



Chapter 17

Offshore Marine Environment Impact Assessment

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The information in the EIS that relates to Golpu Ore Reserves is based on information compiled by the Competent Person, Mr Pasqualino Manca, who is a member of The Australasian Institute of Mining and Metallurgy. Mr Pasqualino Manca, is a full-time employee of Newcrest Mining Limited or its relevant subsidiaries, holds options and/ or shares in Newcrest Mining Limited and is entitled to participate in Newcrest's executive equity long term incentive plan, details of which are included in Newcrest's 2017 Remuneration Report. Ore Reserve growth is one of the performance measures under recent long term incentive plans. Mr Pasqualino Manca has sufficient experience which is relevant to the styles of mineralisation and type of deposit under consideration and to the activity which he is undertaking to qualify as a Competent Person as defined in the JORC Code 2012. Mr Pasqualino Manca consents to the inclusion of material of the matters based on his information in the form and context in which it appears.

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17. OFFSHORE MARINE ENVIRONMENT IMPACT ASSESSMENT

17.1. Introduction

This chapter of the environmental impact statement (EIS) assesses the residual impacts of deep sea tailings placement (DSTP) on the offshore marine pelagic and benthic environment after proposed management measures have been implemented.

This chapter is based on the results of various technical studies and physical oceanographic investigations including the following appendices to the EIS:

- Density Current, Plume Dispersion and Hydrodynamic Modelling, conducted by Tetra Tech, Inc. (Appendix J)
- Oceanographic Investigations of the Huon Gulf, conducted by IHAconsult (Appendix K)
- Tailings Ecotoxicology and Geochemistry, conducted by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (Appendix L). This appendix includes two separate reports: 1) Ecotoxicology and Chemistry of Wafi-Golpu Bench-scale Tailings and 2) Long-term lab study of Wafi-Golpu tailings: metal geochemistry, release and bioavailability in deposited tailings-sediment mixtures - Stage 1.
- Physical, Chemical and Biological Sedimentology of the Huon Gulf, conducted by IHAconsult (Appendix M)
- Assessment of Metal Bioaccumulation and Biomagnification from DSTP in the Huon Gulf, Papua New Guinea, conducted by Tetra Tech, Inc. (Appendix N)
- Benthic Video Characterisation, conducted by Coffey (Appendix O)
- Deep-slope and Pelagic Fish Characterisation, conducted by Marscco and Coffey (Appendix P)
- Zooplankton and Micronekton Characterisation, conducted by Marscco and Coffey (Appendix Q)
- Nearshore Marine Characterisation, conducted by Coffey (Appendix R)
- Fisheries and Marine Resource Use Characterisation, conducted by EnviroGulf Consulting and Coffey (Appendix S)
- Socioeconomic Baseline, conducted by Coffey (Appendix T)
- Tailings Management Engineering Design, conducted by Tetra Tech, Inc. (Appendix Z)

17.2. Approach to Impact Assessment

As discussed in Chapter 4, Overview of Impact Assessment Methods, the environmental impact assessment approach generally adopts one of two methods to assess the level of residual environmental impacts of the Project on the identified receptors, a significance method or a compliance method. Unless otherwise stated, this impact assessment was conducted by Coffey Environments Australia Pty Ltd.

The approach to the assessment involved numerical modelling of the behaviour and fate of tailings solids and liquids in the offshore marine environment due to DSTP discharge (Appendix J, Density Current, Plume Dispersion and Hydrodynamic Modelling). A compliance method was used for assessing water quality impacts.

The modelling and ecotoxicology results were then used to assess the impacts to offshore marine ecology using a significance assessment method. The approach considers the existing offshore marine environment as described in Chapter 11, Offshore Marine

Environment Characterisation, identifies the nature of potential impacts on offshore marine ecology, and assesses the significance of these impacts based on the sensitivity of environmental values or receptors (e.g., individual species or biological communities) and the magnitude of the predicted impact.

For the purposes of assessing the 27-year[1] duration of the DSTP operation, the assessment criteria have been modified but remain consistent with those described in Chapter 4, Overview of Impact Assessment Methods

A conceptual model of the marine environment that relates solely to the effects typical of a DSTP system was developed by NSR (1993), which allows physical and chemical interactions and their associated biological responses to be assessed. This conceptual model has been adapted and modified for the Project's proposed DSTP system and receiving marine environment within the inner Huon Gulf. Four major components (zones) of the conceptual model relevant to the offshore marine ecological impact assessment are:

1. Surface mixed layer zone: This zone encompasses the offshore surface epipelagic environments and includes the biologically productive euphotic zone.
2. Deep-water pelagic zone: This zone encompasses that part of the water column overlying the deep-slope and deep-sea benthic zones (see below) and below the surface mixed layer zone (more than 200m water depth).
3. Deep-slope benthic zone: This zone includes the deep-slope benthic habitats and biological communities of the submarine slope below the DSTP outfall to depths of between 650m and 750m where the base of the Markham Canyon is located, which will be influenced by tailings solids deposition from the tailings density current. This zone also includes the deep-slope areas adjacent to the descending tailings density current where tailings solids are deposited from the delayed settling (cascade suspension) of fine-grained tailings solids carried in suspension (e.g., subsurface turbidity plumes shearing off from the main density current) as well as being transported in the direction of ambient currents.
4. Deep-sea benthic zone: This zone includes deep-sea benthic habitats, sediment/water interface and biological communities of the Markham Canyon and the seafloor of the northwestern Solomon Sea, including the western portion of the New Britain Trench of which the Markham Canyon is an extension. This zone will be the main repository for coarse-grained tailings solids.

For the purpose of residual impact assessment in this chapter (2), (3) and (4) above have been combined to avoid unnecessary repetition of benthic impact assessment text. Therefore, the residual impacts assessment of DSTP on the offshore marine ecological environment are based on two key environmental compartments:

- Residual impacts of DSTP to marine pelagic ecology (Section 17.5.1)
- Residual impacts of DSTP to marine benthic ecology (Section 17.5.2)

17.2.1. Significance Assessment Method

The significance assessment method outlined in Chapter 4, Overview of Impact Assessment Methods, and used in previous impact assessment chapters of this EIS has some limitations when assessing the predicted residual impacts of DSTP on the offshore marine environment. Despite some limitations this method was the most appropriate to

[1] While the nominal DSTP discharge is 360Mt over 28 years, the modelling of the fate and behaviour of tailings discharged by DSTP was undertaken assuming 361Mt of tailings discharged over a 27-year period. This difference is expected to have an immaterial and unmeasurable effect on the modelling results.

assess potential impacts on the offshore marine environment since it allowed the potential sensitivity of various specific receptors to be assessed individually. This approach has also been complemented by the compliance method where required.

It is difficult to assign environmental values to the various biological components of the deep-sea environment, which would mainly relate to their intrinsic value rather than an exploited resource value (which is absent from the DSTP area). It is also difficult to assign sensitivity values to deep-sea receptors (e.g., zooplankton, fish and benthic invertebrates) within a naturally highly perturbed system (high sedimentation rates, persistently elevated suspended sediment concentrations and frequent redistribution of deposited tailings solids by turbidity current events).

Notwithstanding, this impact assessment identifies environmental values in terms of various biological communities within pelagic water column zones and benthic zones and assigns a sensitivity to these based on the attributes of the different zones (see Section 17.2.1.5).

17.2.1.1. Sensitivity Criteria

Table 17.1 presents criteria for assessing the sensitivity of a deep-water environmental value, or receptor, which are met if one or more of the definitions apply.

Table 17.1: Sensitivity of a marine environmental value or receptor

Sensitivity	Definition
Very high	An internationally recognised site of environmental or conservation value. Highly restricted distribution of the environmental value or receptor. No capacity to adapt to change (low resilience). Environmental value is in very good condition. Extremely or very rare natural resource.
High	A nationally recognised site, value or receptor. Restricted distribution of the environmental value or receptor. Limited capacity to adapt to change. Environmental value is in good condition. Rare natural resource.
Medium	Limited abundance and distribution of environmental value or receptor. Some resilience to change. Environmental value is in moderate to good condition. Restricted natural resource.
Low	Abundance and distribution of environmental value or receptor is common and widespread. Resilient to change. Environmental value is in disturbed condition. Common natural resource.
Very low	Abundance and distribution are very common. High resilience to change. Environmental value or receptor is in poor condition. Abundant natural resource.

17.2.1.2. Magnitude of Impact Criteria

The criteria for assessing the magnitude of potential impact due to DSTP considers three different aspects of an impact as follows:

- Severity of the impact: in terms of the degree of change from the environmental value's existing condition
- Spatial extent of the impact: the geographic extent over which DSTP may directly or indirectly impact the environmental value
- Duration of impact: the duration of the impact and whether the impact will be immediate or delayed, occur during the day or at night, intermittent, experience seasonality or be short or long term

In the case of the proposed DSTP operation, the duration of impact is for 28 years; therefore the 'duration of impact' criterion is not included in the assessment of the 'magnitude of impact'. However where there is a temporal aspect in assessing an impact, the duration of the impact has been assessed on a case-by-case basis. For example, the passage of zooplankton and micronekton undertaking diel vertical migrations and passing directly through a tailings subsurface plume is transient (say, less than one hour), so the duration of the exposure has been taken into account.

Table 17.2 presents criteria for assessing the magnitude of a potential impact to an offshore marine environmental value. A magnitude rating is assigned if one or more of the definitions apply.

Table 17.2: Magnitude of offshore marine environmental impacts

Magnitude	Contributing factor	Definition
Very high	Severity of impact	• Total loss of, or severe alteration to a deep-water marine ecological value, and/or loss of a high proportion of the known population or range of the value with a strong likelihood that the viability of the value will be severely reduced.
	Spatial extent	• Effects are extremely widespread and may be national or international in extent. • Very high impacts to deep-water ecosystem functions or environmental values.
High	Severity of impact	• Major loss of or alteration to a deep-water marine ecological value and/or loss of a significant proportion of the known population or range of the value, with the viability of the biological value reduced. • Significant effect to deep-water ecosystem functions or other relevant environmental values.
	Spatial extent	• Effects extend large distances beyond the tailings and mass movement footprints such as to the New Britain Trench and western Solomon Sea. • Effects are regional.
Moderate	Severity of impact	• Moderate changes to a deep-water marine ecological value that is readily detectible with respect to natural variability. • Moderate effect to ecosystem functions or other relevant environmental or marine environmental values.
	Spatial extent	• Effects extend short distances beyond the tailings and mass movement footprints but remain within the Huon Gulf. • Effects are localised.

Magnitude	Contributing factor	Definition
Low	Severity of impact	• Minor effect compared to existing baseline conditions. Effects unlikely to reduce the overall viability of a deep-water marine environmental value. • Effect barely detectable with respect to natural variability.
	Spatial extent	• Effects within the area described by the tailings and mass movement footprints.
Very low	Severity of impact	• Effects likely to be very low or barely detectable and reduction in the viability of the deep-water marine environmental values is highly unlikely. • Impacts within statutory limits or guideline values and no detectable change to the existing environment beyond natural variability.
	Spatial extent	• Effects are confined to a small area or areas within the tailings and mass movement footprints.

17.2.1.3. Magnitude of Impact Context

The magnitude of offshore marine environmental impacts needs to be considered in the following context.

The Huon Gulf receives very high rates of terrestrial sediment input from rivers draining the hinterland areas. It is conservatively estimated that about 60Mtpa of suspended sediment enters the gulf from these rivers (Appendix M, Physical, Chemical and Biological Sedimentology of the Huon Gulf). During flood events, large surface plumes of turbid water form at river mouths and are transported laterally by ocean currents. Below the surface, persistent plumes of turbid water occur near the seafloor. As a result, high rates of sedimentation occur on the floor of the Huon Gulf, particularly along the northern coastline. Submarine slope failures have been frequently observed at the current mooring locations and can lead to the formation of turbidity current events that transport sediment down the Markham Canyon eastwards towards the New Britain Trench. The turbidity current events are sufficiently energetic to re-suspend deposited terrestrial sediments and transport them further down the Markham Canyon. These submarine slope failures and turbidity current events are episodic but frequent.

It is into this environment that the proposed DSTP discharge will occur and discharge a further 16.5Mtpa[2] of tailings solids onto the northern wall of the Markham Canyon from an outfall at depth of approximately 200m. The tailings slurry will be rapidly diluted as it moves as a density current in the vicinity of the Outfall Area down the submarine slope of the north wall of the Markham Canyon (average slope of 20°), until intersecting with the relatively flat and gently sloping bed of the Markham Canyon, and continuing in the down canyon direction to over 1,000m water depth (Appendix J, Density Current, Plume Dispersion and Hydrodynamic Modelling). Dilute subsurface tailings plumes that will shear off the descending density current will also occur in the water column below the discharge depth and be moved laterally by ocean currents. Tailings solids will eventually deposit on the ocean floor from the density current and from subsurface tailings plumes. The depositional footprint for tailings solids has been predicted by numerical modelling (called the 'tailings footprint'). Submarine slope failures will continue to occur and some of the deposited tailings solids will be re-suspended by turbidity current events and be mixed with natural

[2] The EIS has assessed the impacts of up to 16.5Mtpa of discharge via DSTP. This is based on the Project's nominal design production rate of 16.84Mtpa, with the remaining amount comprising concentrate.

sediments before being redeposited further down the Markham Canyon. This has also been predicted by numerical modelling and is called the 'mass movement footprint'.

17.2.1.4. Significance Assessment of Impacts

The aim of proposed management measures is to reduce the magnitude of a predicted impact. Therefore, assuming management measures are successfully implemented, the remaining residual impact should be lessened. Residual impacts were determined using the significance matrix presented in Table 17.3.

Engineering design measures have been included in the DSTP system to avoid impacts, such as discharging only well below the surface mixed layer and well below the euphotic zone where the highest biological productivity occurs and where the bulk of marine biological resources that are used by people are located. The significance of the residual impacts has been assessed on the assumption that DSTP design mitigation and management measures will have been successfully implemented.

Table 17.3: Matrix of significance

Magnitude of impact	Sensitivity of value				
	Very low	**Low**	**Medium**	**High**	**Very high**
Very high	Moderate	High	Major	Major	Major
High	Low	Moderate	High	Major	Major
Moderate	Low	Low	Moderate	High	High
Low	Low	Low	Low	Moderate	Moderate
Very low	Very low	Low	Low	Low	Moderate

17.2.1.5. Summary of Environmental Values and Sensitivities

Identification of the offshore marine environmental values (or 'receptors') that require protection is a key step in assessing potential DSTP impacts. The *Environment Act 2000* provides the following definition of an environmental value (actually termed 'beneficial value' in the legislation):

"*Beneficial value means a quality or characteristic of the environment or any element or segment of the environment, which:*

- *is conducive to ecological health, public benefit, welfare, safety, health or aesthetic enjoyment and which requires protection from environmental harm*
- *or is declared in an Environment Policy or permit to be a beneficial value*"

The environmental values of the marine environment reflect the interaction of the physical and biological environment, local communities and other relevant stakeholders. Under the *Environment Act 2000*, the environmental values and sensitivities summarised in Table 17.4 are representative of 'elements or segments of the marine environment' (e.g., pelagic and benthic zonation) that are relevant to the assessment of the residual impact of DSTP in the context of the existing marine environment of the Huon Gulf and western Solomon Sea. The sensitivity of the environmental values is given in Table 17.4 based on the attributes of the pelagic and benthic zonation within which they exist.

The environmental values of the epipelagic zone are included in Table 17.4, despite the tailings discharge depth (approximately 200m) being within the mesopelagic zone (i.e., more than 200m deep), and the tailings solids and liquids not being likely to rise and penetrate into the epipelagic zone. However, consideration of potential impacts of DSTP to the epipelagic zone also takes account of the potential for vertically migrating zooplankton and micronekton exposed to tailings subsurface plumes in the mesopelagic zone to become a source of trace metal-contaminated organisms entering the epipelagic zone. This potential impact source is addressed in the pelagic marine ecology residual impact assessment of trace metal bioaccumulation and biomagnification (Section 17.5.1).

17.2.2. Compliance Standard Assessment Method

The compliance standard assessment method was used to compare the results of modelling or other predictive techniques with statutory limits or guidelines. The compliance method comprises two components:

- Compliance with receiving water quality criteria to be applied at the edge of a regulatory mixing zone
- Consistency with PNG's Draft General Guidelines for DSTP

Compliance or consistency with the assessment criteria are described briefly below.

17.2.2.1. Compliance with Receiving Water Quality Criteria

Water quality criteria, developed to protect the marine ecosystems drive the compliance criteria for DSTP-derived contaminants in the marine environment. These are the ambient water quality criteria applicable to dissolved metals (<0.45µm filtered) stipulated in the State of Papua New Guinea Environment (Water Quality Criteria) Regulation 2002 – Schedule 1 – Water Quality Criteria for Aquatic Life Protection (Seawater).

The liquid component of the tailings discharge after dilution within the mixing zone (the dimensions of which will be stipulated by the PNG Government) will be required to comply with the receiving water criteria defined in Schedule 1 of the PNG Environment (Water Quality Criteria) Regulation 2002 at the edge of the mixing zone.

In the case of the Project's DSTP system, a site-specific mixing zone will be developed within which the prescribed water quality criteria may be exceeded.

Reference is also made to the ANZECC/ARMCANZ (2000) guidelines for the protection of 95% of marine species. As the ANZECC/ARMCANZ guidelines are more stringent than the PNG ambient water quality criteria, comparison to these guidelines provides an additional level of rigour to the assessment.

Table 17.4: Summary of Marine Environmental Values and Sensitivities

Environmental Value	Description	Sensitivity
Marine pelagic environment:		
Depth range 0 to 200m (epipelagic zone) Key environmental receptors: phytoplankton, zooplankton, micronekton, nekton (near surface water macroinvertebrates (e.g., squid) and fish, and top fish predators such as tuna), sea turtles and marine mammals.	• A zone of high biological productivity in which primary producers (e.g. phytoplankton) within the euphotic zone (0 to 60m in present study area) provide the basis of the food web for secondary producers (e.g., zooplankton and micronekton), which in turn are consumed by fish. • A moderate diversity and abundance of secondary producers (e.g., zooplankton and micronekton) feeding on phytoplankton and terrigenous particulate and dissolved organic matter from riverine inflows. • Increased night time presence of zooplankton and micronekton for those species that undertake diel vertical migration. • Elevated nutrient levels from riverine inflows of particulate and dissolved organic matter. • Moderate diversity and standing stocks of epipelagic fish including smaller fish species and baitfish consumed by higher trophic level fish species. • A minor marine resource use area (i.e., DSTP outfall area) for subsistence and artisanal fisheries based on epipelagic fish resources, such as sharks, tuna, rainbow runners caught by longline and trolling (in clearer waters outside influence of river plumes). Some species of which are sold at the Lae fish markets or consumed locally. • Presence of top trophic level secondary consumers, such as sea turtles and marine mammals.	High
Depth range 200 to 500m (upper mesopelagic zone) Key receptors: deep-water zooplankton, micronekton, mid- to deep-water fish including gulper sharks and some tuna species, deep-diving sea turtles (e.g., leatherback) and marine mammals.	• A zone of lower biological productivity due to absence of primary producers (phytoplankton), owing to the lack of photosynthetically active light penetration. • Biological productivity attributable mainly to secondary consumers (zooplankton and micronekton), with lower densities at night time when species that undertake diel vertical migration move from this depth range to the epipelagic zone (0 to 200m). • Zooplankton and micronekton are the food resource to higher trophic levels (e.g., fish). • A zone of reduced nutrient levels due to uptake by phytoplankton in the epipelagic zone. • Absence of subsistence or artisanal fisheries in this depth zone at the DSTP outfall area. • Low fish resource potential for deep-water fisheries.	Low
Depth range 500 to 1,000m (lower mesopelagic zone) Key receptors: Deep-water fish (e.g., gulper sharks), lantern fish (Myctophidae), anglerfish (Lophiiformes) and pelagic macroinvertebrates such as jellyfish (Medusozoa) and squid (Cephalopoda)	• A zone of low biological productivity based on secondary consumers (e.g., deep water zooplankton, micronekton, gelatinous nekton (jellyfish) and squid) of low diversity and density. • Presence of very low diversity and standing stocks of deep slope fish comprised mainly of mainly centrophorid sharks or dogfish and deep-water bony fish (*Teleosteii*). • Absence of subsistence, artisanal or commercial fisheries that could target this depth zone.	Low

Environmental Value	Description	Sensitivity
Depth range 1,000 to 4,000m (bathypelagic zone) Key receptors: Deep-water benthic macroinvertebrates, meiobenthic infauna and epibenthic and demersal fish species.	• A zone of very low biological productivity based on secondary consumers (e.g., deep-water zooplankton, micronekton, gelatinous nekton (jellyfish) and squid) of low diversity and density. • Likely presence of bathypelagic species of fish typical of these depths generally but in low abundance in the depths/areas affected by frequent turbidity currents. • Absence of subsistence, artisanal or commercial fisheries that could target this depth zone.	Low
Marine benthic environment:		
Depth range 0 to 200m (sublittoral zone) Key receptors: Benthic macroalgae and benthic macroinvertebrates and meiofauna. Benthic and epibenthic fish including gulper sharks. Sea turtles.	• A zone of moderate biological productivity by benthic primary producers (e.g., macroalgae (seaweeds) and invertebrates containing symbiotic zooxanthellae) and benthic secondary producers (e.g., invertebrate benthos), which provide a key food resource to fish and higher trophic levels (e.g., sea turtles). • A moderate diversity of standing stocks of fish. • A zone of subsistence and artisanal fisheries that target benthic, epibenthic and demersal fish species via netting, spearfishing and longlining. • Some macroinvertebrate and fish resources are sold at the Lae fish markets or consumed locally.	Medium
Depth range 200 to 1,000m (upper bathyal zone) Key receptors: Deep-slope benthic macroinvertebrates and meiobenthic infauna, benthic and epibenthic fish including gulper sharks, deep-diving fish (e.g., tuna species), deep-diving sea turtles (e.g., leatherbacks)	• A zone of progressively lower secondary benthic biological productivity with increasing depth, and absence of primary producers and absence of marine benthic invertebrates with symbiotic zooxanthellae. • A zone of lower diversity and abundance and secondary benthic biological productivity, owing to naturally high sedimentation rates from terrigenous sediments, mass movements (slumping) of deposited sediments, and constant bed sediment reworking and smothering of benthic fauna. • General absence of subsistence and artisanal fishing for benthic, epibenthic and demersal fish within this depth range. • Insufficient standing stocks of fish for a potential commercial fishery.	Low
Depth range 1,000 to 2,000m (lower bathyal zone) and 2,000 to 6,000m (abyssal zone*) Key receptors: Very deep-water benthic macroinvertebrates and meiobenthic infauna, and benthic and demersal fish.	• A benthic zone of progressively lower secondary biological productivity with increasing depth and absence of primary producers. • Very low diversity of standing stocks of benthic macroinvertebrates and benthic or demersal fish. • Very low diversity of standing stocks of benthic macroinvertebrates with most biomass represented by meiobenthic infauna within soft seabed sediments (e.g., muds and clays). • A zone of lower secondary benthic biological productivity, owing to bed sediment transport along the Markham Canyon, including periodic mass movements (slumping) of deposited sediments on the canyon walls and within the canyon itself, causing frequent exposure and smothering of benthic fauna. • Absence of any subsistence, artisanal or commercial fisheries.	Low

* The whole of the abyssal zone depth range (2,000 to 6,000m) is unlikely to be affected as the zone of potential Project-related benthic impact is mostly within the deep canyon floor to a depth of around 3,000m, which is subject to downslope movement of natural sediment (and later tailings solids).

17.2.2.2. Consistency with Papua New Guinea Draft General Guidelines for DSTP

The PNG Government engaged the Scottish Association for Marine Science (SAMS) to conduct an independent assessment of DSTP systems in PNG in 2010 with consideration to international best practice and to prepare Draft General Guidelines for DSTP in PNG. The completion of data collection and modelling for DSTP related studies for the Wafi-Golpu Project was undertaken in accordance with the Draft General Guidelines for DSTP in PNG, to the maximum practicable extent. Attachment 1 presents the key environmental considerations for DSTP systems identified by SAMS (2010a) and assesses the extent to which these guidelines are fulfilled by the Project's proposed DSTP system either by design or by the results of the residual impact assessment described in this chapter.

17.3. Potential Impacts

A range of mechanisms associated with DSTP are likely to generate physico-chemical changes to the offshore marine environment, which in turn lead to potential consequential effects on marine ecology. These are summarised below.

- Physiography and oceanography:
  - Formation of dilute subsurface tailings plumes at various depths below the DSTP outfall and the subsequent ecological impact on the biota in the ocean water column.
  - Resuspension of tailings deposits by bottom currents (including episodic and strong turbidity currents) and redistribution of tailings solids.
- Water and sediment quality:
  - Following deposition on the seafloor, potential contaminants within the tailings solids may undergo physical, chemical and biological changes, which may result in the adsorption or desorption of contaminants from the particulate to the dissolved phase, thus increasing or decreasing contaminant concentrations in the interstitial waters of the deposited tailings. Mixtures of contaminants can result in biological effects that can cause a synergistic, additive or antagonistic effect. A synergistic effect is observed when the toxicity of the mixture is more than the sum of the toxic effects of each individual component (contaminant). Additive effects are observed when the mixture has the same toxicity as the sum of the toxicity of the individual components. An antagonistic effect is observed when the mixture toxicity is less than the sum of the toxicity of the individual components.
- Physical (smothering and burial) effects on the seabed and benthic communities:
  - Discharge of tailings solids resulting in the smothering and permanent burial of the existing deep-water benthic habitats and consequential effects on the biological communities in the main zone of tailings solids deposition.
  - A major effect will be from obliterative impacts of physical smothering and burial due to high tailings deposition rates; however, in semi-obliterative impact zones of light tailings deposition rates, the effects of contaminants may potentially be more significant than physical smothering.
  - The above tailings deposition rates will occur within a deep slope and seabed environment that has very high sedimentation rates of natural terrestrial-derived sediments.
- Potential for the bioconcentration and bioaccumulation of metals and metalloids in pelagic marine fauna from increased metals and metalloids in tailings subsurface plumes.

- Potential for biomagnification of metals and metalloids within the benthic food web, as well as the pelagic food web if bentho-pelagic coupling were to be a significant pathway.

This chapter assesses bioaccumulation and biomagnification effects on the biophysical environment only (i.e., effects on marine fauna). Risks to human health from metal burdens in fish are assessed in Chapter 19, Health Risk Assessment.

Residual impacts on the environmental values of deep-water habitats and biological communities (i.e., receptors) were assessed according to each source where possible or holistically where multiple factors are present.

Potential rupture or breakage of the submarine section of the DSTP outfall pipelines is not expected as a part of normal operations and is therefore assessed in Chapter 21, Unplanned Events (Natural Hazards and Accidental Events).

17.4. Management Measures

The WGJV proposes to implement the following management measures to reduce the potential impacts of DSTP:

- Selecting a DSTP outfall site on a sufficiently steep submarine slope, such that the tailings solids will flow as a bottom-attached density current to the deep sea and will not accumulate or plug the DSTP outfall pipelines.
- Selecting the DSTP outfall at a depth that is below the:
  - Base of the biologically productive surface mixed layer[3] that includes the euphotic zone[4] where light penetration from the surface allows photosynthesis in phytoplankton to take place.
  - Deepest measured base of the surface mixed layer.
  - Depth of any upwelling (if present).
- Providing adequate de-aeration of the tailings slurry prior to discharge to avoid air being entrained into the DSTP outfall pipelines.
- Ensuring that the tailings slurry has a higher density than the receiving ocean water so that a density current will form and flow by gravity down the submarine slope.
- Locating the DSTP outfall pipelines so that the tailings solids will co-deposit with natural riverine sediments in the receiving canyon system that has existing low biodiversity due to high rates of natural background sediment deposition and transport.
- Taking advantage of the natural submarine slope failures and resultant turbidity current events that will re-suspend both tailings and natural seafloor sediments and transport them further down the Markham Canyon before redepositing them in deeper water as mixed deposits.

