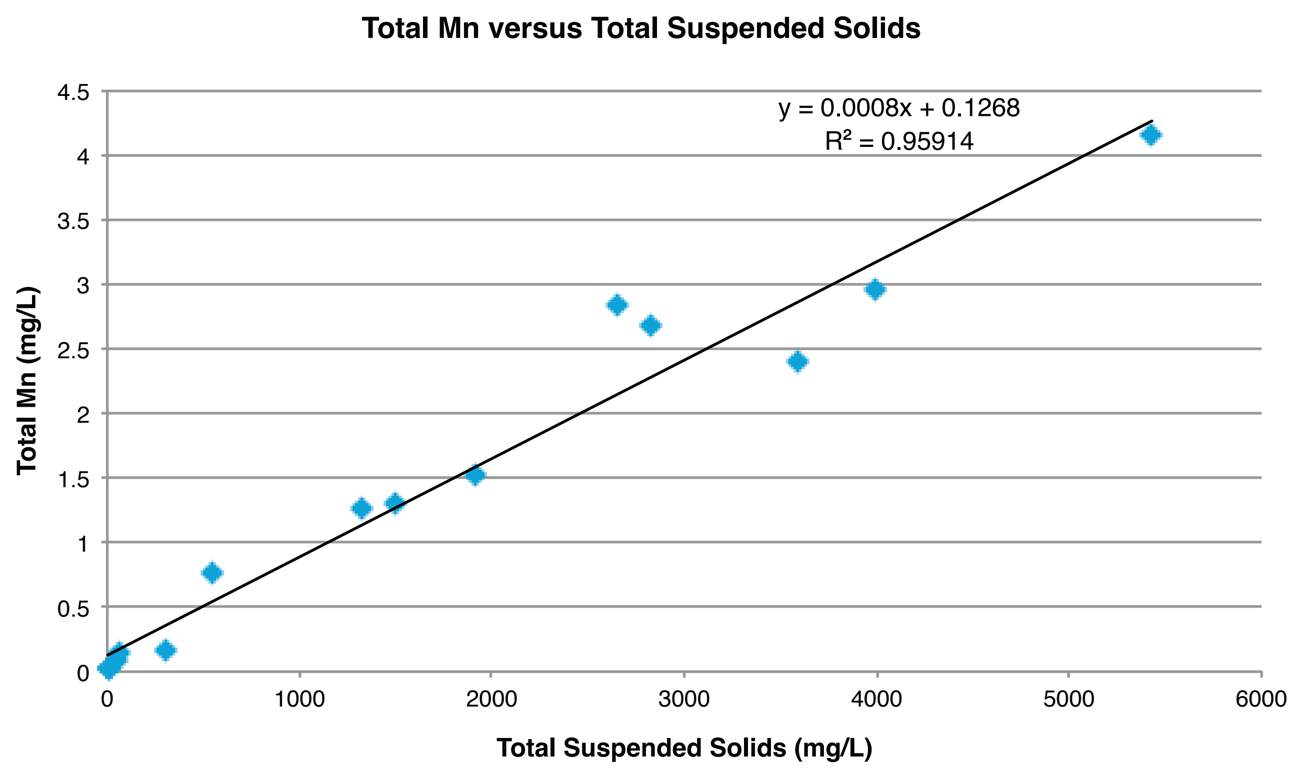

Major Anions
Concentration (mg/L)
600
500
400
300
200
100
0
HCO3
SO4
Cl
Trib G-1; 31/03/2016
Trib G-1; 29/09/2016
Trib G-1; 14/12/2016
Trib C-2 (JC); 30/03/2016
Trib C-2; 30/09/2016
Trib C-2; 14/12/2016
Mark-1; 30/03/2016
Mark-1; 30/09/2016
Mark-1; 14/12/2016
Mark-2 (JC); 30/03/2016
Mark-2; 29/09/2016
Mark-2; 14/12/2016
Rumu-2; 31/03/2016
Rumu-2; 29/09/2016
Rumu-2; 14/12/2016

FIGURE 3.2

PNG BIOMASS Oil Search ERIAS GROUP





Appendix 1.
Sampling and Analysis Plan

1. Water Sampling

1.1 Sampling Sites

Sampling sites will include three of the sites sampled by Aligned Energy in March 2016, plus two new site locations from the most recent sampling event in September 2016. Sampling sites and coordinates are listed in Table 1.1 and shown in Figure 1.1.

Table 1.1 – Water Sampling Sites

Site Name	Site ID	Description	Latitude	Longitude
Markham River (Downstream)	Mark_1 (Adrian's site)	Downstream of potential project impacts	-006° 37' 05.27"	146° 39' 58.54"
Markham River (Upstream)	Mark_2	Upstream of potential project impacts	-006° 38' 12.16"	146° 32' 14.10"
Rumu River	Rumu_2	Rumu River	-006° 35' 30.70"	146° 35' 14.21"
Maralumi Creek	TribC_2 (Adrian's site)	Fed from multiple streams from the north; connects to Markham River	-006° 34' 46.60"	146° 39' 48.82"
Klin wara River	TribG_1	Drains western part of project area; connects to Markham River	-006° 35' 0.28"	146° 31' 03.40"

1.2 Field Measurements

In situ water quality parameters (pH only) will be determined at the time of sampling using a handheld water quality meter. If the unit has been recently calibrated, proceed with the measurements. If not, refer to the appropriate section of the instrument's manual for the calibration procedure. Record both the actual values of the calibration solutions and the values obtained by the meter before and after calibration.

Inspect and maintain sensors in accordance with the manual. Check battery indicator and charge or replace as necessary.

Email in situ water quality results, including calibration data, to ERIAS Group.

1.3 Sampling Procedures

Collection of water samples for storage and, ultimately, delivery to the laboratory for analysis, is described below.

Figure 1.1 – Water Sampling Sites

1.3.1 Equipment

Sample bottles as detailed in Table 1.2 (which also summarises sampling and preservation requirements) are required for water quality sample collection. Unless otherwise directed by ERIAS Group, each sampling event requires all of the containers in Table 1.2 to be filled. For photos of sample bottles, see Attachment 1.

Table 1.2 – Water Quality Sample Bottles

Variable	Sample	Label	Bottle Size/Type & Preservatives	Sampling	Preservative and Storage
Physical properties, anions, cations, TDS, TSS, BOD, Reactive P	Unfiltered	Green	500 mL, plastic Nil preservatives	Rinse bottle 3 times with sample water. Completely fill bottle	Refrigerate
Chlorophyll a	Unfiltered	Green	2x 500 mL bottles (1,000 mL), white plastic Nil preservatives		Refrigerate
Faecal coliforms	Unfiltered	Grey	250 mL, clear plastic Sodium thiosulfate		Sodium thiosulfate; refrigerate
Oil and grease	Unfiltered	Purple & White Stripe	250mL, wide mouth glass jar Sodium bisulphate		Sodium Bisulphate Chill to $\leq$ 5°
NO_x, TKN, total N, total P, ammonia, COD	Unfiltered	Purple	60 mL, plastic Sulfuric acid	Do not rinse the bottle. Completely fill bottle	H_2SO_4 to pH<2; refrigerate
Unfiltered metals	Unfiltered	Red & green stripe*	60 mL, plastic Nil preservatives*	Rinse bottle 3 times with sample water. Completely fill bottle	Refrigerate; HNO_3 to pH<2 on receipt at laboratory*
Filtered metals	Filtered	Red & green stripe*	60 mL, plastic Nil preservatives*	Rinse bottle 3 times with deionised water/rinsate water and then filtrate (i.e., the sample after filtration). Field filter, note on COC and tick label. Completely fill bottle	Field filter and refrigerate; HNO_3 to pH<2 on receipt at laboratory*
TPH/TRH (C10-C40) ***plus*** standard PAH/ Phenols (etc.)	Unfiltered	Orange	100 mL, amber glass Nil preservatives	Do not rinse the bottle. Completely fill bottle	Refrigerate
TOC	Unfiltered	Purple	40 mL amber glass vial Sulfuric acid	Do not rinse the bottle. Completely fill the bottle	H_2SO_4 to pH<2; refrigerate
TRH/TPH (C6-C10) **plus** BTEX/ BTEXN/VOCs	Unfiltered	Purple	2x 40 mL amber glass vial Sulfuric acid	Fill to zero headspace, minimising exposure to air	H_2SO_4 to pH<2; refrigerate

*If metals bottles are plain red (rather than red and green striped), then they contain nitric acid as a preservative, which is not suitable for airfreight. Contact ERIAS Group for instruction.
NOTE: 100 mL glass bottles with green and white labels have been provided; these DO NOT need to be filled.

