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PAPUA LNG PROJECT

UPSTREAM ENVIRONMENTAL IMPACT STATEMENT

VOLUME 1: MAIN REPORT

Chapter 7: Existing Environment - Terrestrial

TOTAL E&P PNG LIMITED

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7. Existing Environment – Terrestrial

This chapter has drawn on information generated by a series of interdependent terrestrial studies that have involved detailed bibliographic reviews, numerical modeling (where required) and field surveys. Based on this information, descriptions are provided of the following components of the upstream terrestrial environment:

- Geology, terrain and soils (Section 7.2) derived from the Upstream Geology, Terrain and Soils Baseline Report (Part 1 of Volume 2).
- Hydrology and meteorology (Section 7.3) derived from the Upstream Hydrology and Meteorology Baseline Report (Part 2 of Volume 2).
- Surface water and sediment quality (Section 7.4) derived from the Upstream Surface Water and Sediment Quality Baseline Report (Part 3 of Volume 2).
- Groundwater (Section 7.5) derived from the Upstream Groundwater Baseline Report (Part 4 of Volume 2).
- Freshwater and estuarine biodiversity (Section 7.6) derived from the Upstream Freshwater and Estuarine Biodiversity Baseline Report (Part 5 of Volume 2).
- Terrestrial biodiversity (Section 7.7) derived from the Upstream Terrestrial Biodiversity Baseline Report and the Upstream Deforestation Baseline Report (Parts 6 and 7 of Volume 2, respectively).
- Vegetation regeneration (Section 7.8) derived from the Upstream Vegetation Regeneration Baseline Report (Part 8 of Volume 2).

The baseline characterization of the upstream terrestrial environment primarily focused on:

- PRL-15.
- The onshore export pipeline corridor.
- The Purari River catchment and subcatchments.

7.1 General Setting

The terrestrial biophysical setting of the upstream Project is the Purari River catchment, the third largest catchment in Papua New Guinea, covering a total area of approximately 33,730 km^2. The Purari River catchment lies between the Kikori and Vailala rivers and commences at Mount Wilhelm, which, at 4,150 m above sea level (asl), is the highest mountain in the Central Highlands of Papua New Guinea. The Project will be developed in the lower part of the Purari River catchment within PRL-15 and along the onshore export pipeline corridor to the coast at Orokolo Bay. While most of the Project is located in the Purari River catchment, waterways of the Era River catchment drain the central and western area of PRL-15, including the area of the Elk-Antelope gas field. The topography is a ridge and ravine landform of low-altitude hills to the north of PRL-15, descending to the broad, flat floodplains of the Purari River delta, featuring ephemeral oxbow lakes, alluvial floodplains and wetlands. Isolated perched, shallow groundwater occurs in superficial and weathered material throughout the Project area.

The Project area experiences a high-rainfall, humid tropical climate characterized by two distinct seasons, the southeast trade wind season and the northwest monsoon season. The climate, along with landform, topography, geology, flooding and tidal regimes, supports the growth of a dense and varied natural vegetation cover comprising hill and alluvial forests on inland hills and

ravines, lowland swamp forests on river plains, nipa and sago palms lining river channels and mangrove-fringing estuaries and coastlines.

While human settlement is low and principally confined to villages along the coastal fringes and river banks, anthropogenic disturbance to natural forest cover resulting from commercial logging operations has been pervasive since the early 2000s. These logging activities have resulted in degradation of large areas of primary forest south of PRL-15 to the coast at Orokolo Bay. Other minor anthropogenic effects on forest cover relate to subsistence farming and more recent oil and gas exploration activities, including those relating to this Project.

7.2 Geology, Terrain and Soils

7.2.1 Regional Context

The geology, terrain and soils study area, encompassing PRL-15, including the production, processing and related facilities, and the onshore export pipeline corridor is located in central Papua New Guinea in the foothills, alluvial plains and beach areas south of the Central Range. Geologically, this area is located in the Papuan Fold and Thrust Belt and the Aure Deformation Zone (Figure 7.1). The Central Range, or Central Highlands, is a 150-km-wide, 3,000-m-high, rugged mountain belt that extends over 1,300 km from Indonesia's Irian Jaya in the west to Milne Bay in the southeast. The Central Range has been formed as a result of collisions between the Pacific and Australian tectonic plates, with movement between these two plates accommodated by four microplates: North Bismarck Plate, South Bismarck Plate, Woodlark Plate and the New Guinea Highlands Block. Crustal deformation and seismicity are concentrated along these boundaries (Wallace et al., 2004; Williamson & Hancock, 2005).

The study area is located in the eastern section of the Papuan Basin, a geological sedimentary basin that covers the southern part of the Papuan mainland. The eastern Papuan Basin comprises sedimentary rock formations up to 4 km thick with Triassic- and Jurassic-age[1] deposits at its base. Sediments of the Papuan Basin underlie the southern plains and are exposed in the adjacent fold-thrust belt in which the Elk-Antelope gas field is located.

The upstream terrestrial Project area from PRL-15 to the coast at Orokolo Bay is located in Seismic Zone 3 based on the zoning provided by the PNG building standards (PNGNSC, 1982) (Figure 7.2). This zone is a moderate seismic hazard zone for building construction in Papua New Guinea. The offshore export pipeline corridor through the Gulf of Papua to Caution Bay is located in Seismic Zone 4, which is a low seismic hazard zone. Irrespective, recent structural and geohazard investigations indicate several active faults in the Project area, presenting moderate to high geohazard risks. There are no volcanoes in the study area. The closest active volcanoes are Crater Mountain and Yelia, which are located 65 km north and 85 km east of PRL-15, respectively (Figure 7.2).

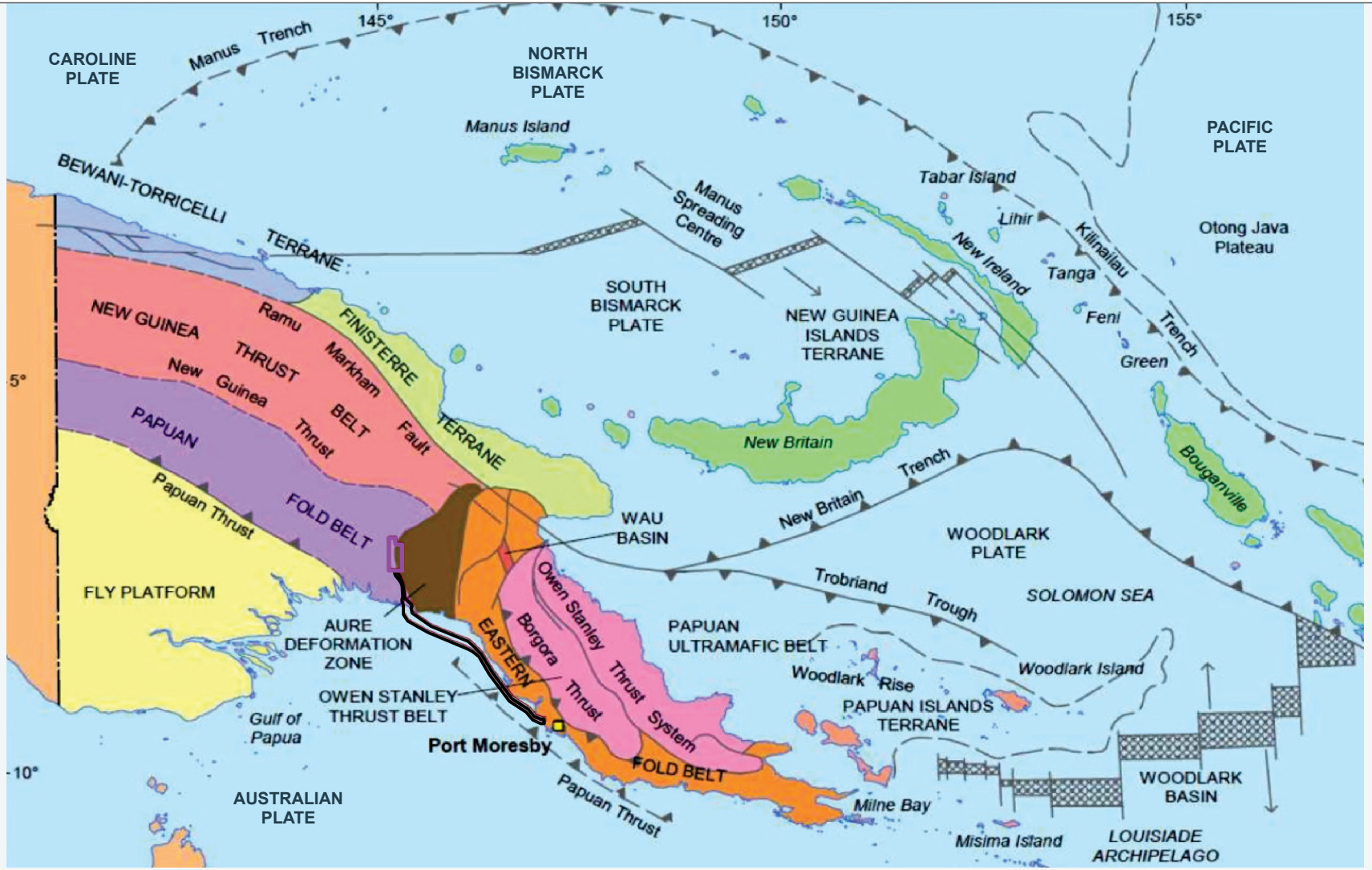
The whole of the Gulf of Papua, where the offshore export pipeline corridor is located, is in the lowest tsunami hazard zone, Zone 3, which is considered to experience a low frequency of tsunamis (PNGNSC, 1982). This low level of concern reflects the fact that no active submarine tectonic trenches or volcanoes exist in the region.

1 Sedimentary rocks in the basin date back more than 250 million years.

TECTONIC DOMAIN MAP OF PAPUA NEW GUINEA

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FIGURE 7.1

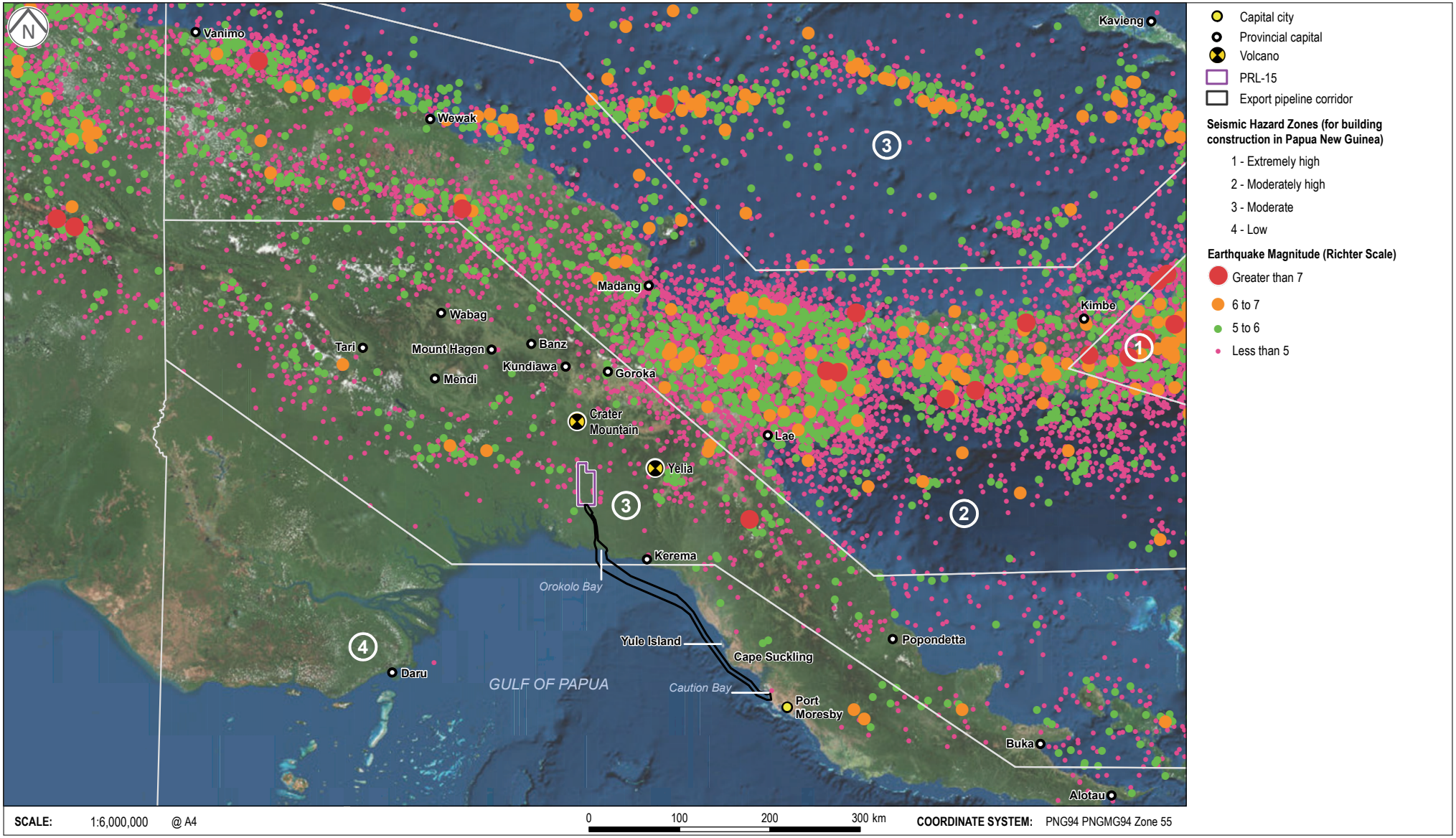


Source: Adapted from William son and Hancock, 2005.

SEISMIC ZONES AND HISTORICAL SEISMIC ACTIVITY IN THE PAPUA NEW GUINEA REGION 1900 TO 2012

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FIGURE 7.2



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7.2.2 Study Overview

Description of the geology, terrain and soils of the study area is based on existing information from previous studies, the scientific literature, and field studies undertaken of sites in PRL-15 and the onshore export pipeline corridor during November 2016. The field survey investigated 27 sites located in and around the proposed upstream components of the Project, including the wellpad areas, the central processing facility (CPF) and associated infrastructure, and the onshore export pipeline corridor. Several ground-truthing assessments were undertaken at these sites including:

- Localized geology assessment.
- Geomorphology and terrain assessment.
- Soil profile excavation and assessment of soil type and characteristics.
- Collection of soil samples from nominated sites for laboratory testing, including particle size, pH, salinity, organic carbon and matter, cation exchange capacity, Emerson aggregate test, total nitrogen and phosphorus, heavy metals, total petroleum hydrocarbons and potential acid sulfate soils.

7.2.3 Geology Baseline Characterization

The geology of the study area is shown in Figure 7.3. Most of PRL-15 and the eastern edge of the export pipeline corridor are dominated by two lithologies:

- Tmup1: mudstone, siltstone, minor sandstone, rare conglomerate and calcarenite and is generally carbonaceous and calcareous in places.
- TQe: lithic sandstone, siltstone, mudstone, minor conglomerate with regressive sequence from shallow marine to continental deposits and coal seams.

In the southwest section of PRL-15, including the proposed CPF area, and the western edge and coastal area of the export pipeline corridor, the dominant lithology is:

- Qa5: gravel, sand, silt, mud, carbonaceous mud, clay, minor peat, alluvial soils, alluvium and littoral deposits.

This lithology also occurs on the alluvial plains of the Purari River and the beach ridges and plains landforms toward the coast, which are further described in Section 7.2.4.

The predominant rock types observed in outcrops in the study area include interbedded mudstones, siltstones, sandstones, conglomerates and limestone (Plate 7.1). Carbonaceous rocks in the form of carbonaceous mudstones and coal occurred as detrital angular, cobble-sized particles in Oyomo Creek in the proposed CPF area.