The principal proposed management measures relate to the design and operation of the proposed DSTP system in accordance with the Draft General Guidelines for DSTP in PNG (SAMS, 2010a). Account will also be taken of best practice in DSTP operation based on experience gained from other past (e.g., Misima Gold Mine) and operating (e.g., Lihir Gold Mine) DSTP systems in PNG and overseas. Another key management measure will be compliance with water quality criteria applied at the regulatory mixing zone boundary.

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[3] The uppermost part of the ocean water column that is kept well mixed by the turbulent action of wind and waves.

[4] The layer close to the surface that receives enough light for photosynthesis to occur.

No additional management measures relating specifically to offshore marine ecology are proposed.

17.5. Offshore Marine Environment Impacts

17.5.1. Residual Impacts of DSTP to Pelagic Marine Ecology

The principal stressors on deep-water pelagic ecology during DSTP operation relate mainly to changes in water quality and include:

- Increased tailings suspended solids concentrations and associated turbidity in subsurface and bottom-attached tailings plumes and potential physical effects on pelagic organisms
- Increased concentrations of trace metals in tailings liquor within the descending density current and within tailings subsurface plumes and potential toxicity to pelagic fauna
- Potential for trace metal bioaccumulation within marine pelagic organisms
- Potential for biomagnification in the pelagic food web

The residual impacts of these stressors on deep-water pelagic ecology are assessed below.

17.5.1.1. Suspended Tailings Solids and Turbidity Physical Impacts

This section assesses the physical impacts of DSTP-related increases in TSS concentrations and turbidity in the water column and the consequential impacts to deep-water pelagic fauna. There are two main types of subsurface plumes that will be generated by the proposed DSTP operation. These are:

- The descending tailings density current itself that will flow down the steep submarine slope below the outfall. The tailings slurry is driven downslope by its higher density compared to the receiving seawater at 200m depth and is called 'negatively buoyant'.
- Subsurface tailings plumes comprised of highly dilute fine tailings solids (generally with a particle size diameter less than 20µm) and tailings liquor (i.e., process water containing residual trace metals, reagents and chemicals) that shear off from the tailings density current into the water column. Because these plumes are so dilute they will be neutrally buoyant and initially will neither rise nor fall, but spread out horizontally as they are transported laterally by ocean currents at the depth at which they form. Observations of subsurface tailings plumes from the Misima Gold Mine's DSTP discharge showed plumes moving in opposing directions at different depths (NSR, 1993). A similar situation is predicted for the Huon Gulf where complex shearing patterns have been observed during current meter measurements of the full water column. All subsurface plumes are predicted to be trapped below the base of the surface mixed layer of the ocean while they disperse and the solids settle.

Prior to assessing the residual impacts of these subsurface tailings plumes and bottom-attached density current plumes on deep-water pelagic ecology, natural background suspended sediment plumes and associated turbidity are summarised first so that the DSTP-derived tailings plumes may be compared.

17.5.1.1.1. Background Natural Suspended Sediment and Turbidity

As mentioned in Section 17.2.1.3, the Huon Gulf receives very high rates of terrestrial sediment input from rivers draining the mountainous hinterland areas that are prone to erosion. An estimated 60Mtpa of suspended sediment enters the gulf from these rivers. During flood events, large surface plumes of turbid water form at river mouths and are transported laterally by ocean currents. Below the surface, persistent plumes of turbid water occur near the seafloor. Figure 17.1 shows turbidity (purple line) by depth in the water column overlying the Markham Canyon at Conductivity-Temperature-Depth (CTD) site A3, which is approximately 3km south of the Outfall Area (Appendix K, Oceanographic Investigations of the Huon Gulf).

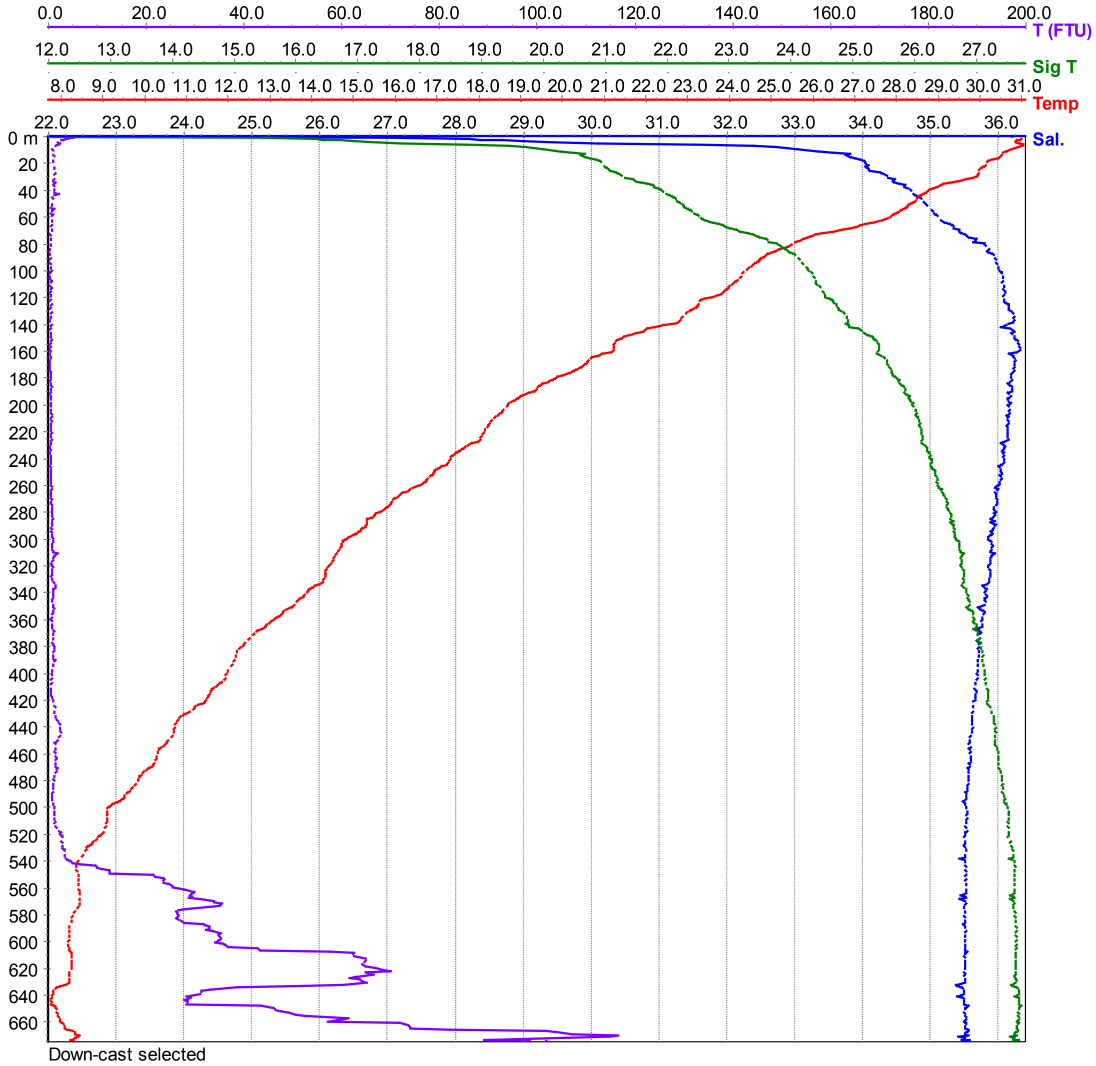
In addition to the turbid surface plumes near river mouths and the persistent plumes of turbid water that occur near the seafloor, there will be frequent occasions of flood flows in both the Markham and Busu rivers that will generate coalescing large, spreading surface turbidity plumes over the inner Huon Gulf. Under these conditions, the delayed settlement of dispersing surface turbidity plumes (cascade suspension) is expected to increase background TSS concentrations and turbidity in the water column overlying the deep slope, including the DSTP outfall. However, oceanographic investigations to date near the floor of the Markham Canyon show that submarine slope failures or mass movements of deposited sediments (e.g., slumps) occur and result in the generation of turbidity current events that flow at considerable speed down canyon causing very high but short-term increases in TSS concentrations and associated turbidity within lower parts of the canyon. The driving force behind a turbidity current is gravity acting on the high density of the sediments temporarily suspended within a fluid. These semi-suspended solids make the average density of the sediment-bearing water greater than that of the surrounding, undisturbed water, and because they flow at great speed they can erode and resuspend even more sediment particles during passage down the canyon.

Once an oceanic turbidity current reaches the calmer waters of the flatter seabed area, the suspended particles settle out of the water column. The velocities of these turbidity currents have been estimated by IHAconsult (Appendix K, Oceanographic Investigations of the Huon Gulf) to range from 1.8 to 8.4m/s based on the travel times between different Acoustic Doppler Current Profiling (ADCP) mooring locations. Between October 2016 and August 2017, over 50 turbidity current events had been recorded by the various oceanographic moorings located on the floor of the Markham Canyon, which shows that these turbidity current events are episodic but frequent. Such current speeds are sufficient to re-suspend any deposited (and consolidated) tailings material. IHAconsult (Appendix K, Oceanographic Investigations of the Huon Gulf) report that currents of 0.83m/s will be sufficient to resuspend tailings material that has consolidated for six months. The frequently high current speeds in the Markham Canyon means that deposited tailings will have little time to consolidate and will be readily resuspended and transported further down the canyon.

In addition to major mass movement events within the Markham Canyon, there are localised smaller mass movements on the submarine deep slope, which also generate bottom-attached turbidity plumes with increased TSS concentrations (Appendix K, Oceanographic Investigations of the Huon Gulf).

It is against this background of naturally high terrigenous suspended sediments and mass movements of deposited sediments that the residual physical impacts of tailings subsurface and bottom-attached turbidity plumes are compared and contrasted, including assessment of admixtures of both sources in the pelagic environment.

18 December 2016



Note:

T = turbidity in formazin turbidity units (FTU)

Sig T = density in Sigma-t (σt)

Temp = temperature in degrees Celsius

Sal = salinity in practical salinity units

Source:
IHAconsult (2018a, Appendix K)

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Date:
23.04.2018

Project:
754-ENAUABTF100520DD

File Name:
0520DD_10_F17.01_GRA

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CTD profile of turbidity at Site A3 in the Markham Canyon

Figure No:
17.1

INDD Reference: 0520DD_10_GRA088.indd_5

17.5.1.1.2. Tailings Particle Size Distribution

Particle size analysis of two tailings samples produced from a pilot flotation testwork program in October 2017 was undertaken by the CSIRO (Appendix L, Tailings Ecotoxicology and Geochemistry). The two samples comprised approximate porphyry and metasediment compositions of 90:10 and 25:75, representing the general range of tailings characteristics that will be produced during the Life of Mine. For the purposes of the present marine ecology impact assessment, the first tailings sample (i.e., Tailings 1, porphyry to metasediment ratio of 90:10) has been selected to be on the side of conservatism, owing to its higher content of fine-grained solids (63% of solids are less than 20µm particle size diameter). The second tailings sample (i.e., Tailings 2, porphyry to metasediment ratio of 25:75) has a lower content of fine-grained solids (42.3% of solids less than 20µm particle size diameter).

Table 17.5 provides the solids particle size distribution of the Tailings 1 sample.

Table 17.5: Particle size distribution of solids in the Tailings 1 sample

Category	Particle size diameter	Proportion of tailings
Clay	1µm to <4µm	25.5%
Very fine to coarse silts	4µm to <62µm	61.5%
Very fine sand	62µm to <125µm	7.5%
Fine sand	125µm to <250µm	4.5%
Medium to coarse sands	250µm to <1,000µm	1.0%
Total		100.0%

Source: IHAconsult (pers. com., 2017). Based on the finer Tailings 1 sample particle size distribution rating curve.

The Tailings 1 sample comprises very fine sediments with 87% being classified as clay and silts. Approximately 63% of the tailings solids are finer than 20µm, which is the size fraction that has been modelled by Tetra Tech (Appendix J, Density Current, Plume Dispersion and Hydrodynamic Modelling) as forming subsurface turbidity plumes that will travel in the direction of ambient currents.

17.5.1.1.3. Tailings Subsurface Plume Physical Impacts

Prior to entering the DSTP outfall pipelines, the tailings slurry will be diluted with seawater, drawn from 60m depth, in a mix/de-aeration tank located some 140m inland from the shoreline. Each part of tailings slurry will be diluted with four parts of seawater in a dilution ratio of 1:4 (v/v). The density of the tailings and seawater mixture will be 1,122 kg/m^3 compared with the receiving seawater at the outfall depth of 200m that averages about 1,026 kg/m^3 (Appendix K, Oceanographic Investigations of the Huon Gulf; Appendix Z, Tailings Management Engineering Design).

The higher relative density of the tailings and seawater mixture means that it will be negatively buoyant when it exits the DSTP outfall and will run down the sloping seafloor under the influence of gravity. Immediately after discharge, the tailings exiting the pipeline outfall will form a turbulent jet and as the jet slows down it will gradually change into a coherent density current, and entrain more seawater as it moves further downslope (NSR, 1997). Figure 17.2 shows a tailings density current descending a steep submarine slope at the Misima Gold mine in PNG that operated with DSTP from 1989 to 2004. Note the abrupt transition between the clear seawater showing outcropping rocks on the seabed slope (left) and the turbidity within the tailings density current (right).

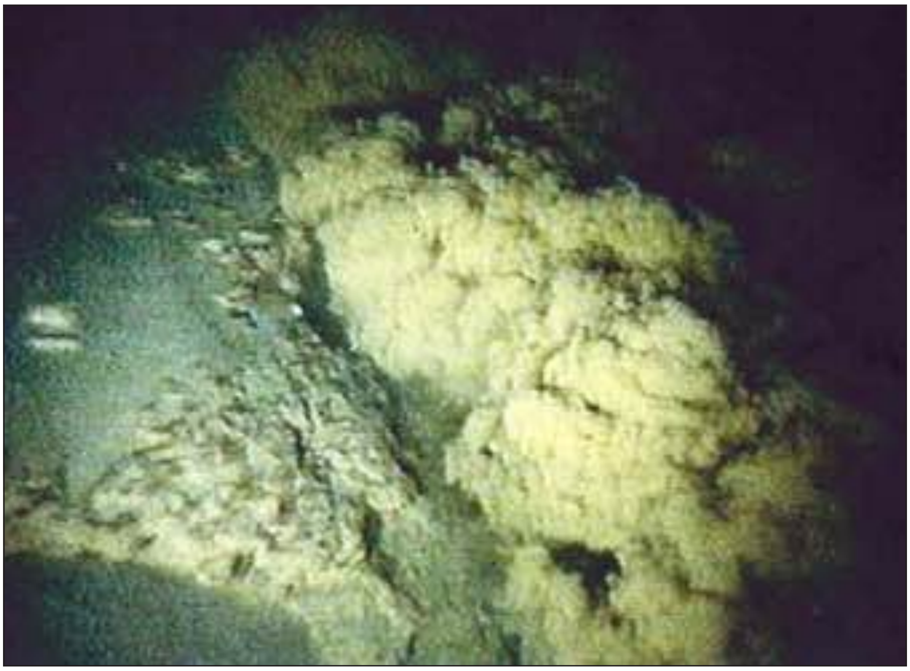


Figure 17.2
Coherent tailings density current 10m below the Misima Gold Mine DSTP outfall in 1993

Modelling results show that the tailings density current will continue all the way down the canyon wall slope to the floor of the Markham Canyon at 650 to 700m depth and then turn eastwards and continue flowing downslope along the floor of the canyon.

Observations of other DSTP operations in PNG (Misima, Lihir and Simberi) and also at the Batu Hijau mine in Indonesia have all shown that tailings subsurface plumes shear off the descending density current and form horizontal (neutrally buoyant) plumes in the ocean water column, especially at density discontinuities. Similar dilute tailings subsurface plumes are also predicted to shear off the descending density current below the WGJV DSTP outfall.

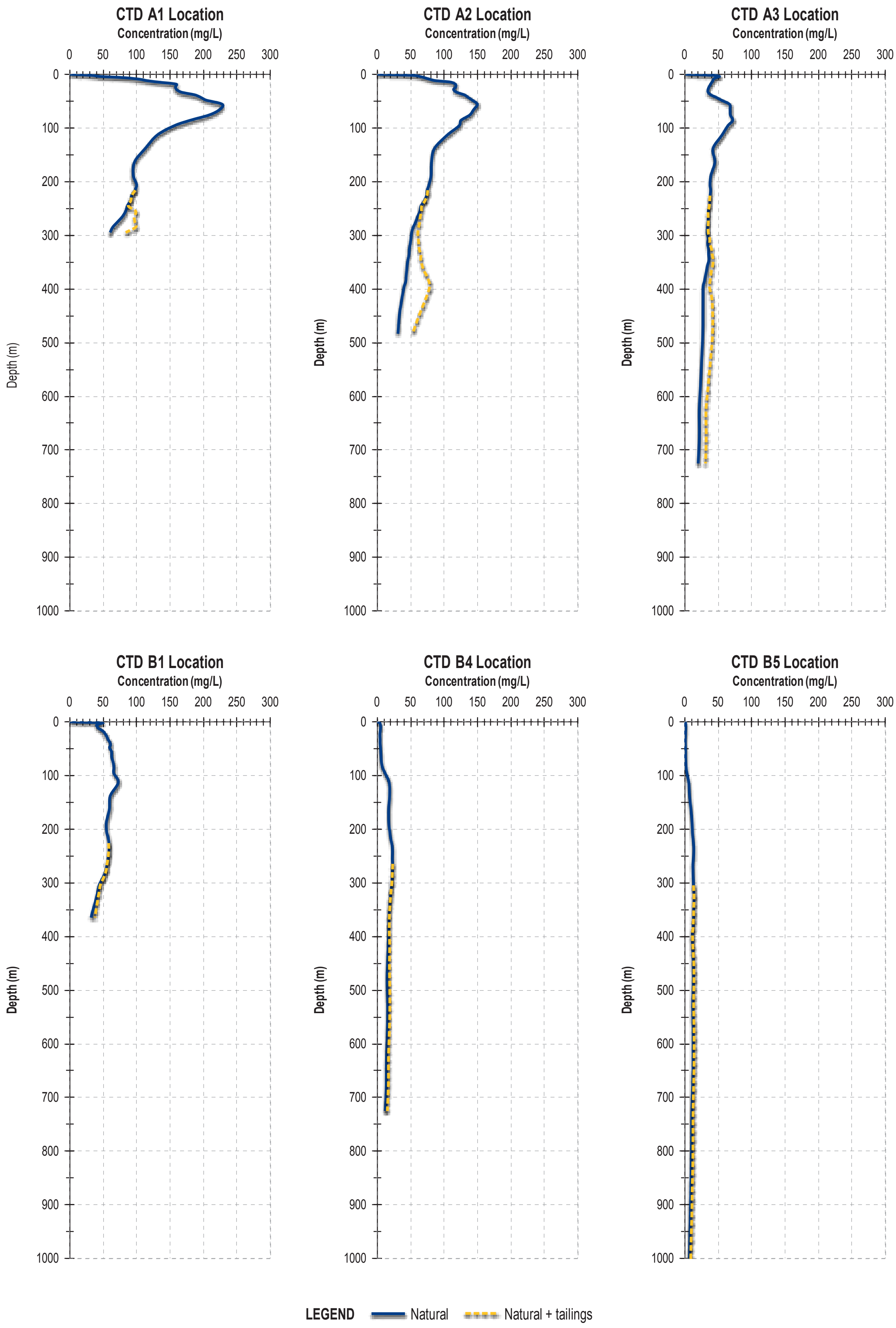
Figure 17.3 and Figure 17.4 show predictions of mean TSS concentration through the water column (but excluding the bottom layer) as profiles with increasing depth at the locations of six CTD profiling sites (Figure 17.3) and three ADCP Moorings (Figure 17.4). Figure 17.3 and Figure 17.4 plot profiles of simulated TSS concentrations from natural sedimentation (shown in blue) and show the incremental change in TSS concentrations when natural sedimentation is combined with the contribution from tailings subsurface plumes (shown in yellow). Along the deep-slope adjacent to the Outfall Area (CTD monitoring sites A1 and A2; where the bulk of the subsurface tailings plumes are predicted to form between 250 to 500m depth), suspended tailings solids in subsurface plumes are predicted to increase TSS concentrations by up to a maximum of about 40mg/L above the background TSS concentrations of 60mg/L and 40mg/L, at sites A1 and A2, respectively.

The TSS concentrations, whether from natural sedimentation or tailings subsurface plumes, have the potential to affect marine biota at the same depth within the ocean water column, depending on the duration of exposure to increased TSS concentrations or turbidity. Tailings subsurface plumes will be diluted progressively by ocean current transport (advection) and by mixing via turbulence (diffusion), ultimately being spread more widely beyond the main tailings density current. In addition, flocculation of the fine-grained (less than 20µm) tailings solids will be assisted by the natural coagulating action of seawater, which will reduce TSS concentrations and associated turbidity within the forming tailings subsurface plumes. Furthermore, as the fine-grained tailings solids are transported in the direction of prevailing currents, TSS concentrations will reduce further via the effect of dilution. The tailings solids suspended in these subsurface plumes will eventually settle on the ocean floor (see Section 17.5.2.1.2).

Figure 17.5 shows the modelled distribution of tailings subsurface plumes by depth (Appendix J, Density Current, Plume Dispersion and Hydrodynamic Modelling). Observation of tailings subsurface plumes at operating mines with DSTP elsewhere in PNG has shown these tailings subsurface plumes to be always present in the water column below the outfall terminus when outfall is operating. The modelling predicts that 39% of tailings will shear off as dilute subsurface plumes. Of that, about 43% of the subsurface plumes are predicted to occur between 300 and 400m, while 32% are predicted to occur between 400 and 500m depth. Additional subsurface plumes are predicted to occur between 600 and 900m, a depth which lies within the Markham Canyon.

17.5.1.1.4. Physical Impacts of Tailings Subsurface Plumes to Zooplankton and Micronekton

The subsurface tailings plumes represent a source of suspended solids to which both midwater zooplankton and micronekton may be exposed. Data collected as part of the zooplankton and micronekton characterisation study in the Huon Gulf (Appendix Q, Zooplankton and Micronekton Characterisation) found that there was diel vertical migration of zooplankton and micronekton from the 250 to 500m depth range (i.e., within the mesopelagic waters) to the 0 to 250m depth range (i.e., within the epipelagic zone).



Source: Modelling_Results_Final_Mar02.ppt, Slide 36 & 37

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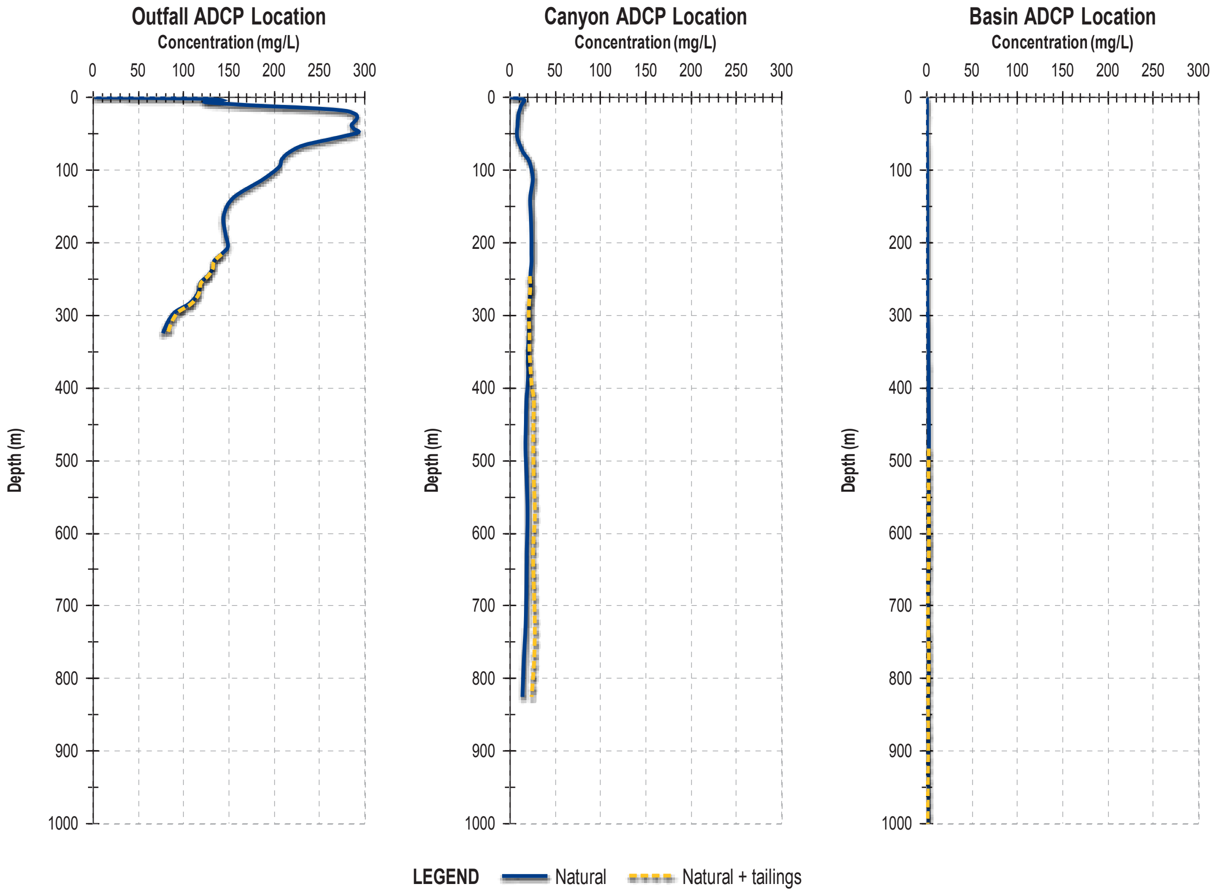
INDD Reference: 0520DD_10_GRA089.indd_4



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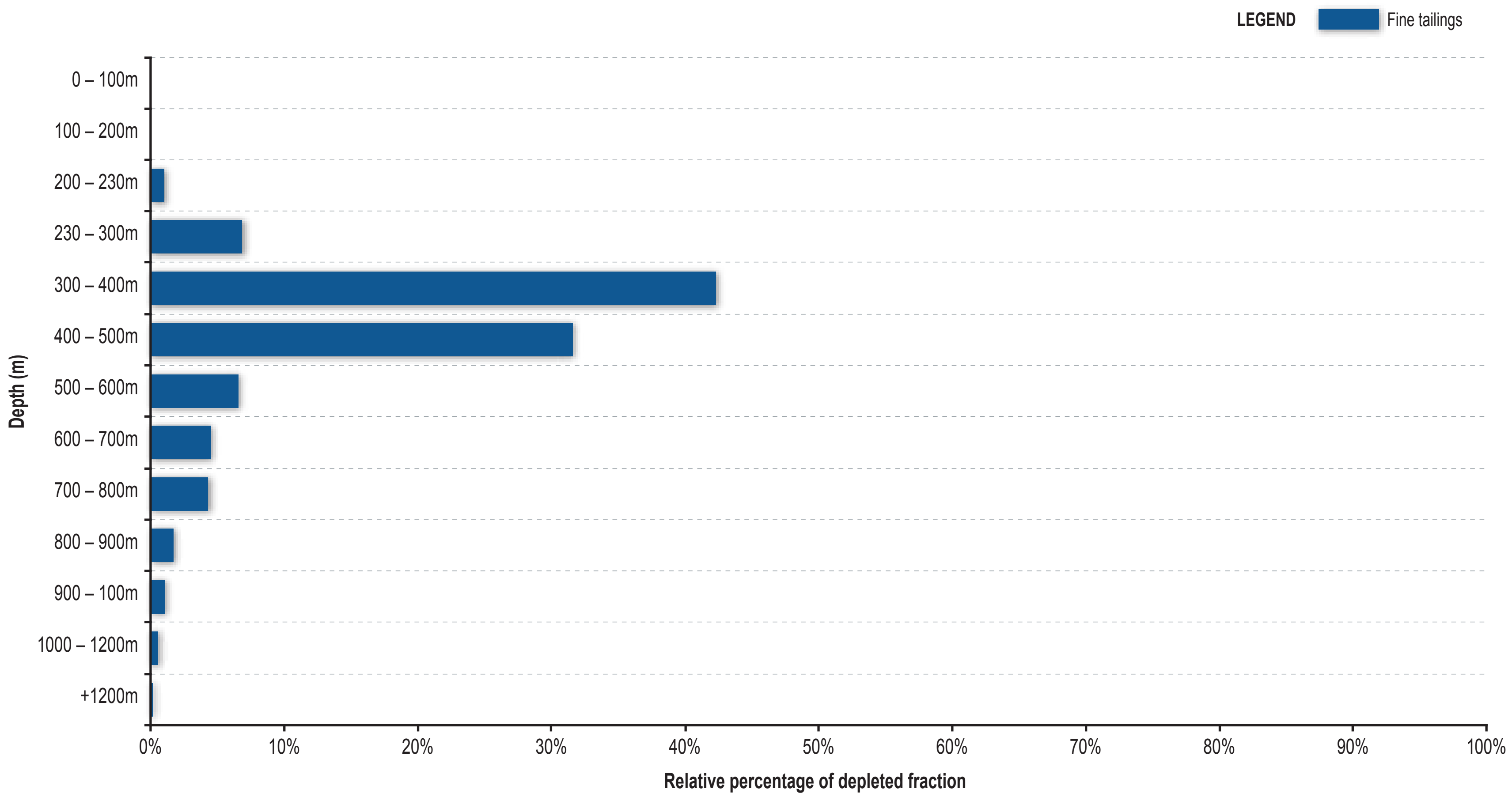
Project: 754-ENAUABTF100520DD
File Name: 0520DD_10_F17.04_GRA

Wafi-Golpu Project

Average incremental increase in TSS from tailings subsurface plumes at ADCP mooring sites

Figure No: 17.4



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WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Predicted distribution of tailings subsurface plumes in the water column

Figure No: **17.5**

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This diel vertical migration occurs at night, as evidenced in the higher abundances of zooplankton in night-time samples collected within the epipelagic zone (Appendix Q, Zooplankton and Micronekton Characterisation). This finding is confirmed by zooplankton data collected at other sites in PNG (e.g., Misima and Lihir DSTP locations), which indicate that zooplankton and micronekton undertake diel vertical migration, with the bulk of the zooplankton species concentrated between 100 and 600m water depth during the daytime and in the uppermost 100m during the night (Brewer et al., 2007; 2012; Morello et al., 2016). This mesopelagic-epipelagic coupling represents a potential pathway for tailings subsurface plume trace metals to enter the more biological productive euphotic zone (0 to 60m water depth).