Additional equipment includes:

- Esky(s) with freezer blocks.
- Water quality meter, probes and calibration solutions.
- Powder-free gloves.
- Syringes/filters.
- Wash bottles/paper towel/clear plastic.
- Safety glasses.
- Camera.
- Deionised water.
- Weatherproof notebooks and pens/pencils.
- Shipping labels, AQIS permits, chain of custody (COC) forms.
- Allocated space in refrigerator (for storage of samples) or freezer (for freezer blocks for esky(s)).

1.3.2 Preparation

Before taking samples, label the sample bottles appropriately:

- Sampled by: Sampler's name.
- Sample ID: **Job number_SiteID_Sample matrix**, e.g. 01183B_TribC_2_**WQ**. Please see Attachment 2 for an example of the chain of custody document to be provided to ALS Laboratories.
- Date/time: This should be left blank and completed once sampling has been completed with the correct sampling data and time.

All work areas must be inspected and cleaned, with sources of contamination such as oil or galvanised surfaces, lubricants and/or rust being removed, cleaned or covered with plastic. Exposure to ambient dust should be minimised.

Sampling should occur at a time that will allow prompt dispatch to the laboratory, preferably the same day. Samples should be despatched to the laboratory as soon as possible after sampling.

1.3.3 Water Sampling

Apply the following procedure for sampling:

- Put on powder-free disposable gloves (a new pair is required for each sampling event or if the gloves are ripped or their integrity otherwise compromised).

- Make sure that any people using the river/stream (e.g., for cleaning or washing) or vessels (e.g., canoes) in the general vicinity are downstream of the sampling site. Ensure that the sampling point is upstream any obvious point source contaminants in the water.
- Collect samples in each of the bottles from the sampling point. Samples should be collected from the middle of the watercourse if feasible and safe to do so, just below the surface of the water, **with the bottle being held upstream of the sampler and submerged pointing upstream**.
- For those variables for which sample bottles should be rinsed, partially fill the bottle with river water, screw on the lid, shake the bottle and then discard the contents downwind and down-current, i.e., behind the sampler; repeat the rinsing at least two more times.
- Sample bottles that contain preservatives or buffers should NOT be rinsed. Take care when handling these bottles and wear safety glasses. For the current sampling, bottles containing preservatives include:
  - Purple label, 60 ml plastic bottle, sulfuric acid: for NOx, TKN, Ammonia, TN, TP.
  - Purple label, 40 ml glass vial, sulfuric acid: for TOC.
  - Purple label, 40 ml glass vials x2, sulfuric acid: for TPH/TRH(C6-C10), BTEXN.
  - Grey label, 250 ml clear plastic bottle, sodium thiosulfate: for faecal coliforms.
- If sampling from the side of the watercourse is necessary, avoid stirring up bed sediment and consequently increasing turbidity in the water column.
- If sampling from a boat or canoe, point the vessel upstream and take the sample from as close to the bow as possible **with the bottle being held upstream away from the vessel and submerged pointing upstream.** Sampling should also occur as far as possible from the vessel's engine.
- Both the sampler and, if available, a person assisting the sampler with labelling and handling bottles must use powder-free disposable gloves to minimise contamination.
- Seal the bottle and place into the esky.
- Take detailed notes in a field logbook including:
  - Site name, location (including GPS coordinates) and ID, and sampler’s name.
  - Date and time the water samples are taken.
  - Water depth.
  - Field conditions (weather).
  - River conditions.
  - General comments about the sampling event (as applicable).
  - Deviations from the work plan.

An estimate should be made of river velocity at the time of sampling for all streams and rivers (excluding the Markham River). This can be done by recording the time it takes for a float that has been thrown into the centre of the river to travel a given distance (e.g., 10 m) and multiplying the resultant velocity by a factor of 0.7 to allow for velocity variations across the river profile. If using this method, several measurements should be undertaken and the average velocity calculated. Velocity can also be calculated by creating a stagnation point (by holding a ruler or flat sided pole still in the water) and measuring the height of the resulting 'lump' it produces. The velocity is calculated as $V = \sqrt{2gD_s}$, where V is velocity, g is acceleration due to gravity (9.807 m/s^2), and D is the height of the water as altered by the obstruction.

River discharge at the time of each sampling event can then be calculated based on the velocity and an estimate (a 'best guess' is acceptable) of the depth and width of the stream (average velocity x cross-sectional area).

1.3.4 Sample Filtration

The 'filtered metals' water samples need to be filtered at the time of sampling or as soon as possible thereafter. The following equipment is required:

- Powder-free disposable gloves.
- Water samples to be filtered.
- Un-used 'filtered metals' water sample bottles; these should be appropriately labelled.
- Syringes.
- 0.45 µm filters.

Sample filtration involves the following:

- Ensure that the area is clean and no-one is smoking in or close to the area. It is also important that obvious sources of contamination are removed from the immediate sampling vicinity, and that nothing comes into contact with the inside surface of the water sample bottles or the syringe.
- Put on the powder-free gloves.
- Place a clean filter cartridge/container (the filter is contained within the cartridge/container and can be used 'as supplied') firmly on the protruding end of a clean syringe.
- Take the lid off the new water sample bottle.
- Take the plunger out of the syringe and rinse the plunger and syringe 3 times with the sample. Pour in some of the sample. Replace the barrel in the syringe and filter the sample into new water sample bottle, discarding the first few millilitres of filtrate and ensuring that contact between the sample and the end of the plunger is minimised.
- Repeat the above step until the new water sample bottle is full.
- Screw on the lid of the water sample bottle now containing the filtered sample.
- Repeat the above steps for all of the water samples to be filtered.

An additional point to note is that:

- Filtrates should be contained in bottles that clearly differentiate between filtered and unfiltered water samples.

A chain-of-custody (COC) form must be filled out and provided to the laboratory with the samples, inside the esky/s (forward a copy to ERIAS Group, and keep a copy for AEL records). This form will list all sample numbers and locations and the analyses and detection limits required.

1.3.5 Sample Treatment, Storage and Dispatch

- Place all sample bottles into an esky (upright) with frozen freezer blocks as soon as possible (using wet ice instead of freezer blocks is not recommended). Store sample bottles in plastic bags (one site per plastic bag) to ensure that the bottles remain clean and the risk of bottle loss or bottles becoming unidentifiable is minimised. Add sufficient bubble wrap or similar to ensure no movement of bottles during transport. Include the COC form inside the esky/s.
- Place the samples in a refrigerator as soon as possible.
- Ensure that samples are clearly and appropriately labelled, including sample ID number of the external surface of each bottle cap.
- Currently, ERIAS Group uses ALS Laboratory in Brisbane for sample analysis. Organise an Aligned Energy-preferred courier to transport the eskies to the below address (ERIAS Group has used both DHL and TNT, you may need a PNG-based courier such as Pentagon to get the samples from site to POM).
- Label the top of the eskies with a large ‘receiver’ label and smaller ‘sender’ label (an example is provided by ERIAS Group with this procedure). These should be inside a plastic pocket and/or thoroughly taped down with wide clear packing tape. Also attach ‘fragile’ and ‘keep chilled’ stickers, IF these were provided with the bottles. The receiver details are as follows:

RECEIVER:	Australian Laboratory Services Pty Ltd (ALS)
ADDRESS:	2 Byth Street, Stafford QLD 4053
CONTACT PERSON:	Charles Tibbitts
CONTACT PHONE NO.:	+61 07 3243 7222

- On the side of the esky, attach (and tape down) a plastic pocket that contains:
  - The current ALS ‘Permit to Import Quarantine Material’ (provided by ERIAS Group).
  - A completed Aligned Energy Limited (AEL) customs declaration form (part-filled template provided by ERIAS Group). Include a 'Value of Freight', where this is the cost for freighting the consignment (and an estimate can be used if the actual pre-paid freight value is not known).
  - A completed AEL packing list indicating dimensions and estimated weight of each esky, along with total number of bottles and other contents (template provided).

- Also attach the courier's waybill form to the esky. Advise ERIAS Group when the eskies have been dispatched (along with the courier's waybill/tracking reference number), and we will advise our ALS contact that the samples are en route.

2. Sediment Sampling

2.1 Sampling Sites

Sediment[1] sampling sites will be at two locations from the sampling event in September 2016. Sampling sites and coordinates are listed in Table 1.3 and shown in Figure 1.2.

Table 2.1 – Sediment Sampling Sites

Site Name	Site ID	Description	Latitude	Longitude
Markham River (Downstream)	Mark_1 (Adrian's site)	Downstream of potential project impacts	-006° 37' 05.27"	146° 39' 58.54"
Maralumi Creek	TribC_2 (Adrian's site)	Fed from multiple streams from the north; connects to Markham River	-006° 34' 46.60"	146° 39' 48.82"

Figure 2.1 – Sediment Sampling Sites

[1] 'Sediment' in this section refers to bed sediment.