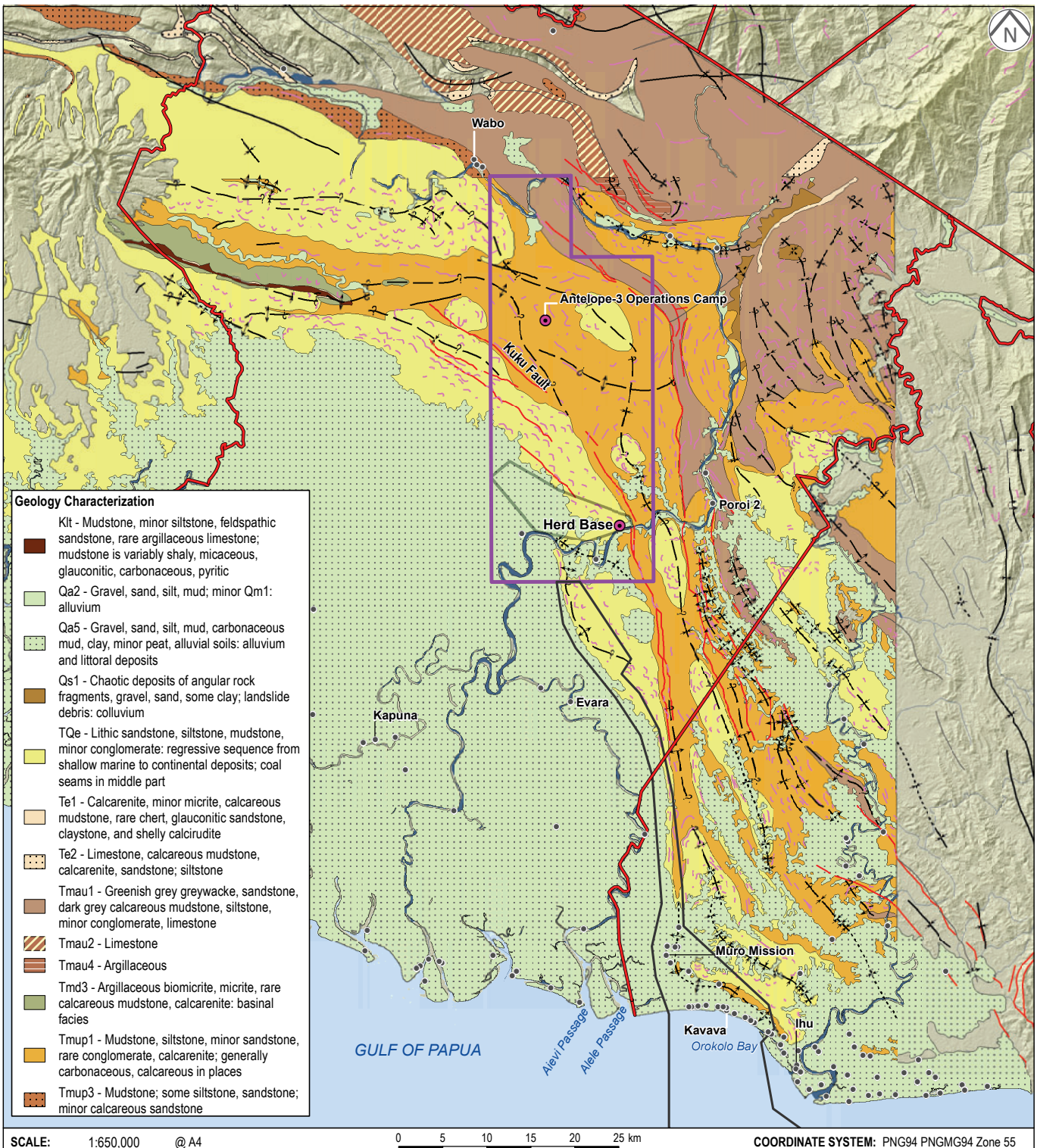
There are varying levels of structural deformation in PRL-15, from relatively gently dipping strata to strongly faulted and folded materials. Landslides, debris flows, rockfalls (Plate 7.2) and gullying are common geohazards in the ridge and ravine landforms, triggered by large rainfall events. These geohazards can cause significant land movement due to the topography and steeply dipping strata, which have weak, clay-rich rock masses interbedded with strong rock masses.

The deeper stratigraphy of the study area around the gas field is described in Table 7.1, including the deep carbonate geology of the Kapau Limestone in which the target gas reservoir lies. Mudstones, marls and shales of the Orubadi Formation overlie the hydrocarbon resource (Pieters, 1980; GHD, 2015d).

GEOLOGY OF THE STUDY AREA

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FIGURE 7.3



Communities outside of the Project area of influence have not been verified. Only government administrative centers and notable locations have been labeled for context.

Plate 7.1 – ANT-6 Well Pad Showing Interbedded Siltstone, Sandstone and Fossiliferous Limestone Beds (see Inset)



Photo: SLR Consulting.

Plate 7.2 – Example of a Rockfall on Steep Slopes Near ANT-6



Photo: SLR Consulting.

Table 7.1 – Basic Stratigraphy in the Study Area

Geological Age	Name and Thickness	Description
Holocene	Quaternary Sediments <100 m	Variable depending on parent geology and location in the study area. Accumulations within river valleys and creek lines. Unconsolidated coarse sands and gravels in upper catchments with fine black to dark grey sands and silts in the Purari River basin.
Pliocene to Pleistocene	Era Beds <2,000 m	Sandstone, siltstone and mudstone with rare coal and conglomerate. Commonly carbonaceous. Blue to grey and brown when weathered.
Uppermost Miocene to Pliocene	Orubadi Beds <2,400 m	Mudstone, siltstone, sandstone, minor conglomerate and rare calcarenite and limestone breccia. Blues to grey and brown in more calcareous areas. Fine to medium bedded and occasionally massive.
Upper Oligocene to Lower Miocene	Kapau Limestone >1,000 m	Cream to light brown, mainly thin bedded but occasionally massive limestone. Fossiliferous in places, including fragments of corals, bivalves and gastropods. Reservoir rock, target of gas exploration.

Source: Compiled from Pieters (1980) and GHD (2015d). < = less than; > = more than.

7.2.4 Geomorphology and Terrain Baseline Characterization

7.2.4.1 Ridge and Ravine Landform

The topography of the study area is shown in Figure 7.4. The northern section of PRL-15 is in the foothills of the frontal part of the Papuan Fold and Thrust Belt (see Figure 7.1). The relief in this area is pronounced, with landforms formed by tectonic processes, i.e., ridge and ravines with significant cliffs. These landforms are predominantly determined by their lithologies and structural orientations. Mixed sedimentary rocks form homoclinal (Plate 7.3) or hogback/strike ridge and ravine landforms,[2] with a succession of ridges and valleys orientated north-northwest to south-southeast of the Kuku fault ridge (see Figure 7.3). The landforms are underlain by thickly bedded to massive sandstone and are scarred by numerous slumps, landslides and gullying.

The maximum elevation of the ridge and ravine landform in PRL-15 is about 410 m asl. The ridge and ravine landform continues south at a lower relief (10 to 50 m asl) along the eastern edge of the export pipeline corridor toward the coast.

Plate 7.3 – Homoclinal Ridges Near ANT-3 and ANT-5 Wellpads



Photo: SLR Consulting.

2 The distinction between the homoclinal and hogback/strike landforms is that the dip slopes of the homoclinal ridges generally range from 10° to 25° whereas the hogback/strike ridges have dip slopes generally exceeding 25°.

TOPOGRAPHY AND DRAINAGE OF THE STUDY AREA

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FIGURE 7.4



Communities outside of the Project area of influence have not been verified. Only government administrative centers and notable locations have been labeled for context.

7.2.4.2 Composite Meander and Levee Alluvial Landform

The lower Purari River and its delta are formed of a central meander plain, back plains and swamp landforms (Plate 7.4). The meander plains include oxbow lakes, discontinuous levees, point bars, and scroll complexes. The back plains flood frequently and are permanently swampy where drainage is impeded by levees or meander plains. The drainage status varies greatly, depending on local conditions, from poorly to well drained. Relict alluvial plains, probably of Pleistocene age, occur locally between the Purari and Vailala rivers (Löffler, 1974).

The proposed CPF, logistics base and airstrip area and the western edge of the export pipeline corridor are located in the alluvial plain of the Purari River at the foot of the ridge and ravine landform.

Plate 7.4 – Meandering River and Back Plains Landform of the Purari River Delta



Photo: BMT WBM.

7.2.4.3 Recent Littoral Landform

In the southern portion of the export pipeline corridor adjacent to Orokolo Bay, the recent littoral landform consists of beach ridge complexes and beach plains (Plate 7.5). These beach terrain systems comprise recent sediments shaped as long parallel ridges and swales (Löffler, 1974). Villages are present on the back beach area; and tidal marshes, estuaries and lagoons are found in this area. During storm surges, waves sometimes inundate these populated, low-lying areas.

Immediately to the west of this area, the landform is dominated by the main eastern river mouth distributary of the Purari River, which discharges into the Gulf of Papua. The drainage is tidal, with a maze of channels that mainly comprise swamps, marshes and estuaries. Mud banks along the channels support mangrove vegetation (Section 7.7.5.2).

Plate 7.5 – Recent Littoral Landform at Orokolo Bay



Photo: Iain Woxvold.

7.2.5 Soils Baseline Characterization

7.2.5.1 Soil Complexes and Units

Soils surveys found the soil units in the study area to be broadly consistent with soil mapping provided in the PNG Resource Information System (PNGRIS). Entisol and Inceptisol soil orders dominated the study area. These are poorly formed soils with no to limited soil pedological development. In the ridge and ravine areas in PRL-15 and in the eastern edge of the export pipeline corridor, these soils are thought to result from ongoing erosion that has prevented soil from developing over the bedrock parent material. On the alluvial plains in the southwestern parts of PRL-15 and the western edge of the export pipeline corridor and in beach landforms near the coast, soils are poorly formed due to their young age in the depositional profiles.

The inundated tidal flats, swamps and saturated alluvial soils are dominated by Histosol soils, which typically form under saturated conditions and have high organic matter in the upper layers.

Soils in the study area are categorized into four soil complexes[3] comprised of denudational soils (i.e., soils formed from the weathering of the earth's surface) or aggradational soils (i.e., soils formed from the deposition of material). The occurrences of the four soil complexes in the study area are shown in Figure 7.5 and described as follows:

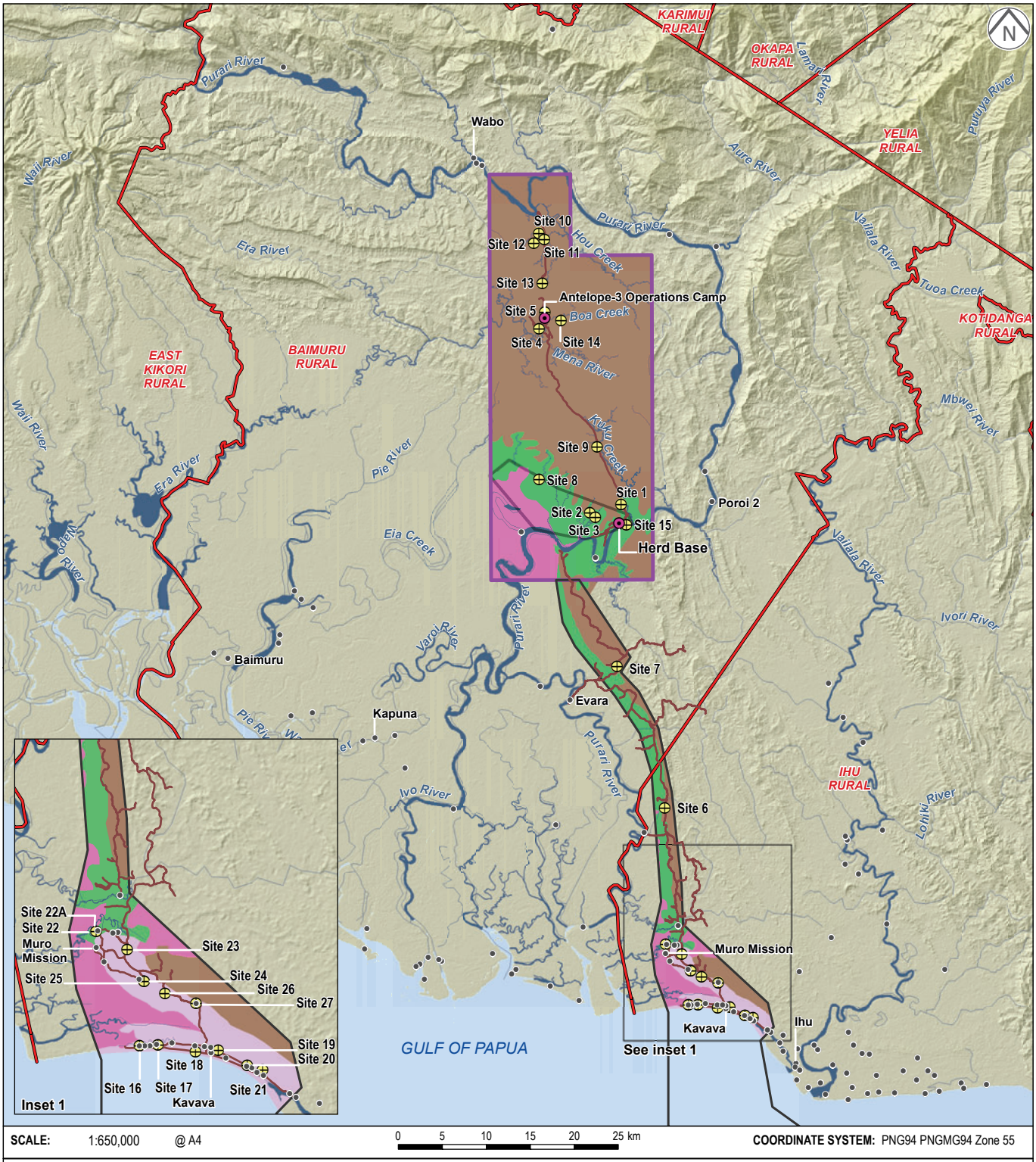
- Soil Complex 1: This denudational soil complex occurs on the ridge and ravine terrain, including the hillslopes, crests, steep valleys and drainage lines located in PRL-15, and on hilly and ridge terrain along most of the eastern side of the export pipeline corridor south of PRL-15. The dominant soils are Entisols, including Lithic Udorthents (fine to coarse textured soils), Dystrudepts (clay soils) and Dystrochrepts (clay loam to clay soils) in the hillslopes and ridges and Sulfaquents (gleyed clays) in the valleys and drainage lines. The soils mapped as Soil Complex 1 in the ridge and ravine terrain are moderate to well drained, have moderate cation exchange capacity and low levels of nutrients and exhibit stable aggregates. These soils are poorly formed with limited to no pedological profiles. High levels of water-induced erosion are evident due to the frequency and intensity of rainfall combined with the sloping landform of the ridge and ravine terrain.
- Soil Complex 2: This aggradational soil complex occurs on the alluvial plains and meander plains in the southwestern corner of PRL-15 and on the flatter terrain below the ridgeline along the western edge of the export pipeline corridor south of PRL-15. The dominant soils are clay loams and clay Inceptisols (alluvial Dystrudepts) and Sulfaquents These soils are moderate to poorly drained, have low to moderate cation exchange capacity depending on the texture in each layer, have low nutrient levels, and exhibit stable aggregates. While these soils are considered stable, there are potential acid issues associated with the disturbance or drainage of the Sulfaquents, with potential acid sulfate soils (PASS)[4] observed on the alluvial plains along the export pipeline approximately 7 km inland from the coast. There are also limitations due to periodic saturation and groundwater within 0.5 m to 1.0 m of the surface where the sandy loams and sandy clay loams overlie the higher clay content subsoils. The field investigations noted many subsistence gardens and tree crops in this soil complex; however, it was observed these required considerable intervention and shaping by villagers to provide drainage and compost mounding to assist plant growth.

3 Soil complexes are mapping units that consider terrain feature, land system and soil unit.
4 Potential acid sulfate soils are soils containing iron sulfides (commonly pyrite) that have the potential to produce sulfuric acid if they are drained or disturbed.

SOIL COMPLEX MAP OF THE STUDY AREA

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FIGURE 7.5



Communities outside of the Project area of influence have not been verified. Only government administrative centers and notable locations have been labeled for context.