The diel vertical migration will bring zooplankton and micronekton species into contact with dilute tailings subsurface plumes, where the biota will be exposed for short periods to elevated TSS concentrations and associated turbidity. Turbidity is not generally an issue within the mesopelagic zone, as it is below the euphotic zone (ranging from 5 to 60m in the Huon Gulf) where primary producers (e.g., phytoplankton) have sufficient light for the photosynthetic reduction of inorganic carbon into simple sugars. However, within the poorly lit waters or in the absence of light in deeper water, the continuously generated tailings subsurface turbidity plumes may have a transient effect on those zooplankton and micronekton species that use or rely on bioluminescence.

Some zooplankton species that ingest fine-grained tailings particles may increase their specific gravity, therefore having to expend additional energy to maintain buoyancy (Shimmield et al., 2010). However, the nearshore and offshore zooplankton assemblages occurring in the Outfall Area and environs are frequently exposed to transient natural terrigenous sediment-derived sources of fine sediment (<63μm particle size diameter, such as silts and clays) settling through the water column from natural surface turbidity plumes. The physical effects will be localised to wherever there is a measureable incremental increase in TSS concentrations due to the dilute subsurface plumes, which should be considered in the context of the naturally high background concentrations of suspended fine-grained sediments within terrigenous-derived surface and subsurface plumes.

The existing context in terms of background TSS is as follows:

- Predictions of mean TSS concentration through the water column (but excluding the bottom layer) in the Outfall Area are described above (see Figure 17.3 and Figure 17.4).
- Within the Markham Canyon, observations have shown bottom-attached plumes extending 200 to 500m above the bed are constantly present (Appendix M, Physical, Chemical and Biological Sedimentology of the Huon Gulf).
- IHAconsult (Appendix M, Physical, Chemical and Biological Sedimentology of the Huon Gulf) does not provide an average sedimentation rate at the Outfall Area. However, measured sedimentation rates presented by IHAconsult (Appendix M, Physical, Chemical and Biological Sedimentology of the Huon Gulf) have been used to calculate an average annual natural deposition rate to allow indicative comparison with natural deposition rates reported at other DSTP sites in deep ocean waters around PNG.

Figure 17.6 shows a plan view and a cross-section of modelled tailings subsurface plumes and tailings-derived TSS concentrations (as a snapshot in time). Note that these tailings subsurface plumes occur at depths greater than about 230m. Highest predicted TSS concentrations of more than 100mg/L occur in tailings subsurface plumes at 400m depth but the predicted initial TSS concentrations at the point of plume formation at most other depths are between 10 and 50mg/L, which is very dilute. As these subsurface tailings plumes are transported along the slope by ocean currents, diffusion and dispersion processes further reduce the predicted TSS concentrations to 1 to 2mg/L within a distance of 5 to 10km from the point of plume formation.

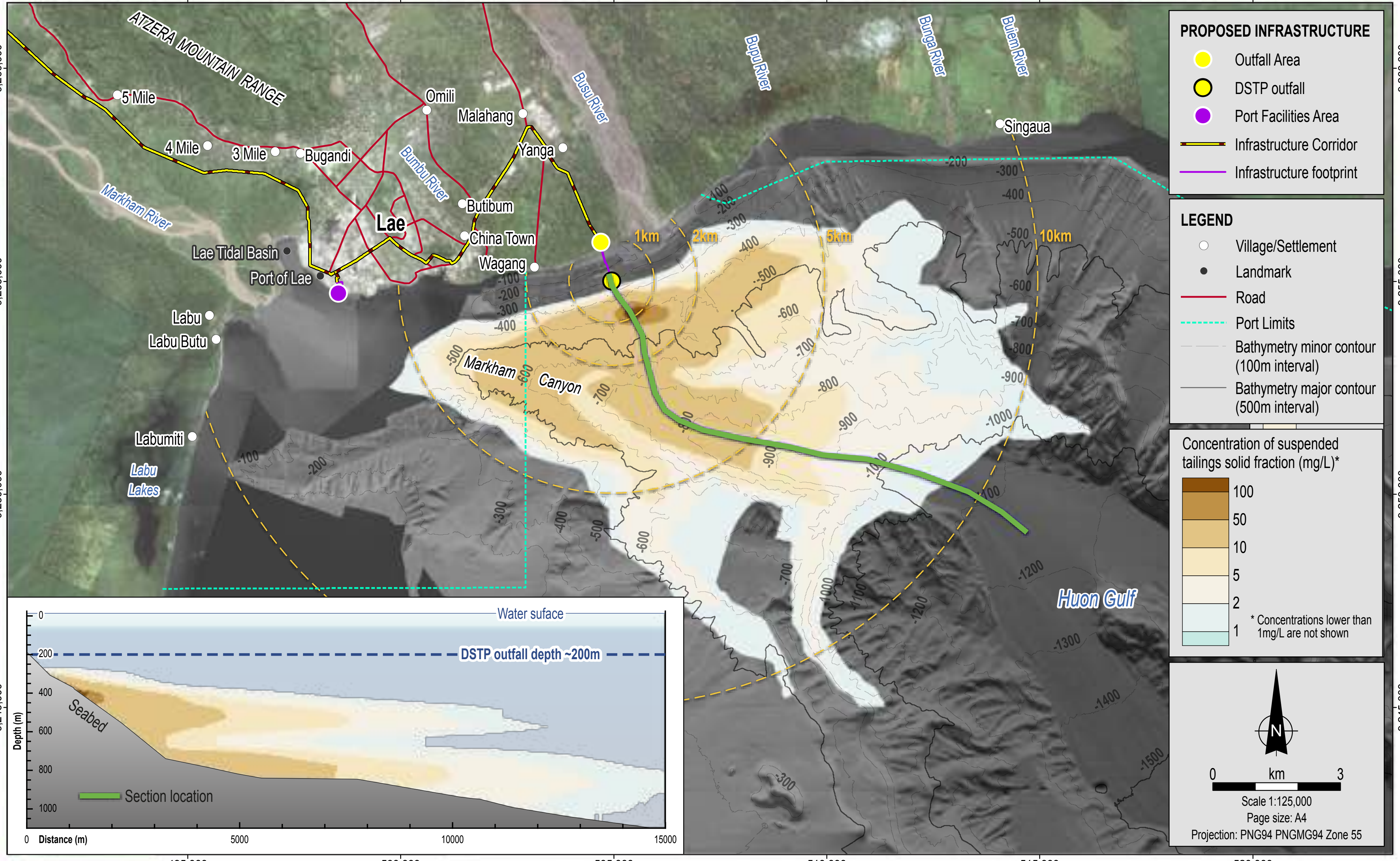
The predicted low average TSS concentrations in the dispersible turbidity plumes diminish rapidly by dilution, such that the TSS concentrations progressively reduce to 50mg/L at 700m from where the subsurface plume shears off from the density current, and reduce to 10mg/L at about 3,650m from where the subsurface plume shears off from the density current. The average natural background TSS concentration at the mid-water tailing plume location is 30mg/L as measured at site CTDA3 (see Figure 17.3), which was located at a depth of 440m. The predicted low average TSS concentrations in the dispersing turbidity plumes is similar to natural background TSS concentrations and is of insufficient magnitude or exposure duration to cause the mortality of or sub-lethal physical effects on zooplankton. Similarly, micronekton organisms are also unlikely to be adversely affected by low, intermittent exposure to elevated TSS concentrations within the turbidity plumes as they dilute and disperse down current.

Overall, the residual physical impact of tailings subsurface plumes on zooplankton and micronekton is assessed to be of **low** significance, based on a **low** magnitude of impact (transient or short-term exposure to low average TSS concentrations) and a **low** sensitivity (common and widespread zooplankton and micronekton assemblages and species, as discussed in Brewer et al., 2008 and 2012). Potential impacts from bioaccumulation or biomagnification of metals in the food chain were also assessed to be low. Additional information on these studies is contained in Chapter 19, Health Risk Assessment and Appendix N, Assessment of Metal Bioaccumulation and Biomagnification from DSTP in the Huon Gulf.

17.5.1.1.5. Physical Impacts of Tailings Subsurface Plumes to Fish

Deep-water pelagic fish may be exposed intermittently to the dilute subsurface tailings plumes and associated increased TSS concentrations. The effects of TSS on fish depend on duration of exposure and the TSS concentration and include the potential for clogging of gill tissues and the interference of prey capture by those fish relying on visibility. The behavioural response of deep-water fish to tailings subsurface plumes may be negative (avoidance) or positive (attraction), and is typically variable (Utne-Palm, 2002). In general, fish are strongly mobile and capable of readily moving away from, out of, or towards the tailings subsurface plumes.

In general, deep-water fish are either solitary or occur in small groups and exhibit different depth preferences. A deep-slope fish characterisation study of the inner Huon Gulf comprised two fishing surveys in waters greater than 100m deep in the vicinity of the Outfall Area and adjacent deep-slope areas during November 2016 and May 2017 (Appendix P, Deep-slope and Pelagic Fish Characterisation). Three species of gulper sharks (Centrophoridae), one squalid shark, a fatspine spurdog (*Squalus crassispinus*) and a bony fish, the black-spotted croaker (*Protonibea diacanthus*) were caught in the DSTP study area (see Chapter 11, Offshore Marine Environment Characterisation). These fish were caught at different water depths: dwarf gulper sharks (100 to 550m), longfin gulper sharks (330 to 360m), a gulper shark (550m), fatspine spurdog (100 to 300m) and a black-spotted croaker (250m).



Source:
DSTP-ModellingReport_Final_R1, Figure 3.13

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WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Modelled tailings subsurface plumes (suspended solids fraction)

Figure No: 17.6

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The main fish species present within and near the Outfall Area is the dwarf gulper shark of which a total of 44 individuals were caught during the combined fish sampling surveys. Of this total, about 32% of the dwarf gulper sharks were caught in surface waters (less than 200m deep) while the other 68% were caught in deep-slope waters (more than 200m deep). Therefore, dwarf gulper sharks are likely to travel between deep-slope waters into the surface mixed layer, and vice versa; and thus, can be exposed to tailings subsurface plumes.

All of these deep-slope cartilaginous and bony fish are turbid water fish and are known to be sediment-tolerant species. In general, the abundance of fish and their foraging rates decline in turbid environments (Eiane et al., 1999; Aksnes et al, 2004), which partially explains the low diversity and biomass of deep slope pelagic fish caught within the Outfall Area and inner Huon Gulf.

The most sediment-tolerant pelagic fish are those epibenthic and demersal species that inhabit the water column-seafloor interface, where they are exposed to higher TSS concentrations when foraging and disturbing bottom sediments (resuspension). Generally, benthic species are more tolerant to suspended sediment than pelagic species (Kjelland et al., 2015). However, deep-slope fish in the Outfall Area are also exposed regularly to natural bottom-attached turbidity plumes from the riverine inflows, as well as occasionally being exposed to very high TSS concentrations associated with mass movements (e.g., slumping) of naturally accumulated soft seabed sediments from riverine bed and suspended sediment loading. These episodic mass movements generate turbidity currents which, in turn, create both subsurface and bottom-attached turbidity plumes on the deep slopes and within the Markham Canyon. Therefore, short-term or transient exposures of fish to the low average TSS concentrations of 20mg/L (range of 10 to 100mg/L) associated with tailings subsurface turbidity plumes, which decrease in TSS concentrations by dilution when transported laterally in ambient currents, are expected to be readily tolerated. In addition, the high mobility of fish allows them to avoid tailings subsurface plumes.

There are a number of epipelagic species within the inner Huon Gulf that are capable of swimming downwards to depths between 200m and 400m (i.e., within upper mesopelagic zone), including most species of tuna. There are no tuna spawning areas in the Huon Gulf and the closest is a skipjack tuna (*Katsuwonus pelamis*) spawning area in the eastern Solomon Sea where spawning is mainly between October and December each year. There are deep-diving tuna species (IUCN, 2018) such as the albacore tuna, *Thunnus alalunga* (0 to 600m depth range) and the southern bluefin tuna, *Thunnus maccoyii* (50 to 2,743m depth range), neither of which spawn in the Huon Gulf or Solomon Sea. Albacore tuna are found mainly in cooler western Pacific Ocean waters to the south of the PNG mainland and are unlikely to be present in the Huon Gulf. The only known spawning area of southern bluefin tuna is located in a region of the Indian Ocean within the exclusive economic zones of Indonesia, Timor Leste and northwestern Australia (WWF, 2017). Therefore, this species is most unlikely to spawn in the Solomon Sea including the Huon Gulf and also unlikely to be present in either. The other western Pacific Ocean tuna species such as yellowfin tuna (*Thunnus albacares*), skipjack tuna (*K. pelamis*) and bigeye tuna (*Thunnus obesus*) are predominantly (given that yellowfin and bigeye tuna are known to dive down to deeper waters on occasion) epipelagic schooling species typically inhabiting water depths between 0 to 250m, hence their vulnerability to purse seining. These depths are also above the minimum depth at which tailings subsurface plumes are predicted to shear off from the descending tailings density current.

No impacts are expected to the critically endangered largetooth sawfish (*Pristis pristis*) that would have to pass through the inner Huon Gulf to reach the turbid Markham and Watut river main channels, where TSS concentrations regularly exceed 1,000mg/L. This sawfish species was collected in the lower Watut River below the Wafi River junction (Powell and Powell, 2000) and is also known to inhabit the turbid waters of the Fly River (average TSS concentration of 120mg/L) and Strickland River (average TSS concentrations of 400mg/L) in southern PNG (Roberts, 1978). Therefore, transient exposure to suspended sediments within the tailings subsurface and bottom-attached plumes (if encountered) is expected to have a negligible impact on this species.

Overall, residual impacts of tailings subsurface plumes and bottom-attached plumes from the tailings density current on fish are assessed to be of **low** significance, based on a **low** magnitude of impact (transient or short-term exposure to low relatively TSS concentrations or avoidance of the plumes) and a **low** sensitivity (common and widespread sediment-tolerant species).

17.5.1.1.6. Physical Impacts of Tailings Subsurface Plumes to Sea Turtles

Marine turtles commonly found in the inner and broader Huon Gulf include the green turtle (*Chelonia mydas*), hawksbill turtle (*Eretmochelys imbricata*) and west Pacific leatherback turtle (*Dermochelys coriacea*), all of which are air-breathing animals that need to surface from time to time to breathe. The green and hawksbill turtles spend most of their time within coral reefs, rocky areas, lagoons, mangroves, oceanic islands, and shallow coastal areas and are generally found within the surface mixed layer, which is not predicted to be impacted by DSTP. The west Pacific leatherback turtle is regularly found in surface waters, as with other sea turtles, but it is the deepest diving turtle. For example, during their foraging migrations, leatherback turtles may dive to water depths greater than 1,000m in search of gelatinous zooplankton (Eckert et al., 1989; Hays et al., 2004). As sea turtles are visual predators, the principal effect of tailings subsurface plumes is one of turbidity, which reduces the visibility of prey in those depths of the water column to which visible light penetrates. Direct physical effects of elevated TSS concentrations from either natural terrigenous or tailings subsurface plumes will be negligible, given the relatively low TSS concentrations of subsurface plumes and the fact that sea turtles are air-breathing reptiles that are unlikely to be affected by suspended sediment.

The sandy beaches of the Huon Gulf south coast (more than 15km south of Lae) are a major nesting area for the west Pacific leatherback turtle, which is classified as Critically Endangered on the IUCN Red List of Threatened Species (IUCN, 2018). In addition, according to local people, about three leatherback turtle nests have been observed annually on the shoreline between Wagang Village and the Busu River mouth (Appendix S, Fisheries and Marine Resource Use Characterisation). This species is known to forage within the Huon Gulf during the inter-nesting season though specific foraging areas within the Huon Gulf have not been identified. However, it is unlikely that the turbid shallow and deeper waters of the inner Huon Gulf would be a key foraging area, given that leatherback turtles feed mainly on jellyfish and other soft-bodied marine animals such as squid in the less turbid and clearer open waters of the Huon Gulf. Notwithstanding, if a group of jellyfish were passively brought into the DSTP Outfall Area, any foraging, diving leatherback turtles are most unlikely to be impacted by the predicted low TSS concentrations and turbidity of tailings subsurface plumes.

Overall, the residual impacts of DSTP-derived subsurface turbidity plumes on sea turtles are assessed to be of **moderate** significance based on a **very low** magnitude of impact (extremely transient exposure) and a **very high** sensitivity (uncommon species and restricted distribution of the west Pacific leatherback turtle subpopulation).

17.5.1.2. Ecotoxicological Impacts of Tailings Liquor to Pelagic Organisms

The predicted behaviour and fate of the liquid fraction of tailings and the results of toxicity testing of tailings liquor are summarised below to provide context for the assessment of the residual toxicity impacts of tailings liquor-derived dissolved trace metal concentrations and other contaminants to pelagic marine organisms.

17.5.1.2.1. Predicted Fate of Tailings Liquor in Subsurface Plumes

Section 17.5.1.1.3 describes the behaviour of the tailings after discharge and the formation of a tailings density current from which tailings plumes will shear off and form neutrally buoyant subsurface plumes in the ocean water column. Numerical modelling (Appendix J, Density Current, Plume Dispersion and Hydrodynamic Modelling) has simulated the expected behaviour of these dilute subsurface tailings plumes.

Figure 17.7 shows a plan view of the modelled liquid fraction of the tailings subsurface plumes. Figure 17.7 shows, in plan view, the extent of the tailings subsurface plumes that will occur 95% of the time (i.e., 95th percentile). Note how the simulated tailings subsurface plumes spread both to the east and west and also down the Markham Canyon in the downslope direction. Figure 17.7 also shows a cross section of the tailings subsurface plumes (as a snapshot in time) through the ocean water column down the canyon slope. The simulation shows that the most concentrated subsurface tailings plumes occur at a depth of about 400m, which is 200m deeper than the depth of the DSTP outfall. However, the simulation shows that even the most concentrated subsurface tailings plumes have already been diluted some 800 and 3,000 times by a combination of pre-discharge dilution and rapid post-discharge entrainment of seawater by the time those tailings subsurface plumes have sheared off the descending tailings density current. Therefore, the tailings subsurface plumes will be highly dilute when they form.

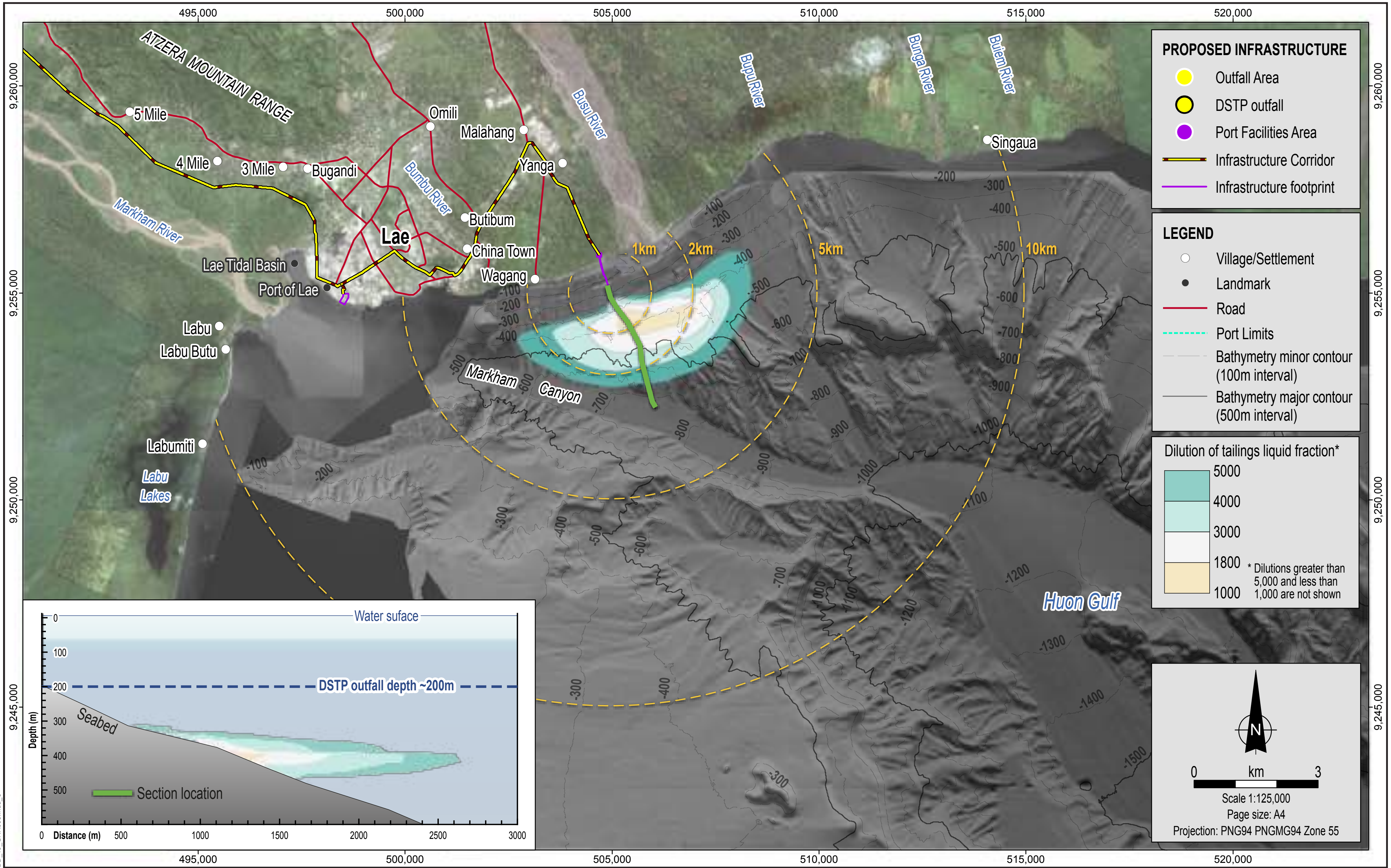
17.5.1.2.2. Tailings Liquor Quality

The tailings liquor is expected to contain low concentrations of residual processing reagents, metals and metalloids. The residual processing reagents, metals and metalloids are discussed in this section.

17.5.1.2.2.1. Residual Processing Reagents

Residual processing reagents include xanthates, thiocarbamates, cresylic acid and sodium metabisulphite. Sodium ethyl xanthate, an organosulphur compound used as a flotation agent, has the highest potential toxicity of the processing reagents to marine life. The estimated concentration of sodium ethyl xanthate in the raw tailings liquor is 20mg/L (Watt, pers. com., 2018). The main degradation pathway of sodium ethyl xanthate in seawater is via hydrolytic decomposition that is accelerated by the presence of dissolved metals (e.g., copper, iron, lead and zinc) (DCE, 2016). These metals are present in the tailings liquor. As a soluble salt, sodium ethyl xanthate will also complex with the metallic ions contained in water and marine organisms and typically has a chemical half-life of 4.1 days (Boening, 1988).

Toxicity of sodium ethyl xanthate reported by DCE (2016) includes an EC_{50} (concentration that has a toxic effect on 50% of the test population) range of 0.025 to 0.065mg/L to freshwater algae, and an LC_{50} (concentration that has a lethal effect on 50% of the test population) range of 11 to 65mg/L to freshwater fish. Xu et al. (1988) found that sodium ethyl xanthate immobilised the freshwater invertebrate (*Daphnia magna*) with an EC_{50} of 0.35mg/L. A literature search did not reveal any comparable toxicity data for marine organisms, but toxicity effects are anticipated to be of similar magnitude.



Source:
Tetra Tech 2018
Note:
The dilution contours shown in plan view are those predicted to occur 95% of the time (95th percentile). The dilution contours shown in cross section view are a snapshot in time.

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WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Predicted extent of subsurface plumes – dilution of the tailings liquid fraction

Figure No: 17.7

INDD Reference: 0520DD_10_GRA093.indd_5

There are no PNG ambient water quality criteria or ANZECC/ARMCANZ (2000) guidelines for xanthates; however, where the PNG ambient water quality standards are predicted to be met (after 1,800 dilutions and 2,174m from the DSTP outfall; see Section 17.5.1.2.2.2), the concentration of sodium ethyl xanthate would be 0.01mg/L, which is below the literature reported EC_{50} range of 0.025 to 0.065mg/L for freshwater algae and well below the LC_{50} range of 11 to 65mg/L for freshwater fish.