2.2 Field Measurements

In situ sediment parameters (pH only) will be determined at the time of sampling using a handheld water quality meter. If the unit has been recently calibrated, proceed with the measurements. If not, refer to the appropriate section of the instrument's manual for the calibration procedure. Record both the actual values of the calibration solutions and the values obtained by the meter before and after calibration.

Email all in situ sediment quality results, including calibration data, to ERIAS Group.

2.3 Sampling Procedures

Collection of sediment samples for storage and, ultimately, delivery to the laboratory for analysis, is described below.

2.3.1 Equipment

Sample containers as detailed in Table 2.1 (which also summarises sampling and preservation requirements) are required for sediment sample collection. Unless otherwise directed by ERIAS Group, each sampling event requires all of the containers in Table 2.1 to be filled.
For photos of sample bottles, see Attachment 1.

Table 2.2 – Sediment Sample Bottles

Parameter	Size, type, label	Storage
Metals, nutrients, TPH, PAHs, phenols, cyanide, TOC/TIC	1 x 150 (or 250) mL wide-mouth glass jar with Teflon-lined lids, orange	Refrigerate
Moisture content, particle size	500 mL plastic bag	Refrigerate
Super ultra-trace PAH and TRH	1 x 150 (or 250) mL wide-mouth glass jar with Teflon-lined lids, orange	Refrigerate

Additional equipment includes:

- Suitable sampling equipment (e.g., stainless steel bowl and spoon/scoop).
- Esky(s) with freezer blocks.
- Water quality meter, probes and calibration solutions.
- Powder-free gloves.
- Weatherproof notebooks and pens/pencils.
- GPS.
- Wash bottles/paper towel/clear plastic.
- Safety glasses.
- Camera.
- Deionised water.
- Shipping labels, AQIS permits, chain of custody (COC) forms.
- Allocated space in refrigerator (for storage of samples) or freezer (for freezer blocks).

2.3.2 Preparation

Before taking samples, label the sample containers appropriately:

- Sampled by: Sampler's name.
- Sample ID: Job number_SiteID_Sample matrix, e.g. 01183B_TribC_2_**SQ**. Please see Attachment 2 for an example of the chain of custody document to be provided to ALS Laboratories.
- Date/time: This should be left blank and completed once sampling has been completed with the correct sampling data and time.

As with the water sampling, all work areas must be inspected and cleaned, with sources of contamination such as oil or galvanised surfaces, lubricants and/or rust being removed, cleaned or covered with plastic. Exposure to ambient dust should be minimised.

Plan to undertake sampling at a time that will allow prompt dispatch to the laboratory, preferably the same day and in conjunction with the water samples. Sample should be despatched to the laboratory as soon as possible after sampling.

2.3.3 Sediment Sampling

Apply the following procedure for sampling:

- Put on powder-free disposable gloves (a new pair is required for each sampling event or if the gloves are ripped or their integrity otherwise compromised).
- Make sure that any people using the river/stream (e.g., for cleaning or washing) or vessels (e.g., canoes) in the general vicinity are downstream of the sampling site. Ensure that the sampling point is upstream any obvious point source contaminants in the water.
- Ideally, riverine bed sediment samples should be from depositional areas. However, this may not possible at some sites and samples may need to be taken where practicable.
- Use a stainless steel sampling spoon/scoop (that has been thoroughly rinsed prior to sampling at each site and washed clean between each sample) to collect three replicate samples at each site.
- Mix the replicates in a clean stainless steel bowl to obtain a homogeneous composite sample. Transfer the sample using the stainless steel spoon/scoop into the sample containers, which are supplied by the analytical laboratory and have been appropriately prepared.
- Both the sampler and, if available, a person assisting the sampler with labelling and handling bottles must use powder-free disposable gloves to minimise contamination.
- Seal the bottles, place into the esky and surround with freezer blocks.
- Take detailed notes in a field logbook including:
  - Site name, location (including GPS coordinates) and ID, and sampler's name.

- Date and time the sediment samples are taken.
- Water depth.
- Field conditions (weather).
- River conditions.
- General comments about the sampling event (as applicable).
- Observations from visual inspection of the sediment taken immediately upon retrieval; these should include a description of sediment type (silt/clay/sand), texture, colour, odour, and presence of organic matter, biota, debris or other material.
- Deviations from the work plan.

♦ Take photographs of the sampling locations and collected sediment samples.

2.3.4 Sample Treatment, Storage and Dispatch

♦ Place all sample containers into an esky (upright) with frozen freezer blocks as soon as possible (using wet ice instead of freezer blocks is not recommended). Store sample bottles in plastic bags (one site per plastic bag) to ensure that the bottles remain clean and the risk of bottle loss or bottles becoming unidentifiable is minimised. Add sufficient bubble wrap or similar to ensure no movement of bottles during transport. Include the COC form inside the esky/s.

♦ Place the samples in a refrigerator as soon as possible.

♦ Ensure that samples are clearly and appropriately labelled, including sample ID number of the external surface of each bottle cap. See Attachment 2 for an example chain of custody document.

♦ Currently, ERIAS Group uses ALS Laboratory in Brisbane for sample analysis. Organise for despatch of the samples to the laboratory as described in Section 1.3.5.

3. Supporting Documents

Supporting documents include the following:

♦ ALS laboratory Chain of Custody (COC) form (file 01183B_AEL_COC_Dec2016).

♦ AEL customs declaration form template (file 01183B_AEL_Customs Declaration Template_Dec2016).

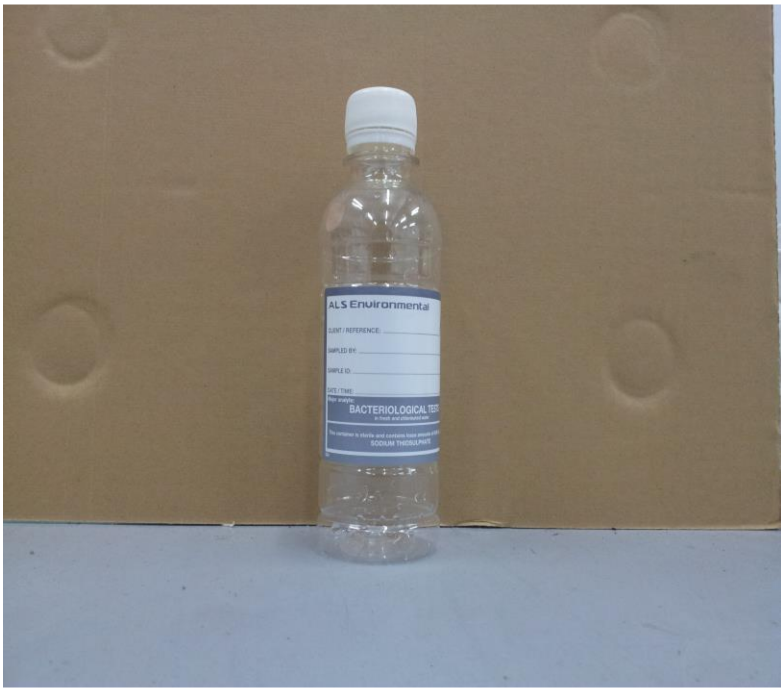
♦ AEL packing list template (file 01183B_AEL_Packing List_Dec2016).

♦ Return address labels template (file 01183B_AEL_Return Address Label Template_Dec2016).

♦ Australian Government ‘Permit to Import Quarantine Material’ (for ALS laboratory) (file 01183B_Permit to Import Quarantine Material (ALS Brisbane - incl Water&Sed) valid to 03.02.2017).