- Soil Complex 3: This aggradational soil complex occurs on the littoral plains, including the beach ridges and beach plains along the coast in the onshore export pipeline corridor. The dominant soils are Psammaquents consisting of weak structured to structureless deep sands and sandy clay loams with high watertables. Some of these soils may also be potentially acid-producing if drained or disturbed. The sandy soils of Soil Complex 3 in the beach ridges and beach plains are typically well drained in the upper layers; however, subsoils are frequently waterlogged due to the low elevation. The soils generally have low cation exchange capacity and very low nutrient levels. These soils are stable if able to form aggregates; however, most soils were found to be sandy with no structure. They have inherent limitations for traditional agriculture, including lack of water-holding capacity within the sandy profiles (although shallow watertables can cause periodic saturation of these layers), salt water ingress, lack of structure, clay and organic matter causing low cation exchange capacity, and potentially high acid levels due to PASS.
- Soil Complex 4: This aggradational soil complex occurs on the inundated plains and swamps including the tidal flats along the coast and Purari River delta in small sections of the onshore export pipeline corridor and on the swampy lowlands in the southwestern corner of PRL-15. The inundated soils of Soil Complex 4 were not sampled due to access constraints, with these soils being largely underwater, and the safety risks due to crocodiles. Given the saturated condition of these soils, they are considered to be Histosols and Hydraquents consisting of inundated organic soils and undifferentiated soft alluvial swamp soils. Histosols are commonly called bogs, moors, peats or mucks. Histosols form in decomposed plant remains that accumulate in water, forest litter, or moss faster than they decay. There is a risk these soils are PASS given their low position in the landscape and their near continuous saturation.

7.2.5.2 Land Capability

The land capability of the study area has been categorized according to the USDA Land Capability Classification (SCS USDA, 1961), an eight-tiered land capability classification system ranging from Class I (soils with few limitations that restrict their use) to Class VIII (i.e., soils with limitations that preclude their use for (commercial) plant production). Soils in the study area are classified as Class VIII in the ridge and ravine terrain and in the frequently flooded alluvial plains and beach landforms. This land capability is essentially unsuitable for broad-scale agriculture or grazing. Only areas within Soil Complex 2, which are the better-drained areas of the alluvial plains, exhibited the possibility of some grazing and tree crops with areas of Class VI land capability evident. All activities associated with subsistence gardening endeavors were observed to rely on high levels of human intervention and inputs, such as creating artificial drainage and compost mounding to provide a suitable growing medium.

Notwithstanding that soil complexes in the study area are categorized as limited in their capability for conventional ‘western’ agriculture, local communities have managed to successfully grow tree crops of sago, coconut, papaya, betel nut and mustard and other food crops, such as potatoes, melons, pineapple, passion fruit and bananas, for many generations.

7.2.5.3 Potential Acid Sulfate Soils

Acid sulfate soils are commonly associated with coastal swamp, mudflat and mangrove environments. These soils contain naturally occurring iron sulfides that are stable in reduced oxygen conditions below the watertable; however, if disturbed and exposed to the atmosphere, oxidation of the sulfides results in the formation of leachates containing sulfuric acid. These leachates, if not managed, may have a localized, adverse impact on vegetation, soil, surface water and groundwater. In the reduced oxygen condition, the soils are regarded as PASS.

Laboratory tests for PASS were performed on 22 samples from nine targeted sites. The results indicate that the study area contains several soil units that may be prone to releasing acid leachate if disturbed or drained and exposed to the atmosphere. With the exception of one site in the southern extent of PRL-15 (site 9, see Figure 7.5), all sites that indicated PASS were located on the alluvial floodplains, beach ridges and beach plains in the lower Purari River delta (sites 18, 19, 22, 22A, 23 and 27, see Figure 7.5), which experience frequent inundation. The site with PASS in PRL-15 (site 9) was located along a saturated drainage line associated with Kuku Creek. The Psammaquents and Sulfaquents of Soil Complexes 2 and 3 typically indicated PASS, while the Sulfaquent of Soil Complex 1 in PRL-15 indicated PASS in the subsoil layers.

While no samples were taken in Soil Complex 4, the presence of PASS in these soils is considered likely based on known physical features of the landform, i.e., saturated soils in coastal margins with a geomorphology developed from the Holocene epoch when sea water levels were higher, bringing sulfates into the present day coastal soils. The majority of coastal soils in the study area are therefore considered likely to be PASS.

7.2.5.4 Contaminants

Laboratory analyses were made of metal concentrations in soil samples collected during the November 2016 survey, and comparisons were made with human health-based screening levels (NEPC, 2013) and US EPA ecological soil screening levels (Eco-SSLs). Metal concentrations were well below the NEPC (2013) health-based screening levels; however, there was wide variation when the analyses results were compared to the US EPA Eco-SSLs with some exceedances for cobalt, copper, lead, manganese, nickel, selenium, tin, vanadium and zinc. Higher concentrations of chromium (106 to 191 mg/kg), selenium (9 to 16 mg/kg), vanadium (321 to 639 mg/kg) and zinc (87 to 178 mg/kg) were measured in samples from sites 23 and 27 inland from the coast in the southern part of the study area (see Figure 7.5) compared to other sites. Whether the source of these metals is related to anthropogenic activities or to natural conditions is not known. These metal concentrations are higher than the average concentration in world soils provided in Alloway (2013) of 42 mg/kg for chromium, 0.7 mg/kg for selenium, 60 mg/kg for vanadium and 62 mg/kg for zinc.

None of the sampling sites showed evidence of hydrocarbon contamination of soil. Total petroleum hydrocarbon (TPH) and benzene, toluene, ethylbenzene and xylene (BTEX) levels in all samples tested were below the limits of reporting and ecological screening levels.

7.3 Hydrology and Meteorology

7.3.1 Regional Context

The hydrology and meteorology study area spans three catchments:

- Purari River.
- Era River.
- Pie River.

These catchments, including the major subcatchments of the Purari River, are shown in Figure 7.6. The Purari River is Papua New Guinea's third largest river (by catchment size) with a catchment area of 33,730 km^2. The catchment covers a large portion of the central and southern part of mainland Papua New Guinea, with its headwaters including the Erave, Kaugel, Wahgi, Tua, Pio and Aure rivers. The river basin covers a wide geographical range extending from Papua New Guinea's highest mountain, Mount Wilhelm (4,510 m asl), to the lowlands of the Gulf of Papua. These areas include high montane and lowland forests, densely populated highland

valleys, and largely unpopulated low montane and lowland forests through to swamps and coastal mangroves.

The study area is in a high-rainfall, humid tropical environment; however, there is a range of climatic conditions within the basin, including Mount Wilhelm having occasional snow cover (Petr, 1983a). In upland areas, cloud and fog are an important source of moisture for most of the year, with areas subject to the most cloud receiving the most rain.

The Project will occur in the lower part of the Purari River catchment, downstream of Hathor Gorge, which is located approximately 60 km upstream of PRL-15 (Figure 7.6); within PRL-15 and along the onshore export pipeline corridor to the coast at Orokolo Bay. At a catchment-wide scale, the Hathor Gorge rapids represent a significant hydraulic and physical barrier (Haines, 1979). The major tributary Aure River joins the Purari River downstream of Wabo near the village of Subu, approximately 8 km east of PRL-15. The two principal waterways in PRL-15 that form part of the Purari River catchment are Hou and Kuku creeks (see Figure 7.4). Hou Creek drains the northeast part of PRL-15, flows east of the Mena plateau and discharges into the Purari River 10 km downstream of Wabo. Kuku Creek drains the southeastern part of PRL-15 (north of the Purari River) and flows into the Purari River at Herd Base (see Figure 7.4).

Downstream of PRL-15 within the delta, the Purari River splits into the three main distributary channels: the Purari River (eastern channel) and the Urika-Ivo River (central channel), both of which flow directly into the Gulf of Papua; and the Wame-Varoi River (western channel), which flows into the gulf via Port Romilly (see Figure 7.4). These river channels are potential transport routes for the Project.

The waterways of the Era River catchment drain most of the central and western areas of PRL-15, with the upper tributaries Mena River and Boa Creek draining the area of the Elk-Antelope gas field (see Figure 7.6). The Era River flows southwest from PRL-15, discharging into the Gulf of Papua west of Port Romilly.

The only Pie River subcatchment in PRL-15 is Eia Creek (see Figure 7.6 and Figure 7.4). This drains from the central western side of PRL-15, west of a small ridge that separates the subcatchment from the Mena River subcatchment to the northeast. While discharge volumes from Eia Creek are not available, Petr (1983b) identifies the creek as having typically low flow resulting in negligible dilution impact on the Pie River. The Pie River flows into the Gulf of Papua at Port Romilly.

7.3.2 Baseline Characterization

7.3.2.1 Study Overview

Description of the hydrology and meteorology of the study area is based on existing information from previous studies, scientific literature, field studies undertaken in 2016 and 2017 and numeric modeling specifically undertaken for the study area. Modeling included:

- Hydrological model and rainfall frequency analysis for parts of the Purari, Era and Pie river catchments to describe likely flows associated with different rainfall events.
- Hydraulic model (TUFLOW) for subcatchments associated with potential infrastructure locations to ascertain likely flooding extents.
- Catchment model for the Purari River catchment to estimate sediment loads from catchment runoff.

Detailed descriptions of the modeling and findings are presented in Part 2 of Volume 2.

The description of existing meteorology in the study area is mainly based on measured data presented in Petr (1983b) and Evesson (1983). These reports provide data from studies conducted for the Wabo Hydroelectric Scheme Project and from long-term climate records from government regional weather stations, including information presented in McAlpine et al. (1983). While more recent meteorological data has been collected in the study area between 2013 and 2015 from monitoring stations at Wabo, Hou Creek and Herd Base, the datasets for these sites are short and incomplete. As such, they are considered unsuitable for characterizing and describing long-term meteorological patterns in the study area. Description of the more recent data collected at Wabo, Hou Creek and Herd Base is provided in the Upstream Air Quality Baseline Report (Part 19 of Volume 2). Meteorological modeling undertaken as part of the air quality baseline study, documented in that report, has also been used to describe wind patterns in the general area of PRL-15.

7.3.2.2 Climate

Wind Patterns

Two surface pressure systems influence wind and overall climate processes in southern Papua New Guinea (McAlpine et al., 1983):

- Southeast trade winds, which prevail from about May to October.
- Northwest monsoon, which prevails from about December to March.

These wind streams are driven by the positioning of the subtropical high-pressure belt and the Pacific Inter Tropical Convergence Zone (ITCZ) (Evesson, 1983). Between April and October, the ITCZ moves over Papua New Guinea while the subtropical high-pressure belt moves over central Australia. This causes southeast trade winds to develop between the ITCZ and the subtropical high-pressure belt. During the southeast trade wind season, the windward slopes that face southeast and the southern face of elevated ranges experience heavier rainfall compared to leeward slopes.

A transitional period in November is characterized by the development of an equatorial trough (McAlpine et al., 1983). This leads to light variable surface winds, i.e., doldrums. Trade winds continue to blow during this time but have a weakened effect.

Following the November transition, from December to March, the northwest monsoon forms following the southward movement of the ITCZ over Australia. This movement of the ITCZ causes the monsoon line to move southwards over Papua New Guinea and northern Australia (McAlpine et al., 1983). This brings winds from the northwest.

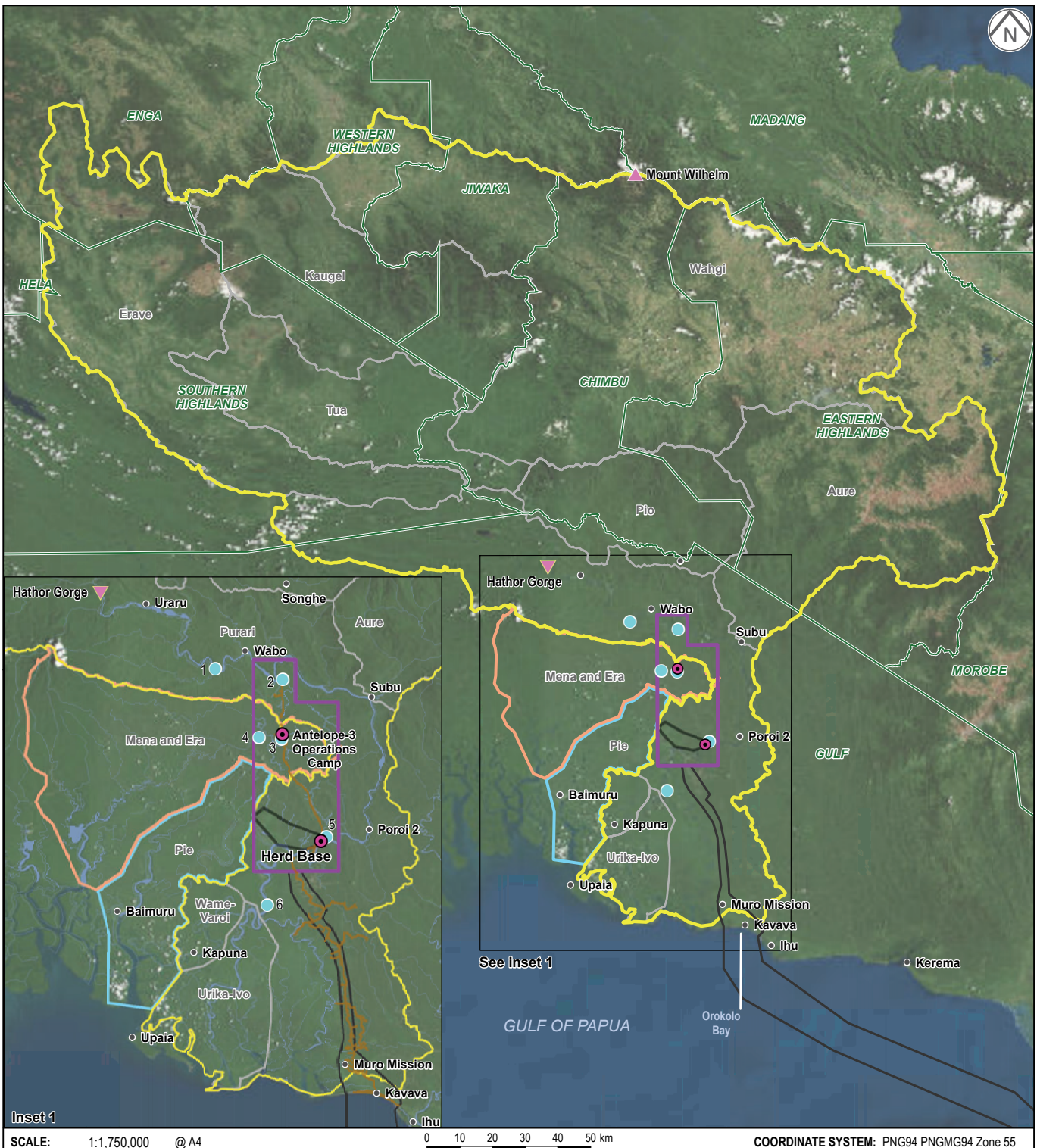
Similar to November, April represents a transition marked by doldrums, following the northward movement of the ITCZ (McAlpine et al., 1983). The length of transition in April is variable, with the start of the southeast trade wind season varying between the start and end of April (Evesson, 1983).

The Purari River catchment is topographically diverse, ranging from sea level to over 4,000 m asl in the Bismarck Range. The majority of the highland valleys in the middle to upper reaches of the catchment occur around 1,000 m asl (McAlpine et al., 1983). As shown schematically in Figure 7.7, the higher topography of the catchment forms barriers to wind movement, inhibiting

CATCHMENT OVERVIEW

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FIGURE 7.6



winds from reaching much of the upper catchment during both southeast trade wind and northwest monsoon seasons.

Annual wind roses for the south of PRL-15 in the area of the proposed CPF and a mid-point along the onshore export pipeline corridor, produced from meteorological modeling of conditions during 2014 and 2015, are presented in Section 10.2.3. These show that the area of the proposed CPF generally experiences low to moderate winds of less than 5 m/s, predominantly from the northeast. The low wind speeds and lack of significant winds from the southeast reflect the topographical barriers to wind movements in the area. Wind patterns and other variables such as temperature and rainfall vary along the export pipeline corridor due to changes in topography and elevation. Modeled wind data shows that this area experiences more varied wind directions than the proposed CPF site, with predominant winds from the northern and southeastern quadrants; and the winds are slightly stronger.