Given that sodium ethyl xanthate is biodegradable and has a short half-life, it is unlikely to bioaccumulate in marine organisms. In addition, NICNAS (1995) assessed that sodium ethyl xanthate is not expected to bioaccumulate in view of its ionic character.

The remainder of this section concentrates on residual metals and metalloids in tailings liquor, which are considered the primary potential toxicants.

17.5.1.2.2.2. Residual Metals and Metalloids

The results of a chemistry and ecotoxicological characterisation study by CSIRO of bench-scale tailings samples are presented in Appendix L, Tailings Ecotoxicology and Geochemistry. The study considered two tailings samples that represent the likely 'bookend' tailings samples expected over the Life of Mine from the Golpu block cave (refer Section 17.5.1.1.2) where 'Tailings 1' sample represented early stage ore feed comprising approximately 90% porphyry and 10% metasediments and the 'Tailings 2' sample represented a late-stage ore feed consisting of only 25% porphyry and 75% metasediments.

The treated filtrate is expected to contain residual low concentrations of metals, metalloids and processing reagents.

Concentrations of metals in the liquor fraction (prior to any dilution with seawater) of the Tailings 1 and Tailings 2 samples are presented in Table 17.6. The concentrations are compared to PNG ambient water quality criteria and Australian and New Zealand water quality guidelines for marine aquatic ecosystem protection (ANZECC/ARMCANZ, 2000).

In Table 17.6, exceedances of the PNG ambient water quality criteria are shown in red, while exceedances of the ANZECC/ARMCANZ (2000) guidelines are shown in bold. Exceedances of both the PNG criteria and the ANZECC/ARMCANZ (2000) guidelines are shown in bold red.

Comparison of dissolved (<0.45µm) metal concentrations in Tailings 1 and Tailings 2 liquors (i.e., prior to any dilution with seawater) to PNG water quality criteria indicate that cobalt, manganese and copper in the Tailings 1 sample exceeded PNG water quality criteria and that cobalt and manganese in the Tailings 2 sample exceeded PNG water quality criteria.

Notwithstanding the limit of detection criterion for cobalt[5], the concentrations of cobalt exceeded the PNG water quality criteria concentration by a factor of 34 and 44 in the Tailings 1 and 2 samples, respectively.

When compared to ANZECC/ARMCANZ guidelines, dissolved concentrations of cobalt, copper and zinc in both tailings samples exceeded applicable the Water Quality Guideline Value (WQGV) for the 95% species protection level.

Upon entering the marine environment, the tailings (having been pre-diluted with sea water in the mixing tank) will mix with seawater and metals in tailings will have the potential to disperse and desorb from the particulate material. To assess the mobilisation of metals

[5] For cobalt, the PNG water quality criterion is the analytical limit of detection. In the CSIRO study (Appendix L, Tailings Ecotoxicology and Geochemistry), the analytical limit of detection of cobalt ranged from 0.01 to 4.0µg/L and a value of 0.1µg/L was adopted as a representative limit of detection for cobalt and used as a proxy for the PNG water quality criterion.

from the particulates, a series of elutriate tests were undertaken in the laboratory as part of the CSIRO study (Appendix L, Tailings Ecotoxicology and Geochemistry).

Table 17.6: Tailings liquor composition – dissolved (<0.45µm) metal concentrations in tailings liquor

Parameter	Tailings 1	Tailings 2	ANZECC/ARMCANZ (2000) 95% Protection (WQGV[a])	PNG Water Quality Criteria
pH	7.4	7.2	NA	Natural pH
Conductivity (µS/cm)	2,210	2,770	NA	NR
Alkalinity (mg/L $CaCO_3$)	103	76	NA	NR
Hardness (mg/L, $CaCO_3$)[b]	876	1420	NA	NR
Metals and metalloids (µg/L)				
Al	NM	NM	24[a]	NR
Ag	0.07	0.14	1.4	NR
As	0.4	0.9	ID	50
Cd	0.1	0.2	5.5	1
Co	**3.4**	**4.4**	1	LoD (0.1)
Cr	1.7	1.0	4.4	10 (as hexavalent)
Cu	**691**	**19**	1.3	30
Fe	2.5	1.4	ID	1,000 (in solution)
Mn	2,020	3,160	ID	2,000 (in solution)
Ni	34	62	70	1,000
Pb	1.1	1.1	4.4	4
Se	1.5	8.3	ID	10
V	<1	1	100	NR
Zn	**145**	**287**	15	5,000
Major ions (mg/L)				
Ca	265	422	NA	NR
K	54	67	NA	450
Mg	52	88	NA	NR
Na	125	102	NA	NR
S	295	494	NA	NR
Sulphate (SO_4)[c]	801	1,341	NA	NR

[a] Water Quality Guideline Value (WQGV) for 95% species protection level, shaded values indicate applicability for slightly-to-moderately disturbed ecosystems, red values indicate concentrations exceeding PNG water quality criteria (Environment Act 2000); bold values indicate concentration exceeds ANZECC/ARMCANZ (2000). Aluminium GVs from Golding et al. (2015);
[b] Water hardness calculated from concentration of calcium and magnesium;
[c] Sulphate concentrations calculated from sulphur concentration (i.e. assuming all S is in the form of SO_4); LoD = Limit of detectability, NM = Not measured; ID = insufficient data; NA = not applicable; NR = not reported.

The ratios of tailings in seawater (on a volume to volume basis) investigated were 1 in 10, 1 in 100, 1 in 1,000, 1 in 10,000 and 1 in 50,000 with dissolved metals measured in the elutriates after 16 hours of mixing time at 30 ± 1°C.

The concentrations of dissolved metals measured in the elutriates were determined in order to establish the dilution required for dissolved metal concentrations to remain below PNG water quality criteria and WQGVs in ANZECC/ARMCANZ (2000). Upon comparison to PNG water quality criteria, concentrations of copper exceeded the criteria only in the 1 in 10 dilution. Concentrations of cobalt were greater than the analytical limit of detection adopted for the CSIRO study of 0.1µg/L in the 1 in 10, the 1 in 100 and the 1 in 1,000 tailings dilutions. Hence, for Tailings 1 and Tailings 2, a dilution of 1 in 10,000 was sufficient to meet PNG water quality criteria. When compared to Australian and New Zealand water quality criteria in ANZECC/ARMCANZ (2000), for the Tailings 1 and Tailings 2 samples, dissolved concentrations of cobalt and zinc met their respective WQGVs by the 1 in 1,000 dilution and dissolved concentrations of copper met its WQGV by the 1 in 50,000 dilution. Nickel in the Tailings 2 sample met its WQGV by the 1 in 100 dilution.

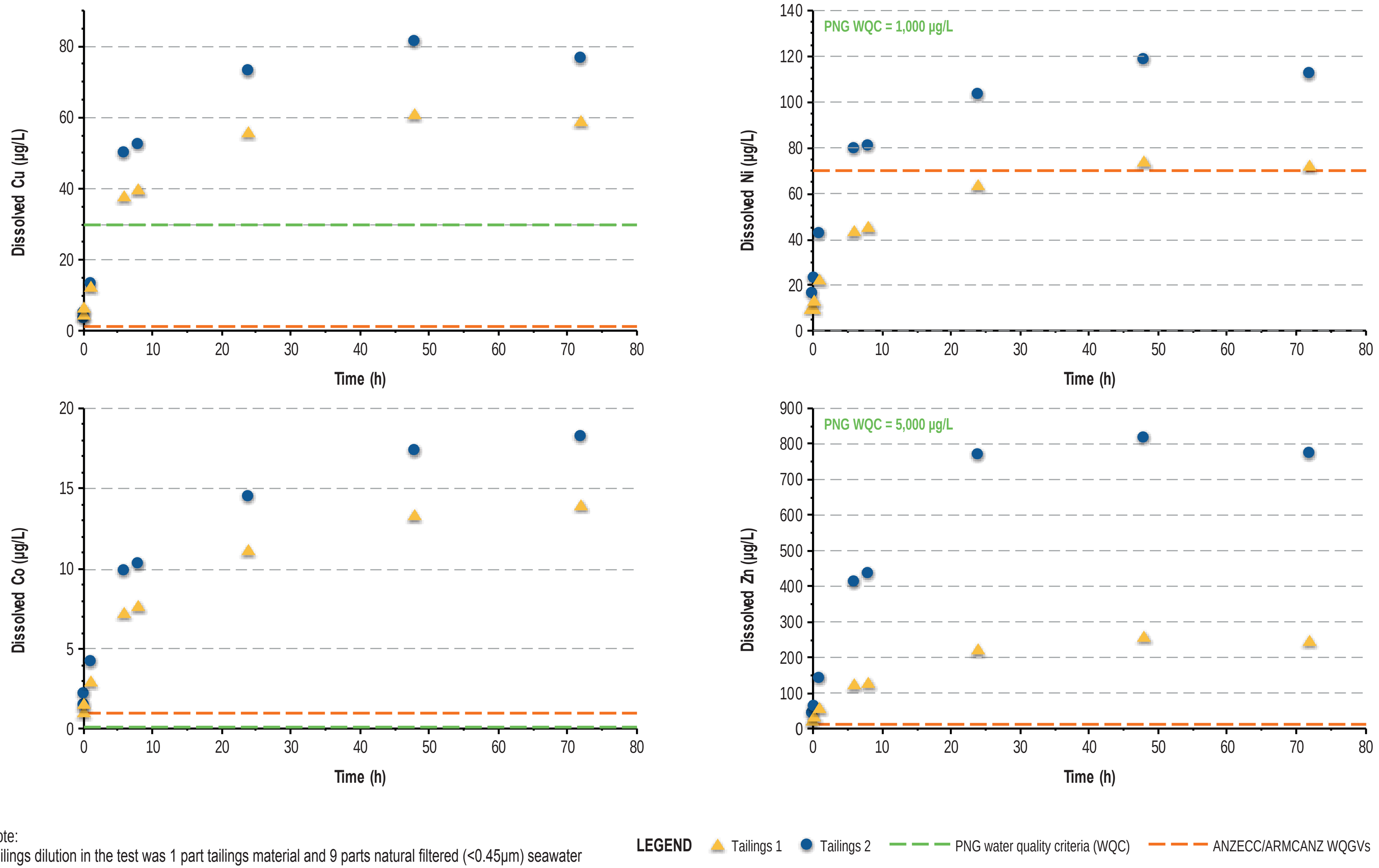
To provide information on whether the dissolved metals released from the tailings to seawater are likely to continue indefinitely or diminish with time, tests were undertaken on both tailings samples diluted in seawater at a ratio of 1 in 10 with dissolved (<0.45µm) metal concentrations measured after 0 minutes, 10 minutes; and 1, 6, 8, 24, 48 and 72 hours.

The results shown in Figure 17.8 indicated a two-stage metal release process for copper, cobalt, nickel and zinc with an initial rapid release of metals into solution over the first one to five hours followed by a much slower metals release phase. Equilibrium metal concentrations (little further increase in dissolved metal concentrations) were typically achieved after 20 hours of mixing.

The PNG water criteria and the ANZECC/ARMCANZ WQGVs for each the four metals analysed are shown in Figure 17.8 as green and orange lines respectively or as a text note. Results for Tailings 1 are shown in orange red and results for Tailings 2 are shown in blue.

Equilibrium metal concentrations exceeded both the PNG water quality criteria and ANZECC/ARMCANZ WQGV for cobalt and exceeded the ANZECC/ARMCANZ WQGVs for copper, nickel and zinc.

The liquid component of the tailings discharge after dilution within a designated, site specific mixing zone (the dimensions of which will be stipulated by the PNG Government) will be required to comply with the receiving water criteria defined in Schedule 1 of the PNG Environment (Water Quality Criteria) Regulation 2002 at the edge of the mixing zone.



Note:
Tailings dilution in the test was 1 part tailings material and 9 parts natural filtered (<0.45µm) seawater (i.e. 1 in 10 dilution).

Source: CSIRO

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WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Concentration of dissolved (<0.45µm) copper, cobalt, nickel and zinc in elutriate tests

Figure No: 17.8

INDD Reference:0520DD_10_GRA094.indd_5

Given the reactivity of the two tailings samples tested by CSIRO (Appendix L, Tailings Ecotoxicology and Geochemistry), and metal release when mixed with seawater, the suggested rationale for setting a site-specific mixing zone for the DSTP discharge is as follows:

- Acknowledge the caveats to the CSIRO ecotoxicological and chemical characterisation of tailings[6] ('Ecotoxicology and Chemistry of Wafi-Golpu Bench-scale Tailings' in Appendix L, Tailings Ecotoxicology and Geochemistry), which has produced conservative results.
- Notwithstanding these caveats, take the equilibrium metal concentrations (negligible further increase in dissolved metal concentrations; conservatively the highest concentration detected in the equilibrium range) from the CSIRO study and multiply those concentrations by ten to account for the 1 in 10 dilution ratio used in the test work and then compare the adjusted equilibrium metal concentrations with Schedule 1 of the PNG Environment (Water Quality Criteria) Regulation 2002 as required by the *Environment Act 2000*. Finally, calculate the number of dilutions required for each parameter to comply with the criteria.
- Determine a priority contaminant (usually a metal) based on the maximum number of dilutions required.
- Apply the results of numerical modelling (Appendix J, Density Current, Plume Dispersion and Hydrodynamic Modelling) to determine the spatial dimensions of a future site-specific mixing zone where PNG water quality criteria are met at the boundary for the priority contaminant and all other contaminants.
- The PNG Government sets the regulatory mixing zone for the DSTP discharge taking the above into account.

Based on the results of the elutriate testwork where metals release was measured over extended mixing times of up to 72 hours, and after correcting for the 1 in 10 dilution of the tailings samples, the dissolved metals requiring dilutions to meet PNG ambient water quality criteria are outlined in Table 17.7. This table shows the expected dilutions required for each metal in the tailings subsurface plumes or liquor to comply with the PNG ambient water quality criteria.

[6] In considering the results of the study, it is important to note the following caveats:

- The tailings samples in the short term bench-scale laboratory tests were prepared from aged core samples. There was up to 12 months between receipt of the first tailings sample and commencement of testwork. It is likely that greater duration of oxidation while in storage resulted in greater concentrations of mobile metals and hence greater bioavailability. This is supported by experiments that showed that greater presence of oxygen increased the mobility of metals from the tailings/sediment mixtures (Apte, pers. com., 2018 and Appendix L, Tailings Ecotoxicology and Geochemistry).
- Long term testwork using fresher tailings samples (analysed immediately after sampling) showed significantly lower concentrations of copper and zinc than the aged tailings used in the short term bench-scale testwork. This may also reflect the variability in metal content within the rock types used to generate the tailings samples.
- The long term testwork was designed to better replicate the deep sea environment by using greater volumes of overlying seawater per amount of tailings/sediment mixtures (in mesocosms). That testwork showed the toxicity of the tailings samples to amphipod test species to be lower than that observed in the short term bench-scale laboratory tests.
- As a result, the tailings samples in the short term bench-scale ecotoxicity and elutriate tests (upon which the ecotoxicity, water quality and bioaccumulation assessments herein are based) are likely to be conservative (i.e. overestimate impact).
- Additionally, the scenarios of mixing, dispersion and settling of tailings solids in the laboratory used in this study were designed to provide a conservative measure of tailings toxicity to aquatic organisms.

Table 17.7: Metals in the subsurface plumes requiring dilution to meet PNG water quality criteria

	Cobalt (µg/L)	Copper (µg/L)	Nickel (µg/L)	Zinc (µg/L)
Tailings 1	140 (1,400)	610 (20.3)	740 (0)	2,620 (0)
Tailings 2	180 **(1,800)**	810 (27)	1,190 (1.2)	8,180 (1.6)
PNG criteria	0.1	30	1,000	5,000

Dilutions required for compliance are shown in parenthesis. The highest dilution required for compliance is shown in bold.

From the results in Table 17.7, cobalt will require the greatest dilutions to meet the PNG ambient water quality criteria (1,400 dilutions for Tailings 1 and 1,800 dilutions for Tailings 2). Therefore, a dilution of 1,800 is predicted to result in compliance with all PNG ambient water quality criteria. As per the caveats outlined herein, this dilution factor is based on a conservative measurement of metals concentrations released from the tailings into seawater. It is therefore expected that a regulatory mixing zone based on this dilution factor will also be conservative.

Dispersion modelling has shown that 1,800 dilutions of the tailings subsurface plumes (liquid fraction) will be achieved at the following distances from the DSTP outfall (Appendix J, Density Current, Plume Dispersion and Hydrodynamic Modelling):

- 1,272m – the distance where 1,800 dilutions will be achieved 50% of the time (i.e., 50th percentile)
- 2,174m – the distance where 1,800 dilutions will be achieved 95% of the time (i.e., 95th percentile)

It is proposed that the 95th percentile distance, 2,174m, be used as a basis to set the regulatory mixing zone. Although for simplicity, it is recommended that the distance be set as 2,200m.

17.5.1.2.3. Ecotoxicological Characterisation of the Tailings Liquor

An ecotoxicological characterisation of the two tailings samples mentioned in the previous section (Tailings 1 and 2) was undertaken by CSIRO (Appendix L, Tailings Ecotoxicology and Geochemistry).

The toxicity of the tailings liquor was measured using eight toxicity tests. Each toxicity test measured chronic toxicity, that is, a biological measurement incorporating a significant part of the organism's life cycle (e.g., reproduction, early life-stage development). The chronic toxicity tests included eight tests on organisms from six general taxonomic groups, seven of which were tropical or sub-tropical species. Each bioassay determined the potential biological toxicity of the bioavailable contaminants present in tailings liquor to the individual aquatic biota. The results from these bioassays were combined in species sensitivity distributions to statistically derive the median concentration of tailings liquor likely to protect 95% of species following methods by Batley et al. (2014) and Warne et al. (2015). The use of chronic toxicity data eliminates the need to apply conversion factors on acute toxicity data prior to incorporation into species sensitivity distributions and hence provides more reliable estimates of the required 'safe' dilutions of tailings liquor.

Test species for this study were selected by CSIRO based on their known sensitivity to contaminants (in particular metals), their availability for use in testing throughout the duration of the study, their known reproducibility as surrogate test species (and test endpoints) for assessing contaminated waters in marine environments and the availability of standard test protocols. Coral species were not included in this study because coral reefs are absent within 20km of the DSTP site in the Huon Peninsula (Appendix R, Nearshore

Marine Characterisation and Appendix S, Fisheries and Marine Resource Use Characterisation).

Table 17.8 presents the number of dilutions required for the Tailings 1 and Tailings 2 sample liquors to achieve the 95% species protection level based on the results of the ecotoxicity testwork. The tailings liquor (after 1 in 4 dilution in seawater) in Table 17.8 is representative of the tailings liquor in the DSTP discharge to the deep slope below the DSTP outfall pipe, having been pre-diluted in the mix/de-aeration tank to reduce water temperature and de-aeration to avoid entrainment of air in the discharge.

Based on Table 17.8, a 1 in 108 dilution (for simplicity written as 1:108 dilution; i.e., 1 part tailings slurry for every 107 parts seawater) of Tailings 1 liquor (after the 1 in 4 pre-discharge dilution in the mix tank) is required to protect 95% of aquatic species using the species sensitivity distribution (SSD) approach (i.e., from all eight life cycle tests). In the case of the Tailings 2 liquor, a 1:263 dilution was required to meet the 95% aquatic species protection level based on the SSD approach.

However, as noted above, the 1 in 4 diluted and filtered tailings liquor was the highest concentration of liquor tested in the toxicity tests, which was represented as 100% tailings liquor. Since the actual tailings will be about 20% more dilute (due to an additional factor of dilution incorporated into the mix/deaeration tank design compared to the laboratory bench tests), the distance to achieving 95% species protection level is likely to be less than predicted by the toxicity test results.

Table 17.8: Dilutions of tailings liquor required to meet species protection levels based on ecotoxicity testing

Sample	Species Protection Level	Tailings Liquor (with 1 in 4 dilution)		Estimated Original Tailings Material
		Concentration	Required Dilutions	Required Dilutions
Tailings 1	Safe concentration as determined by toxicity testing on full suite of organisms (95% protection of species with 50% confidence)	0.93%	1:108	1:430
Tailings 2	Safe concentration as determined by toxicity testing on full suite of organisms (95% protection of species with 50% confidence)	0.38%	1:263	1:1,053

Source: CSIRO (Appendix L, Tailings Ecotoxicology and Geochemistry).

In summary, based on the ecotoxicological tests, total dilutions of 430 and 1,053 will be required for Tailings 1 and Tailings 2 (exiting the mix tank after a 1:4 dilution) to achieve 95% protection of marine species. The maximum dilution of 1,053 is well within with the maximum compliance dilution of 1,800 based on a comparison of dissolved cobalt to PNG ambient water quality criteria (see Section 17.5.1.2.2).

17.5.1.2.4. Residual Toxicity Impacts to Deep-water Pelagic Organisms

In Figure 17.7 there is a major zone between 300m and 500m water depth where the bulk of tailings subsurface liquor/turbidity plumes shear off from the descending tailings density current and will be transported in the direction of ambient currents. In Figure 17.7, the 1,000 to 1,800 dilution contour is shown. In this zone, the tailings liquor may have residual chronic toxicity effects on marine organisms under continuous exposure conditions, although continual exposure is highly unlikely.

The principal marine organisms likely to be exposed to elevated dissolved trace metal concentrations at less than 1,800 dilutions (and therefore exposure to potential toxicity) are zooplankton and micronekton. However, their passage through the continuously generated tailings subsurface plumes is expected to be transient with short-duration exposure (typically less than one hour) to those species that undertake diel vertical migrations. In the case of those zooplankton or weak-swimming micronekton being brought in with ambient currents, if they are trapped within the tailings subsurface plumes, their exposure to dissolved trace metal concentrations will reduce with time of travel as dilution increases with distance from the shearing-off point (see Figure 17.7).

As a result, the dilutions required to protect 95% of marine species with 50% confidence derived by CSIRO in Appendix L, Tailings Ecotoxicology and Geochemistry, are expected to provide a conservative estimate of toxicity. The results of the CSIRO toxicity tests are considered conservative due to the use of constrained marine test organisms, a necessary condition of the tests. In the deep-water marine environment those marine pelagic organisms that are unconstrained (i.e., the more mobile species) have the opportunity to move away from tailings subsurface liquor plumes. Less mobile species passively encounter the plumes carried in by the prevailing currents but are exposed to reducing dissolved trace metal concentrations as the plumes become diluted in the direction of the downstream prevailing currents.

Overall, the residual impacts from mixtures of dissolved trace metals in tailings liquor potentially inducing chronic toxicity to exposed zooplankton and micronekton are assessed to be of **low** significance. This is based on a very **low** magnitude of impact (toxicity will be confined to a small and localised segment of the ocean water column and mostly within a future mixing zone) and a **low** sensitivity (common and widespread zooplankton and micronekton assemblages). No residual toxicity impacts are predicted for the larger more mobile fauna such as fish, sea turtles or marine mammals, given their high mobility in relation to the small mixing zone area and its depth.

17.5.1.3. Pelagic Trace Metal Bioaccumulation Impacts

For the purposes of this section, the USEPA (2010) definitions of bioaccumulation and biomagnification have been slightly modified and adopted, and are defined as:

- Bioaccumulation: the process by which trace metals are taken up by an organism either directly from exposure to a contaminated medium (i.e., seawater) or by consumption of food containing the trace metals.
- Biomagnification: the result of the process of bioaccumulation and biological transfer by which tissue concentrations of trace metals in organisms at one trophic level exceed tissue concentrations in organisms at the next lower trophic level in a food web.

The main marine ecological issues associated with DSTP and subsequent bioaccumulation into marine fauna are:

- The potential for uptake of bioavailable trace metals into the tissues of marine organisms
- The bioaccumulation and biomagnification of these trace metals through food webs and ultimately into fish eaten by humans

The potential for trace metal bioaccumulation within marine pelagic organisms arises from three pathways:

- Direct uptake of dissolved phase trace metals from tailings liquor and from the interstitial pore water in tailings solids
- Indirect uptake of particulate phase trace metals from ingestion of tailings fine suspended sediments (adsorbed metals or internal metal mineralogy) in subsurface and bottom-attached plumes
- Indirect uptake of trace metals through ingestion of food organisms containing body burdens of trace metals above natural background levels via pathways (a) and (b) above

Tetra Tech (Appendix N, Assessment of Metal Bioaccumulation and Biomagnification from DSTP in the Huon Gulf) assessed pelagic bioaccumulation and biomagnification in the inner Huon Gulf, the results of which are summarised below.

In addition, a literature search was undertaken to collate information on observed bioaccumulation of trace metals in deep-sea pelagic communities and examples of biomagnification within the pelagic food web, particularly in regard to observations from other closed or current DSTP operations. This is also summarised below.

17.5.1.3.1. Bioaccumulation and Biomagnification Study

Tetra Tech (Appendix N, Assessment of Metal Bioaccumulation and Biomagnification from DSTP in the Huon Gulf) undertook conceptual modelling based on a trophic analysis methodology (USEPA, 1999) to predict trace metal concentrations within different pelagic trophic levels of the Huon Gulf with a particular emphasis on bioaccumulation pathways in the food web that may lead to increased metal burdens in fish caught and consumed in the Huon Gulf.

The study identified three major pathways by which fish may theoretically accumulate metals from DSTP, which are via:

- Trace metal accumulation in benthos that is in direct contact with the tailings and trophic transfer up the food chain to fish consumed by people
- Trace metals accumulated in micronekton and zooplankton that are exposed to the tailings plume, and then trophic transfer to fish consumed by people
- Bioconcentration[7] of dissolved trace metals directly from the DSTP plume (i.e., tailings liquor) into fish across their gills

The study evaluated each of these pathways using site-specific information collected from the Huon Gulf, metal bioaccumulation information from other DSTP sites and published literature regarding bioaccumulation and trophic transfer of the selected metals of concern. A summary of the key findings is given below:

- General findings:
    - The deep waters in the Huon Gulf are disconnected from upper layers of seawater where fish are collected for consumption. Thus, metals in seafloor sediments would be unlikely to become bioavailable and accumulate in fish consumed by people.
    - Data collected thus far from the Huon Gulf suggest that arsenic and mercury may be naturally bioaccumulated at higher concentrations in top trophic level fish.

[7] A process by which there is net accumulation of a chemical directly from an exposure medium into an organism.

Some fish obtained from the fish market in Lae were found to already exceed food safety standards for arsenic and mercury.

- Given the general low abundance and diversity of benthic organisms at the seafloor in the Huon Gulf, and the disconnect between the upper and lower water column, there is unlikely to be significant transfer of metals from benthic organisms to larger organisms in the Huon Gulf.

- Bioaccumulation and biomagnification findings:
  - For many of the metals examined, tissue metals concentrations are highest in the lower trophic levels such as zooplankton and micronekton in the Huon Gulf compared to higher trophic levels (i.e., fish).
  - The results of trophic pathway modelling indicate that there is limited biomagnification of most metals in upper trophic level fish, and fish tissue metal concentrations that are currently below food safety guidelines are likely to remain so with the proposed use of DSTP for the Project.
  - Tissue concentrations for copper, zinc, nickel and manganese do not biomagnify in fish consumed by people and bioaccumulation factors follow a similar pattern (i.e., not increasing) across all trophic levels for all metals.
  - Fish tissue metals concentrations are predicted to be generally similar to tissue metals concentrations currently measured in the Huon Gulf. The exception was that manganese is predicted to increase two-fold above the maximum background concentration observed in fish tissue (0.241mg/kg predicted compared to the upper background range of 0.12mg/kg). While the concentration of manganese is predicted to be double the observed background range, the predicted concentration is relatively low compared to amounts of manganese required in the human diet. The recommended adequate intake of manganese for adults 19 years and older is established as 2.3mg and 1.8mg per day for males and females, respectively (NAS, 2004). Adequate intakes range from 1.2 to 1.6mg per day for children aged 1 to 18 years old. The tolerable upper intake level (i.e., the maximum usual daily intake level at which no risk of adverse health effects is expected) is 11mg per day for adults 19 and older and 2 to 9mg per day for children aged 1 to 18. The USEPA determined an oral reference dose of 0.14mg/kg per day, which is an estimated dose that is not associated with adverse health effects in the general population (USEPA, 2015). For a 70kg person, this value is 9.8mg per day of manganese. To exceed this value from fish consumption alone, one would need to eat in the order of 40kg of fish per day with a manganese concentration of 0.241mg/kg.