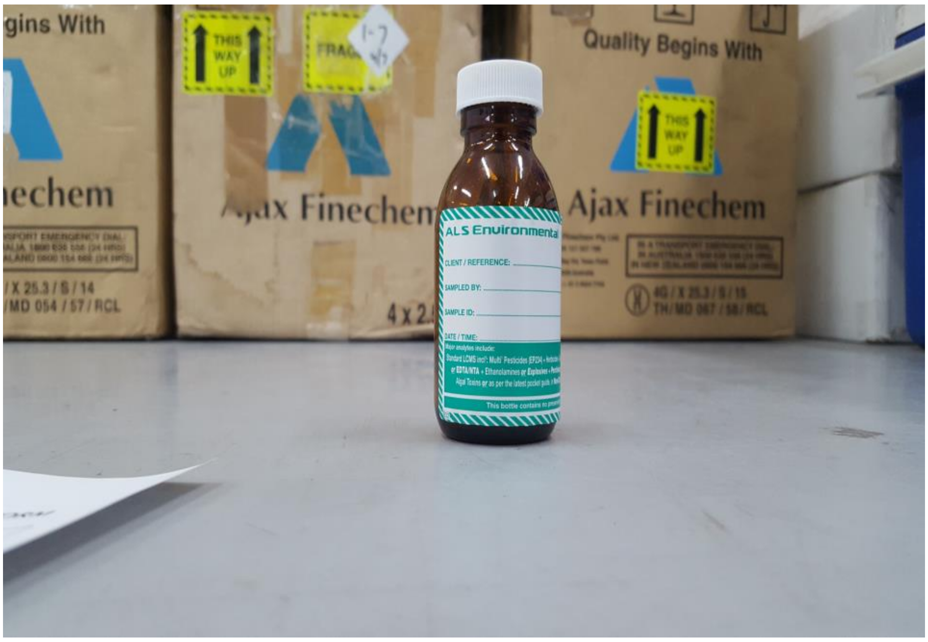
Attachment 1 – Sample Bottles

2 x 40 mL amber vials – VOC



250 mL microbiological plastic

250 mL amber glass – oil and grease



100 mL amber glass – LCMS (Do not fill)

100 mL amber glass – semi volatile organics

TOC-DOC vial

Chlorophyll-a sampling bottles

500 mL – physical properties

250 mL soil jar and PSD bag

60 mL purple label – nutrients


ALS
BRISBANE
(HEAD OFFICE)
ALS
32 Shand Street
STAFFORD QLD 4053
TEL 61-7-3243 7222
FAX 61-7-3243 7218
NEWCASTLE
ALS
5 Rosegum Close
TEL 61-2-4968 9433
FAX 61-2-4968 0349
MELBOURNE
ALS
2 - 4 Westall Road
SPRINGVALE VIC 3171
TEL 61-3-8549 9600
FAX 61-3-8549 9601
PERTH
ALS
10 Hod Way
MALAGA WA 6090
TEL 61-8-9209 7655
FAX 61-8-9209 7600
Environmental
TOTAL METALS

60 mL - metals

Attachment 2 – Example COC Form

CHAIN OF CUSTODY

ALS Laboratory: please tick →

☐ **Sydney:** 277 Woodpark Rd, Smithfield NSW 2176 Ph: 02 8784 8555 E: samples.sydney@alsenviro.com
☐ **Newcastle:** 5 Rosegum Rd, Warabrook NSW 2304 Ph: 02 4968 9433 E: samples.newcastle@alsenviro.com
☐ **Brisbane:** 32 Shand St, Stafford QLD 4053 Ph: 07 3243 7222 E: samples.brisbane@alsenviro.com
☐ **Townsville:** 14-15 Desma Ct, Bohle QLD 4818 Ph: 07 4796 0600 E: townsville.environmental@alsenviro.com
☐ **Melbourne:** 2-4 Westall Rd, Springvale VIC 3171 Ph: 03 8549 9600 E: samples.melbourne@alsenviro.com
☐ **Adelaide:** 2-1 Burma Rd, Pooraka SA 5095 Ph: 08 8359 0890 E: adelaide@alsenviro.com
☐ **Perth:** 10 Hod Way, Malaga WA 6090 Ph: 08 9209 7655 E: samples.perth@alsenviro.com
☐ **Launceston:** 27 Wellington St, Launceston TAS 7250 Ph: 03 6331 2158 E: launceston@alsenviro.com

CLIENT: ERIAS GROUP	TURNAROUND REQUIREMENTS: (Standard TAT may be longer for some tests e.g. Ultra Trace Organics)	3 day TAT pre-approved (10% surcharge)	FOR LABORATORY USE ONLY (Circle)
OFFICE: 13-25 Church Street, Hawthorn 3122			Custody Seal Intact? Yes No N/A
PROJECT: Markham Valley Power Project	ALS QUOTE NO.:	COC SEQUENCE NUMBER (Circle)	Free ice / frozen ice bricks present upon receipt? Yes No N/A
ORDER NUMBER:		COC: 1 2 3 4 5 6 7	Random Sample Temperature on Receipt: °C
PROJECT MANAGER: -	CONTACT PH: -	OF: 1 2 3 4 5 6 7	Other comment:

SAMPLER: Colman Otmar	SAMPLER MOBILE:	RELINQUISHED BY:	RECEIVED BY:	RELINQUISHED BY:	RECEIVED BY:
COC emailed to ALS? (YES / NO)	EDD FORMAT (or default):				
Email Reports to : -		DATE/TIME:	DATE/TIME:	DATE/TIME:	DATE/TIME:
Email Invoice to : -					

COMMENTS/SPECIAL HANDLING/STORAGE OR DISPOSAL: QUARANTINE SAMPLES FROM PNG. Dissolved metals not filtered in the field. Lab to filter samples on receipt and then add HNO3 to samples to pH<2 prior to analysis. Lab to add HNO3 total metals samples to pH<2 on receipt prior to analysis.

ALS USE ONLY	SAMPLE DETAILS MATRIX: Solid(S) Water(W)			CONTAINER INFORMATION		ANALYSIS REQUIRED including SUITES (NB. Suite Codes must be listed to attract suite price) Where Metals are required, specify Total (unfiltered bottle required) or Dissolved (field filtered bottle required).												Additional Information			
LAB ID	SAMPLE ID	DATE / TIME	MATRIX	TYPE & PRESERVATIVE *(refer to codes below)*	TOTAL BOTTLES	EA025H - Suspended solids	NT-1 (Ca, Mg, Na, K)	NT-2A (Cl, SO4, Alk and F)	NT-8 (Total N, TKN, NOx, NO2, NO3, Ammonia, Total P)	Sulphide	W30-T (11 Total Metals PLUS Ag, B, Ba, Co, Mo, Mn, Sb & Sn)	W30-T (11 Dissolved Metals (lab to filter) PLUS Ag, B, Ba, Co, Mo, Mn, Sb & Sn)	W-24 (TPH/TRH (C6-C36/40))	W-24 (BTEXN / PAH / Phenols)	TOC	Oil and Grease	Chlorophyll a				
	01183B_Mark_1_WQ	xx/xx/xx xx:xx	W		12	x	x	x	x	x	x	x	x		x	x	x				
	01183B_Mark_1_SQ		S		2 bottles + 1 bag	x	x	x	x	x	x	x	x	x	x	x	x				
	01183_Mark_2_WQ		W		12	x	x	x	x	x	x	x	x		x	x	x				
	01183_Rumu_2_WQ		W		12	x	x	x	x	x	x	x	x		x	x	x				
	01183B_TribC_2_WQ		W		12	x	x	x	x	x	x	x	x		x	x	x				
	01183B_TribC_2_SQ		S		2 bottles + 1 bag	x	x	x	x	x	x	x	x	x	x	x	x				
	01183B_TribG_1_WQ		W		12	x	x	x	x	x	x	x	x		x	x	x				

Appendix 2.
Example of a Laboratory Report

CERTIFICATE OF ANALYSIS

Work Order	: **EB1608860**	Page	: 1 of 13
Client	: **ERIAS GROUP**	Laboratory	: Environmental Division Brisbane
Contact	: MR MICHAEL JONES	Contact	: Customer Services EB
Address	: 990 TOORAK ROAD CAMBERWELL VIC 3125	Address	: 2 Byth Street Stafford QLD Australia 4053
Telephone	: 614 4194 19134	Telephone	: +61-7-3243 7222
Project	: PNG BIOMASS	Date Samples Received	: 04-Apr-2016 15:40
Order number	: ----	Date Analysis Commenced	: 05-Apr-2016
C-O-C number	: ----	Issue Date	: 18-May-2016 09:22
Sampler	: ----		
Site	: ----		
Quote number	: ----		
No. of samples received	: 6		
No. of samples analysed	: 6		

NATA Accredited Laboratory 825
Accredited for compliance with
ISO/IEC 17025.

WORLD RECOGNISED ACCREDITATION

This report supersedes any previous report(s) with this reference. Results apply to the sample(s) as submitted.

This Certificate of Analysis contains the following information:

- General Comments
- Analytical Results
- Surrogate Control Limits

Additional information pertinent to this report will be found in the following separate attachments: Quality Control Report, QA/QC Compliance Assessment to assist with Quality Review and Sample Receipt Notification.

Signatories

This document has been electronically signed by the authorized signatories below. Electronic signing is carried out in compliance with procedures specified in 21 CFR Part 11.

Signatories	*Position*	*Accreditation Category*
Dilani Fernando	Senior Inorganic Chemist	Melbourne Inorganics, Springvale, VIC
Greg Vogel	Laboratory Manager	Brisbane Inorganics, Stafford, QLD
Greg Vogel	Laboratory Manager	Brisbane Organics, Stafford, QLD
Greg Vogel	Laboratory Manager	WB Water Lab Brisbane, Stafford, QLD
Kim McCabe	Senior Inorganic Chemist	Brisbane Inorganics, Stafford, QLD
Matt Frost	Senior Organic Chemist	Brisbane Organics, Stafford, QLD

General Comments

The analytical procedures used by the Environmental Division have been developed from established internationally recognized procedures such as those published by the USEPA, APHA, AS and NEPM. In house developed procedures are employed in the absence of documented standards or by client request.