Temperature

Evesson (1983) notes that yearly temperature ranges recorded at individual weather stations in the Purari River catchment are mostly insignificant when compared to diurnal ranges. Temperatures at different locations vary depending on elevation, with minima from 11.6ºC to 22.8ºC and maxima from 22.5ºC to 30ºC. The catchment area downstream of Hathor Gorge generally occurs at an elevation less than 150 m asl; although with some areas up to about 400 m asl, and as such, temperatures from PRL-15 to the coast are expected to be toward the higher end of these ranges. Sea breeze effects near the coast may cause maximum temperatures to be lower in this area.

There is no daily temperature data for PRL-15 or downstream areas; however, McAlpine et al. (1983) has published data for stations in the upper catchment. This shows the following patterns for the catchment, which are considered applicable to PRL-15 and the downstream areas:

- Mean annual temperatures throughout the year do not fluctuate dramatically, with 1 to 2.5ºC of variation between months.
- June through to September are the coolest months of the year.
- There is more variability in minimum temperatures throughout the year than in maximum temperatures.

Rainfall

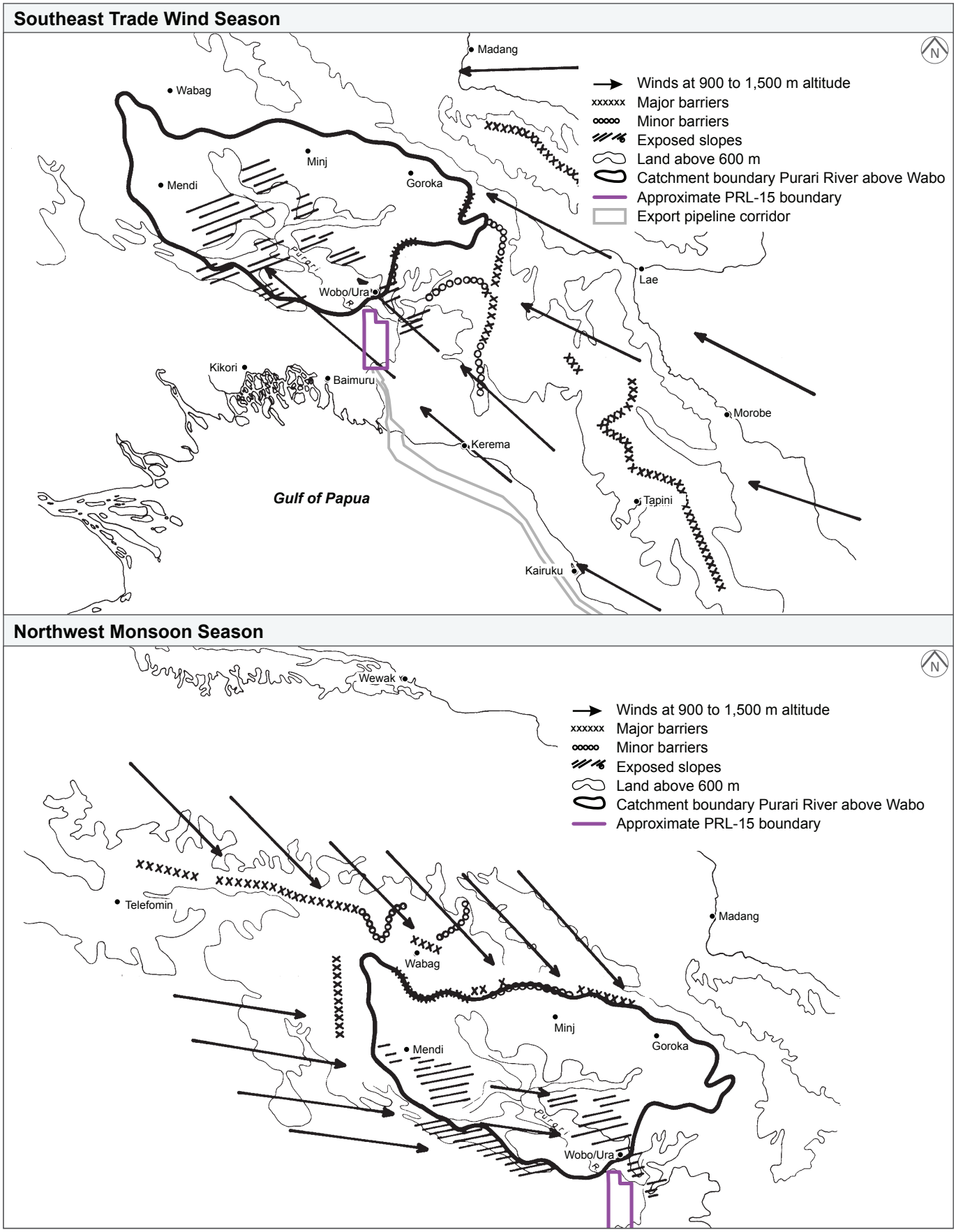
The topographical diversity of the Purari River catchment is a key driver of spatial variability in rainfall, with most rainfall being associated with convergence (i.e., zone where two prevailing air flows meet and interact) caused by topographical features (Evesson, 1983). In the upper areas of the catchment, the annual average rainfall is 2,000 to 3,000 mm, with the highest rainfall received in the northwest monsoon season. This is shown by rainfall data provided in climatic tables (McAlpine et al., 1983) that are presented in Figure 7.8.

In contrast, lower in the Purari River catchment in PRL-15, rainfall is driven primarily by a low level convergence. This brings high levels of rain throughout the year, with an average annual rainfall at Wabo of 8,900 mm (Evesson, 1983). Significantly higher rainfall occurs during the southeast trade wind season from May to October than during the northwest monsoon from December to March, representing a reverse of the rainfall patterns experienced in upper parts of the catchment. Toward the coast, rainfall is lower and more evenly spread throughout the year (i.e., averaging around 300 mm/month at Kerema) (see Figure 7.8).

TOPOGRAPHICAL BARRIERS

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FIGURE 7.7

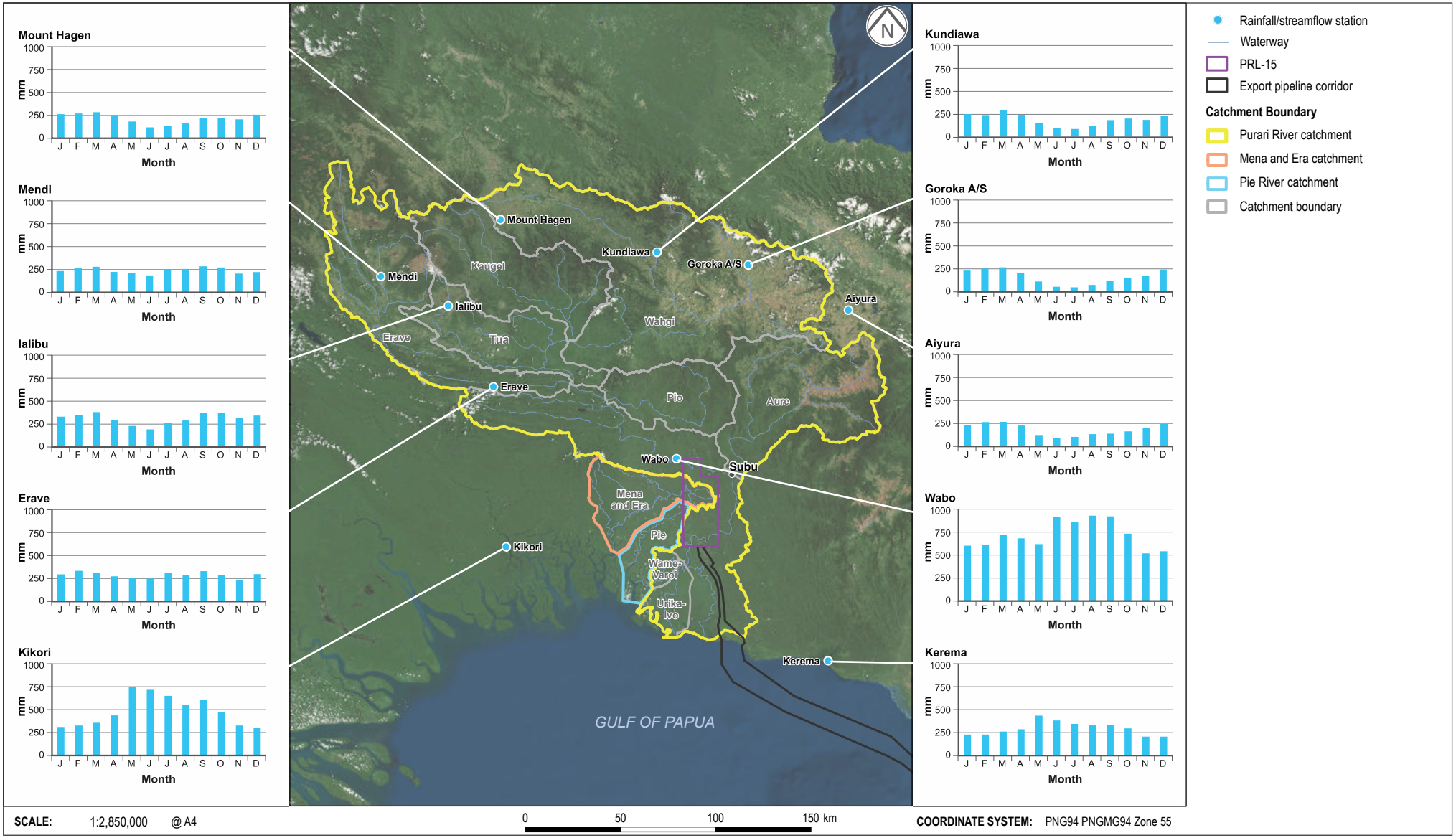


Source: Evesson, 1983.

RAINFALL PATTERNS FOR THE PURARI RIVER CATCHMENT AND ADJACENT AREAS

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FIGURE 7.8



The low level convergence that draws rain to the PRL-15 area also occurs over the Pie and Era river catchments. As a result, a similar temporal distribution in rainfall is expected in these catchments. By contrast, rainfall patterns of the Aure River catchment reported by Pickup and Chewings (1983) reflect those for the rest of the Purari River catchment, i.e., with highest rainfall in the northwest monsoon season. This is expected to be the result of topographical barriers preventing southeast trade winds carrying rain from reaching much of the catchment.

Cyclones do not greatly affect rainfall patterns, as the study area is located north of the main cyclone belt (Evesson, 1983).

Evaporation

Evesson (1983) identifies a likely annual evaporation rate at Wabo, which is at an elevation of approximately 40 m asl, of 1,200 mm. This is derived from an extrapolation by McAlpine et al. (1975) of annual evaporation rates at Kuku, which is near Mount Hagen at an elevation of approximately 1,630 m asl in the upper Purari River catchment, where there is five years of United States Class A evaporation pan measurements.[5] However, Evesson (1983) notes that the US Class A pan measurements provide an overestimate of actual evaporation from a water surface. Alternative estimates based on a comparison of net rainfall and flow in the Purari River with expected ground percolation rates indicate that evaporation rates at Wabo are likely to be closer to 1,000 mm/yr.

The available catchment data shows a weak correlation between rainfall patterns and evaporation, with more evaporation tending to occur in the months when rainfall levels are higher. Lower evaporation levels are also experienced at sites lower in the catchment (i.e., Wabo and Kerema) compared to the upper part of the catchment (i.e., Mount Hagen and Goroka).

7.3.2.3 Hydrology

Purari River Bathymetry and Morphology

The Purari River from the mouth to upstream of PRL-15 is a wide, meandering channel cut into sedimentary coastal plains. As a result, the river features significant scour on the outside of bends, forming a deep channel, with shallow sand and mud banks deposited on inside bends. A bathymetric survey in November 2009 showed a semi-continuous channel deeper than 7 m extending along the Purari River from the river mouth (eastern channel) to Herd Base as a result of this scour.

The Purari River morphology is highly variable. Upstream between Herd Base and the Aure River confluence, the river is more confined with less meandering. This has produced a more consistent area of deep channel, with only small areas of shallow banks and bars. Upstream of the Aure River, the river begins to meander again.

Streamflows

Pickup and Chewings (1983) have previously undertaken some hydrologic modeling for the study area, based on instantaneous stream flow data produced for the Wabo Hydropower Project (SMEC-NK, 1977). The mean daily discharge from the Purari River at Wabo from 1961 to 1978 was estimated to be approximately 2,360 m^3/s (203,900 ML/day), with an annual maximum of between 6,290 m^3/s and 10,405 m^3/s and an average minimum of 1,920 m^3/s. The mean daily discharge from the Aure River was estimated to be 307 m^3/s (26,525 ML/day).

River level measurements of the Purari River at Hou Creek and Herd Base between 2013 and 2016 show rapid changes in water levels in the order of meters associated with changing flow

[5] Standardized evaporation measurements based on a cylinder with a diameter of 120.7 cm and with a depth of 25 cm.

events. These fluctuations occur throughout the year and do not follow a particular seasonal pattern. River level changes measured at Hou Creek appear to be reflected at Herd Base without significant delay, although occasional spikes at Hou Creek are not always reflected at Herd Base.

While Pickup and Chewings (1983) previously described the Purari River hydrology based on hydrologic modeling, comparatively little catchment-specific information is available on the hydrology of the Era and Pie river catchments or the Purari River subcatchments in PRL-15. Catchment modeling, using a deterministic rainfall-runoff modeling approach, was therefore undertaken to provide a comparative assessment of existing conditions of these various catchments and to provide a basis for assessing potential impacts of runoff and sediment loads associated with proposed Project developments. The Unified River Basin Stimulator (URBS) hydrologic model was used to estimate stream flow parameters, including volume, variation, baseflow and duration, for the following six locations in the study area (shown on Figure 7.6):

- Location 1 – representative of Purari River flows upstream of PRL-15.
- Location 2 – representative of Hou Creek flows near its confluence with the Purari River.
- Location 3 – representative of Boa Creek flows near its confluence with the Mena River.
- Location 4 – representative of Mena River flows before its confluence with the Era River.
- Location 5 – representative of Kuku Creek near its confluence with the Purari River.
- Location 6 – representative of Purari River flows downstream of PRL-15.

Figure 7.9 shows modeled average streamflows at these locations. Flows demonstrate obvious seasonality corresponding to rainfall variations. The highest streamflows across the simulated duration (i.e., March 2000 to December 2015) occur during May, June and July at all locations. This period falls within the southeasterly trade wind season when the greatest amount of rainfall is experienced downstream of Wabo. November and December have the lowest streamflows, which is attributed to drier conditions downstream of Wabo during this period. In contrast to the high seasonal variability, there is relatively low inter-annual (i.e., between years) variability in flow regimes, including flooding, and rainfall.

Table 7.2 summarizes the modeled streamflow results for mean daily and mean annual flows. These flows differ from flows described by Pickup and Chewings (1983) due to different data availability and modeling approaches. They do not indicate absolute flow values (i.e., actual instantaneous flows rates) but allow for identification of the relative flow contributions of selected subcatchments to the flow of the Purari River (i.e., Hou and Kuku creeks and Aure River), and for comparison of flows between subcatchments of the Purari and Era rivers (i.e., Hou and Kuku creeks compared to Mena River and Boa Creek).