- Implications for humans consuming epipelagic fish:
  - Available gut content data, as well as fisheries surveys in the Huon Gulf (Appendix P, Deep-slope and Pelagic Fish Characterisation) and another DSTP site in PNG (Brewer et al., 2012), suggests little or no direct forage link between deep-sea organisms and those species that are consumed by people.
  - Top trophic level fish that people consume (e.g., various tuna species) have large home ranges and a varied diet (Appendix N, Assessment of Metal Bioaccumulation and Biomagnification from DSTP in the Huon Gulf, Papua New Guinea) and therefore, are expected to be minimally exposed to trace metals from the tailings subsurface plumes in the inner Huon Gulf.
  - Based on all of the information collected for the Huon Gulf and active DSTP sites in the Asia-Pacific region, trace metal concentrations other than arsenic and mercury are generally very low in fish that people consume and generally below the Australian and New Zealand food standards (FSANZ, 2011). Furthermore,

there appears to be no evidence for metal biomagnification into higher trophic level fish at these DSTP sites as shown by much lower concentrations in higher trophic level fish than in lower trophic levels such as zooplankton and micronekton.

17.5.1.3.2. Other DSTP Bioaccumulation and Biomagnification Findings

The potential for bioaccumulation of mine-derived trace metals through the food web, ultimately into species of pelagic fish that are regularly consumed by coastal people, is a potential impact considered in this EIS.

A further review of the scientific literature revealed that there were very few studies of trace metal bioaccumulation in deep-water pelagic communities as an ecological unit (i.e., a biocoenosis[8]). The vast majority of studies focussed on bioaccumulation of trace metals in benthic communities. In tropical marine ecosystems, several studies have assessed trace metal concentrations in fish communities (Powell and Powell, 2001; Brewer et al., 2007), but none has targeted a relatively broad range of pelagic communities and species groups. However, one study that is relevant to the present impact assessment is that of Brewer et al. (2012) who undertook an in-depth study of the impacts of DSTP at the operating Lihir Gold Mine on deep-water pelagic communities. Analysis of biomagnification factors by Brewer et al. (2012) in different trophic levels at Lihir gold mine found little evidence of widespread biomagnification from lower (zooplankton) to higher trophic levels (large pelagic fish). For most trace metals analysed, there was either decreasing concentrations of trace metals with increasing position in the food web, or some trophic transfer in the lower to mid-levels only (zooplankton to micronekton and baitfish). Overall, very few differences were observed in the metal concentrations of micronekton and pelagic fish between mine and reference regions.

Brewer et al. (2012) concluded that a lack of trophic transfer beyond the zooplankton was indicative that the trace metals were not internalised by the zooplankton but may be on their surfaces, being mineralised and not bioavailable to predators consuming the lower trophic levels. The measured lack of bioaccumulation of metals up the food web indicated that DSTP was unlikely to affect the local people who eat coastal pelagic fish.

In a study by CSIRO (1994), the low risks of uptake of metals via the food chain from mine wastes discharged at sea was shown for the disposal of jarosite (residue from zinc smelting containing high levels of metals, particularly zinc, cadmium, lead, arsenic and mercury), which was discharged at a rate of up to 240,000 tonnes per annum (tpa) by barge dumping off southeast Tasmania between 1972 and 1996. By a combination of field sampling and modelling, CSIRO examined the likelihood of contact with jarosite plumes and uptake via marine animals at different trophic levels, and into a number of predatory species including bluefin tuna, which seasonally migrate past the dumping area. Even though the jarosite material was disposed at the surface and descended through the full 2,000m of the water column, CSIRO concluded that, even under worst case scenarios, the predicted increases in heavy metal from the jarosite disposal were all relatively low, and the increase in heavy metal load predicted on the fish populations would not be expected to be detectable above natural sampling variability without extremely large numbers of samples. The study also concluded that where some metals were elevated in southern bluefin tuna, these had to have been derived from sources other than jarosite.

[8] An association of different organisms forming a closely integrated community.

17.5.1.3.3. Residual Impacts on Zooplankton and Micronekton

Prior to assessing residual impacts on zooplankton and micronekton background trace metal concentrations in these communities are described first and compared with those from a coastal mine in PNG with an operating DSTP system and for which a large database on background trace metal concentrations in PNG tropical zooplankton of the central west Pacific Ocean has been developed.

17.5.1.3.3.1. Background Trace Metals in Zooplankton and Micronekton

Coffey measured background trace metal concentrations in 38 bulk (mixed) zooplankton samples and 21 micronekton (individual) samples from near the Outfall Area and inner Huon Gulf (Appendix Q, Zooplankton and Micronekton Characterisation). Table 17.9 shows the existing background concentrations (median and range) of copper, zinc, cadmium, chromium, nickel and manganese in the bulk samples of zooplankton (base of the food web) collected within three water column sampling depths. Background trace metal data for individual micronekton species are presented in Appendix Q, Zooplankton and Micronekton Characterisation.

The residence time of zooplankton and micronekton within tailings subsurface plumes will be intermittent and dependent upon the transient passage of those species undertaking diel vertical migrations, or of a longer duration for those zooplankton and micronekton species that are passively brought into or favour deep waters within the 300 to 500m depth range, where the bulk of tailings subsurface plumes shear off from the descending tailings density current (see Figure 17.7). The residual impacts on these two groups are assessed below.

17.5.1.3.3.2. Bioaccumulation and Diel Vertical Migration of Zooplankton and Micronekton

The principal pathway of trace metal bioaccumulation in vertical migrating zooplankton and micronekton is expected to be via the direct ingestion of fine-grained tailings solids particles (especially by suspension feeders) or indirectly via particles adsorbed onto the surfaces of other smaller zooplankton species (i.e., a food resource) that have directly ingested fine tailings particles or trace metal-contaminated food organisms themselves.

For those zooplankton and micronekton passing through the tailings subsurface plumes, their transient exposure to dissolved trace metals is not expected to result in chronic toxicity, owing to the high dilutions at distance from the tailings density current and based on the DSTP case studies and findings of Tetra Tech (Appendix N, Assessment of Metal Bioaccumulation and Biomagnification from DSTP in the Huon Gulf). However, as noted by Brewer et al. (2012), zooplankton and micronekton will also ingest fine tailings suspended sediments within the clay and fine silt size fraction (<20µm particle size diameter), which are also transported in the tailings subsurface plumes.

Transient exposure durations of actively mobile zooplankton and micronekton species undertaking diel vertical migrations across predicted subsurface tailings plumes of around 50m vertical thickness are typically less than one hour based on a literature search for diel migration rates. Table 17.10 summarises diel vertical migration velocities from around the world and shows that velocities are typically greater than 50m per hour.

Table 17.9: Background concentrations of trace metals (wet weight basis) in bulk (mixed) zooplankton samples

Trace Metal / Location	Distance From Shore (km)	Sampling Depth Range (m)	Bulk (Mixed) Zooplankton Background Trace Metal Concentrations	
			Median (mg/kg)	Range (mg/kg)
Copper:				
Inshore (upper slope)	0.68 – 0.72	0 – 100	2.10	0.82 – 2.30
Offshore (mid-slope)	1.26 – 1.45	0 – 250	1.06	0.58 – 2.40
Offshore (lower slope)	2.40 – 3.14	0 – 500	0.58	0.16 – 0.90
Zinc:				
Inshore (upper slope)	0.68 – 0.72	0 – 100	5.4	3.0 – 6.7
Offshore (mid-slope)	1.26 – 1.45	0 – 250	5.55	3.2 – 8.6
Offshore (lower slope)	2.40 – 3.14	0 – 500	3.18	1.2 – 4.2
Cadmium:				
Inshore (upper slope)	0.68 – 0.72	0 – 100	0.09	0.06 – 0.16
Offshore (mid-slope)	1.26 – 1.45	0 – 250	0.11	0.07 – 0.15
Offshore (lower slope)	2.40 – 3.14	0 – 500	0.09	<0.05 – 0.11
Chromium:				
Inshore (upper slope)	0.68 – 0.72	0 – 100	0.19	0.12 – 0.24
Offshore (mid-slope)	1.26 – 1.45	0 – 250	0.15	0.15 – 0.21
Offshore (lower slope)	2.40 – 3.14	0 – 500	0.12	0.10 – 0.13
Nickel:				
Inshore (upper slope)	0.68 – 0.72	0 – 100	0.19	0.09 – 0.32
Offshore (mid-slope)	1.26 – 1.45	0 – 250	0.09	0.08 – 0.11
Offshore (lower slope)	2.40 – 3.14	0 – 500	0.14	<0.06 – 0.23
Manganese:				
Inshore (upper slope)	0.68 – 0.72	0 – 100	4.11	1.78 – 8.02
Offshore (mid-slope)	1.26 – 1.45	0 – 250	1.86	0.86 – 3.13
Offshore (lower slope)	2.40 – 3.14	0 – 500	0.79	0.41 – 3.23

Source: Appendix Q, Zooplankton and Micronekton Characterisation*.

Table 17.10: Literature Plankton and Micronekton Vertical Migration Velocities

Group	Vertical Migration Rate		Source
	cm/s	m/h	
Invertebrate larvae	0.042 – 8.3	1.5 – 298.6	Chia et al. (1984)
Some copepod species	1.2 – 2.5	43.2 – 90	Dagg and Wymann (1983)
Medusae and euphausiids	1.4 – 2.1	50.4 – 75.6	Dagg and Wymann (1983)
Zooplankton	2.0 – 6.0	72.0 – 216	Heywood (1996)
Copepods and euphasuiids	1.0 – 6.0	36.0 – 216	Wiebe et al. (1992)

Group	Vertical Migration Rate		Source
	cm/s	m/h	
Euphausius krohni	2.0	72	Angel (1985)
Various backscatter average descent speed	8.5	306	Klevjet et al. (2012)
Various backscatter average ascent speed	4.8	174	Klevjet et al. (2012)

Overall, the residual impacts of tailings subsurface plumes on zooplankton and micronekton species undertaking diel vertical migrations are assessed to be of **low** significance, based on a **low** magnitude of impact (transient/temporary passage and short-term exposure to tailings plumes containing highly diluted dissolved trace metals and **low** TSS concentrations having particulate-associated trace metals) and a **low** sensitivity (common and widespread zooplankton and micronekton assemblages and species).

17.5.1.3.3.3. Bioaccumulation and Passively Transported Zooplankton

In the case of those deep-water zooplankton and micronekton species that do not undertake diel vertical migration or have low mobility, they can be carried passively in ambient currents into the Outfall Area and be exposed for longer periods to dissolved and particulate-associated trace metals within the tailings subsurface plumes as they are transported laterally in the direction of prevailing currents. Under these conditions, the affected zooplankton and micronekton are exposed to decreasing concentrations of dissolved trace metals in the dispersing tailings liquor as it becomes more dilute in the direction of travel.

Overall, the residual impacts on zooplankton and micronekton species passively exposed to tailings subsurface plumes are assessed to be of **low** significance, based on a **low** magnitude of impact (temporary passage within the tailings plumes and short-term exposure to diluting dissolved trace metals; and exposure to low TSS concentrations having particulate-associated trace metals in the direction of prevailing currents) and a **low** sensitivity (common and widespread species).

The above residual impact assessment for zooplankton and micronekton concurs with the findings of Tetra Tech (Appendix N, Assessment of Metal Bioaccumulation and Biomagnification from DSTP in the Huon Gulf) and Brewer et al. (2007, 2008 and 2012).

17.5.1.3.4. Bioaccumulation Impacts to Higher Trophic Levels

The principal higher trophic level pelagic communities include megaloplankton[9] (e.g., jellyfish and salps) and macroinvertebrate nekton (e.g., squid), as well as vertebrate nekton (bony and cartilaginous fish). There are two major pathways by which higher trophic level pelagic fauna may theoretically accumulate metals from DSTP, including:

- Indirect consumption of trace metals bioaccumulated in zooplankton and micronekton that are exposed to the dilute tailings sub-surface plumes. This may subsequently result in trophic transfer to larger pelagic invertebrates (e.g. megaloplankton) and fish, then to top-level predators (e.g., apex fish such as tuna and billfish, and sea turtles and marine mammals) and ultimately to humans if deep-water fish are consumed by people (provided such potential pathway exists).

[9] Weak-swimming gelatinous plankton (>20mm size), such as salps and jellyfish.

- Direct bioconcentration of bioavailable metals from the dilute sub-surface tailings plume into megaloplankton and fish across their body integuments or gills.

The residual impacts of trace metal bioaccumulation within higher trophic level fauna exposed directly to tailings subsurface plumes, or indirectly through the consumption of potentially contaminated lower trophic level fauna within the deep-water pelagic environment, are assessed below.

17.5.1.3.4.1. Bioaccumulation Impacts to Pelagic Macroinvertebrates

The larger pelagic macroinvertebrates of the water column include megaloplankton (20 to 200mm size range), such as large gelatinous fauna including jellyfish (Medusozoa), salps (Tunicata) and comb jellies (Ctenophora). Most of the megaloplankton are weak-swimming forms that are carried passively in the direction of prevailing currents in much the same way as do zooplankton and micronekton. The strong-swimming macroinvertebrate nekton includes squid and other cephalopods.

In the baseline zooplankton and micronekton characterisation study (Appendix Q, Zooplankton and Micronekton Characterisation), large megaloplankton were not caught in the bongo nets. However, less than 0.5% of the total catch of zooplankton and micronekton included a mix of the juvenile stages of squid (Cephalopoda), small species of salp (Thalacea), as well as small siphonophore species (Hydrozoa). Overall, the megaloplankton assemblages within the Outfall Area and the inner Huon Gulf appear to be of low species richness and density, which may be attributable to the influence of freshwater and high suspended sediment loads delivered by the Markham River and another eleven rivers along the northern Huon Gulf coast.

Based on the results from the conceptual modelling study based on trophic analyses methods (Appendix N, Assessment of Metal Bioaccumulation and Biomagnification from DSTP in the Huon Gulf) and the assessment of bioaccumulation and biomagnification at the Lihir Gold Mine DSTP operation by Brewer et al. (2007, 2008 and 2012), biomagnification of trace metals from zooplankton and micronekton to higher trophic levels pelagic macroinvertebrates (e.g., megaloplankton) and macroinvertebrate nekton (e.g., squid) is predicted to not occur. The study by Brewer et al. (2012) indicated that there was no evidence for metal biomagnification at the Lihir Island DSTP sites in the mine area as shown by lower concentrations in higher trophic level organisms than in lower trophic levels

Overall, the residual impacts of trace metal bioaccumulation to higher trophic level pelagic macroinvertebrates are assessed to be of **low** significance, based on a **low** magnitude of impact (bioaccumulation restricted largely to lower trophic food organisms such as zooplankton) and a **low** sensitivity (expected widespread distribution of pelagic macroinvertebrate species).

17.5.1.3.4.2. Bioaccumulation Impacts to Pelagic Fish

Potential bioaccumulation and biomagnification of DSTP-derived trace metals to higher trophic level deep-water pelagic fish and epipelagic fish has a mix of different pathways.

Fish within the deep-water upper mesopelagic zone (200m to 500m) may be exposed directly to dissolved trace metals in tailings subsurface plumes if they are encountered, which represents a direct pathway of trace metal uptake across the gills. However, given the very high dilution of tailings liquor as the plumes disperse and the resulting low and decreasing concentrations of dissolved trace metals, this exposure route is not expected to be significant. In addition, fish have a higher capacity to regulate metals within their tissues by active excretion and depuration, as well as storing refractory deposits within their organs.

The main pathway is likely to be indirectly via consumption of trace metal-contaminated food organisms.

Fish within the epipelagic zone (0 to 200m), while not exposed directly to tailings subsurface plumes (which are predicted to form at more than 300m depth), may be exposed to those zooplankton and micronekton that have been exposed to tailings subsurface plumes and that undergo night-time vertical migration; hence, providing an indirect food web pathway for trace metal bioaccumulation to epipelagic fish.

The residual impacts of bioaccumulation of trace metals to fish has taken account of the conceptual modelling based on a trophic analysis methodology (USEPA, 1999) used by Tetra Tech (Appendix N, Assessment of Metal Bioaccumulation and Biomagnification from DSTP in the Huon Gulf) as well as the in-depth studies of fish bioaccumulation of trace metals at the Lihir Gold Mine's DSTP operation by (Brewer et al., 2007, 2008 and 2012). The findings of these studies directly relevant to trace metal bioaccumulation to fish are summarised below

The results of trophic pathway modelling indicate that there is limited biomagnification of most metals in upper trophic level fish (Appendix N, Assessment of Metal Bioaccumulation and Biomagnification from DSTP in the Huon Gulf). The findings of Brewer et al. (2007 and 2012) indicates that there was no evidence for widespread bioaccumulation from the lower trophic levels of the food web (e.g., zooplankton and micronekton) to the highest trophic levels (e.g., apex predatory pelagic fish, such as tuna). For most trace metals analysed at the Lihir Island mine and reference areas, there was either:

- Decreasing concentrations of trace metals with 'higher' positions in the food web (i.e., biodiminishment)
- Some bioaccumulation via trophic transfer from the lower to the mid-levels of the food web only (zooplankton to micronekton)

Furthermore, the bioaccumulation observed was occurring at both the mine and reference areas of the study.

Based on the above analysis, the modelling results of Tetra Tech (Appendix N, Assessment of Metal Bioaccumulation and Biomagnification from DSTP in the Huon Gulf) and key observations of the bioaccumulation impacts to pelagic fish at the Lihir Gold Mine (Brewer et al., 2007; 2012), the residual impacts of bioaccumulation to pelagic fish for the present Project are assessed to be of **low** significance, based on a **low** magnitude of impact (transient or short-term exposure to tailings plumes and bioaccumulation largely confined to lower trophic food organisms with biodiminishment of trace metal bioaccumulation to fish) and a **low** sensitivity (common, widespread pelagic fish assemblages and species).

17.5.1.3.4.3. Bioaccumulation Impacts to Sea Turtles

The principal sea turtle species found in the Huon Gulf is the critically endangered west Pacific leatherback turtle (*Dermochelys coriacea*), which has nesting sites mainly along the south coastline of the Huon Gulf, including the sandy beaches from the Labu Lakes to Salamaua within the inner Huon Gulf. Adults or juveniles of this species would only be exposed transiently to tailings subsurface plumes, if they were encountered, during their known deep diving to more than 1,000m water depth and ability to remain underwater for well over an hour (IUCN, 2018). However, the main pathway of trace metal bioaccumulation and biomagnification to species is from its preferred diet of gelatinous megaloplankton, such as jellyfish, which is a major component in its diet.

The inner Huon Gulf is not a key foraging area for leatherback turtles due partly to natural turbidity of the waters near the mouths of the Markham and Busu rivers and eleven other turbid rivers along the north shore of the Huon Gulf. The leatherback turtles are highly mobile species that forage over a much larger area of the Huon Gulf and northwestern Solomon Sea.

While the residual impacts for trace metal bioaccumulation and biomagnification impacts in jellyfish and other gelatinous megaloplankton (i.e., leatherback turtle prey) are assessed to be low, the residual impacts of DSTP-derived trace metal bioaccumulation or biomagnification up the food chain to leatherback turtles are assessed to be of **moderate** significance. This is based on a **very low** magnitude of impact (large foraging areas of leatherback turtles outside the inner Huon Gulf and low trace metal exposure to jellyfish) and a **very high** sensitivity due to this being an uncommon species with a declining population and with a restricted nesting habitat range in PNG. This species is also one of the few turtle species that dive to the depths where tailings subsurface plumes are predicted to form.

17.5.2. Residual Impacts of DSTP to Benthic Marine Ecology

The potential stressors arising from the proposed DSTP operation on the deep-slope and seafloor benthic habitats and biological communities (benthos) are:

- Benthic habitat loss or deterioration:
  - Loss of benthic habitat by smothering within the path of the tailings density current and depositional footprint, and other downslope and lateral areas of sedimentation due to gradual settling (cascade suspension) of fine-grained suspended tailings solids.
  - Deterioration of benthic habitat structural diversity due to granulometric changes (altered particle size distribution) compared to pre-disturbance deep slope and seafloor bed sediment particle size distributions.
- Changes in bottom sediment quality and pore water quality:
  - Exposure of benthic organisms to particulate-associated trace metals ingested by benthic fauna and infauna or incidentally ingested by benthic and epibenthic fish.
  - Alteration of nutrient content of benthic sediments compared to natural pre-disturbance levels.
  - Potential for toxicity due to bentho-pelagic coupling i.e., trace metals mobilised from deposited tailings solids into pore (interstitial) waters and overlying waters to infauna and epibenthic fauna and potential trace metal bioaccumulation.
- Reduction in species composition/abundance and biodiversity of benthic marine communities resulting from the above physico-chemical effects.
- Potential for bioaccumulation or biomagnification of trace metals in the benthic food web.

The residual impacts of the above key stressors on deep slope and seabed benthic ecology are assessed below.

17.5.2.1. Physical Impacts of Tailings Solids Deposition

Tailings solids deposition on the walls and floor of the receiving Markham Canyon is an inevitable consequence of DTSP operation, which will have significant physical impacts on benthic habitats, benthic macroinvertebrates and infauna communities.

Assessment of the depositional impact, based on the tailings solids discharge rate of 16.5Mtpa, is made particularly challenging because of the contemporaneous depositional impact of 60Mtpa of terrigenous sediment that is delivered to the Huon Gulf by the Markham, Busu and the other rivers along the north coast of the Huon Gulf.

In addition, episodic but frequent mass movement events (e.g., slumping) on the walls and floor of the Markham Canyon are expected to resuspend settled tailings solids and natural sediments, and transport both further down canyon as a turbidity current, resulting in their re-deposition at greater depths and greater dilutions of the tailings with natural sediments.

Prior to assessing the physical impacts of tailings solids on benthic habitats and benthos, summaries are provided of background natural sediment deposition and particle size distributions of natural sediments and tailings solids.

17.5.2.1.1. Background Natural Sediment Deposition

Numerical modelling, based on an estimate of 60Mtpa, of the behaviour and fate of terrigenous suspended sediment from river inputs reporting to the Huon Gulf, has been undertaken. The simulated depositional footprint of natural sediment over one year is shown in Figure 17.9 (Appendix J, Density Current, Plume Dispersion and Hydrodynamic Modelling), where it can be seen that the simulated deposition of natural sediment extends more than 20km offshore and includes the walls and floor of the Markham Canyon. The heaviest natural sediment deposition is predicted to occur offshore of the mouths of the Markham and Busu rivers in the same area where the proposed DSTP discharge will be located.

Over the deep slope below the DSTP outfall to the seabed of the Markham Canyon, the modelled natural background sedimentation rates of between 0.05 and 0.20m per year have been adopted. It is against these sedimentation rates that the tailings solids deposition rates from the modelling results (see below) have been compared.

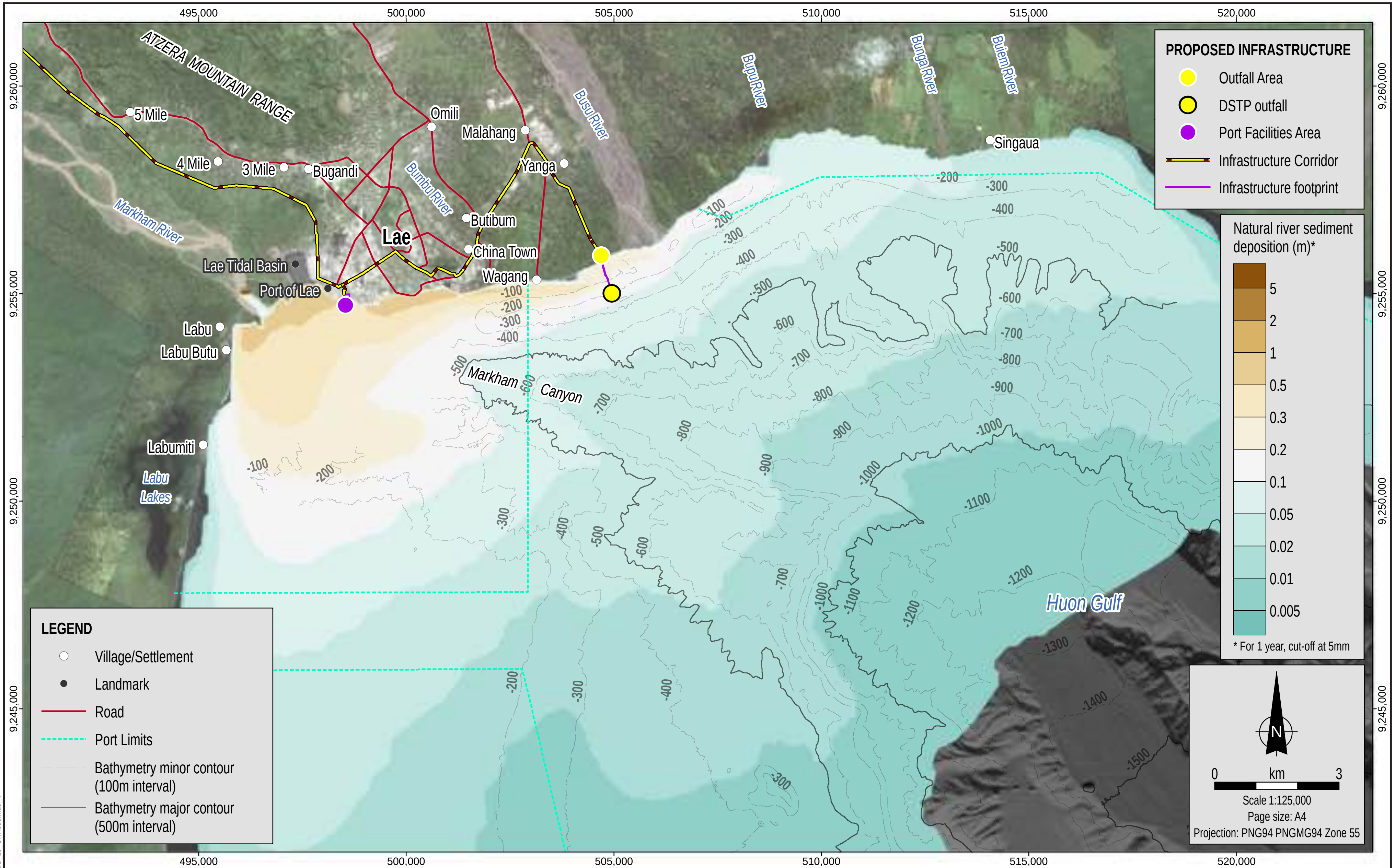
17.5.2.1.2. Results of Tailings Solids Deposition Modelling

Numerical modelling (Appendix J, Density Current, Plume Dispersion and Hydrodynamic Modelling) has simulated the deposition of tailings solids from the tailings density current (Figure 17.10), the deposition from tailings subsurface plumes (Figure 17.11) and the combined deposition of both the tailings density current and tailings subsurface plumes (Figure 17.12) after one year. These figures do not show deposition from natural (background) terrigenous sediments.

Figure 17.10 shows no deposition is predicted above the DSTP outfall. The figure also shows linear deposition as levees that are predicted to form either side of the main flow path for the tailings density current as it descends the steeply sloping north wall of the Markham Canyon. Similar features were observed at the Island Copper Mine in Canada (now closed) where tailings flowed in a leveed channel system on the floor of a fjord.