Where moisture determination has been performed, results are reported on a dry weight basis.

Where a reported less than (<) result is higher than the LOR, this may be due to primary sample extract/digestate dilution and/or insufficient sample for analysis.

Where the LOR of a reported result differs from standard LOR, this may be due to high moisture content, insufficient sample (reduced weight employed) or matrix interference.

When sampling time information is not provided by the client, sampling dates are shown without a time component. In these instances, the time component has been assumed by the laboratory for processing purposes.

Where a result is required to meet compliance limits the associated uncertainty must be considered. Refer to the ALS Contact for details.

Key : CAS Number = CAS registry number from database maintained by Chemical Abstracts Services. The Chemical Abstracts Service is a division of the American Chemical Society.
LOR = Limit of reporting
^ = This result is computed from individual analyte detections at or above the level of reporting
ø = ALS is not NATA accredited for these tests.

- EP008 (Chlorophyll): Reduced volume used for sample 3 (MARK-1) due to sediment loading, LOR raised acordingly.
- It is recognised that EG020-T (Total Metals by ICP-MS) is less than EG020-F (Dissolved Metals by ICP-MS) for sample MARK - 1. However, the difference is within experimental variation of the methods.
- Benzo(a)pyrene Toxicity Equivalent Quotient (TEQ) is the sum total of the concentration of the eight carcinogenic PAHs multiplied by their Toxicity Equivalence Factor (TEF) relative to Benzo(a)pyrene. TEF values are provided in brackets as follows: Benz(a)anthracene (0.1), Chrysene (0.01), Benzo(b+j) & Benzo(k)fluoranthene (0.1), Benzo(a)pyrene (1.0), Indeno(1.2.3.cd)pyrene (0.1), Dibenz(a.h)anthracene (1.0), Benzo(g.h.i)perylene (0.01). Less than LOR results for 'TEQ Zero' are treated as zero.

Analytical Results

Sub-Matrix: WATER (Matrix: WATER)			Client sample ID	TRIB G - 1	TRIB C - 2	MARK - 1	MARK - 2	RUMU - 2
			Client sampling date / time	[31-Mar-2016]	[31-Mar-2016]	[30-Mar-2016]	[30-Mar-2016]	[31-Mar-2016]
Compound	CAS Number	LOR	Unit	EB1608860-001	EB1608860-002	EB1608860-003	EB1608860-004	EB1608860-005
				Result	Result	Result	Result	Result
EA010P: Conductivity by PC Titrator								
Electrical Conductivity @ 25°C	----	1	µS/cm	465	415	242	350	232
EA025: Total Suspended Solids dried at 104 ± 2°C								
Suspended Solids (SS)	----	5	mg/L	14	298	2820	1910	5430
EA041: Colour (True)								
Colour (True)	----	1	PCU	15	5	6	10	6
pH Colour	----	0.01	pH Unit	8.18	8.20	8.03	8.00	8.01
ED037P: Alkalinity by PC Titrator								
Hydroxide Alkalinity as CaCO3	DMO-210-001	1	mg/L	<1	<1	<1	<1	<1
Carbonate Alkalinity as CaCO3	3812-32-6	1	mg/L	9	7	<1	<1	<1
Bicarbonate Alkalinity as CaCO3	71-52-3	1	mg/L	246	219	122	118	169
Total Alkalinity as CaCO3	----	1	mg/L	255	226	122	118	169
ED040T: Total Major Anions								
Sulfur as S	63705-05-5	1	mg/L	6	7	6	6	13
ED041G: Sulfate (Turbidimetric) as SO4 2- by DA								
Sulfate as SO4 - Turbidimetric	14808-79-8	1	mg/L	18	20	15	14	34
ED045G: Chloride by Discrete Analyser								
Chloride	16887-00-6	1	mg/L	<1	1	1	1	1
ED093F: Dissolved Major Cations								
Calcium	7440-70-2	1	mg/L	47	30	31	31	37
Magnesium	7439-95-4	1	mg/L	11	9	5	4	9
Sodium	7440-23-5	1	mg/L	48	64	15	15	31
Potassium	7440-09-7	1	mg/L	<1	1	<1	<1	1
EG020F: Dissolved Metals by ICP-MS								
Aluminium	7429-90-5	0.01	mg/L	<0.01	<0.01	0.05	0.03	0.04
Antimony	7440-36-0	0.001	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
Arsenic	7440-38-2	0.001	mg/L	<0.001	<0.001	0.002	0.002	<0.001
Boron	7440-42-8	0.05	mg/L	0.10	0.09	<0.05	<0.05	0.08
Barium	7440-39-3	0.001	mg/L	<0.001	<0.001	0.003	0.003	0.001
Beryllium	7440-41-7	0.001	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
Cadmium	7440-43-9	0.0001	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cobalt	7440-48-4	0.001	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
Chromium	7440-47-3	0.001	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
Copper	7440-50-8	0.001	mg/L	0.001	<0.001	0.001	0.001	<0.001
Manganese	7439-96-5	0.001	mg/L	0.005	<0.001	0.002	0.002	0.005

Analytical Results

Sub-Matrix: WATER (Matrix: WATER)

Compound	CAS Number	LOR	Unit	TRIB G - 1	TRIB C - 2	MARK - 1	MARK - 2	RUMU - 2
			Client sampling date / time	[31-Mar-2016]	[31-Mar-2016]	[30-Mar-2016]	[30-Mar-2016]	[31-Mar-2016]
				EB1608860-001	EB1608860-002	EB1608860-003	EB1608860-004	EB1608860-005
				Result	Result	Result	Result	Result
EG020F: Dissolved Metals by ICP-MS - Continued								
Nickel	7440-02-0	0.001	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
Lead	7439-92-1	0.001	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
Selenium	7782-49-2	0.01	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Vanadium	7440-62-2	0.01	mg/L	**0.02**	**0.03**	**0.01**	<0.01	**0.01**
Zinc	7440-66-6	0.005	mg/L	<0.005	<0.005	<0.005	<0.005	<0.005
Molybdenum	7439-98-7	0.001	mg/L	<0.001	<0.001	<0.001	<0.001	**0.001**
Silver	7440-22-4	0.001	mg/L	<0.001	<0.001	**0.002**	<0.001	<0.001
Tin	7440-31-5	0.001	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
Iron	7439-89-6	0.05	mg/L	<0.05	<0.05	<0.05	<0.05	<0.05
EG020T: Total Metals by ICP-MS								
Aluminium	7429-90-5	0.01	mg/L	**0.32**	**7.54**	**101**	**49.6**	**156**
Antimony	7440-36-0	0.001	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
Arsenic	7440-38-2	0.001	mg/L	<0.001	**0.001**	**0.014**	**0.014**	**0.010**
Boron	7440-42-8	0.05	mg/L	**0.12**	**0.10**	**0.08**	<0.05	**0.12**
Barium	7440-39-3	0.001	mg/L	<0.001	**0.017**	**0.220**	**0.137**	**0.187**
Beryllium	7440-41-7	0.001	mg/L	<0.001	<0.001	<0.001	<0.001	**0.002**
Cadmium	7440-43-9	0.0001	mg/L	<0.0001	<0.0001	**0.0003**	**0.0002**	**0.0005**
Cobalt	7440-48-4	0.001	mg/L	<0.001	**0.004**	**0.065**	**0.031**	**0.114**
Chromium	7440-47-3	0.001	mg/L	<0.001	**0.008**	**0.100**	**0.049**	**0.168**
Copper	7440-50-8	0.001	mg/L	**0.001**	**0.014**	**0.216**	**0.105**	**0.411**
Manganese	7439-96-5	0.001	mg/L	**0.027**	**0.163**	**2.67**	**1.53**	**4.15**
Nickel	7440-02-0	0.001	mg/L	<0.001	**0.009**	**0.149**	**0.063**	**0.273**
Lead	7439-92-1	0.001	mg/L	<0.001	<0.001	**0.017**	**0.015**	**0.017**
Selenium	7782-49-2	0.01	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
Vanadium	7440-62-2	0.01	mg/L	**0.02**	**0.05**	**0.29**	**0.14**	**0.49**
Zinc	7440-66-6	0.005	mg/L	<0.005	<0.005	**0.181**	**0.099**	**0.273**
Molybdenum	7439-98-7	0.001	mg/L	<0.001	<0.001	**0.001**	<0.001	**0.002**
Silver	7440-22-4	0.001	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
Tin	7440-31-5	0.001	mg/L	<0.001	<0.001	<0.001	<0.001	<0.001
Iron	7439-89-6	0.05	mg/L	**0.32**	**7.01**	**111**	**59.0**	**190**
EG035F: Dissolved Mercury by FIMS								
Mercury	7439-97-6	0.0001	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
EG035T: Total Recoverable Mercury by FIMS								
Mercury	7439-97-6	0.0001	mg/L	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Analytical Results