Table 7.2 – Modeled Existing Streamflow at the Selected Report Locations (Subcatchments)

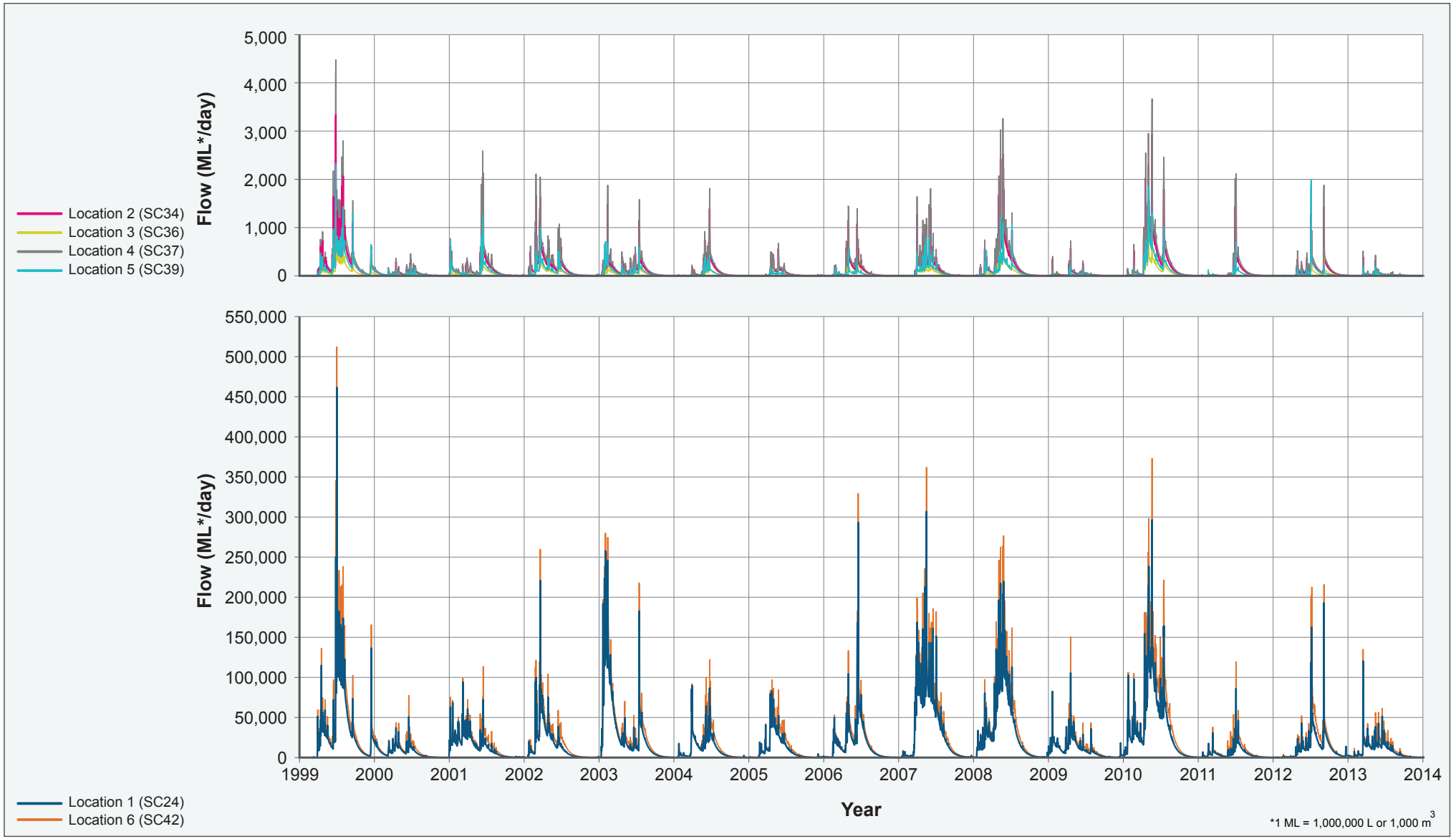
Location		Modeled Catchment Area (km^2)	Mean Daily Flow (ML/day)	Mean Annual Flow (ML/yr)
1	Purari River upstream of PRL-15	30,700	17,500	6,325,430
2	Hou Creek	136	102	36,791
3	Boa Creek	53	40	14,389
4	Mena River	177	133	48,076
5	Kuku Creek	89	58	20,929
6	Purari River downstream of PRL-15 (including the Aure River subcatchment)	32,920	22,400	8,106,615

Note: 1 ML is equivalent to 1,000,000 L and 1,000 m^3.

DOWNSTREAM FLOW VOLUMES AT REPORTING LOCATIONS

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FIGURE 7.9



The Hou Creek and Kuku Creek subcatchments of the Purari River in PRL-15 (i.e., modeling locations 2 and 5) represent a negligible amount of the total flow in the Purari River, contributing only 3.3% of flow downstream of PRL-15. The increase of 4,900 ML/day in mean daily flow between locations upstream and downstream of PRL-15 is mostly due to inflows from the Aure River.

Flow duration curves, presented in Part 2 in Volume 2 show that there is a large difference between ninetieth and ninety fifth percentile flows at all locations, suggesting the entire system is highly responsive to runoff, particularly as it becomes saturated during prolonged rainfall events.

Flooding

Pickup and Chewings (1983) present a flood frequency curve for the Purari and the Aure rivers, from which the following observations regarding flow events are made:

- Flood variability for both rivers across years is low, due in part to the regularity and length of the wet season, which ensures saturation remains high throughout the year and across years.
- While floods can occur throughout the year in both rivers, flood events in the Purari River at Wabo are generally linked to southeasterly weather patterns that occur from June to September. By contrast, flooding in the Aure River appears to be dominated by northwesterly patterns in February to March.
- Low flow events can occur at any time of the year but are more directly correlated to seasons than to flooding. For both rivers, the lowest flow events in the upper Purari River catchment and in the Aure River catchment tend to occur during the southeasterly season. This is also the season when floods occur on the Purari River downstream of Hathor Gorge. The difference is attributable to the reverse seasonality experienced in the lower part of the catchment compared to the upper catchment (Section 7.3.2.2).

No information is available regarding flooding and low flow events in the Pie and Era river catchments, but these are expected to strongly correlate to the Purari River downstream of Hathor Gorge.

To further understand flood behavior in the study area, TUFLOW hydraulic modeling of 20 subcatchments was undertaken for 10-, 50- and 100-year average recurrence interval (ARI) events (Part 2 of Volume 2). The modeling identified two types of channels/floodplains in the study area:

- Well-defined channels/floodplains with a single main channel within the flood extent, mainly found in smaller tributaries of the upper Era and Purari River catchments in PRL-15. The Purari River from Herd Base to the PRL-15 oxbow wetlands also has these characteristics.
- Poorly defined channels/floodplains with multiple intermingling channels across a wide floodplain, mainly found in the tributaries flowing to the Purari River delta and the PRL-15 oxbow wetlands.

Modeling outputs are provided in Part 2 of Volume 2. For subcatchments with well-defined channels, flood extents tend to be similar for each ARI event as floodwaters are constrained by the channel limits. Flood velocities range from 2.2 to 7.8 m/s. In contrast, flood extents are larger for poorly defined channels/floodplains, but flood velocities tend to be lower, from 1.8 to 3.5 m/s. Stream velocity does not change greatly between 10-, 50- and 100-year ARI events for either type of channels.

The PRL-15 oxbow wetland experiences flood behavior consistent with a poorly defined channel/ floodplain, with widespread, shallow flooding with a low velocity. Wetland inundation from the river occurs in each of the 10-, 50- and 100-year ARI events, with little difference between these.

Although details of inundation of the PRL-15 oxbow wetlands on a more frequent basis is unavailable from the modeling, flows from the Purari River are expected to inundate the oxbow lake within the wetlands on an annual basis. Highly localized rainfall in the area north of the wetlands may also cause backflow events to occur, where water in the oxbow lake overflows into the tie channels and 'pushes back' water flow in these channels from the Purari River.

The model simulations for 10-, 50- and 100-year ARI events show flood heights of less than 3 m in the PRL-15 oxbow wetlands, Oyomo Creek and Herd Base, with low flow velocities. Flooding at Herd Base is associated with backflow from Kuku Creek and is confined to areas immediately adjoining the creek. Oyomo Creek has a similar flooding pattern but with a larger extent. Flooding in the PRL-15 oxbow wetlands is very widespread and is deepest in the area between the tie channels, oxbow lake and Purari River.

Sediment Transport and Loads

Sediment transported in the Purari River in the area of PRL-15 predominantly comprises silts and clays, with much of the clay contributed by the Aure River (Pickup, 1983).

Sediment transport rates in the Purari and Aure rivers are closely aligned to rainfall runoff. Pickup (1983) reported up to 57 million tons of sediment is transported in the Purari River at Wabo each year. The Aure River was estimated to deliver an additional 48 million tons downstream of Wabo, making an annual average of around 90 million tons of sediment discharged to the Purari River delta (Pickup, 1983). Based on these results, approximately 50% of the sediment transported in the Purari River downstream of PRL-15 originates from the Aure River.

Catchment modeling of runoff volumes and total suspended solid (TSS) loads was undertaken for the study area at the six locations described in Tables 7.2 and 7.3 and is further described in Part 2 of Volume 2. This modeling indicates that the sediment contribution from the Aure River may be closer to 20%, based on a comparison of loads in the Purari River at locations upstream and downstream of Aure River. The modeling results, presented in Table 7.3, indicate that the mean annual TSS load in the Purari River area is 23 million tons per annum (tpa) upstream of PRL-15 and 29 million tpa downstream of PRL-15. The majority of this 6 million tpa increase in TSS load is due to inflows from the Aure River. The differences in the Pickup (1983) and Part 2 of Volume 2 results are likely due to the different modeling techniques and data limitations and to the inclusion of bedload sediment and TSS in estimates by Pickup (1983).

Table 7.3 – Modeled Total Suspended Solid Loads

Reporting Location		Mean Daily TSS Loads (t/day)	Mean Annual TSS Loads (tpa)
1	Purari River upstream of PRL-15	64,702	23,390,045
2	Hou Creek	67	24,332
3	Boa Creek	14	4,931
4	Mena River	112	40,506
5	Kuku Creek	27	9,771
6	Purari River downstream of PRL-15 (includes the contribution from the Aure River subcatchment)	80,948	29,263,023

Peak TSS loads are predicted to occur between June and September in the Purari, Pie and Era river catchment streams in the vicinity of PRL-15 and to occur between February and March for

the Aure River catchment. These periods coincide with peak rainfall, and consequently peak runoff and streamflows, at these times for these areas.

As described above, the dominant contribution to TSS loads in the Purari River downstream of Hathor Gorge comes from the Aure River catchment rather than the Hou Creek and Kuku Creek catchments in PRL-15. Total volumes discharged from the PRL-15 subcatchment are negligible; representing less than 1% of the 6 million tpa difference in TSS loads between modeling location 1 upstream of PRL-15 and location 6 downstream of PRL-15.

7.4 Surface Water and Sediment Quality

7.4.1 Study Overview

Description of surface water and sediment quality focuses on the waterways in the vicinity of PRL-15 and downstream in the Purari River delta. Description of the regional context of these waterways is provided in Section 7.3.1. The study area in PRL-15 includes the Purari River and its tributary streams and the tributary streams of the Era River including Boa Creek and Mena River. Downstream of PRL-15, the study area includes the freshwater streams and estuarine reaches of the Purari River delta. Estuarine areas of the Vaihua River, which flows into Caution Bay, are discussed in Section 7.4.2.3.

The Purari River delta includes both freshwater and estuarine components, with the estuarine boundary delineated by the inland extent of mangrove vegetation, as defined by Shearman (2010) and shown in Figure 7.10. It also includes the three main delta distributaries, the Purari, Urika-Ivo and Wame-Varoi rivers.

Description of the surface water and sediment quality of these waterways considers existing information from previous studies but is mostly based on field studies completed in June and July 2016 and in January and February 2017 (Part 3 of Volume 2).

The surface water quality surveys involved in situ measurements of physicochemical parameters (turbidity, conductivity, salinity, temperature and dissolved oxygen) and collection of surface water grab samples for laboratory analysis of the following parameters:

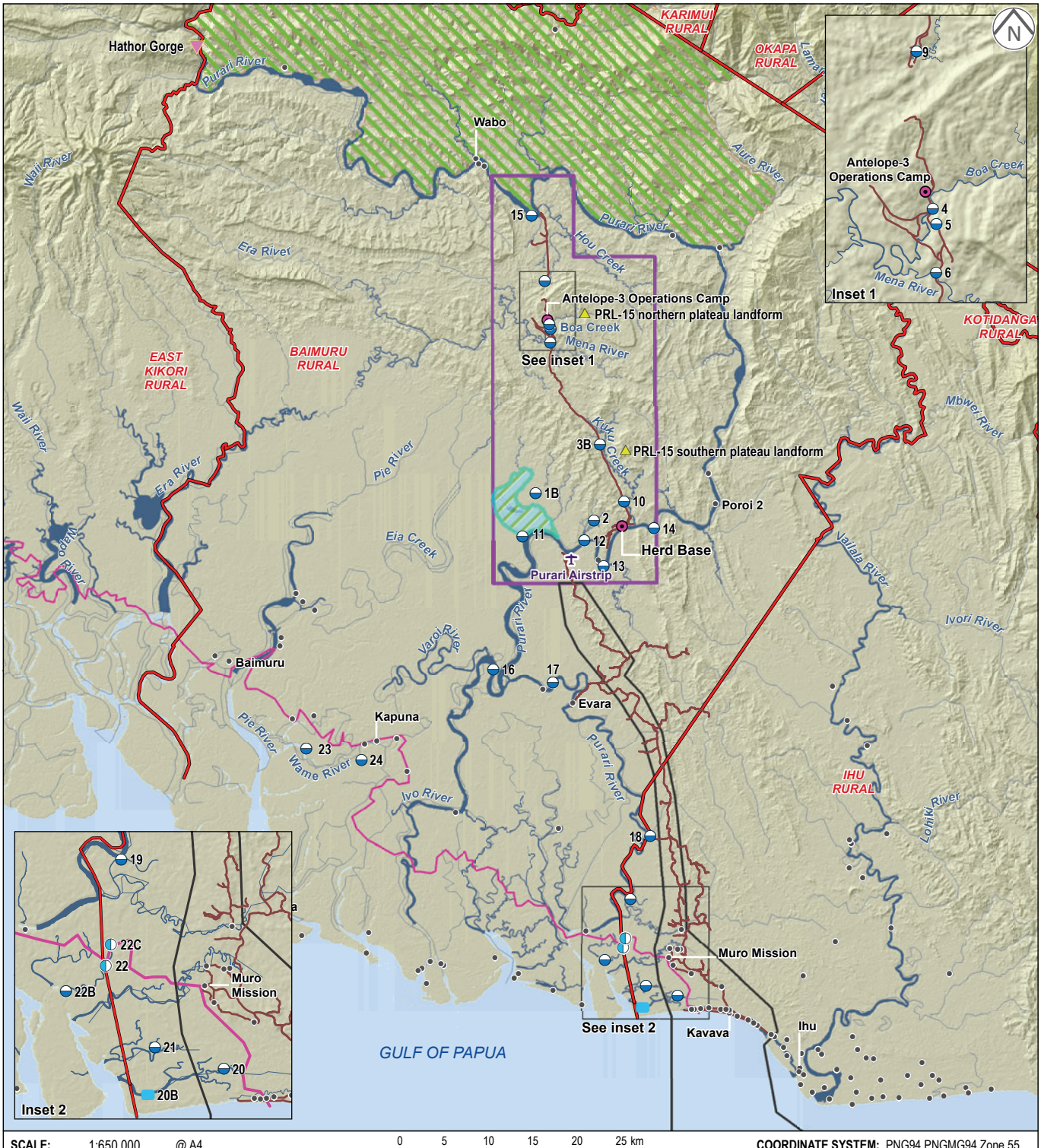
- Total suspended solids (TSS), major ions (i.e., calcium, magnesium, sodium, potassium, chloride, sulfate and bicarbonate), and total and dissolved organic carbon.
- Nutrients (i.e., ammonia, nitrate/nitrite, total nitrogen, filterable reactive phosphorus and total phosphorus).
- Toxicants (i.e., total and dissolved metals/metalloids, TPH, polycyclic aromatic hydrocarbons (PAH) and BTEX).
- Microbiological water quality (total coliforms).

Water quality instruments were also deployed in the Purari River at Herd Base to continuously measure and log turbidity during the field surveys.

FRESHWATER AND ESTUARINE SURVEY SITES

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FIGURE 7.10



Communities outside of the Project area of influence have not been verified. Only government administrative centers and notable locations have been labeled for context.

To provide a benchmark for assessment, water quality results were compared to the following criteria for protection of aquatic life:[6]

- Schedule 1 of the *Environment (Water Quality Criteria) Regulation 2002*, which provides legally enforceable freshwater and marine water quality criteria in Papua New Guinea.
- Australian and New Zealand guidelines for fresh and marine water quality (ANZECC/ ARMCANZ, 2000)[7], which provide good international industry practice guidance for water and sediment quality assessment relevant to the region and are applicable to estuarine and freshwater environments.