However, the simulation shows that deposition of 1 to 2m per year will occur on the floor of the Markham Canyon to a depth of about between 900 to 1,000m. In addition, thin areas of deposition (0.005m per year) are predicted to extend up to 3km to the east.

Figure 17.11 shows the predicted depositional footprint from subsurface tailings plumes after one year. The effects of ocean currents are clearly evident in this figure, indicated by the modelled transport of subsurface tailings plumes both to the east and to the west until the tailings solids within the plumes settle onto the ocean floor. The simulation of predicted deposition from subsurface tailings plumes shows no deposition shallower than the outfall depth at approximately 200m. Predicted deposition is highest at 0.3m per year around the 400m contour downslope from the DSTP outfall and is similar to the simulated deposition from natural sediment from river inflows shown in Figure 17.9. This means that that tailings solids will co-settle with natural sediment from riverine sources.



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File Name: 0520DD_10_F17.09_GRA

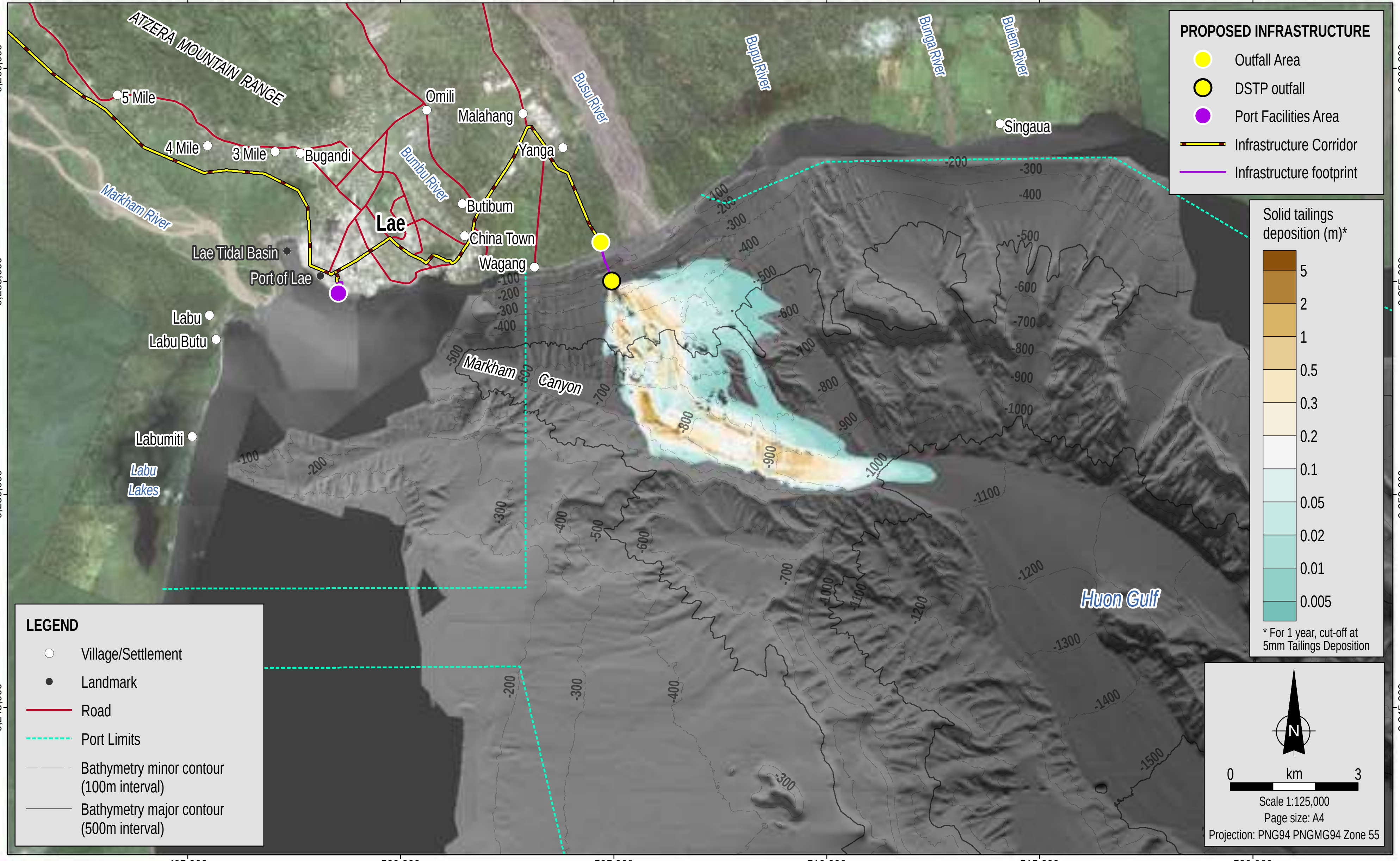
WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Modelled natural riverine sediment deposition footprint after one year

Figure No: 17.9

INDD Reference: 0520DD_10_GRA095.indd 4



Source:
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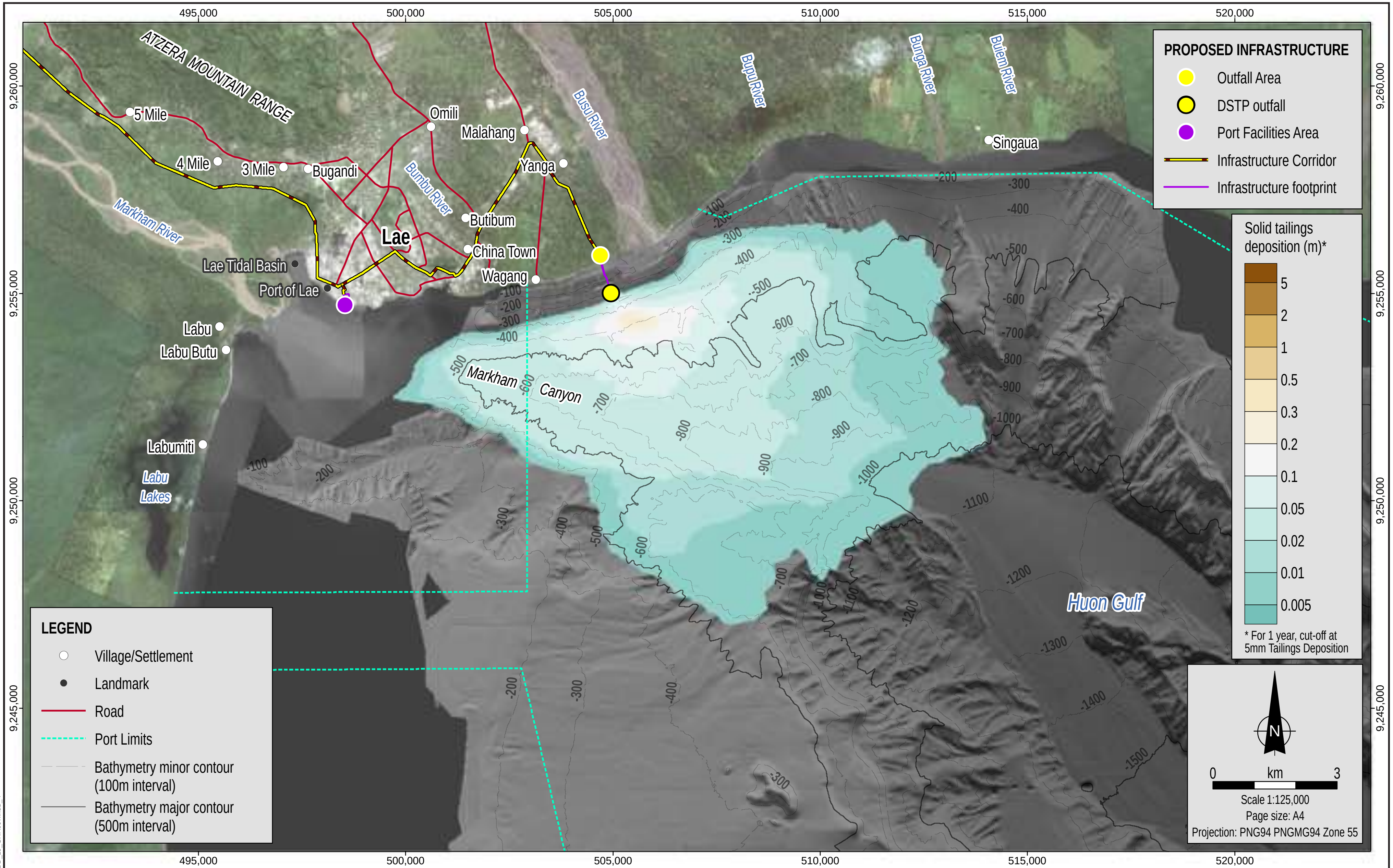
WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Modelled tailings footprint from the density current after one year

Figure No: 17.10

INDD Reference: 0520DD_10_GRA096.indd 4



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WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Modelled tailings footprint from subsurface plumes after one year

Figure No: 17.11

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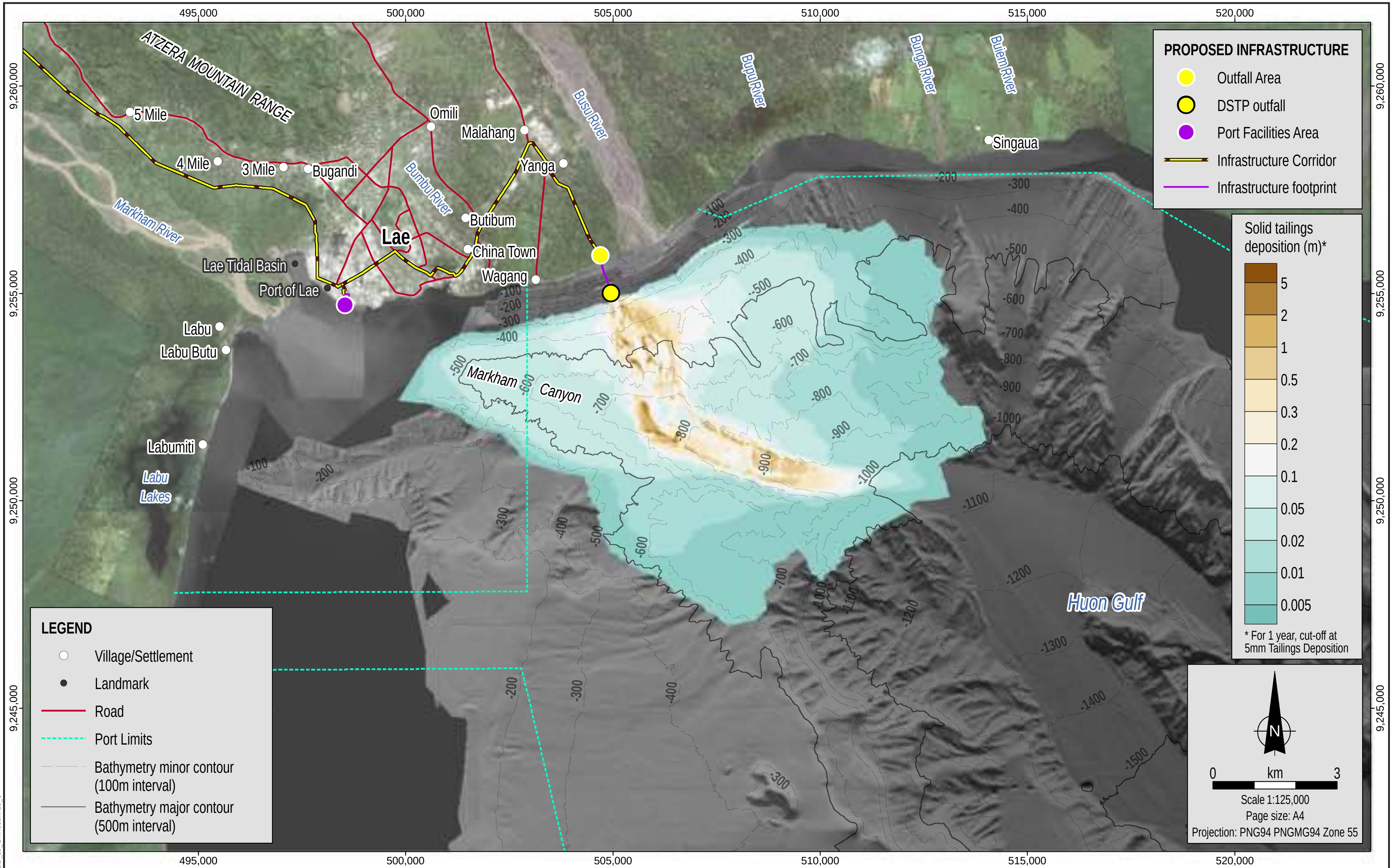

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File Name: 0520DD_10_F17.12_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Modelled total tailings footprint from subsurface plumes and density current after one year

Figure No: 17.12

Figure 17.12 shows the predicted depositional footprint from both the tailings density current and the subsurface tailings plumes combined and shows that the thickest deposition is predicted to occur along the pathway of the density current.

The anticipated DSTP discharge duration is 28 years, although modelled for 27 years (which was based on an earlier Project description at the time the modelling commenced), and a similar pattern of deposition is expected to occur each year such that considerably thicker sequences of tailings and natural sediment will build up on the ocean floor than shown indicated in Figure 17.10, Figure 17.11 and Figure 17.12.

However, given that the year-long oceanographic and sedimentological measurements in the Markham Canyon (Appendix K, Oceanographic Investigations of the Huon Gulf and Appendix M, Physical, Chemical and Biological Sedimentology of the Huon Gulf) show the occurrence of the episodic but frequent mass movement events triggering turbidity currents, it is expected that considerable reworking of deposited sediments will occur. A proportion of the settled tailings solids and natural sediments will be eroded by the turbidity currents and transported further down canyon before being redeposited at greater depth.

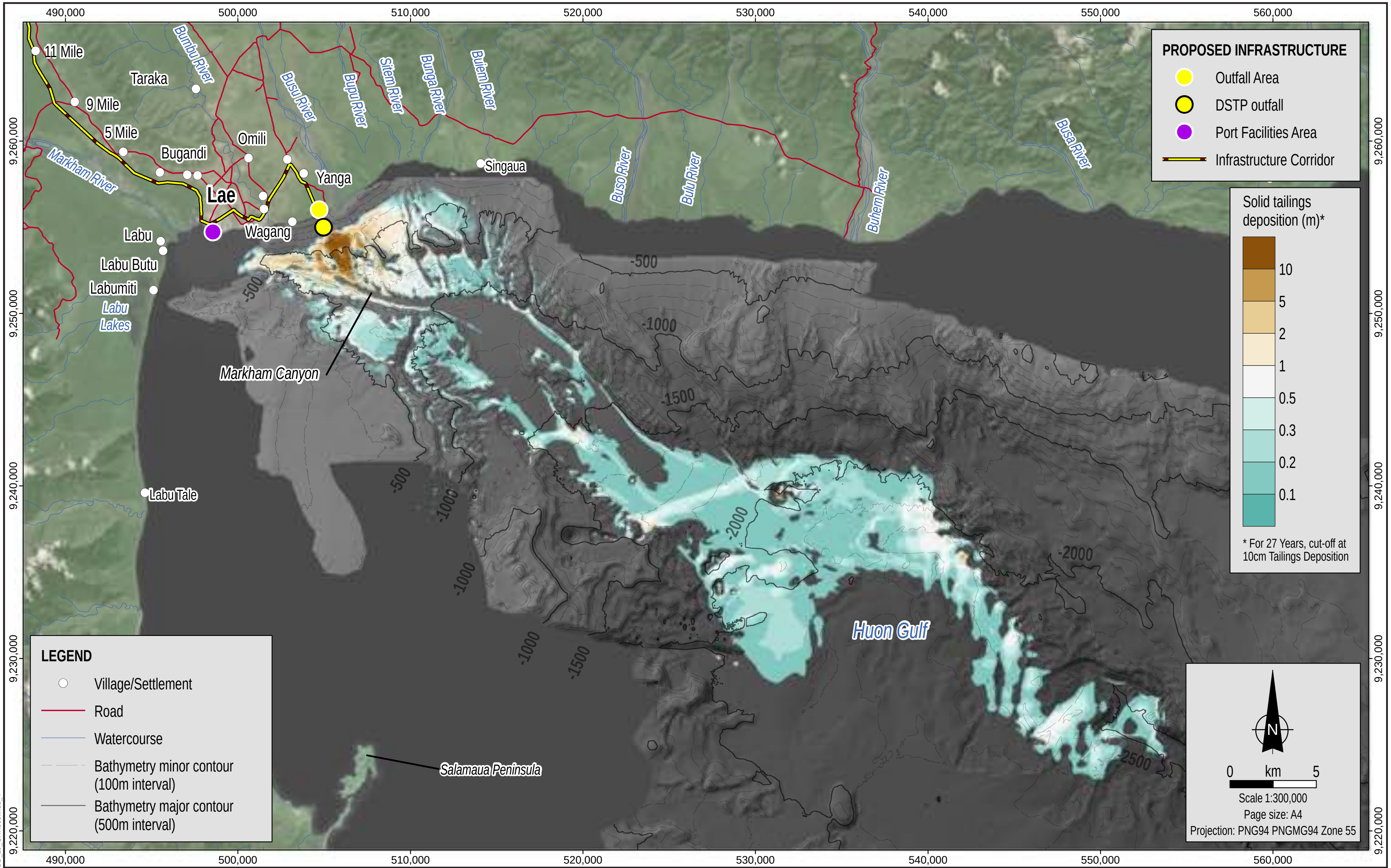
Numerical modelling has simulated the combined deposition over 27 years from both the tailings density current and subsurface tailings plumes, and simulated the effect of one ten-minute mass movement event per year. The mass movement event simulated 408,000m^3 (about 1.08Mt) of natural sediment being mobilised by a slope failure located at approximately 400m water depth on the opposite canyon wall to the DSTP outfall.

The simulation was set up on a coarse resolution grid, assumed a slumping event of three 50m resolution cells (150m length) by two cells (100m width) over a 27m depth range, and included sediment composition based on box core samples collected by IHAconsult (Appendix M, Physical, Chemical and Biological Sedimentology of the Huon Gulf). Simulated mass movement event density current speeds have compared well with observed episodic turbidity current speeds in the Huon Gulf (Appendix J, Density Current, Plume Dispersion and Hydrodynamic Modelling).

The simulated depositional footprint after 27 years, inclusive of a single mass movement event in each year, is shown in Figure 17.13 and reveals that the thickest deposits of tailings solids (more than 10m) occur between the DSTP outfall and the bottom of the north wall of the Markham Canyon.

The 10m deposits shown on the canyon wall in Figure 17.13 are a conservative model result because it is expected that ongoing episodic natural slumping would occur on the canyon wall, which would deliver the tailings deposits to deeper depths. Additionally, the presence of down-slope channels, both active and abandoned, enable downslope migration of natural sediments and would similarly serve to allow deposited tailings to move downslope to the Markham Canyon on an episodic basis (Appendix J, Density Current, Plume Dispersion and Hydrodynamic Modelling). The modelling did not include these mechanisms for redistributing the 10m tailings deposits deeper down in the canyon.

Figure 17.13 also shows that the previous thick deposition of tailings solids on the canyon floor has been eroded and transported through the canyon to be redeposited mostly in thin deposits on the canyon floor at water depths of between 1,500m and 2,500m.



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WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Modelled total tailings footprint after 27 years of DSTP operation and inclusive of one mass movement event per year

Figure No: 17.13

To appreciate the incremental deposition that the proposed future discharge of tailings solids will bring to the Huon Gulf, the ratio of tailings deposition to existing natural deposition has been modelled and is displayed in Figure 17.14. Following the 27 years of simulated tailings discharge (Figure 17.13 and Figure 17.14), the top panel of Figure 17.14 displays the ratio of tailings solids deposition to natural sediment deposition: a brown colour indicates that more tailings solids than natural sediment have deposited, whereas a green colour indicates that more natural sediment deposited than tailings solids. A value of 10% means that the deposition in this area is made of 10% tailings and 90% natural sediment. A value greater than 50% means that there is predicted to be more tailings deposited on this location than natural sediments, while a value less than 50% means there is predicted to be more natural sediment deposited at a given location. The ratio is not shown for cells where the deposition from both natural sediment and tailings are each less than 0.1m after 27 years.

As an example, towards the mouth of the Markham River, the colour is green and indicates that 100% of predicted deposition is made of natural sediment. On the other hand, at a depth of 2,000m, the brown colours indicate that the predicted deposition is predominantly composed of tailings solids. That being said, the bottom panel of Figure 17.14 shows the predicted tailings deposition thickness after 27 years (the same as Figure 17.13): in deep water, tailings solids deposition is predicted to be the predominant deposit compared to natural sediment and where the predicted tailings thickness after 27 years is less than 0.5m.

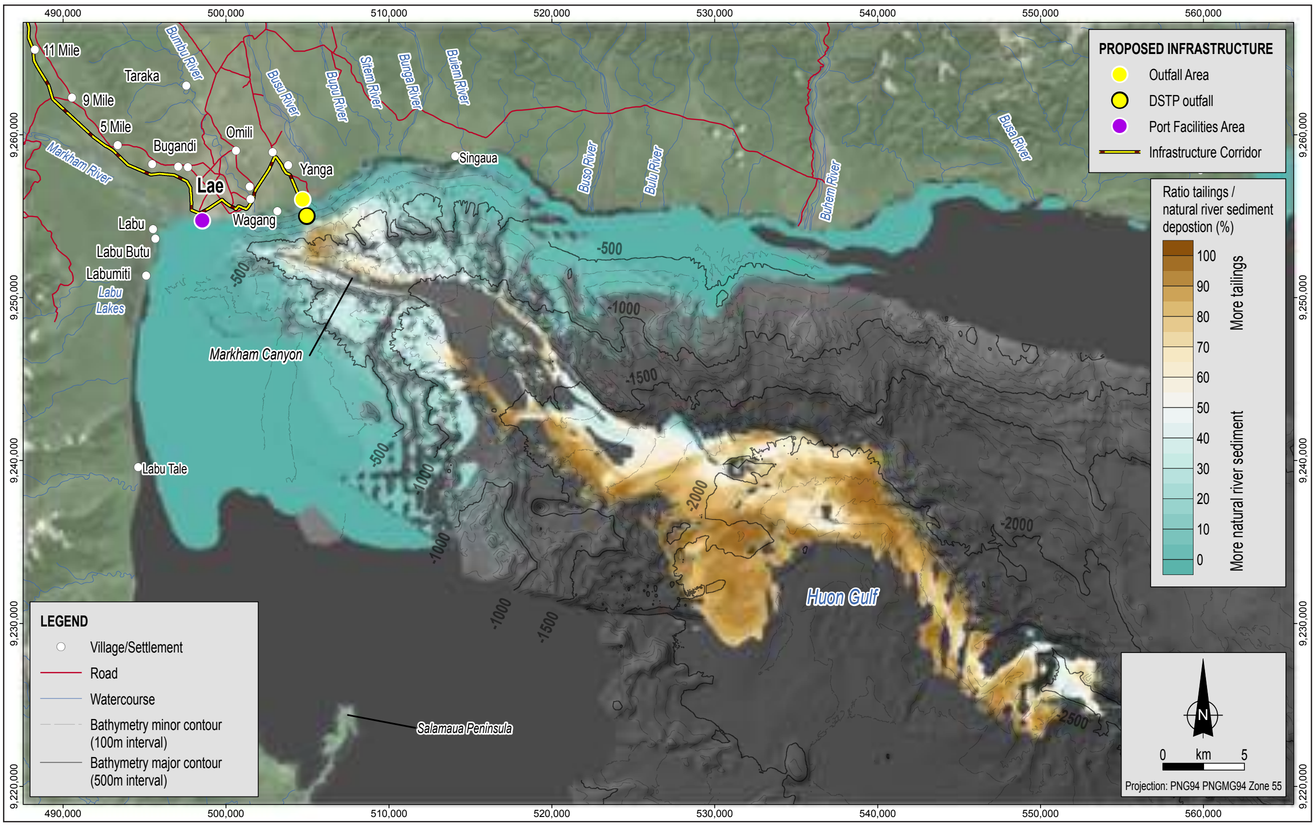
In summary, once sediment (tailings solids or natural sediments) deposits on the floor of the Markham Canyon, mass movement events will erode and convey these sediments into deeper water to the east, leaving the canyon floor clear of accumulations of tailings (and fresh natural sediment), as is evident in the existing bathymetric maps. This is consistent with field measurements of turbidity currents occurring in succession at ADCP moorings in the Markham Canyon and then in the deeper basin, indicating that the mass movement events transport material through the canyon into deeper waters toward the New Britain Trench (Appendix K, Oceanographic Investigations of the Huon Gulf).

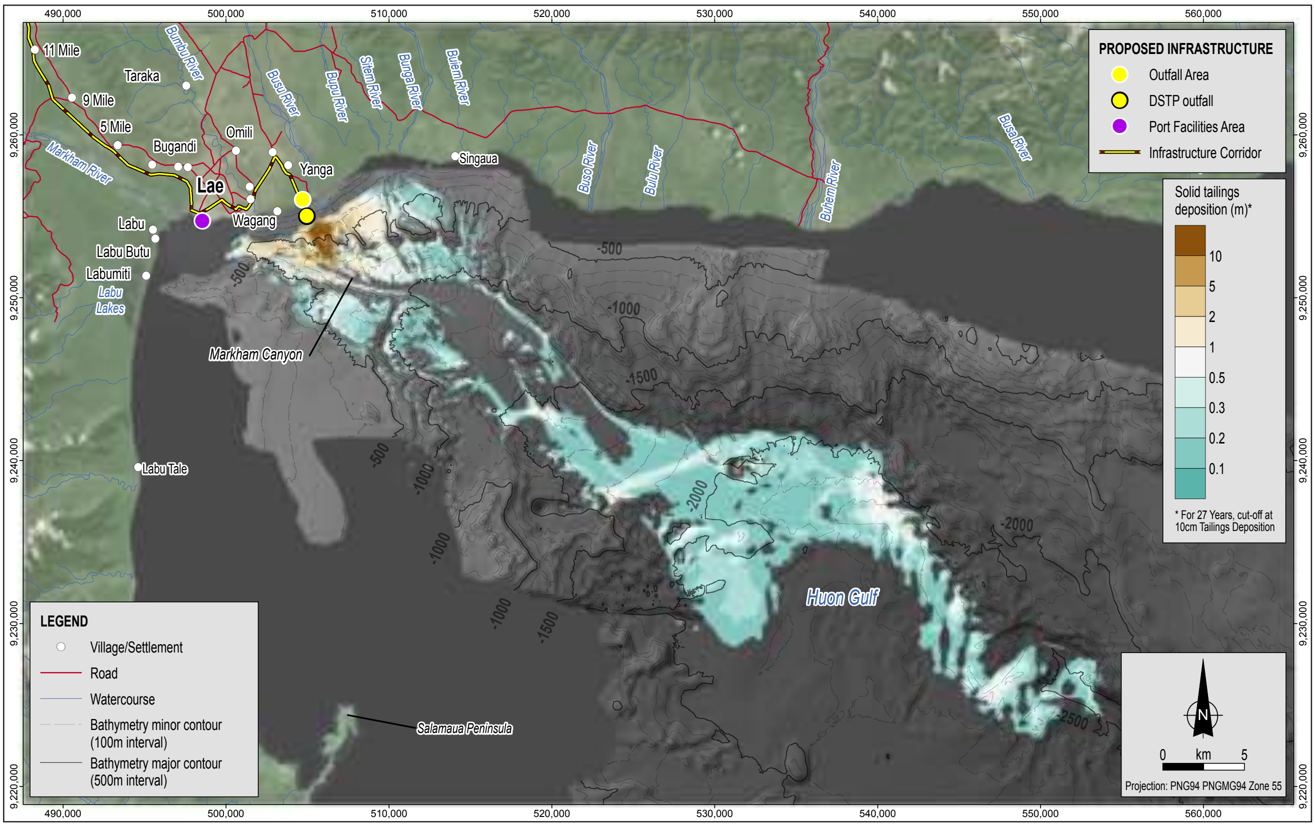
After closure of the mine and cessation of DSTP, natural sedimentation from riverine sediment and mass movement events in the Markham Canyon will continue to occur and is expected to rework the tailings deposits and eventually bury the deposits. Figure 17.15 shows the predicted annual rate of natural sedimentation after tailings discharge ceases. Burial is predicted to occur slowly (less than 1mm per year) in deep water below about 1,000m, but quickly (up to about 600mm per year) on the north wall of the canyon between 300 and 400m water depth.