Sub-Matrix: WATER (Matrix: WATER)			Client sample ID	TRIB G - 1	TRIB C - 2	MARK - 1	MARK - 2	RUMU - 2
			Client sampling date / time	[31-Mar-2016]	[31-Mar-2016]	[30-Mar-2016]	[30-Mar-2016]	[31-Mar-2016]
Compound	CAS Number	LOR	Unit	EB1608860-001	EB1608860-002	EB1608860-003	EB1608860-004	EB1608860-005
				Result	Result	Result	Result	Result
EK040P: Fluoride by PC Titrator								
Fluoride	16984-48-8	0.1	mg/L	**0.4**	**0.3**	**0.2**	**0.2**	**0.2**
EK055G: Ammonia as N by Discrete Analyser								
Ammonia as N	7664-41-7	0.01	mg/L	<0.01	<0.01	**0.03**	<0.01	<0.01
EK057G: Nitrite as N by Discrete Analyser								
Nitrite as N	14797-65-0	0.01	mg/L	<0.01	<0.01	<0.01	<0.01	<0.01
EK058G: Nitrate as N by Discrete Analyser								
Nitrate as N	14797-55-8	0.01	mg/L	**0.04**	<0.01	<0.01	<0.01	<0.01
EK059G: Nitrite plus Nitrate as N (NOx) by Discrete Analyser								
Nitrite + Nitrate as N	----	0.01	mg/L	**0.04**	<0.01	<0.01	<0.01	<0.01
EK061G: Total Kjeldahl Nitrogen By Discrete Analyser								
Total Kjeldahl Nitrogen as N	----	0.1	mg/L	**0.3**	**0.2**	**1.3**	**1.1**	**1.2**
EK062G: Total Nitrogen as N (TKN + NOx) by Discrete Analyser								
^ Total Nitrogen as N	----	0.1	mg/L	**0.3**	**0.2**	**1.3**	**1.1**	**1.2**
EK067G: Total Phosphorus as P by Discrete Analyser								
Total Phosphorus as P	----	0.01	mg/L	**0.02**	**0.20**	**2.14**	**1.35**	**3.82**
EK071G: Reactive Phosphorus as P by discrete analyser								
Reactive Phosphorus as P	14265-44-2	0.01	mg/L	<0.01	**0.01**	**0.02**	**0.02**	<0.01
EN055: Ionic Balance								
Total Anions	----	0.01	meq/L	**5.47**	**4.96**	**2.78**	**2.68**	**4.11**
Total Cations	----	0.01	meq/L	**5.34**	**5.05**	**2.61**	**2.53**	**3.96**
Ionic Balance	----	0.01	%	**1.23**	**0.84**	----	----	**1.88**
EP005: Total Organic Carbon (TOC)								
Total Organic Carbon	----	1	mg/L	**1**	<1	**1**	**1**	<1
EP008: Chlorophyll a & Pheophytin a								
Chlorophyll a	----	1	mg/m³	<1	<1	<2	<1	<1
EP026SP: Chemical Oxygen Demand (Spectrophotometric)								
Chemical Oxygen Demand	----	10	mg/L	<10	<10	<10	<10	**16**
EP030: Biochemical Oxygen Demand (BOD)								
Biochemical Oxygen Demand	----	2	mg/L	<2	<2	<2	<2	<2
EP075(SIM)A: Phenolic Compounds								
Phenol	108-95-2	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
2-Chlorophenol	95-57-8	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
2-Methylphenol	95-48-7	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0

Analytical Results

Sub-Matrix: WATER (Matrix: WATER)			Client sample ID	TRIB G - 1	TRIB C - 2	MARK - 1	MARK - 2	RUMU - 2
			Client sampling date / time	[31-Mar-2016]	[31-Mar-2016]	[30-Mar-2016]	[30-Mar-2016]	[31-Mar-2016]
Compound	CAS Number	LOR	Unit	EB1608860-001	EB1608860-002	EB1608860-003	EB1608860-004	EB1608860-005
				Result	Result	Result	Result	Result
EP075(SIM)A: Phenolic Compounds - Continued								
3- & 4-Methylphenol	1319-77-3	2	µg/L	<2.0	<2.0	<2.0	<2.0	<2.0
2-Nitrophenol	88-75-5	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
2.4-Dimethylphenol	105-67-9	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
2.4-Dichlorophenol	120-83-2	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
2.6-Dichlorophenol	87-65-0	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
4-Chloro-3-methylphenol	59-50-7	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
2.4.6-Trichlorophenol	88-06-2	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
2.4.5-Trichlorophenol	95-95-4	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Pentachlorophenol	87-86-5	2	µg/L	<2.0	<2.0	<2.0	<2.0	<2.0
EP075(SIM)B: Polynuclear Aromatic Hydrocarbons								
Naphthalene	91-20-3	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Acenaphthylene	208-96-8	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Acenaphthene	83-32-9	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Fluorene	86-73-7	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Phenanthrene	85-01-8	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Anthracene	120-12-7	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Fluoranthene	206-44-0	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Pyrene	129-00-0	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Benz(a)anthracene	56-55-3	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Chrysene	218-01-9	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Benzo(b+j)fluoranthene	205-99-2 205-82-3	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Benzo(k)fluoranthene	207-08-9	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Benzo(a)pyrene	50-32-8	0.5	µg/L	<0.5	<0.5	<0.5	<0.5	<0.5
Indeno(1.2.3.cd)pyrene	193-39-5	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Dibenz(a.h)anthracene	53-70-3	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
Benzo(g.h.i)perylene	191-24-2	1	µg/L	<1.0	<1.0	<1.0	<1.0	<1.0
^ Sum of polycyclic aromatic hydrocarbons	----	0.5	µg/L	<0.5	<0.5	<0.5	<0.5	<0.5
^ Benzo(a)pyrene TEQ (zero)	----	0.5	µg/L	<0.5	<0.5	<0.5	<0.5	<0.5
EP080/071: Total Petroleum Hydrocarbons								
C6 - C9 Fraction	----	20	µg/L	<20	<20	<20	<20	<20
C10 - C14 Fraction	----	50	µg/L	<50	<50	<50	<50	<50
C15 - C28 Fraction	----	100	µg/L	<100	<100	<100	<100	<100
C29 - C36 Fraction	----	50	µg/L	<50	<50	<50	<50	<50
^ C10 - C36 Fraction (sum)	----	50	µg/L	<50	<50	<50	<50	<50

Analytical Results

Sub-Matrix: WATER (Matrix: WATER)			Client sample ID	TRIB G - 1	TRIB C - 2	MARK - 1	MARK - 2	RUMU - 2
			Client sampling date / time	[31-Mar-2016]	[31-Mar-2016]	[30-Mar-2016]	[30-Mar-2016]	[31-Mar-2016]
Compound	CAS Number	LOR	Unit	EB1608860-001	EB1608860-002	EB1608860-003	EB1608860-004	EB1608860-005
				Result	Result	Result	Result	Result
EP080/071: Total Recoverable Hydrocarbons - NEPM 2013 Fractions								
C6 - C10 Fraction	C6_C10	20	µg/L	<20	<20	<20	<20	<20
^ C6 - C10 Fraction minus BTEX (F1)	C6_C10-BTEX	20	µg/L	<20	<20	<20	<20	<20
>C10 - C16 Fraction	----	100	µg/L	<100	<100	<100	<100	<100
>C16 - C34 Fraction	----	100	µg/L	<100	<100	<100	<100	<100
>C34 - C40 Fraction	----	100	µg/L	<100	<100	<100	<100	<100
^ >C10 - C40 Fraction (sum)	----	100	µg/L	<100	<100	<100	<100	<100
^ >C10 - C16 Fraction minus Naphthalene (F2)	----	100	µg/L	<100	<100	<100	<100	<100
EP080: BTEXN								
Benzene	71-43-2	1	µg/L	<1	<1	<1	<1	<1
Toluene	108-88-3	2	µg/L	<2	<2	<2	<2	<2
Ethylbenzene	100-41-4	2	µg/L	<2	<2	<2	<2	<2
meta- & para-Xylene	108-38-3 106-42-3	2	µg/L	<2	<2	<2	<2	<2
ortho-Xylene	95-47-6	2	µg/L	<2	<2	<2	<2	<2
^ Total Xylenes	1330-20-7	2	µg/L	<2	<2	<2	<2	<2
^ Sum of BTEX	----	1	µg/L	<1	<1	<1	<1	<1
Naphthalene	91-20-3	5	µg/L	<5	<5	<5	<5	<5
EP075(SIM)S: Phenolic Compound Surrogates								
Phenol-d6	13127-88-3	1	%	30.3	33.3	29.7	26.7	32.3
2-Chlorophenol-D4	93951-73-6	1	%	74.1	71.6	64.8	59.9	69.5
2.4.6-Tribromophenol	118-79-6	1	%	90.6	86.2	78.8	73.4	82.6
EP075(SIM)T: PAH Surrogates								
2-Fluorobiphenyl	321-60-8	1	%	75.6	69.3	62.4	61.1	67.8
Anthracene-d10	1719-06-8	1	%	96.7	92.5	83.7	78.9	85.6
4-Terphenyl-d14	1718-51-0	1	%	91.7	87.6	77.4	73.4	78.5
EP080S: TPH(V)/BTEX Surrogates								
1.2-Dichloroethane-D4	17060-07-0	2	%	100	102	105	104	109
Toluene-D8	2037-26-5	2	%	100.0	98.0	101	101	99.5
4-Bromofluorobenzene	460-00-4	2	%	95.4	94.7	99.4	96.3	97.6