Suitability for use as drinking water was also assessed considering PNG *Public Health (Drinking Water) Regulation* (PNG PHR) 1984 and the WHO (2011) drinking water guidelines.

Bed sediment samples were collected at all sites for analysis of particle size, total nitrogen and phosphorus, metals/metalloids, TPH, PAH and BTEX. No freshwater or estuarine sediment quality guidelines are provided in the PNG regulations, although the *Marine Pollution (Sea Dumping) Regulation 2013* provides contaminant guidelines for dredged material proposed to be placed at sea. Assessment of results was therefore undertaken considering interim sediment quality guidelines described in ANZECC/ARMCANZ (2000) and revisions to those guidelines described in Simpson et al. (2013).

Detailed water quality and sediment quality results are presented in Part 3 of Volume 2.

7.4.2 Surface Water Baseline Characterization

In describing the study sites in the following sections, distinction has been made between the following areas:

- PRL-15 sites (see Figure 7.10) – freshwater sites occurring in PRL-15 in the Purari River catchment and the Era River catchment, including tributary streams and the Purari River main channel. This includes sites 1B, 2, 3B, 4, 5, 6, 9, 10, 11, 12, 13, 14 and 15.
- Purari River delta sites (see Figure 7.10), including:
  - Freshwater sites occurring in the Purari River main channel from the split of the Purari River into the Purari, Urika-Ivo and Wame-Varoi distributary channels downstream to the indicative estuarine boundary within these channels. This includes sites 16, 17, 18 and 19.
  - Estuarine sites occurring from the indicative estuarine boundary downstream to the coast. This includes sites 20, 20B, 21, 22, 22B, 22C, 23 and 24.
- Vaihua River estuary – estuarine sites of the Vaihua River at Caution Bay, including sites 28 and 29 (Figures 8.11 and 8.21 in Chapter 8).

6 There is an absence of toxicity data specific to estuarine environments upon which guideline values can be based. As a precautionary approach, therefore, where both freshwater and marine guidelines are available, the more stringent of the two was applied for estuarine waters.

7 ANZG (2018) water quality guidelines have recently superseded the ANZECC/ARMCANZ (2000) water quality guidelines, however default trigger guideline values in the new guidelines currently remain the same as described in ANZECC/ARMCANZ (2000).

7.4.2.1 PRL-15

Surface water quality at sites in PRL-15, including tributary streams and the Purari River main channel, is characterized by low electrical conductivity (less than 400 µS/cm), with minimal seasonal variability (Figure 7.11). Stream pH was slightly to moderately alkaline, from pH 7.2 to 8.5, which is likely attributable to the carbonate parent geology in the area. Water was well-oxygenated (i.e., 85 to 120% saturation) at most tributary sites in PRL-15, except for site 11 on Nea Creek in a tie channel to the PRL-15 oxbow wetlands, which had 30% saturation (see Figure 7.11). The low dissolved oxygen level and lower pH (pH 7.2) at this site was most likely due to water outflow from the oxbow wetlands. Such water features typically have low dissolved oxygen levels, low pH and high dissolved organic carbon levels, due to breakdown of organic material. Tannin-stained waters observed entering the Purari River at this location during the field survey also provided evidence of such water in the wetlands.

Turbidity levels in tributary streams of the Purari River in PRL-15 were generally less than 50 nephelometric turbidity units (NTU) and lower than in the main channel; however, there was notable variation (see sites 11 to 15, Figure 7.11). The highest turbidity measured (300 NTU) was at site 12 in the tributary stream at the mouth of Oyomo Creek in the proposed CPF area during the southeast trade wind season survey. This was higher than turbidity in the main channel of the Purari River immediately downstream of this location, where turbidity was 145 NTU. During the northwest monsoon season survey, turbidity in Oyomo Creek (91 NTU) was lower than in the Purari River main channel (263 NTU). In general, turbidity in the Purari River main channel was higher during the northwest monsoon season than during the southeast trade wind season.

Total suspended sediment (TSS) in the Purari River showed the same trend as turbidity, with concentrations from 21 to 428 mg/L (Figure 7.12). This is similar to the findings of Petr (1983c), who reported TSS levels from 29 to 778 mg/L with an average of 254 mg/L. Continuous turbidity measurements undertaken by a fixed instrument in the Purari River at Herd Base during the 2017 northwest monsoon season survey recorded turbidity levels around 200 to 400 NTU, increasing to about 1,000 NTU following rainfall events in the catchment when river flows increased (Figure 7.13).

During both seasons, tributary streams in PRL-15 in the area of the gas field (i.e., sites 4, 5, and 9) had generally low but variable turbidity and TSS levels, with median values of 6 NTU and 7 mg/L, respectively. The highest levels in these tributary streams were measured in the Mena River (site 6) during the southeast trade wind season, when turbidity and TSS levels were 90 NTU and 130 mg/L, respectively. Previous studies reported in GHD (2015a, 2015b, 2015c, 2015d) also found that TSS levels in tributary streams in PRL-15 were usually low (less than 5 mg/L).

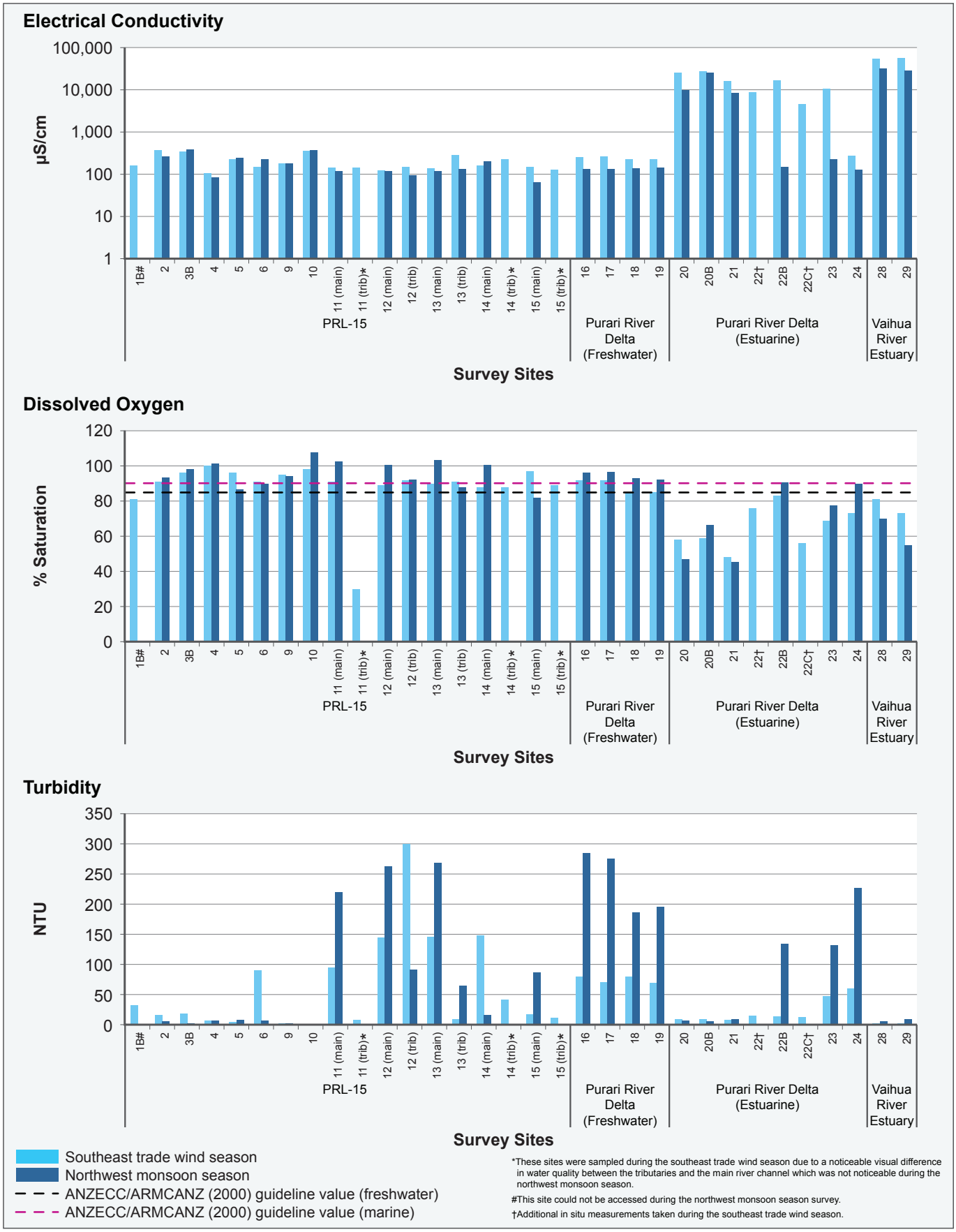
All monitoring sites had water with total alkalinity well above 20 mg $CaCO_3$/L and up to 168 mg $CaCO_3$/L, indicating that the waters have good acid-buffering capacity. Major ion analyses show that the waters are calcium and carbonate dominated, reflecting the widespread presence of calcareous rocks in the catchment (Petr, 1983c).

Nutrients and organic carbon were present in generally low concentrations at all sites during both the southeast trade wind and northwest monsoon season surveys. Total nitrogen and phosphorus concentrations in the tributary streams were less than 0.1 to 0.4 mg/L and between 0.02 to 0.15 mg/L, respectively, and were lower than in the main channel of the Purari River where the range was 0.2 to 1.5 mg/L for total nitrogen and 0.04 to 0.4 mg/L for total phosphorus. Ammonia concentrations were similar at all locations and were less than 0.01 to 0.08 mg/L, except at site 11 in the northwest monsoon season where a concentration of 0.83 mg/L was measured. All ammonia results were below water quality guidelines. Nitrate, nitrite and soluble reactive phosphorus concentrations were low (i.e., less than 0.07 mg/L) at all locations.

ELECTRICAL CONDUCTIVITY, DISSOLVED OXYGEN AND TURBIDITY DATA

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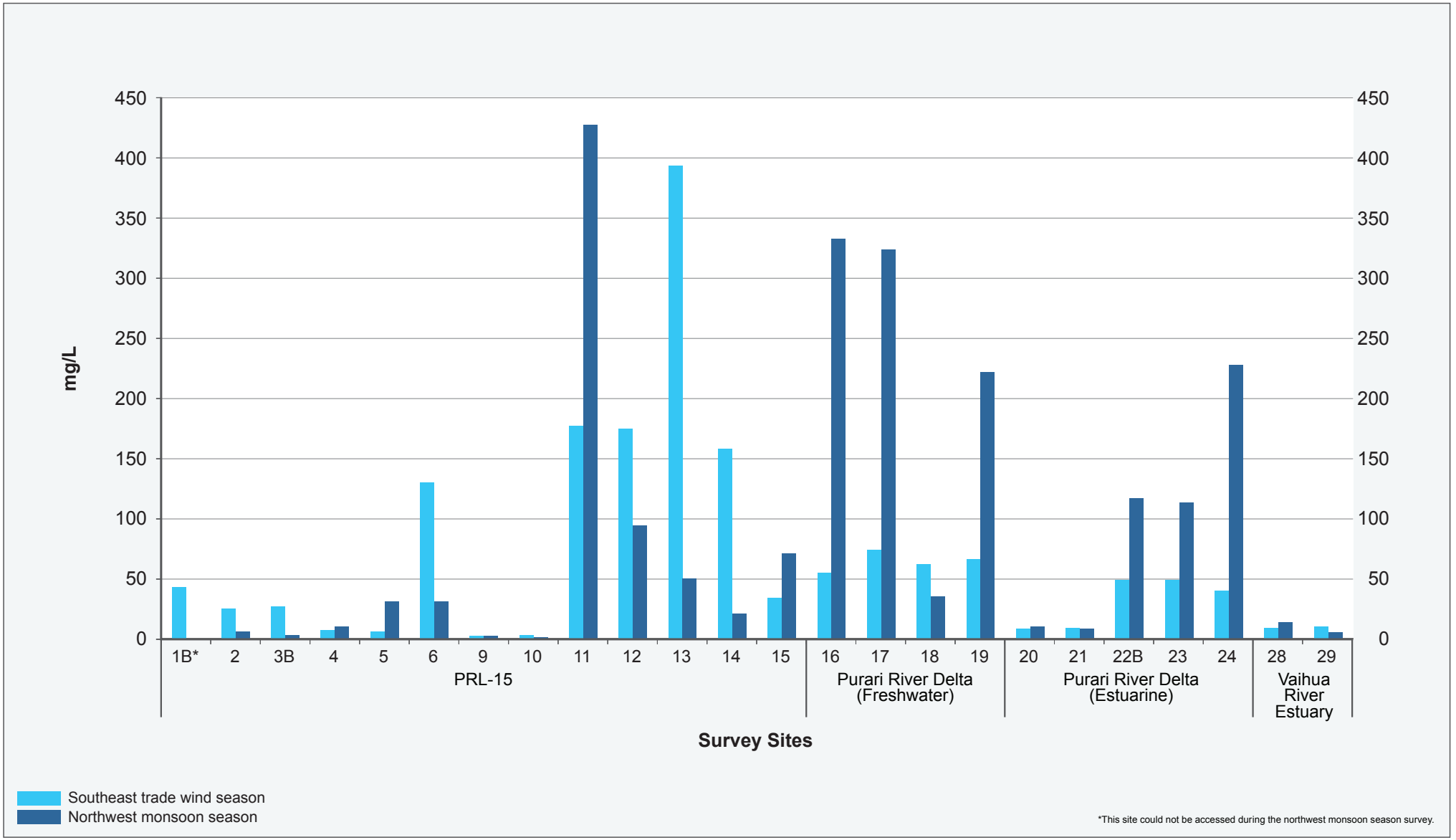
FIGURE 7.11



TOTAL SUSPENDED SOLIDS DATA

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FIGURE 7.12

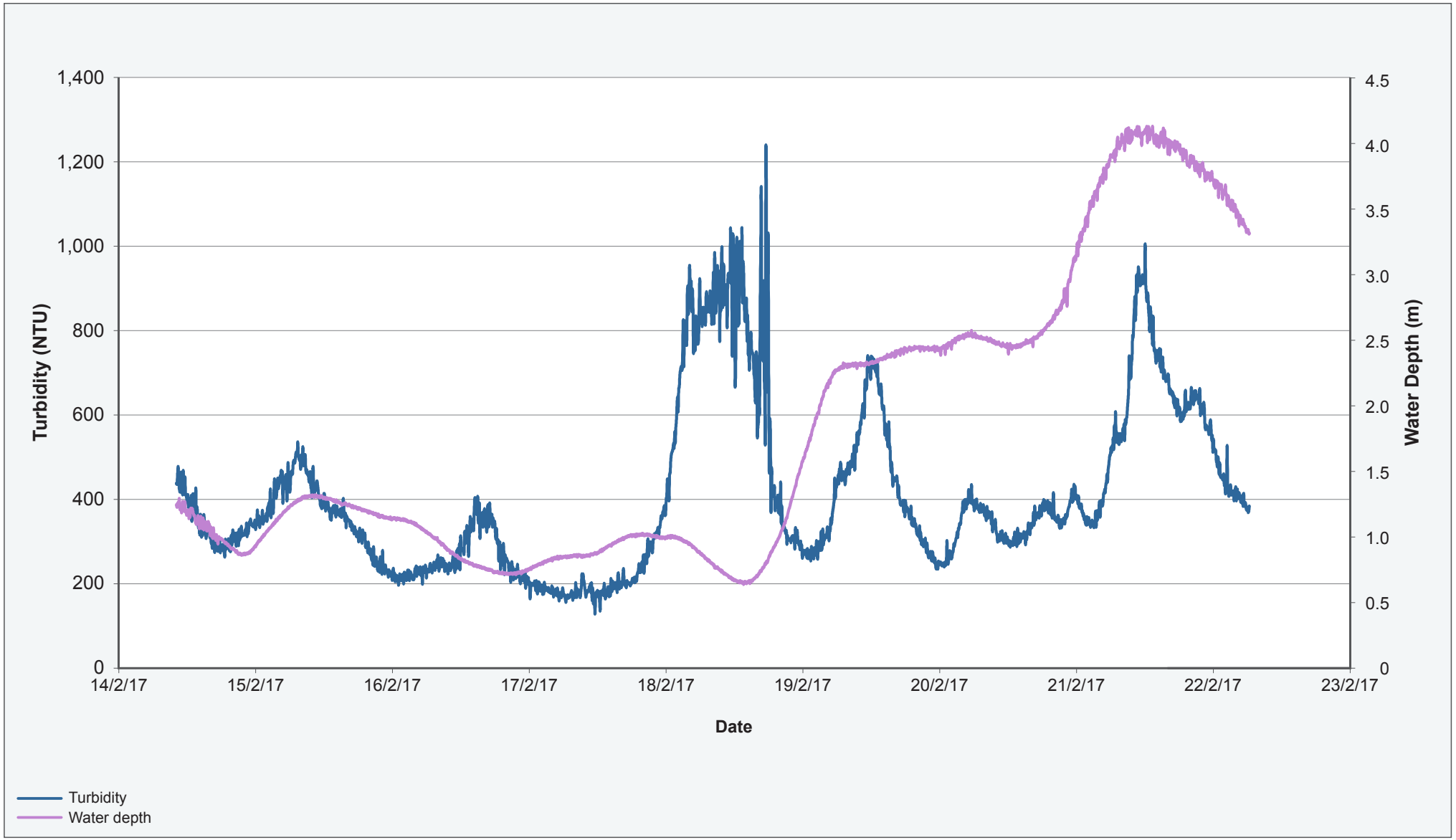


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TURBIDITY AND WATER DEPTH OF THE PURARI RIVER (HERD BASE)

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FIGURE 7.13



ERIAS Group | 01215B_23_F7.13_v1

Dissolved metal and metalloid concentrations at all sites in tributary streams and the Purari River main channel were also low; most results were below the limit of reporting and were similar between seasons. There were no exceedances of relevant water quality guidelines for protection of aquatic ecosystems or drinking water quality.[8] Total aluminum and iron concentrations were particularly high in the Purari River main channel (i.e., 0.9 to 16.8 mg/L and 1.3 to 21.4 mg/L, respectively), reflecting the elevated levels of suspended sediment present.