17.5.2.1.3. Sediment and Tailings Solids Particle Size Distributions

Besides the potential for physical smothering impacts associated with tailings solids deposition on benthic habitats and benthos, changes in the particle size distribution of benthic sediments as a result of tailings solids deposition can also affect the benthos.

Table 17.11 gives the particle size distribution of box sediment cores collected along the Markham Canyon and at two deep slope areas. The table also presents particle size information on the tailings.





Source: DSTP-ModellingReport_Final_R1, Figure 4.7

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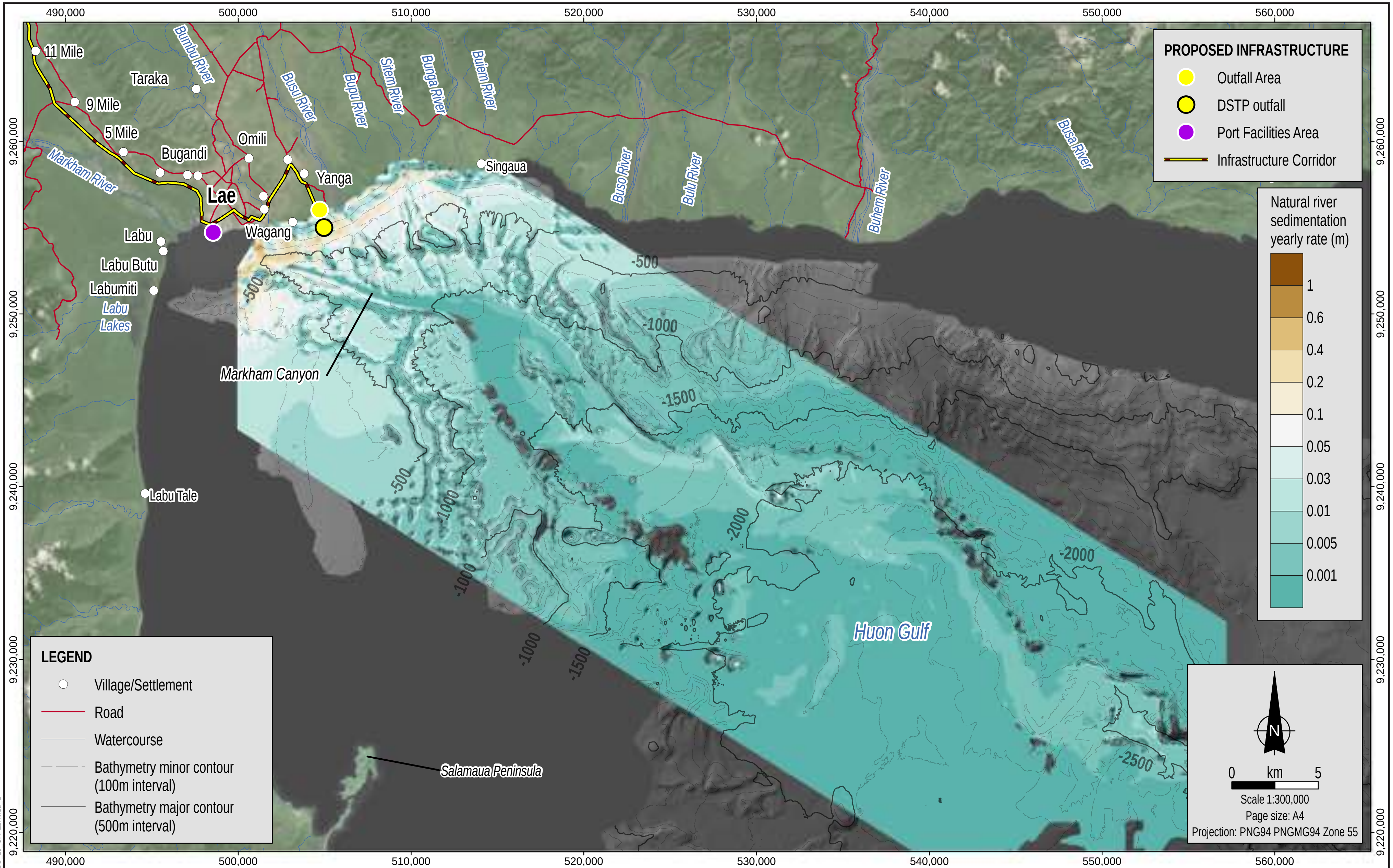
WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Ratio of tailings solids to natural sediments (top panel) and predicted tailings depositional thickness (bottom panel) after 27 years

Figure No: 17.14



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File Name: 0520DD_10_F17.15_GRA

WAFI-GOLPU JOINT VENTURE

Wafi-Golpu Project

Predicted annual rate of natural sedimentation after cessation of DSTP

Figure No: 17.15

Table 17.11: Particle sizes of natural sediments and tailings solids

Site Code	Description	Distance from DSTP outfall (km)	Depth (m)	Particle Size Distribution (µm)		
				D_{10}	D_{50}	D_{90}
Tailings samples:						
TS1	Tailings 1 bench-scale pilot test sample	0	200	2.5	27.0	110
TS2	Tailings 2 bench-scale pilot test sample	0	200	2.5	27.0	110
Deep slope natural bed sediment box core samples:						
BC01	Soft muds progressively consolidating with depth	10.7*	355	2.38	8.50	37.3
BC15	30 to 50mm deep soft brown mud over semi-plastic clay grading to plastic clay with depth	17.0#	1,656	2.57	9.86	87.1
Markham Canyon natural bed sediment box core samples:						
BC04	1 to 3mm deep, fine brown silt over lithic black sands	2.8	1,489	3.58	31.6	441
BC06	1 to 2mm deep, fine brown silt over coarse black sands with gravels and pebbles	11.3	1,098	17.6	220.0	733
BC12	20mm of soft brown mud over coarse black sand grading to gravel	20.8	1,489	3.53	32.6	441
BC13	80mm of soft brown mud over 80mm of fine dark-grey sand	33.3	2,001	3.56	30.9	199

Source: Bed sediment box core samples (Appendix M, Physical, Chemical and Biological Sedimentology of the Huon Gulf); Tailings samples (Appendix J, Density Current, Plume Dispersion and Hydrodynamic Modelling); * BC1 site is located on deep slope 10.7km south of Markham Canyon; # BC15 is located on deep slope 17km north of Markham Canyon.

In Table 17.11, the median particle size distribution (i.e., D_{50}) of deep slope bed sediments (i.e., sediment box core sites BC01 and BC15) are low, being between 8.50 and 9.86µm. Although the raw tailings samples have a D_{50} value of 27µm, it is only the very fine fraction having a D_{50} value of 13.5µm that was modelled by Tetra Tech (Appendix J, Density Current, Plume Dispersion and Hydrodynamic Modelling) as being transported in dilute subsurface plumes that would reach these outlying deep slope areas. For example, in Figure 17.11, very fine tailings solids deposition contributes very little (<0.1m) to deposition compared to the natural sediment deposition (1.3 to 2.2m) after 27 years of DSTP operation.

Similarly, the tailings solids median particle size value of 27µm is similar to most of the median particle size values (D_{50} ranging from 30.9 to 32.6µm) for the Markham Canyon seabed sediments, with the exception of the D_{50} value of 220µm for sediment box core site BC06, where there is a natural high proportion of coarser natural bed sediments. Site BC06 is located in a region of the floor of the Markham Canyon where coarse-grained bed load sediments and sand waves are present.

In general, the particle size distribution of settleable tailings solids is similar in magnitude to background natural bed sediments and, with the inevitable mixing of tailings solids with natural sediments, substantial differences between the particle size distributions of post-discharge tailings and natural sediments is not expected.

17.5.2.1.4. Residual Impacts on Benthic Habitats and Benthos

The continuous discharge of tailings solids is expected to cause obliterative and semi-obliterative impacts on the deep slope benthic habitats and biological communities, particularly below the DSTP outfall where tailings will likely form most of the settling material.

These impacts will be similar to the existing impacts from the natural sediment deposition in the Huon Gulf.

The loss or degradation of deep slope, Markham Canyon and deep sea benthic habitats and benthos is expected to occur within the following different zones of tailings solids deposition and sedimentation:

- Obliterative sedimentation impact zone:
  - A zone characterised by the rapid settling of the coarser fraction of tailings solids (greater than 125µm size fraction) such as fine particles and larger sized components up to 1,000µm (based on predicted maximum tailings solids particle size grading).
- Semi-obliterative sedimentation impact zone:
  - A zone characterised by the slower settling of the coarser fraction of tailings solids (i.e., solids greater than 20µm and less than 125µm size fraction corresponding to medium silts to very fine sands). This zone will be adjacent to or on the periphery of the descending tailings density current, which may vary as the route of the density current changes with time.
- Non-obliterative sedimentation impact zone:
  - The delayed settlement of fine tailings solids (typically less than 20µm and averaging around the 14µm size fraction) present in tailings subsurface plumes and transported laterally in the direction of ambient deep-water currents.

After discharge from the DSTP outfall, the tailings density current will flow by gravity down the deep slope towards the Markham Canyon. During this deep slope descent, the larger size fractions of tailings solids will settle rapidly and smother the seabed downslope of the discharge and the immediately adjacent area.

Within the obliterative impact zone, benthic habitats and biological communities will be blanketed by a deep layer of tailings solids resulting in the burial and mortality of most of the meiobenthos and macroinvertebrate infauna. The more mobile macroinvertebrates, including epibenthic forms such as decapod crustaceans (e.g., ghost shrimps, Callianassidae), as well as benthic and epibenthic fish (e.g., marine gobies, Gobiidae) will be able to move away from areas of high sedimentation, whereas sessile macroinvertebrates or macroinvertebrates of low mobility are likely to be buried and not survive.

IHAconsult (Appendix M, Physical, Chemical and Biological Sedimentology of the Huon Gulf) undertook box core sampling of benthic macroinvertebrates along the Markham Canyon and at off-canyon sites on the deep slopes (sample sites BC01 and BC15 shown in Table 17.11 above). While box core sampling could not be undertaken on the steep slope (slope of 20°) below the DSTP outfall, the macrobenthos of the deep slope off-canyon sites BC01 and B15 have been used as a surrogate for the macrobenthos likely to be present downslope of the DSTP outfall.

The macrobenthos was comprised of very low densities (two individuals per box core) of polychaete worms (Capitellidae and Spionidae) and one marine goby (Gobiidae). Polychaete worms have low mobility but also have the ability to burrow to the surface if their habitat is blanketed in tailings solids, but this may depend on the species.

In the zone of very light tailings solids sedimentation, primarily from the delayed settling (cascade suspension) of fine tailings solids in progressively diluting subsurface plumes, physical impacts on benthic habitats and benthos will be less pronounced, owing to the settling of tailings with particle sizes similar to natural settling sediments and the mixing with these natural sediments.

The benthic macrofauna of the Markham Canyon was found to be very low in abundance with many bed sediment samples (e.g., box core sites BC04 through BC09) having zero counts of macroinvertebrates (Appendix M, Physical, Chemical and Biological Sedimentology of the Huon Gulf). However, one box core site (BC14) had a wider diversity of benthic macroinvertebrates (five species) but still of very low abundance, comprising mainly polychaete worms (Capitellidae and Syllidae), one sea cucumber (Holothuria) and two unidentified species. This site may have been a sheltered site less exposed to bed sediment transport along the Markham Canyon, such as the episodic but frequent turbidity currents resulting from mass movements, and the fact that a mobile bed substratum is not conducive to macroinvertebrate colonisation and establishing viable populations.

The meiobenthic fauna in all box core bed sediment samples revealed low diversities and abundances, which varied between sites. Relatively higher meiofauna densities were observed outside the Markham Canyon compared to on the canyon floor. The meiobenthic assemblages were dominated by marine nematode worms (Nematoda) followed by much lower numbers of herpacticoid copepods (Harpacticoida), small species of polychaete worms (Polychaeta) and predatory hydrozoans (Hydrozoa). Many of these species will perish in the obliterative and sub-obliterative impact zones of high tailings solids deposition within the canyon floor. In addition, there is predicted frequent reworking (e.g., erosion, re-suspension and redistribution) of previously settled tailings solids by episodic but frequent turbidity currents arising from mass movement events.

The literature was reviewed for case studies of impacts within tailings solids deposition footprints at other DSTP operations. However, the findings may also take into account the sediment quality of the settled tailings solids.

Studies of the macrobenthos and meiobenthos at the Lihir Gold Mine showed a decrease in the densities of animals in the areas affected by mine-derived sediments (i.e., where tailings/sediment mixtures were more than 10mm thick) compared to natural sediment reference sites, particularly in the areas of thicker deposits closest to the mine (CNS, 2009). An additional finding was that, while the diversity of meiofauna decreased in tailings/sediment mixtures more than 10mm thick, the densities and biomass remained the same. This indicated that the remaining sediment-tolerant meiofauna species could build up their populations in the absence of competition from meiobenthic species that were less sediment tolerant.

For the Island Copper Mine at Rupert Inlet, British Colombia., Canada, Ellis and Heim (1985) monitored macroinvertebrate infauna at three levels of tailings solids deposition during operations: light (3.5cm depth), moderate (60cm depth) and heavy (>60cm depth). That study reported the following findings:

- Within the light and moderate tailings deposition zones, there was a clear trend of decreasing infauna abundances.
- Within the heavy tailings solids depositional zone (i.e., the most impacted zone), there was an increase of infauna abundances, which was attributed to the presence of opportunistic marine worms (Polychaeta) in response to population bursts of a few small food species.
- Burd (2002) then monitored infauna at stations within three distance zones from the outfall: near-field (<5km), mid-field (5 to 16km) and far-field (>20km), with the following findings:
    - There were distinct spatial zones of influence, evident from tailings and sediment copper based on consistent differences in tailings thickness, sediment copper levels, and univariate and multivariate biotic factors.

- A persistent and clear decline in near- and mid- field species richness to below far-field levels was coincident with sediment copper levels greater than 300mg/kg.
- Abundance and taxa numbers increased rapidly (within two years) in stations recovering from the heaviest tailings deposition. However, the overall community composition was still significantly distinct in the near- and mid-field three years after mine closure.

In general, the diversity of benthic macroinvertebrate and meiofauna is expected to increase progressively to natural levels as tailings sedimentation rates decrease with distance from the tailings density current and from the main downslope and lateral zones of tailings deposition. This general pattern of decreasing biological impact with decreasing tailings solids deposition has been recorded for other coastal mines having DSTP systems, such as the aforementioned Island Copper Mine in Canada (Ellis, 1989; Ellis et al., 1995), the Misima Gold mine at Misima Island in PNG (NSR, 1986) and the Lihir Gold Mine in PNG (CNS, 2009), where the densities and biomass of invertebrate fauna were inversely proportional to tailings solid deposition. A similar scenario is predicted for the benthic impact of tailings solids deposition on the submarine deep slopes in the inner Huon Gulf and the Markham Canyon.

In 2007, in part to address general concerns about impacts of tailings in the marine environment, the Scottish Association for Marine Science (SAMS, 2010b) was engaged to conduct an independent scientific review of the studies and impacts of DSTP in PNG, funded by the European Union[10]. The study included a detailed quantitative survey to investigate the effects of deep sea tailings placement on deep-sea benthic communities at an operating mine (Lihir) and a closed mine (Misima). The findings are summarised as follows:

- At Lihir, a detailed comparison of depth-matched stations showed the abundance, diversity and community structure of meio- and macrofauna was unambiguously reduced in seafloor areas of containing mine derived sediment (including tailings) to a depth of at least 2,020m when compared to reference sites.
- At Misima, three years after cessation of the tailings discharge, the benthic community where tailings solids and soft waste rock had deposited was very different from that at reference locations in terms of diversity, abundance and in the structure of the assemblage. It was observed that while tailing deposits had been rapidly colonised by meiofauna and the community structure at some impacted stations had moved closer to the nematode-dominated pattern typical of deep-sea sediments, SAMS concluded that it would be premature to consider the Misima stations in terms of recovery.

At the Lihir and Misima island DSTP locations, many of the benthic fauna comprises sediment-intolerant species that are exposed mainly to light sedimentation and marine snow[11] compared to the large volumes of terrigenous natural sediments (60Mtpa) that enter the Huon Gulf where the benthic fauna would be expected to display a greater sediment tolerance.

[10] As part of the SAMS study, Draft Guidelines for Deep Sea Tailings Placement in PNG were prepared and define the environmental criteria and studies required to assess a DSTP option, and are the first independently developed guidelines specifically to assess DSTP anywhere in the world. Although not yet included in the Regulations to the *Environment Act* 2000, the guidelines are given force through the regulatory EIS process, by demonstrating conformance to the satisfaction of the PNG Government. Attachment 1 describes the Project's conformance with the guidelines.

[11] The settling of flocculated fine suspended sediments and particulate organic matter falling to the seabed from higher up in the water column.

Overall, the residual physical impacts of tailings on the benthic habitats and benthos of the deep slope below the DSTP outfall and adjacent lateral areas of the tailings density current are assessed to be of **low** significance based on a **moderate** magnitude of impact (large areal extent combined obliterative and sub-obliterative footprint compared to natural background) and a **low** sensitivity (common and resilient, widespread deep slope macrobenthos species). Similarly, the residual physical impacts of tailings solids depositing on the floor of the receiving Markham Canyon and deep-sea environment are assessed to be of **low** significance, based on a **low** magnitude of impact (high bed sediment transport and occasional turbidity flows from mass movement events) and a **low** sensitivity (common and widespread sediment tolerant benthic species).

Due to the high natural sedimentation rates, recovery of the oceanic benthos on the ocean floor in the Huon Gulf is likely to be substantially faster compared to settings where there is low natural sedimentation. This recovery of the pre-existing benthic environment is due to the opportunistic colonisation of deposited sediments that is heavily influenced by episodic major disturbances from mass movement and turbidity current events, which erode, re-transport and re-deposit previously deposited material in increasingly deeper water. These processes are occurring now and are expected to continue during the 28 years of proposed DSTP discharge and afterwards in the post closure period, the latter without the addition of tailing solids. Besides the physical impacts of tailings solids deposition on the seabed habitats and benthos, an assessment of sediment quality (e.g., potential trace metals toxicity and bioaccumulation) is assessed below.

17.5.2.2. Sediment and Pore Water Quality Impacts on Deep-water Benthos

The main potential stressors on benthic macroinvertebrates and the meiobenthos of the deep slope and seabeds of the Markham Canyon and deep sea are:

- Changes in the nutritive content to natural sediments due to tailings solids
- Residual toxicity of deposited tailings and interstitial pore waters
- Bioaccumulation of trace metals in benthic fauna and potential biomagnification of trace metals in the food web

The residual impacts of these potential stressors are assessed below. However, prior to assessing trace metal toxicity and bioaccumulation impacts the trace metals in natural sediments and raw tailings solids have been summarised and compared to ANZECC/ARMCANZ sediment quality guidelines (ANZECC/ARMCANZ, 2000) and updates made by Simpson et al., 2012. There are no PNG guidelines for sediment quality.

17.5.2.2.1. Comparison with Sediment Quality Guidelines

Table 17.12 presents total trace metal concentrations in natural sediments and raw tailings solids in comparison with ANZECC/ARMCANZ sediment quality guidelines. In Table 17.12, light grey shading denotes exceedance of Sediment Quality Guideline Value (SQGV) and dark grey shading denotes exceedance of SQGV-High. The SQGV is a value that if not exceeded, is unlikely to result in effects to benthic biota. The SQGV-High is a value that if exceeded there will be a high probability of effects to benthic biota.

In Table 17.12, the total metals in Tailings 1 and 2 were of the same order of magnitude. In comparison with average values of Markham Canyon bed sediments (i.e., sites BC04 through BC13), the averages of the raw tailings solids were significantly higher than the natural sediments by 3-fold for arsenic, 80-fold for chromium, 19.3-fold for copper, 7.3-fold for nickel and 9.3-fold for zinc. The concentrations of lead in the raw tailings solids were of similar magnitude as the natural bed sediments of Markham Canyon.

Table 17.12 reveals that, with the exception of box core sediment sampling site BC15, there is no apparent spatial trend in the benthic sediment geochemistry concentrations of total trace metals with distance from the major rivers or by depth. All of the total nickel natural sediment values exceeded the SQGV and, in one case, exceeded the SQGV-High for natural sediment at site BC15. Most of the tailings solids trace metal concentrations (measured as total recoverable metals) exceeded their respective SQGV and SQGV-High trigger values, with the exception of cobalt and lead. Arsenic concentrations in the Tailings 1 sample were equal to the SQGV (20mg/kg) and arsenic in the Tailings 2 sample were less than the SQGV, and both were well below the SQGV-High value of 70mg/kg.

In terms of EDTA weak-acid extractable trace metal concentrations (i.e., the form that is more bioavailable), all the values were below their respective SQGVs.

Analysis of tailings samples equivalent to Tailings 1 and Tailings 2 (referred to as BT3 and BT4) was conducted during a long term study on tailings geochemistry, metals release and bioavailability (Appendix L, Tailings Ecotoxicology and Geochemistry: report 'Long-term lab study of Wafi-Golpu tailings: metal geochemistry, release and bioavailability in deposited tailings-sediment mixtures - Stage 1'). That study found that there was high variability in the metals content of the tailings compared to the previous short-term testwork by CSIRO (upon which the data in Table 17.12 is based) – particularly for copper and zinc. In the long-term tailings testwork, total copper and zinc were 37 to 63% and 4 to 12%, respectively, of the concentrations in tailings used in the short-term testwork. Weak acid extractable concentrations (i.e., potentially bioavailable) copper and zinc were 62 to 69% and 2 to 3%, respectively, of the concentrations in tailings used in the short-term testwork. This indicates the values from the short-term CSIRO study used in this assessment are conservative.

Table 17.12: Comparison of natural sediments and tailings with sediment quality guidelines

Site	Distance from Outfall (km)	Site Depth (m)	Total metal concentration in sediment (mg/kg, dry weight)						
			Co	As	Cr	Cu	Ni	Pb	Zn
Raw tailings solids:									
Tailings 1	0	200	19	20	578	1,240	267	8.0	656
Tailings 2	0	200	18	15	622	990	289	7.3	522
Off-canyon wall sites:									
BC01	10.7 S	355	–	–	–	–	–	–	–
BC15	17.0 N	1,656	32	9	32	92	103	8	79
Markham Canyon floor sediment sites:									
BC04	2.8	1,489	15	6	15	48	34	5	59
BC06	11.3	1,098	16	<5	16	54	33	<5	62
BC12	20.8	1,489	19	5	19	63	40	5	64
BC13	33.3	2,001	20	7	20	66	46	7	69
ANZECC/ARMCANZ marine sediment quality guidelines:									
SQGV	N/A	N/A	N/A	20	80	65	21	50	200
SQGV-High	N/A	N/A	N/A	70	370	270	52	200	410
Global average crustal abundance:									
Seabed *	N/A	N/A	13	5	60	56	35	–	92

Source: Appendix M, Physical, Chemical and Biological Sedimentology of the Huon Gulf; ANZECC/ARMCANZ (2000); N/A denotes not applicable; Dash (–) denotes not measured. Light grey shading denotes exceedance of Sediment Quality Guideline Value (SQGV) and dark grey shading denotes exceedance of SQGV-High. *Denotes literature value for shallow coastal water bed sediments (Salomons and Förstner, 1984).

17.5.2.2.2. Changes in the Nutritive Content of Tailings Solids Deposits

IHAconsult (Appendix M, Physical, Chemical and Biological Sedimentology of the Huon Gulf) assessed the background concentrations of total organic carbon in bed sediment samples and in settling suspended sediments in sediment traps.

Concentrations of total organic carbon, which are used as a surrogate measurement of the nutritive content of sediments, were low. All natural suspended sediment samples comprised less than 1% total organic carbon, indicating that while the dominant source of suspended sediment in the Huon Gulf is riverine it does not contain a significant organic component and is likely dominated by freshly eroded sediment, being predominately mineralised (i.e., lacking a biofilm) from the Finisterre Range.

The organic carbon content of highly diluted tailings slurry after discharge has very low dissolved organic carbon concentrations (from milling and process plant reagents and chemicals) and the tailings solids are of raw mineralogical composition lacking in nutritive value. Any dissolved organic carbon present will report in the tailings liquor, which will be transported within the tailings subsurface plumes that shear off from the descending tailings density current.

Overall, the residual impacts of lowered nutritive value of suspended tailings solids on benthic sediments are assessed to be of **low** significance, based on a **moderate** magnitude of impact (limited areas of high to moderate tailings solids sedimentation) and a **low** sensitivity (common and widespread benthic macroinvertebrates, meiobenthos and deep-water benthic fish).

17.5.2.2.3. Residual Toxicity Impacts on Benthic Fauna and Infauna

The pathways of trace metal exposure contributing to potential toxicity to benthic organisms include:

- Dissolved trace metals in the overlying water
- Dissolved trace metals in the sediment interstitial pore water
- Ingestion of particulate-associated trace metals

The potential impacts of residual toxicity within settled tailings deposits, interstitial pore waters and overlying waters has been assessed on the basis of the following two key ecotoxicological laboratory-based studies carried out in support of the EIS:

- A short-term study: Ecotoxicology and Chemistry of Wafi-Golpu Bench-Scale Tailings by CSIRO (Appendix L, Tailings Ecotoxicology and Geochemistry: report ‘Ecotoxicology and Chemistry of Wafi-Golpu Bench-scale Tailings’)
- A long-term study: Ongoing long-term laboratory study of Wafi-Golpu tailing: metal geochemistry, release and bioavailability in deposited tailing-sediment mixtures by CSIRO (Appendix L, Tailings Ecotoxicology and Geochemistry: report, ‘Long-term lab study of Wafi-Golpu tailings: metal geochemistry, release and bioavailability in deposited tailings-sediment mixtures - Stage 1’)

The results of these ecotoxicological studies are summarised below.

17.5.2.2.3.1. CSIRO Short-term Laboratory Study of Tailings Samples

The results of the ecotoxicological tests on tailings samples are summarised as follows:

- Within the tailings solids overlying water (supernatant) test treatments, trace metal analyses revealed:
  - An ongoing release of copper from solids into the dissolved phase (<0.45µm).