Analytical Results

Sub-Matrix: WATER (Matrix: WATER)			Client sample ID	TRIP BLANK	----	----	----	----
			Client sampling date / time	[31-Mar-2016]	----	----	----	----
Compound	CAS Number	LOR	Unit	EB1608860-006	--------	--------	--------	--------
				Result	----	----	----	----
EA010P: Conductivity by PC Titrator								
Electrical Conductivity @ 25°C	----	1	µS/cm	----	----	----	----	----
EA025: Total Suspended Solids dried at 104 ± 2°C								
Suspended Solids (SS)	----	5	mg/L	----	----	----	----	----
EA041: Colour (True)								
Colour (True)	----	1	PCU	----	----	----	----	----
pH Colour	----	0.01	pH Unit	----	----	----	----	----
ED037P: Alkalinity by PC Titrator								
Hydroxide Alkalinity as CaCO3	DMO-210-001	1	mg/L	----	----	----	----	----
Carbonate Alkalinity as CaCO3	3812-32-6	1	mg/L	----	----	----	----	----
Bicarbonate Alkalinity as CaCO3	71-52-3	1	mg/L	----	----	----	----	----
Total Alkalinity as CaCO3	----	1	mg/L	----	----	----	----	----
ED040T: Total Major Anions								
Sulfur as S	63705-05-5	1	mg/L	----	----	----	----	----
ED041G: Sulfate (Turbidimetric) as SO4 2- by DA								
Sulfate as SO4 - Turbidimetric	14808-79-8	1	mg/L	----	----	----	----	----
ED045G: Chloride by Discrete Analyser								
Chloride	16887-00-6	1	mg/L	----	----	----	----	----
ED093F: Dissolved Major Cations								
Calcium	7440-70-2	1	mg/L	----	----	----	----	----
Magnesium	7439-95-4	1	mg/L	----	----	----	----	----
Sodium	7440-23-5	1	mg/L	----	----	----	----	----
Potassium	7440-09-7	1	mg/L	----	----	----	----	----
EG020F: Dissolved Metals by ICP-MS								
Aluminium	7429-90-5	0.01	mg/L	----	----	----	----	----
Antimony	7440-36-0	0.001	mg/L	----	----	----	----	----
Arsenic	7440-38-2	0.001	mg/L	----	----	----	----	----
Boron	7440-42-8	0.05	mg/L	----	----	----	----	----
Barium	7440-39-3	0.001	mg/L	----	----	----	----	----
Beryllium	7440-41-7	0.001	mg/L	----	----	----	----	----
Cadmium	7440-43-9	0.0001	mg/L	----	----	----	----	----
Cobalt	7440-48-4	0.001	mg/L	----	----	----	----	----
Chromium	7440-47-3	0.001	mg/L	----	----	----	----	----
Copper	7440-50-8	0.001	mg/L	----	----	----	----	----
Manganese	7439-96-5	0.001	mg/L	----	----	----	----	----

Analytical Results

Sub-Matrix: WATER (Matrix: WATER)			Client sample ID	TRIP BLANK	----	----	----	----
			Client sampling date / time	[31-Mar-2016]	----	----	----	----
Compound	CAS Number	LOR	Unit	EB1608860-006	--------	--------	--------	--------
				Result	----	----	----	----
EG020F: Dissolved Metals by ICP-MS - Continued								
Nickel	7440-02-0	0.001	mg/L	----	----	----	----	----
Lead	7439-92-1	0.001	mg/L	----	----	----	----	----
Selenium	7782-49-2	0.01	mg/L	----	----	----	----	----
Vanadium	7440-62-2	0.01	mg/L	----	----	----	----	----
Zinc	7440-66-6	0.005	mg/L	----	----	----	----	----
Molybdenum	7439-98-7	0.001	mg/L	----	----	----	----	----
Silver	7440-22-4	0.001	mg/L	----	----	----	----	----
Tin	7440-31-5	0.001	mg/L	----	----	----	----	----
Iron	7439-89-6	0.05	mg/L	----	----	----	----	----
EG020T: Total Metals by ICP-MS								
Aluminium	7429-90-5	0.01	mg/L	<0.01	----	----	----	----
Antimony	7440-36-0	0.001	mg/L	<0.001	----	----	----	----
Arsenic	7440-38-2	0.001	mg/L	<0.001	----	----	----	----
Boron	7440-42-8	0.05	mg/L	<0.05	----	----	----	----
Barium	7440-39-3	0.001	mg/L	<0.001	----	----	----	----
Beryllium	7440-41-7	0.001	mg/L	<0.001	----	----	----	----
Cadmium	7440-43-9	0.0001	mg/L	<0.0001	----	----	----	----
Cobalt	7440-48-4	0.001	mg/L	<0.001	----	----	----	----
Chromium	7440-47-3	0.001	mg/L	<0.001	----	----	----	----
Copper	7440-50-8	0.001	mg/L	<0.001	----	----	----	----
Manganese	7439-96-5	0.001	mg/L	<0.001	----	----	----	----
Nickel	7440-02-0	0.001	mg/L	<0.001	----	----	----	----
Lead	7439-92-1	0.001	mg/L	<0.001	----	----	----	----
Selenium	7782-49-2	0.01	mg/L	<0.01	----	----	----	----
Vanadium	7440-62-2	0.01	mg/L	<0.01	----	----	----	----
Zinc	7440-66-6	0.005	mg/L	<0.005	----	----	----	----
Molybdenum	7439-98-7	0.001	mg/L	<0.001	----	----	----	----
Silver	7440-22-4	0.001	mg/L	<0.001	----	----	----	----
Tin	7440-31-5	0.001	mg/L	<0.001	----	----	----	----
Iron	7439-89-6	0.05	mg/L	<0.05	----	----	----	----
EG035F: Dissolved Mercury by FIMS								
Mercury	7439-97-6	0.0001	mg/L	----	----	----	----	----
EG035T: Total Recoverable Mercury by FIMS								
Mercury	7439-97-6	0.0001	mg/L	<0.0001	----	----	----	----

Analytical Results

Sub-Matrix: WATER (Matrix: WATER)			Client sample ID	TRIP BLANK	----	----	----	----
			Client sampling date / time	[31-Mar-2016]	----	----	----	----
Compound	CAS Number	LOR	Unit	EB1608860-006	--------	--------	--------	--------
				Result	----	----	----	----
EK040P: Fluoride by PC Titrator								
Fluoride	16984-48-8	0.1	mg/L	----	----	----	----	----
EK055G: Ammonia as N by Discrete Analyser								
Ammonia as N	7664-41-7	0.01	mg/L	----	----	----	----	----
EK057G: Nitrite as N by Discrete Analyser								
Nitrite as N	14797-65-0	0.01	mg/L	----	----	----	----	----
EK058G: Nitrate as N by Discrete Analyser								
Nitrate as N	14797-55-8	0.01	mg/L	----	----	----	----	----
EK059G: Nitrite plus Nitrate as N (NOx) by Discrete Analyser								
Nitrite + Nitrate as N	----	0.01	mg/L	----	----	----	----	----
EK061G: Total Kjeldahl Nitrogen By Discrete Analyser								
Total Kjeldahl Nitrogen as N	----	0.1	mg/L	----	----	----	----	----
EK062G: Total Nitrogen as N (TKN + NOx) by Discrete Analyser								
^ Total Nitrogen as N	----	0.1	mg/L	----	----	----	----	----
EK067G: Total Phosphorus as P by Discrete Analyser								
Total Phosphorus as P	----	0.01	mg/L	----	----	----	----	----
EK071G: Reactive Phosphorus as P by discrete analyser								
Reactive Phosphorus as P	14265-44-2	0.01	mg/L	----	----	----	----	----
EN055: Ionic Balance								
Total Anions	----	0.01	meq/L	----	----	----	----	----
Total Cations	----	0.01	meq/L	----	----	----	----	----
Ionic Balance	----	0.01	%	----	----	----	----	----
EP005: Total Organic Carbon (TOC)								
Total Organic Carbon	----	1	mg/L	----	----	----	----	----
EP008: Chlorophyll a & Pheophytin a								
Chlorophyll a	----	1	mg/m^3	----	----	----	----	----
EP026SP: Chemical Oxygen Demand (Spectrophotometric)								
Chemical Oxygen Demand	----	10	mg/L	----	----	----	----	----
EP030: Biochemical Oxygen Demand (BOD)								
Biochemical Oxygen Demand	----	2	mg/L	----	----	----	----	----
EP075(SIM)A: Phenolic Compounds								
Phenol	108-95-2	1	µg/L	<1.0	----	----	----	----
2-Chlorophenol	95-57-8	1	µg/L	<1.0	----	----	----	----
2-Methylphenol	95-48-7	1	µg/L	<1.0	----	----	----	----