Total petroleum hydrocarbon, PAH and BTEX concentrations were below laboratory limits of reporting at all sites during both surveys and less than relevant water quality criteria.

Total coliform levels at all PRL-15 sites during both surveys were greater than 80 colony-forming units (CFUs) per 100 mL. This does not conform with drinking water requirements for protection of human health, which are that coliforms should be less than 3 CFUs/100 mL (PNG PHR) or 0 CFU/100 mL (WHO, 2011). Such exceedances are often observed in waterways in Papua New Guinea with 60% of the population lacking access to sanitation facilities and safe water, particularly in rural areas (WaterAid, 2017). Information on coliform levels in groundwater sources, including community water and sanitation uses and practices, the effects of which are likely contributing to high coliform levels in watercourses in the study area, is provided in Section 7.5.4.

7.4.2.2 Purari River Delta

The freshwater reaches of the Purari River delta include sites 16 to 19 (see Figure 7.10). Electrical conductivity at these sites was 132 to 266 µS/cm, similar to conductivities measured further upstream in PRL-15 (see Figure 6.11), and is consistent with previous results of 115 to 265 µS/cm reported for the lower Purari (Petr, 1983c). Other water quality properties of these freshwater sections of the Purari River delta were also found to be similar to the Purari River main channel upstream in the vicinity of PRL-15 described in Section 7.4.2.1.

The indicative estuarine boundary in the Purari River delta, coincident with the extent of mangrove forest, is shown in Figure 7.10 and includes sites 20 to 24. Electrical conductivity varied between sites and seasons and was around 100 to 28,000 µS/cm; the highest values were at sites closest to the coast due to the marine influence from the Gulf of Papua (see Figure 7.11).

Water column profiling at the estuarine sites showed that water quality was relatively consistent through the water column, indicating minimal stratification when sampled, except one site near the Purari River mouth (site 22B) during the northwest monsoon season survey, which recorded low conductivity (approximately 100 µS/cm) in surface layers and much higher conductivity in bottom water (approximately 20,000 µS/cm). This indicates a salt wedge (i.e., saline marine waters underlying fresh fluvial waters), which is typical of river mouth environments.

Dissolved oxygen concentrations were generally lower (down to 45% oxygen saturation) at the estuarine sites compared to freshwater sites in the Purari River delta (85% to 97% oxygen saturation). Low dissolved oxygen is typical in estuarine waters where degradation of settled detrital material and lack of oxygenation due to water column stratification and poor water mixing depletes oxygen levels.

Estuarine reaches of the Purari River delta had a median TSS concentration of 45 mg/L with a range of 8 to 228 mg/L and a median turbidity of 13 NTU with a range of 5 to 227 NTU. Turbidity

8 The guideline values are applicable to dissolved concentrations. Dissolved zinc at site 4 (9 µg/L) marginally exceeded the ANZECC/ARMCANZ (2000) guideline for aquatic ecosystem protection (8 µg/L); however, the total zinc concentration was less than 5 µg/L, indicating that the filtered dissolved sample may have been contaminated during sampling or analysis.

and TSS levels in the upper reaches of the brackish creeks (sites 20 and 21) were much lower than the sites located in or near main river channels, such as site 22B where turbidity was up to 134 NTU (see Figure 7.11). This is likely to be due to these waters being calmer, allowing solids to settle.

Major ion concentrations in the estuarine reaches were much higher than those in the freshwater reaches, reflecting the influence of seawater, particularly at sites 21 and 22. Alkalinity was quite high, ranging from 66 to 132 mg $CaCO_3$/L, with the highest levels at sites 21 and 22; however, pH was lower than usually observed in marine waters (approximately pH 8), ranging from pH 7.1 to 7.7, and generally lower than measured at freshwater sites in the Purari River delta and further upstream.

Nutrient and organic carbon concentrations in estuarine reaches were within the ranges found at the freshwater sites in the Purari River delta and further upstream in the vicinity of PRL-15, with no trends evident. Chlorophyll levels were low at both freshwater and estuarine sites and were less than or equal to the limit of reporting (2 µg/L).

Dissolved metal and metalloid concentrations at all sites in the Purari River delta were low, with most results being below the limit of reporting. Higher strontium levels observed in estuarine reaches (up to 2.5 mg/L) were a notable exception, which is attributed to it being a major element naturally present in seawater (at concentrations of approximately 8 mg/L). Relevant water quality guidelines for protection of aquatic ecosystems or drinking water were not exceeded. Similar to results for the Purari River main channel in PRL-15, higher total aluminum and iron concentrations observed at some sites (5 to 11 mg/L) reflect the elevated suspended sediment levels present from natural geological sources.

Total petroleum hydrocarbon, PAH and BTEX concentrations were below laboratory limits of reporting at all Purari River delta sites during both surveys and were less than relevant water quality criteria.

Total coliform levels were very high at most Purari River delta sites and did not conform to drinking water requirements for protection of human health that coliforms should be less than 3 CFUs/100mL (PNG PHR) or 0 CFU/100mL (WHO, 2011). Coliform levels also exceeded the PNG Schedule 1 criteria for protection of aquatic life of 200 CFUs/100 mL at all but one site. Total coliforms were highly variable between sites with the highest count of 16,000 CFUs/100 mL occurring at site 24 in the Wame River. Such exceedances, as also noted above for freshwater sites, are often observed in waterways in Papua New Guinea with 60% of the population lacking access to safe water, particularly in rural areas (WaterAid, 2017).

7.4.2.3 Vaihua Estuary

The Vaihua River catchment adjacent to Caution Bay drains a relatively small area and features a low relief and slope.

The Vaihua River at Caution Bay is considered estuarine up to the edge of the salt flats immediately southeast of the existing PNG LNG facilities. The river experiences highest flows between December and March, with only low or intermittent flows in May to October, which leave isolated pools of standing water (CNS, 2009). Most of the tributary streams of the river are ephemeral. As a result, freshwater inputs are negligible during the dry season but high during the wet season, leading to a transition between a ‘negative’ and a ‘positive’ estuary and creating areas of hypersaline wetland in intertidal and supratidal flats (CNS, 2009).

Two sites in the Vaihua River estuary were sampled (sites 28 and 29) during the 2016 and 2017 field surveys. The site locations are shown in Figure 8.11 in Chapter 8.

Electrical conductivity and salinity in the Vaihua River estuary is reflective of a marine environment, with electrical conductivity around 55,000 µS/cm and salinity around 35 parts per thousand. Major ion concentrations were correspondingly high. The pH was from 7.5 to 7.9, slightly below the typical pH for seawater. Turbidity was low from 1.9 to 8.3 NTU, while TSS was 6 mg/L to 14 mg/L. Dissolved oxygen levels were low, from 57% to 81% saturation, and slightly below water quality guidelines for protection of aquatic ecosystems.

Nutrient concentrations were low, usually below laboratory limits of reporting, and similar to or less than concentrations measured in the Purari River delta. Ammonia was an exception with concentrations from 0.08 to 0.16 mg/L, which were slightly higher than concentrations measured in the Purari River delta (0.02 to 0.10 mg/L). Ammonia concentrations were slightly higher in the southeast trade wind season (0.14 to 0.16 mg/L compared to 0.08 to 0.11 mg/L). Total and dissolved organic carbon and chlorophyll levels were similar to those measured in the Purari River delta.

Dissolved metal and metalloid concentrations were low, usually below the limits of reporting and less than water quality guidelines.[9] Similar to estuarine reaches of the Purari River delta, the notable exception was strontium, with concentrations between 5.6 and 8.0 mg/L and higher in the southeast trade wind season. Strontium is a major element naturally present in seawater and may be lower in the northwest monsoon season due to increased freshwater inputs from higher rainfall. Total metal and metalloid concentrations, except aluminum and iron, were generally similar to dissolved concentrations; however, total concentrations of these two metals were not particularly high (less than 0.3 mg/L), reflecting the relatively low TSS levels at the two sites.

Total petroleum hydrocarbon, PAH and BTEX concentrations were below laboratory limits of reporting and less than relevant water quality criteria at all Vaihua River estuary sites during both surveys. Total coliforms were detected at both sampling sites; with 920 CFUs/100 mL measured at site 29 and 7 CFUs/100 mL at site 28 during the 2017 northwest monsoon season survey. Both results were above drinking water requirements for protection of human health that coliforms should be less than 3 CFUs/100mL (PNG PHR) or 0 CFU/100mL (WHO, 2011), while the result from site 29 was also above PNG Schedule 1 criteria of 200 CFUs/100 mL for protection of aquatic life.

7.4.3 Sediment Quality Baseline Characterization

Bed sediment samples were collected during the southeast trade wind season at each of the sampling sites described in Section 7.4.2, except the Vaihua River estuary.[10] Locations of PRL-15 sites[11] and Purari River delta sites are shown in Figure 7.10.

7.4.3.1 PRL-15

The particle size distribution (PSD) results for bed sediment in the vicinity of PRL-15, including tributary streams and the Purari River main channel, indicate that grain size is variable, with some sites consisting of predominantly sand and gravel, while other sites were predominantly silts and clays (Figure 7.14).

9 The guideline values are applicable to dissolved concentrations. Dissolved copper marginally exceeded the ANZECC/ARMCANZ (2000) guideline value at site 29 during the 2017 northwest monsoon season survey; however, the total copper concentration was lower and less than the guideline value, indicating that the filtered dissolved sample was contaminated during sampling or analysis.

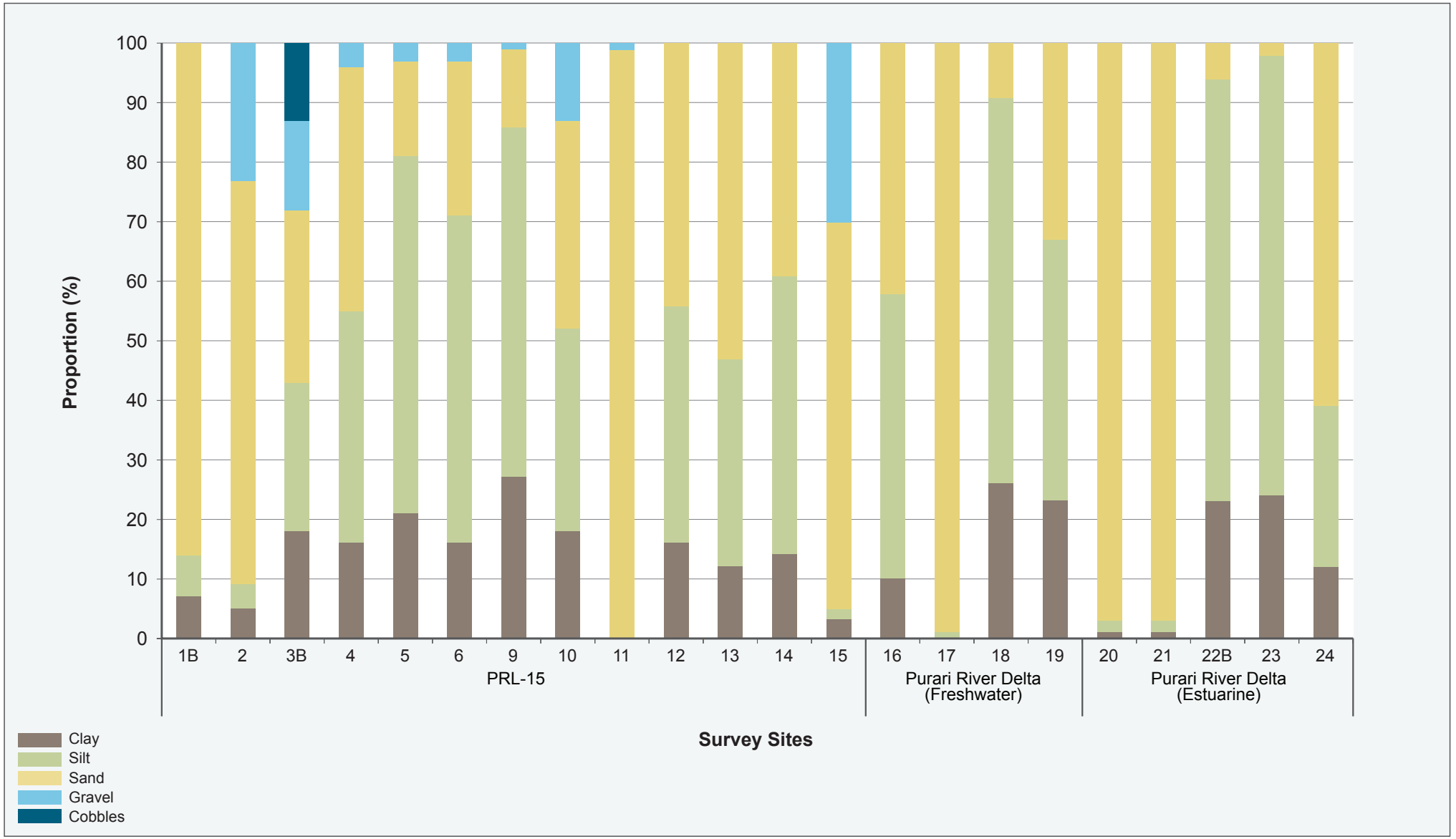
10 Intrusive sediment sampling in Caution Bay was unable to be undertaken due to the safety risk from unexploded ordnances, possibly present due to activities during World War II at the nearby Boera battery.

11 Sediment sampling at sites 11 to 15 was undertaken in the Purari River main channel; no sediment sampling was undertaken in the adjacent tributary stream.

SEDIMENT PARTICLE SIZE DISTRIBUTION

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FIGURE 7.14



In the Purari River main channel in PRL-15, the furthest upstream site (site 15) and the furthest downstream site (site 11) were mostly sand or sand with some gravel respectively, while sites in between (sites 12, 13 and 14) consisted of approximately 50% sands and 50% silts and clays. Coarser bed sediments (i.e., sands) typically occur in high-energy environments, whereas finer sediments (i.e., silts and clays) typically occur in depositional environments and therefore reflect the particular dynamics of the site sampled.

Sites sampled on tributary streams of the Era and Purari rivers in PRL-15 (i.e., sites 4, 5, 6 and 9) have large proportions (55% to 85%) of silts and clays.