    - Release of manganese, nickel and zinc from the tailings solids into the dissolved phase, but the release of these metals into seawater started to decrease after about six days.
- The toxicity and bioaccumulation of the tailings solids was assessed using various admixtures of natural sediment collected from the Huon Gulf; the first time this approach has been employed. The results indicated:
    - The Huon Gulf natural sediment resulted in a lower reproductive output (but not lower survival) of the test organisms (amphipod and copepod) compared to a standard sediment control.
    - The reduced reproduction of the benthic organisms may be due to a lack of natural organic matter and possibly sediment-bound metals.
    - Toxicity of tailings solids to the amphipods and copepods was observed when concentrations were more than 10% for Tailings 1 and more than 1% for Tailings 2.
    - The toxicity of tailings was likely to be attributed to copper (Tailings 1 and 2) and to zinc (Tailings 2) partitioned into the liquid phase (e.g. overlying water and pore water), direct contact with solids (adsorbed and particulate-associated metals) and dietary (ingestion) exposure to the tailings solids.
- Ecotoxicological testing of natural Huon Gulf sediments was also carried out, with following observations:
    - The survival of the amphipod and copepod test species were normal (no acute effects) in the Huon Gulf sediment tested; however, the reproductive outputs (chronic effects) of both species were lower when compared to a standard control sediment.
    - Amphipod reproduction in the Huon Gulf sediment ranged from 47 to 69% over seven separate tests.
    - Copepod reproduction ranged from 62 to 97% over two separate tests.
    - The reduced reproductive output of the amphipod in the Huon Gulf sediment compared to the standard coastal estuarine control may also be attributed to a poorer nutritional quality (e.g. reduced total organic carbon amount and quality) of the deep-sea sediment (Huon Gulf sediment had a range of <0.05 to 0.62% compared to 4.0 ± 0.5% for the standard control sediment); but this has not yet been confirmed.

One important finding of these high sensitivity tests and the chronic toxic conditions in the Huon Gulf natural bed sediments, is that these same natural sediments have a diversity of meiobenthos and marine bacteria (Appendix M, Physical, Chemical and Biological Sedimentology of the Huon Gulf), indicating greater tolerance of seemingly elevated metal concentrations in their sedimentary environment.

17.5.2.2.3.2. CSIRO Long-term Laboratory Study of Tailings Samples

The CSIRO conducted further long-term testing under conditions that better simulated the open ocean environment and better represented potential interactions between contaminants from the deposited tailings solids with benthic biota (Appendix L, Tailings Ecotoxicology and Geochemistry). The work assessed the release of metals from tailings/sediment mixtures and assessed toxicity to, and bioaccumulation in, benthic organisms.

The testwork was conducted using fresher tailings samples compared to the short-term testwork; i.e., the analysis commenced immediately after the sample collection. These tests were conducted over 17 weeks (at the time of reporting) and assessed the release of copper and zinc from tailings into overlying seawater. These two metals were identified as potentially being the most toxic to marine biota based on their noted exceedance of ANZECC/ARMCANZ water quality guidelines in preliminary work.

The work to date assessed mixtures of 20% tailings to 80% Huon Gulf sediment. Testwork using an 80% tailings to 20% Huon Gulf sediment mixture is ongoing with complete results not available at the time of writing. For the 80%/20% tailings/sediment mixture, results of metals release analysis were available at the time of writing but the ecotoxicity and bioaccumulation results were incomplete.

The ratio of 20% tailings to 80% Huon Gulf sediment reflects an anticipated likely tailings/sediment mixture based on the rate of tailings discharge compared to the deposition of natural riverine sediment. Given the approximate discharge of 60Mtpa of suspended riverine sediment (Appendix M, Physical, Chemical and Biological Sedimentology of the Huon Gulf), and the average annual tailings discharge of 12.9Mt (360Mt discharged over 28 years), sediments depositing on the ocean floor of the Huon Gulf are expected to be in the ratio of approximately 20% tailings and 80% natural sediment. The 80% tailings to 20% Huon Gulf sediment mixture represents a ‘majority tailings’ scenario.

The tailings used in the long-term study were new master composites with the same rock type compositions as used in the CSIRO short-term study for Tailings 1 and 2 (refer Section 17.5.1.1.2). In the long-term study, sample ‘Tailings BT3’ was comprised of 90% porphyry and 10% metasediments and ‘Tailings BT4’ was comprised of 25% porphyry and 75% metasediments. The tailings samples were freshly prepared before the long-term study, whilst those used in the short-term study had remained in cold storage for 6 months before testing. Tailings and Huon Gulf sediment compositions of 20% and 80% tailings were examined for both Tailings BT3 and Tailings BT4 and compared to a Huon Gulf control sediment (i.e., with no tailings).

The experiments in the long-term study were conducted in large tanks called mesocosms that directed a flow of seawater across the sediment-water interface to promote mixing and to better simulate the effect of current flow in the deep ocean.

The assessment showed some variability of the composition of the tailings in the long-term study compared to the tailings used in the short-term study. The key differences were that copper and zinc concentrations were significantly lower in the tailings used in the long-term study compared to the short-term study, and may reflect the variability in metal content within the rock types used to generate the tailings samples. In the long-term study tailings samples, total copper was between 33 and 50% of the concentration of tailings used in the short term testwork and total zinc in the long-term study tailings samples was some 7% of the concentration of tailings used in the short term testwork. Dilute-acid extractable copper concentrations in the long-term study tailings samples were between 62 and 70% of the concentrations in the tailings from the short term testwork. Dilute-acid extractable zinc concentrations in long-term study tailings samples were 2 to 3% of the concentrations of the tailings used in the short term work. This indicates the values from the short-term CSIRO study used in this assessment are conservative.

The results from the first 17 weeks of the long-term ecotoxicology study are summarised below:

- The dissolved copper concentrations in the long-term tailings mesocosms were lower than those measured in the smaller bench-scale tests of the short-term study which had a lower ratio of seawater to the tailings/sediment mixture. The higher ratios of seawater to tailings/sediment mixture used in the mesocosms in the long term testwork are more comparable to an open-ocean environment. The lower dissolved copper concentrations released into overlying waters from the tailings/sediment mixtures are also consistent with the lower metal concentrations in the tailings samples measured in the long term study.

- The maximum concentration of copper in porewaters within the tailings/sediment mixtures occurred at 5 to 15mm below the sediment-water interface for all tailings/sediment mixtures. The copper concentration at this depth range was highest for both the 80% tailings/20% sediment mixtures and 20% tailings/80% sediment mixtures. However, the copper concentration at this depth range in the 20% tailings/80% sediment mixture was not higher than the Huon Gulf sediment-only control sample. Below 30mm depth, iron and manganese reduction mobilisation processes were evident and were associated with lower relative copper concentrations below this depth.
- The copper released by the tailings/sediment mixtures into overlying waters was found to exceed the ANZECC/ARMCANZ guideline for all tailings/sediment mixtures; however this did not translate into toxicity to, or bioaccumulation in, two test species known to be sensitive to copper (see below). Concentrations of zinc released were below the ANZECC/ARMCANZ guideline for all treatments.
- A supporting experiment that examined the effect of natural sediment covers over tailings and sediment mixtures concluded that covers as thin as 5mm over 100% tailings significantly reduced copper release to overlying waters. This finding and related CSIRO studies (Apte, pers. com. 2018) have shown that copper mobility is dependent on dissolved oxygen (oxidation) and that the exclusion of oxygen by both mixing and burial by natural sediments to depths of more than 20mm will reduce copper mobility and mitigate potential copper exposure to benthic fauna.
- The test species were noted to interact with the surficial sediment porewaters with the amphipod (small shrimps) burrowing to 5 to 10mm and the bivalve (mussels) to 60 to 80mm respectively, during the respective bioassays.
- The ecotoxicology assessment for the 20% tailings/80% sediment mixture, which commenced in week 11, was completed at the time of reporting. The assessment found there to be:
  - No acute (survival) toxicity or chronic (reproductive) toxicity to amphipods (small shrimps) over a 10-day standard test period.
  - No acute (survival) toxicity to bivalves (mussels) and no bioaccumulation of metals over the 30-day standard exposure test period.

It is expected that these results better represent the potential toxicity and bioaccumulation of tailings in the deep sea, compared to the earlier short term testwork.

Related testwork conducted by CSIRO investigated the effect of temperature on release of copper, manganese, nickel and zinc from the suspended tailings (Apte, pers. com., 2018). That work found that lower temperatures significantly reduced copper release but did not affect release of the other metals. Copper concentrations released were observed to reduce from 10µg/L at 30ºC to 4µg/L at 5ºC. As the long term tailing testwork was conducted at 19±2ºC in a temperature controlled laboratory, this finding indicates the measured metals concentrations released in the testwork were conservative given that the actual temperature measured in the deep sea in the Huon Gulf is far lower than laboratory conditions (e.g., 6°C at 700m and 1.9°C at 3,200m depth; Appendix M, Physical, Chemical and Biological Sedimentology of the Huon Gulf). This work is continuing with investigation of potential deep sea pressure effects.

17.5.2.2.3.3. Residual Toxicity Impact to Benthos

The assessment of residual toxicity of trace metals in tailings solids (i.e., via ingestion) and released to sediment pore waters and the overlying seawater in the inner Huon Gulf environment is conservatively based on the results of the short-term and long-term ecotoxicological studies described above.

There appears to be a trend of observed reduced toxicity being reported in the long-term ecotoxicological study (Appendix L, Tailings Ecotoxicology and Geochemistry) compared to the results of the short-term study (Appendix L, Tailings Ecotoxicology and Geochemistry). At the time of writing, the long-term study had several weeks until completion and may show further reductions in toxicity. Notwithstanding, the Project's long-term environmental monitoring program (see Section 17.6) will have a component that samples the benthos in areas of variable tailings solids deposition, and the presence of those benthic organisms opportunistically colonising and establishing (at least temporarily due to ongoing natural sediment burial and seafloor mass movement events) successful self-reproducing populations in the tailings deposits will be the true arbiters of toxicity from tailings solids.

Overall, the residual impacts of tailings solids toxicity to the benthos will be different for areas of heavy and light tailings solids deposition, as summarised below.

In areas of high tailings solids deposition (e.g., downslope of the DSTP outfall and lateral areas adjacent to the tailings density current), the residual tailings solid toxicity impacts are assessed to be of **moderate** significance, based on a **high** magnitude of impact (higher chronic toxicity in tailings solids concentrations of 80% or more) and a **low** sensitivity (common and widespread benthic macroinvertebrate infauna and meiobenthos). However, the tailings solids toxicity impacts may be reduced by the masking effects of high tailings solids sedimentation rates, which may cause physical obliterative impacts on colonising macroinvertebrates and meiofauna.

In areas of light tailings solids deposition experiencing dilution or mixing with natural sediments, the residual impacts of tailings solids toxicity are assessed to be of **low** significance, based on a **moderate** magnitude of impact (lower chronic toxicity within a reduced tailings solids content and increased natural sediment content) and a **low** sensitivity (common and widespread benthic macroinvertebrate infauna and meiobenthos).

17.5.2.3. Benthic Trace Metal Bioaccumulation and Biomagnification

The potential for trace metal bioaccumulation only within marine benthic organisms arises from the three pathways outlined in Section 17.5.1.3.

Three studies that addressed potential bioaccumulation and biomagnification via benthic pathways were undertaken in support of this EIS; namely:

- CSIRO Short-term Laboratory Study of Tailings Samples (Appendix L, Tailings Ecotoxicology and Geochemistry: report 'Ecotoxicology and Chemistry of Wafi-Golpu Bench-scale Tailings')
- CSIRO Long-term Laboratory Study of Tailings Samples (Appendix L, Tailings Ecotoxicology and Geochemistry: report 'Long-term lab study of Wafi-Golpu tailings: metal geochemistry, release and bioavailability in deposited tailings-sediment mixtures - Stage 1')
- Tetra Tech Bioaccumulation and Biomagnification Study (Appendix N, Assessment of Metal Bioaccumulation and Biomagnification from DSTP in the Huon Gulf)

A case studies from another DSTP site has also been considered, namely the the Island Copper Mine DSTP operation in Rupert Inlet, Canada.

17.5.2.3.1. CSIRO Short-term Study of Bioaccumulation

The CSIRO (Appendix L, Tailings Ecotoxicology and Geochemistry) undertook a trace metal bioaccumulation and biomagnification assessment using trophic analyses and the pelagic component of the food web has been summarised in Section 17.5.2.2 above. This section summarises the findings of laboratory studies of the benthic component of the food web.

The results from the CSIRO short-term study revealed the following:

- During the bioaccumulation tests using aged oxidised tailings, both Tailings 1 and 2 caused lethality to the estuarine bivalve in the lower dilutions of tailings solids to natural sediment. This prevented bioaccumulation from being assessed in those treatments. However, bioaccumulation was repeated in a long-term testwork program designed to better represent deep ocean conditions and produced useable results (see Section 17.5.2.3.2).
- For the tailings solids to natural sediment dilution of 30% for Tailings 1 and Tailings 2, there was no indication of significant differences (compared to the control test with natural sediment) in the bioaccumulation of copper and zinc in the estuarine bivalve mollusc. The only significant difference detected was for cobalt, which bioaccumulated more from the Huon Gulf sediments than the tailings treatments.
- Estuarine bivalve molluscs exposed to the Huon Gulf sediment (i.e., with no tailings present) showed significant increases in bioaccumulated cadmium, cobalt, chromium, copper, manganese, iron, nickel and vanadium when compared to bivalve molluscs exposed to tailings. There were no effects to the survival of the bivalves in the Huon Gulf sediments despite the indication that these natural sediments contained metals that were bioavailable. As a consequence, bioaccumulation of some metals (cobalt, chromium, manganese, iron, nickel and vanadium) was also significantly greater in the 10% and 20% Tailings treatments.

A data limitation of the bioaccumulation study is the use of the estuarine bivalve mollusc, which appears to have a high sensitivity to the natural bed sediments collected from the Huon Gulf, whereas the tropical marine bacteria and meiobenthos are more likely to be less sensitive having established populations in the natural bed sediments of the Huon Gulf, which have elevated background metal concentrations to which the bivalve molluscs are sensitive.

17.5.2.3.2. CSIRO Long-term Study of Bioaccumulation

Available results from this study are described in Section 17.5.2.2.3.2 and are not repeated here. More detail on this study can be found in Appendix L, Tailings Ecotoxicology and Geochemistry.

17.5.2.3.3. Tetra Tech Bioaccumulation and Biomagnification Study

Tetra Tech (Appendix N, Assessment of Metal Bioaccumulation and Biomagnification from DSTP in the Huon Gulf) conducted conceptual modelling based on a trophic analysis methodology (USEPA, 1999) to predict trace metal concentrations within different trophic levels of the Huon Gulf. The modelling had a particular emphasis on bioaccumulation and biomagnification pathways in the food web, including fish consumed by people in the Huon Gulf. Section 17.5.1.3.1 addressed Tetra Tech's trophic analysis of the pelagic food web component, while this section addresses the benthic food web component.

The Tetra Tech trace metal bioaccumulation and biomagnification study concluded that the benthic sediment pathway is not likely to be a complete trophic pathway in the Huon Gulf.

As a result, the study focused the trophic analysis on the pelagic food web rather than the benthic food web. This was because:

- The deep waters in the Huon Gulf are disconnected from upper layers of seawater where fish are collected for consumption.
- Site information indicates that the benthos is generally very sparse at the seafloor in the Huon Gulf and the benthic habitat is covered by a thick layer of silts and clays originating from the nearby rivers, which is characterised by episodic mass movements.
- The benthic habitat and fauna data collected from the Huon Gulf indicate that the habitat at the seafloor is relatively homogeneous, and the fauna is generally low in density and diversity.

17.5.2.3.4. Benthic Bioaccumulation Case Study

Ellis (1989) and Ellis et al. (1995) reported on the bioaccumulation of trace metals (mainly copper) in mussels and the commercially fished shallow water Dungeness crabs (*Metacarcinus magister*) at the Island Copper Mine DSTP operation in Rupert Inlet, British Columbia, Canada. The crabs exposed to tailings solids had a pre-discharge copper tissue concentration of 6mg/kg (wet weight) and were no higher in Rupert Inlet near the DSTP outfall than elsewhere. Given that crabs have a copper-based blood (haemocyanin), it may be expected that the crabs regulated their internal tissue copper concentrations. There appeared to be little evidence of bioaccumulation in the crabs. However, bioaccumulation was found in mussels that were attached to the wharf walls where they were exposed to copper concentrate dust; however, there were no mussels on the tailings deposits to assess bioaccumulation from this pathway.

17.5.2.3.5. Residual Trace Metal Bioaccumulation Impacts to Benthos

Based on the abovementioned ecotoxicological studies, review of other DSTP operations and a review of the literature, it is anticipated that those opportunistic macroinvertebrates and meiobenthos that do colonise and establish populations on or in areas of the tailings solids deposits may bioaccumulate trace metals from both ingestion of tailings particles and exposure to elevated trace metal concentrations within the deposited tailings solids' pore waters and to a lesser extent in seawater overlying the deposits (owing to bottom currents continually replenishing the overlying water). However, given the very low diversity and abundance of benthic, epibenthic or demersal fish in the Markham Canyon where DSTP discharge is proposed and where the main depositional area of tailings is predicted, and the weak bentho-pelagic coupling within the Markham Canyon, bioaccumulation or biomagnification in the benthos is unlikely to be a significant source for the higher trophic levels in the water column, which is dominated by the stronger mesopelagic-epipelagic coupling of the zooplankton and micronekton species that undertake diel vertical migrations to epipelagic waters.

The CSIRO long-term laboratory study of tailings samples in mesocosms (exposure chambers) using an amphipod (*Melita plumulosa*) and a bivalve mollusc (*Tellina deltoidalis*) with known high sensitivity to trace metals, indicated that the bioaccumulated trace metals in the 20%/80% tailings solids/sediment mixtures (treatments T4, T5, T6 and T7) after a 30-day exposure were not significantly different to those of the Huon Gulf natural sediment control (treatment T1). The results of the CSIRO long-term studies using 80%/20% tailings solids/natural sediment (i.e., treatments T2 and T3) using the same test organisms are not available as the experiments are underway at the time of writing. However, initial results from a 10-day survival and reproduction test using the amphipod (*M. plumulosa*) indicated that no acute toxicity was observed to the survival of the amphipods in any of the test treatments (CSIRO, 2018). In terms of chronic toxicity of treatment T2 compared to the Huon Gulf natural sediment control (T1), chronic toxicity to the reproduction of the amphipods was observed (CSIRO, 2018). There were no chronic toxicity differences between the T3 and the control (T1). The chronic toxicity observed in the T2 treatment was attributed to the higher average dissolved copper concentration (25µg/L) in the water overlying the sediment in the test mesocosm. However, this may be an artefact of the low rate (i.e., weekly) renewal of overlying seawater, whereas in the Huon Gulf benthic marine environment, the water overlying the tailings solids and natural sediment co-deposits will be replenished continuously by near-bottom currents, which would serve to reduce chronic toxicity in the overlying water. Notwithstanding, these preliminary chronic toxicity effects indicate the potential for chronic effects of increased concentrations of tailings-derived trace metals in the long term and, as a consequence, bioconcentration and bioaccumulation of trace metals may be expected in marine benthic epifauna and infauna.

The benthic infauna of the Huon Gulf is dominated in descending order by deposit-feeding roundworms (Nematoda), burrowing copepods (Harpacticoida), marine worms (Polychaeta) and hydrozoans. Near the DSTP outfall, nematodes form about 80% of the benthic infauna. The low densities and biomass of benthic macroinvertebrates and fish the inner Huon Gulf (see Chapter 11, Offshore Marine Environment Characterisation), indicates that there is a weak bentho-pelagic coupling. Therefore, the assessment of bioaccumulation of trace metals associated with tailings solids deposits and pore waters has been based on a potential bioaccumulation route to pelagic predators and ultimately humans who consume pelagic fish.

Overall, the residual impacts of bioaccumulation to the benthos colonising and establishing populations in tailings deposits are assessed to be of **low** significance, based on a **low** magnitude of impact and **low** sensitivity. A low impact magnitude is expected given the exposure to raw tailings solids, or highly concentrated tailings of 80% or more compared to natural sediment mixtures, is likely to be short term due to the frequent and episodic mass movement events constantly reworking the deposition area. Also, the low magnitude of impact is due to low bentho-pelagic coupling. The low sensitivity is due to the common and widespread meiobenthic assemblages dominated by nematodes.

The main pathway to potential bioaccumulation and biomagnification is the mesopelagic-epipelagic coupling dominated by the daily vertical migrations of certain zooplankton and micronekton species, which was assessed in Section 17.5.1.3.

17.5.3. Residual Impact Summary

Table 17.13 presents a summary of the predicted residual impacts of the Project on the offshore marine environment. Given the magnitude of natural sediment input and the down-canyon transportation processes described in Sections 17.5.1 and 17.5.2, these residual impacts reflect the incremental changes to an environment with a sensitivity reflective of the dynamic sedimentation characteristics of this study area.

Table 17.13: Summary of predicted residual impacts to the offshore marine environment

Impact	Causes	Environmental Value or Receptor Affected	Sensitivity of Environmental Value	Impact Magnitude	Residual Impact Significance
Physical effects of tailings subsurface plumes	Increased TSS concentrations associated with tailings subsurface plumes	Pelagic zooplankton and micronekton	Low	Low	Low
Physical effects of tailings subsurface and bottom-attached plumes	Increased TSS concentrations associated with tailings subsurface and bottom-attached plumes	Deep-water pelagic and demersal fish	Low	Low	Low
Physical effects of tailings subsurface plumes	Increased TSS concentrations associated with subsurface tailings plumes	Deep-diving west Pacific leatherback turtles	Very high	Low	Moderate
Tailings liquor residual toxicity impacts	Residual toxicity of tailings liquor contaminants within the mixing zone	Pelagic zooplankton and micronekton	Low	Very low	Low
Pelagic trace metal bioaccumulation impacts	Direct uptake of dissolved tailings contaminants and/or indirect uptake of particulate phase contaminants in food or sediment ingestions	Pelagic zooplankton and micronekton undertaking diel vertical migrations through tailings subsurface plumes	Low	Low	Low
Pelagic trace metal bioaccumulation impacts	Direct uptake of dissolved tailings contaminants and/or indirect uptake of particulate phase tailings contaminants in food or sediment ingestions	Pelagic zooplankton and micronekton carried in ambient currents and passively encountering tailings subsurface plumes	Low	Low	Low
Pelagic trace metal bioaccumulation impacts	Direct uptake of dissolved tailings contaminants and/or indirect uptake of particulate phase tailings contaminants in food	Pelagic macroinvertebrates (e.g., salps, jellyfish and comb jellies)	Low	Low	Low
Pelagic trace metal bioaccumulation impacts	Direct uptake of dissolved tailings contaminants and/or indirect uptake of particulate phase tailings contaminants in food	Pelagic fish	Low	Low	Low
Pelagic trace metal bioaccumulation impacts	Direct uptake of dissolved tailings contaminants and/or indirect uptake of particulate phase tailings contaminants in food (mainly jellyfish)	Deep-diving west Pacific leatherback turtles	Very high	Very low	Moderate

Impact	Causes	Environmental Value or Receptor Affected	Sensitivity of Environmental Value	Impact Magnitude	Residual Impact Significance
Physical smothering impacts of tailings solids deposition on deep-slope benthic habitats and benthos	Smothering of benthic habitats and benthos or tailings solids sedimentation rates above background natural sedimentation rates	Submarine deep-slope (i.e., canyon wall) benthic habitats and benthos	Low	Moderate	Low
Physical smothering impacts of tailings solids deposition on the floors of the canyon and deep-sea benthic habitats and benthos	Smothering of benthic habitats and benthos or tailings solids sedimentation rates above background natural sedimentation rates	Submarine deep-slope (i.e., canyon wall) benthic habitats and benthos (e.g., macroinvertebrates and meiofauna)	Low	Low	Low
Impact of lower nutritive content of settling tailings solids on deep-slope sediment quality	Settling of nutrient-poor tailings solids affecting sediment quality (i.e., nutrient status) of deep-slope bed sediments and benthos	Partial food resource to marine bacteria, meiofauna and benthic macroinvertebrates	Low	Moderate	Low
Impact of lower nutritive content of settling tailings solids on the nutritive quality of the canyon and deep sea floor sediments	Settling of nutrient-poor tailings solids affecting sediment quality (i.e., nutrient status) of canyon and deep sea bed sediments and benthos	Partial food resource to marine bacteria, meiofauna and benthic macroinvertebrates	Low	Low	Low
Residual toxicity of settled tailings solids (i.e. deposition) and dissolved metals in pore and overlying water	Direct uptake of dissolved tailings contaminants in deposited tailings solid pore water and/or overlying water, and indirect uptake of particulate phase tailings contaminants in food or via ingestion of tailings solids	Deep slope benthos in areas of heavy tailings deposition (80% or more tailings solids concentrations) associated with higher chronic toxicity	Low	High	Moderate
Residual toxicity of settled tailings solids (i.e. deposition) and dissolved metals in pore and overlying water	Direct uptake of dissolved tailings contaminants in deposited tailings solid pore water and/or overlying water, and indirect uptake of particulate phase tailings contaminants in food or via ingestion of tailings solids	Benthos in areas of light tailings solids deposition with lower chronic toxicity in tailings solids deposits diluted by natural terrigenous sediments	Low	Moderate	Low
Trace metal bioaccumulation impacts to benthic fauna	Direct uptake of dissolved tailings contaminants in sediment pore or overlying water, direct uptake of particulate phase tailings contaminants (sediment ingestion) via or via contaminants in food	Benthos colonising and establishing populations in tailings deposits	Low	Low	Low

17.6. Monitoring

As part of the approval process for the EIS, WGJV is required to submit an Environmental Management Plan (EMP), which includes a proposed Environmental Monitoring Program. Marine biological characterisation and baseline sampling was undertaken in support of the present EIS, and will continue in order to complete the baseline monitoring component of the EMP, to fully characterise pre-mining conditions prior to the Project's operations phase (i.e., the period before and until the date that tailings will be discharged). The results of the baseline monitoring will provide the statistical basis against which future DSTP-related changes to offshore marine ecology can be compared. Monitoring will also continue throughout DSTP operations.

This section provides an overview of the proposed offshore marine ecological monitoring relating to DSTP.

The proposed offshore marine environmental monitoring is as follows:

- Complete baseline monitoring of offshore water quality, and spatial and temporal changes in biological communities (zooplankton, micronekton and benthic communities) prior to operations, and continue validation monitoring thereafter.
- Continue the benthic sediment geochemistry and infauna sampling program during operations.
- Conduct validation and ongoing DSTP performance monitoring in line with the SAMS Draft Guidelines for Deep-sea Tailings Placement (SAMS, 2010a). This will include validation ground-truthing of modelling predictions and recalibration of models where necessary.
- Assess compliance with receiving water quality criteria at the proposed mixing zone boundary, to confirm that the tailings behaves as predicted and that there is sufficient dilution between the point of discharge and the mixing zone boundary.
- Routinely sample the physico-chemical properties of tailings to characterise tailings liquor and tailings solids chemistry prior to discharge (i.e., after mixing with return seawater and de-aeration) and to ensure that the maximum allowable concentrations of potential contaminants do not exceed discharge quality criteria specified in the environment permit, or, alternatively, at the edge of a designated mixing zone.
- Develop and implement methods to trace the tailings after deposition. This may include development of a conceptual model identifying the pathways for tailings and how these may differ from natural sediments. Such a model would inform a monitoring program (potentially incorporating trace element signature and mineralogy analysis) that is appropriate to detect the extent of near- and far- field distribution of deposited tailings.
- Prior to and during operations, conduct oceanographic profiling to confirm that the base of the surface mixed layer remains above the DSTP outfall.
- Conduct baseline sampling of the zooplankton and micronekton communities to identify differences in the depth strata spatially and temporally occupied by these pelagic communities.
- Although no pelagic fish were caught during characterisation studies, conduct precautionary monitoring, prior to and during operations, of tissue metal and metalloid burdens in deep-slope and pelagic fish that have the potential to be caught and consumed by local people. On a regular basis continue sampling of deep-slope and pelagic fish species for tissue metal and metalloid concentrations prior to DSTP start up and continue during operations to determine the presence of bioaccumulation and/or biomagnification of tailings contaminants.

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