Analytical Results

Sub-Matrix: WATER (Matrix: WATER)			Client sample ID	TRIP BLANK	----	----	----	----
			Client sampling date / time	[31-Mar-2016]	----	----	----	----
Compound	CAS Number	LOR	Unit	EB1608860-006	--------	--------	--------	--------
				Result	----	----	----	----
EP075(SIM)A: Phenolic Compounds - Continued								
3- & 4-Methylphenol	1319-77-3	2	µg/L	<2.0	----	----	----	----
2-Nitrophenol	88-75-5	1	µg/L	<1.0	----	----	----	----
2.4-Dimethylphenol	105-67-9	1	µg/L	<1.0	----	----	----	----
2.4-Dichlorophenol	120-83-2	1	µg/L	<1.0	----	----	----	----
2.6-Dichlorophenol	87-65-0	1	µg/L	<1.0	----	----	----	----
4-Chloro-3-methylphenol	59-50-7	1	µg/L	<1.0	----	----	----	----
2.4.6-Trichlorophenol	88-06-2	1	µg/L	<1.0	----	----	----	----
2.4.5-Trichlorophenol	95-95-4	1	µg/L	<1.0	----	----	----	----
Pentachlorophenol	87-86-5	2	µg/L	<2.0	----	----	----	----
EP075(SIM)B: Polynuclear Aromatic Hydrocarbons								
Naphthalene	91-20-3	1	µg/L	<1.0	----	----	----	----
Acenaphthylene	208-96-8	1	µg/L	<1.0	----	----	----	----
Acenaphthene	83-32-9	1	µg/L	<1.0	----	----	----	----
Fluorene	86-73-7	1	µg/L	<1.0	----	----	----	----
Phenanthrene	85-01-8	1	µg/L	<1.0	----	----	----	----
Anthracene	120-12-7	1	µg/L	<1.0	----	----	----	----
Fluoranthene	206-44-0	1	µg/L	<1.0	----	----	----	----
Pyrene	129-00-0	1	µg/L	<1.0	----	----	----	----
Benz(a)anthracene	56-55-3	1	µg/L	<1.0	----	----	----	----
Chrysene	218-01-9	1	µg/L	<1.0	----	----	----	----
Benzo(b+j)fluoranthene	205-99-2 205-82-3	1	µg/L	<1.0	----	----	----	----
Benzo(k)fluoranthene	207-08-9	1	µg/L	<1.0	----	----	----	----
Benzo(a)pyrene	50-32-8	0.5	µg/L	<0.5	----	----	----	----
Indeno(1.2.3.cd)pyrene	193-39-5	1	µg/L	<1.0	----	----	----	----
Dibenz(a.h)anthracene	53-70-3	1	µg/L	<1.0	----	----	----	----
Benzo(g.h.i)perylene	191-24-2	1	µg/L	<1.0	----	----	----	----
^ Sum of polycyclic aromatic hydrocarbons	----	0.5	µg/L	<0.5	----	----	----	----
^ Benzo(a)pyrene TEQ (zero)	----	0.5	µg/L	<0.5	----	----	----	----
EP080/071: Total Petroleum Hydrocarbons								
C6 - C9 Fraction	----	20	µg/L	<20	----	----	----	----
C10 - C14 Fraction	----	50	µg/L	<50	----	----	----	----
C15 - C28 Fraction	----	100	µg/L	<100	----	----	----	----
C29 - C36 Fraction	----	50	µg/L	<50	----	----	----	----
^ C10 - C36 Fraction (sum)	----	50	µg/L	<50	----	----	----	----

Analytical Results

Sub-Matrix: WATER (Matrix: WATER)			Client sample ID	TRIP BLANK	----	----	----	----
			Client sampling date / time	[31-Mar-2016]	----	----	----	----
Compound	CAS Number	LOR	Unit	EB1608860-006	--------	--------	--------	--------
				Result	----	----	----	----
EP080/071: Total Recoverable Hydrocarbons - NEPM 2013 Fractions								
C6 - C10 Fraction	C6_C10	20	µg/L	<20	----	----	----	----
^ C6 - C10 Fraction minus BTEX (F1)	C6_C10-BTEX	20	µg/L	<20	----	----	----	----
>C10 - C16 Fraction	----	100	µg/L	<100	----	----	----	----
>C16 - C34 Fraction	----	100	µg/L	<100	----	----	----	----
>C34 - C40 Fraction	----	100	µg/L	<100	----	----	----	----
^ >C10 - C40 Fraction (sum)	----	100	µg/L	<100	----	----	----	----
^ >C10 - C16 Fraction minus Naphthalene (F2)	----	100	µg/L	<100	----	----	----	----
EP080: BTEXN								
Benzene	71-43-2	1	µg/L	<1	----	----	----	----
Toluene	108-88-3	2	µg/L	<2	----	----	----	----
Ethylbenzene	100-41-4	2	µg/L	<2	----	----	----	----
meta- & para-Xylene	108-38-3 106-42-3	2	µg/L	<2	----	----	----	----
ortho-Xylene	95-47-6	2	µg/L	<2	----	----	----	----
^ Total Xylenes	1330-20-7	2	µg/L	<2	----	----	----	----
^ Sum of BTEX	----	1	µg/L	<1	----	----	----	----
Naphthalene	91-20-3	5	µg/L	<5	----	----	----	----
EP075(SIM)S: Phenolic Compound Surrogates								
Phenol-d6	13127-88-3	1	%	**29.2**	----	----	----	----
2-Chlorophenol-D4	93951-73-6	1	%	**70.3**	----	----	----	----
2.4.6-Tribromophenol	118-79-6	1	%	**88.3**	----	----	----	----
EP075(SIM)T: PAH Surrogates								
2-Fluorobiphenyl	321-60-8	1	%	**73.2**	----	----	----	----
Anthracene-d10	1719-06-8	1	%	**91.5**	----	----	----	----
4-Terphenyl-d14	1718-51-0	1	%	**88.3**	----	----	----	----
EP080S: TPH(V)/BTEX Surrogates								
1.2-Dichloroethane-D4	17060-07-0	2	%	**103**	----	----	----	----
Toluene-D8	2037-26-5	2	%	**101**	----	----	----	----
4-Bromofluorobenzene	460-00-4	2	%	**100.0**	----	----	----	----

Surrogate Control Limits

Sub-Matrix: **WATER**

Compound	CAS Number	Recovery Limits (%) Low	High
EP075(SIM)S: Phenolic Compound Surrogates			
Phenol-d6	13127-88-3	10	72
2-Chlorophenol-D4	93951-73-6	27	130
2.4.6-Tribromophenol	118-79-6	19	181
EP075(SIM)T: PAH Surrogates			
2-Fluorobiphenyl	321-60-8	14	146
Anthracene-d10	1719-06-8	35	137
4-Terphenyl-d14	1718-51-0	36	154
EP080S: TPH(V)/BTEX Surrogates			
1.2-Dichloroethane-D4	17060-07-0	66	138
Toluene-D8	2037-26-5	79	120
4-Bromofluorobenzene	460-00-4	74	118

ERIAS Group Pty Ltd
ACN: 155 087 362
E info@eriasgroup.com
W eriasgroup.com

Melbourne, Australia
13-25 Church Street
Hawthorn, Victoria, 3122
Phone: +61 3 9023 9281

Adelaide, Australia
22B Beulah Road
Norwood, South Australia, 5067
Phone: +61 419 012 698

Brisbane, Australia
Level 4, 46 Edward Street
Brisbane, Queensland, 4000
Phone: +61 417 564 702

Papua New Guinea
ERIAS Group PNG Limited
PO Box 569
Port Moresby, National Capital District

www.eriasgroup.com