Total nitrogen concentrations varied considerably between sites in PRL-15 in tributary streams and the Purari River main channel from 160 to 1,120 mg/kg. Nearly all nitrogen was organically bound, with sites with the highest total nitrogen concentrations also having the highest amounts of total organic matter (up to 3%) and total organic carbon (up to 1.7%). There was less variation in total phosphorus concentrations between sites, with levels from 295 to 885 mg/kg.

Metal and metalloid concentrations in sediment were similar at sites in PRL-15, which included samples from both the main Purari River channel and smaller tributary streams. All concentrations were below sediment quality guideline values, except nickel, which exceeded the guideline value of 21 mg/kg at all sites with values from 31 to 53 mg/kg; however, as found elsewhere in Papua New Guinea and Australia, it is not unusual for natural background nickel concentrations in sediment to exceed this guideline due to the regional geology and climatic conditions.[12] Similar exceedances were found in baseline studies for the PNG LNG Project (Hydrobiology, 2008).

Total petroleum hydrocarbon, PAH and BTEX concentrations at all sites were below the laboratory limits of reporting and less than sediment quality guidelines where available for the various parameters.

7.4.3.2 Purari River Delta

Similar to sites in PRL-15, bed sediment particle size in the Purari River delta – including freshwater main channel and estuarine reaches – is highly variable, with some sites consisting of predominantly sand (sites 17, 20 and 21), while other sites were predominantly silts and clays (sites 18, 19, 22B and 23), with the latter indicating depositional environments (see Figure 7.14).

Also similar to PRL-15, there was considerable variation in total nitrogen concentrations in sediments within the Purari River delta, from 140 to 1,560 mg/kg. As found in PRL-15, this nitrogen was all organically bound; and concentrations were highest in sediments containing higher amounts of organic matter (which was present at levels up to 5%). Total phosphorus levels throughout the Purari River delta were from 482 to 908 mg/kg.

Metal and metalloid concentrations in the Purari River delta, including freshwater main channel and estuarine reaches, were similar between sites and within the ranges determined in sediment from PRL-15. All concentrations were below sediment quality guideline values except nickel, which exceeded the guideline value of 21 mg/kg at all sites with from 29 to 47 mg/kg. Total petroleum hydrocarbon, PAH and BTEX concentrations at all sites within the Purari River delta were below the laboratory limits of reporting.

12 In high-rainfall tropical environments, soils can become enriched in particular elements due to weathering of the parent rock by rainfall, resulting in removal of more soluble elements, such as calcium and magnesium, and concentrating less soluble elements, such as nickel and cobalt.

7.4.3.3 Vaihua River Estuary

Although no sediment samples were collected in the Vaihua River estuary during the 2016 and 2017 surveys due to safety risks from unexploded ordnances, sampling previously undertaken for the PNG LNG Project (Hydrobiology, 2009) indicates that grain size is variable, with sediment at some sites predominantly comprised of sand and at other sites predominantly comprised of silt. Metal concentrations were below sediment quality guidelines, with the notable exception of nickel, which exceeded the guideline value of 21 mg/kg at three out of four sites, with values from 24 to 48 mg/kg. This is similar to the findings of the 2016 and 2017 surveys of PRL-15 and the Purari River delta discussed above, providing further evidence that nickel is present at naturally elevated levels in the study area. Arsenic also slightly exceeded the sediment quality guideline at one of the four locations sampled in the Vaihua River estuary.

7.5 Groundwater

7.5.1 Regional Context

Groundwater assessment in the study area to date has been limited, and little detail is known about the area's hydrogeology. The few groundwater access points in the study area comprise the Project's Herd Base abstraction bores in the southern area of PRL-15 adjacent to the Purari River. No known bores occur in the onshore export pipeline corridor. Groundwater springs are understood to be relatively common in the upper reaches of the study area, particularly during and following the wet season (GHD, 2015d). Hand-dug village wells used for domestic water supply are common in the coastal areas (Part 14 of Volume 2). There is little quantitative data regarding groundwater levels or the water flow or quality from these shallow groundwater features.

Some interpretation of potential deeper groundwater occurrence can be made based on the understanding of the stratigraphy of the study area described previously in Table 7.1. Based on this geological information, four potential hydro-stratigraphic units are likely to be present:

- Perched or shallow groundwater (i.e., minor occurrences of groundwater above regional groundwater) in upper weathered rock material, alluvium or back beach deposits, which is considered to represent the primary source of creek discharge in their upper reaches. In the higher altitude terrain in the northern part of PRL-15, in the gas field area, this groundwater may not be present year round and is unlikely to be laterally continuous. Close to rivers and water bodies, alluvial sediments may support groundwater capable of providing sustainable and valuable groundwater yields to these surface waters. In the lower coastal areas, this groundwater may be very shallow, less than 1 m below ground level (bgl), and is an important water supply for some villages. The perched groundwater is likely to be predominantly controlled by topography.
- Shallow permanent groundwater within sandstones, siltstones, mudstones and minor conglomerates of the Era Beds in certain areas of the study area, with Era Beds largely absent from the northern part of PRL-15 in the gas field area. This groundwater is understood to exist at depths corresponding to the levels of nearby watercourses; hence, beneath ridgelines and high points, depth to groundwater could be greater than 200 m. Groundwater occurrence in this hydro-stratigraphic unit is likely to be variable, with permeability and hydraulic conductivity controlled by sediment variation.
- Formation (interstitial) water is likely to be present at various levels throughout the stratigraphy of the Orubadi Beds. The hydraulic conductivity of this material is likely to be low, and only low volumes of water have been encountered during the drilling of exploration wells; hence, this hydro-stratigraphic unit is not considered to represent an aquifer.

- Deep groundwater, greater than 1,600 m bgl, may be present in the Kapau Limestone that contains the gas reservoir, although only in low quantities, as hydrocarbons occupy pore space in this geology. Exploration drilling to date has shown very little water is associated with gas and condensate. This hydro-stratigraphic unit is considered to be confined by low permeability material of the overlying Orubadi Beds and unconnected to surface water of shallower hydro-stratigraphic units. The volume of water expected in this formation and its status as a hydrocarbon reservoir, means that this hydro-stratigraphic unit is not considered to represent an aquifer.

On the basis of observations and information collected during the field survey, only one of these potential hydro-stratigraphic units that is accessed by the community as a groundwater resource is the perched or shallow groundwater within upper weathered rock material, alluvium or back beach deposits.

7.5.2 Study Overview

Description of the groundwater in the study area is based on existing information available from previous studies, the scientific literature and a field survey undertaken in PRL-15 and the onshore export pipeline corridor in November 2016.

The field survey involved general observations of the surrounding environment in PRL-15 and the onshore export pipeline corridor. Gauging and sampling was also undertaken of groundwater bores at Herd Base and of springs and shallow wells at coastal and inland villages along the onshore export pipeline corridor.

Forty-three sites were observed, gauged, sampled or sighted during the field survey (Figure 7.15). Thirty-one groundwater features (e.g., wells, springs or bores) were observed and documented, while observations of springs, seepages or erosional features were made at 12 additional sites, to inform groundwater conceptualization (see observation sites in Figure 7.15). Of the 31 groundwater features documented, water levels were gauged at 28 sites; in situ water quality measurements were undertaken at 17 sites; and water samples were collected at 16 sites, of which 14 were analyzed for general water quality parameters and contaminants, including metals, hydrocarbons and coliforms.

The suitability of groundwater for use as drinking water was assessed considering PNG PHR and the WHO (2011) drinking water guidelines. Given the close connectivity of surface waters with groundwater, which occurs close to the surface at most of the sampling locations, consideration was also given to Papua New Guinea and international freshwater guidelines for aquatic ecosystem protection (i.e., Schedule 1 of the *PNG Environment (Water Quality Criteria) Regulation 2002*, and ANZECC/ARMCANZ (2000)[13], respectively). These assessment criteria are provided and further described in Part 4 of Volume 2. Based on the review of existing information relating to the study area and field observations, a conceptual understanding of known and likely groundwater conditions in various parts of the study area has been developed and is described in Section 7.5.3. The results from groundwater quality sampling undertaken in the study area in November 2016 are summarized in Section 7.5.4.

13 ANZG (2018) water quality guidelines have recently superseded the ANZECC/ARMCANZ (2000) water quality guidelines, however default trigger guideline values in the new guidelines currently remain the same as described in ANZECC/ARMCANZ (2000).

GROUNDWATER SURVEY SITES

Papua LNG Project | Environmental Impact Statement

FIGURE 7.15



Communities outside of the Project area of influence have not been verified. Only government administrative centers and notable locations have been labeled for context.

7.5.3 Groundwater Conceptualization

7.5.3.1 PRL-15

The Elk-Antelope gas field area in the north of PRL-15 is characterized by steep slopes and incised valleys and experiences high rainfall. In this area, localized bodies of shallow, unconfined, perched groundwater are thought to be present within superficial sedimentary material, including alluvium, colluvium, landslide debris and weathered material. Where present, this perched groundwater is likely to exist within 10 m of the ground surface. The superficial sedimentary material in this area is thought to have a high capacity to contain and transmit water, releasing it slowly from springs and seeps, and to act as a buffer that sustains stream baseflow for some time after rainfall events. These shallow groundwater systems are thought to be localized (i.e., confined to single valleys), with recharge and discharge areas in close proximity to each other. Since there was little to nil rainfall prior to and during the field survey, limited evidence of this was observed in the field, although this interpretation is supported by multiple examples of spring-type erosion and minor seeps observed within the area.

Permanent groundwater is likely to occur in more extensive alluvial deposits in the major river valleys. This groundwater is likely to be connected to surface water. With the possible exception of sandstones within the Era Beds, the deeper geology is unlikely to support sufficient groundwater to classify aquifers as being present. The Orubadi Beds are dominated by mudstones and siltstones (see Table 7.1), which are likely to have low hydraulic conductivities. This, in addition to the depth to this formation, supports the interpretation that this sedimentary material does not support significant groundwater systems.

The proposed CPF area and Herd Base have low relief when compared to the gas field area, yet it still includes steep slopes and incised valleys. Major surface rivers and streams, including the Purari River and Kuku Creek, are also present. Local shallow, perched groundwater is considered likely in superficial sedimentary materials, as evidenced by seeps and spring type erosion. Similar to the gas field area, these shallow groundwater systems are likely to be localized, with recharge and discharge areas close to each other.

At Herd Base, four groundwater abstraction bores target groundwater from the alluvial material associated with the Purari River and its tributary, Kuku Creek. These bores encounter groundwater between 3 and 6.5 m bgl in fine-grained sand lenses, which are interpreted to be alluvial deposits from historical river channels. Two of the bores have reliably supplied water to Herd Base for several years. The groundwater encountered by these bores is thought to have connectivity with the surface waters of Kuku Creek and the Purari River. Testing of one of the bores has shown that the intersected aquifer is capable of yielding at least 0.8 L/s.

7.5.3.2 Onshore Export Pipeline Corridor

The onshore export pipeline corridor from the Purari River near Herd Base passes through an area topographically similar to PRL-15 with steep slopes and strike ridges, albeit of lower relief, before descending to the coast in the south (see Section 7.2). The weathered sedimentary material overlying competent geology is considered to support a perched groundwater system recharged by local rainfall. Evidence of spring erosion was observed in this area during the field survey. No information regarding deeper groundwater is known in this area; however, the geology of the ridgelines (Orubadi Beds) is dominated by mudstones and siltstones that are not thought to represent aquifer materials.

Villages at the southern end of the onshore export pipeline corridor, inland from the coast, use groundwater for domestic purposes (e.g., drinking water, washing and stock water;

Section 9.5.4.3). The communities of these inland villages often access groundwater from springs (Plate 7.6) and wells, excavated to approximately 2 m deep. These provide reliable year-round water from shallow alluvial sediments, recharged during local rainfall. This groundwater is considered to be laterally extensive and, given the very shallow depths, is likely to support groundwater-dependent ecosystems (freshwater swamps) where such ecosystems occur.

Plate 7.6 – Excavated Inland Village Spring at Kilavi (left) and Traditional Coastal Palm Stump Well at Harevavo (right)



Photos: SLR Consulting.

Villagers on the coastal strip within the onshore export pipeline corridor also use shallow groundwater wells (see Plate 7.6). The wells target shallow, approximately 1 m bgl, freshwater in marine, sandy beach and back beach deposits. The freshwater is likely to lie on top of more saline water in the deeper sediments below. The recharge zone for this freshwater is likely to be very localized, with high levels of infiltration due to the sandy substrate. Surface flows of seawater may inundate wells during major storm events.

7.5.4 Groundwater Quality Baseline Characterization

The groundwater features sampled during the November 2016 field survey included three drilled groundwater supply bores at Herd Base and 14 wells and springs in villages along and inland of the coast in the onshore export pipeline corridor (see Figure 7.15).

The bores sampled at Herd Base are 16.8 to 22.6 m deep, with groundwater levels from 3 to 6.5 m bgl in November 2016. The village wells and springs are 1 to 2.7 m deep, with groundwater levels from 0.05 to 2.1 m bgl.

7.5.4.1 Physicochemical Parameters

In situ measurements were undertaken for various physicochemical parameters, including temperature, pH, electrical conductivity, dissolved oxygen and turbidity.

The groundwater pH was moderately alkaline at pH 8.6 to 9.5, with a median value of pH 9.1. The most alkaline groundwater measurement was at Herd Base. All field pH measurements exceeded the aesthetically-based highest desirable limits of the PNG PHR and the WHO (2011) drinking water guidelines. The high pH is attributed to the carbonate parent geology in the area.

Groundwater electrical conductivity in bores at Herd Base was 765 to 992 µS/cm and is classified in the WHO (2011) drinking water guidelines as representing fair drinking water based on aesthetic considerations, i.e., taste. Groundwater conductivity in the village springs and wells was lower at 75 to 400 µS/cm and was within the range considered to represent good drinking water.

The low conductivities in village wells close to the coast indicate that salt water ingression into the shallow groundwater system has not occurred through either ground intrusion or overland flow (e.g., storm surges).

Groundwater at all locations was well-oxygenated, having greater than 95% oxygen saturation, at all locations, which is high for groundwater. This is attributed to the large area of air-water interface of the shallow wells and springs and the large volumes of standing water precluding conventional purged sampling.

Groundwater turbidity ranged from less than 0.5 to 55 NTU, with an average of 12 NTU. Turbidity at nine locations exceeded the PNG PHR and WHO (2011) aesthetically-based drinking water guideline of 5 NTU.

7.5.4.2 Laboratory Analyses

Water samples were collected at 14 sites during the November 2016 field survey for analysis of the following parameters:

- Major cations and anions, including alkalinity.
- Total suspended solids (TSS).
- Total and dissolved organic carbon.
- Total nitrogen, total phosphorus, nitrate/nitrite, ammonia and orthophosphate.
- Total and dissolved metals (i.e., aluminum, arsenic, barium, cadmium, chromium, cobalt, copper, lead, nickel, selenium, silver, vanadium, zinc, iron and mercury).
- Total petroleum hydrocarbons (TPH), BTEX and PAH.
- Microbiological water quality (i.e., total coliforms and fecal streptococci (enterococci)).

Detailed analytical results are presented in Part 4 of Volume 2.

Coastal village groundwater was dominated by magnesium and carbonate, with the magnesium likely reflecting marine influences in this area. At the inland villages, the major ion composition of groundwater was similar to surface waters (Part 3 of Volume 2), being calcium-carbonate dominated but with slightly higher chloride concentrations and lower calcium dominance. The similarity of groundwater and surface water at the inland villages suggests a linkage between these systems, with shallow groundwater being very young and readily replenished by rainwater recharge moving through the system. Concentrations of all major ions were below the PNG PHR and WHO (2011) aesthetically-based drinking water criteria at all locations sampled.

Nitrate concentrations in groundwater at all locations were below PNG PHR and WHO (2011) drinking water criteria. Ammonia concentrations exceeded aquatic ecosystem protection criteria as per the *Environment (Water Quality Criteria) Regulation 2002* and ANZECC/ARMCANZ (2000), which are applicable to surface waters, at seven locations; however, concentrations in all samples were less than the aesthetically-based WHO (2011) drinking water guideline of 35 mg/L. The highest ammonia concentration of 2.39 mg/L was measured in groundwater at Herd Base (site HB BH02). The maximum concentration measured in village wells was 0.15 mg/L at site V1-01(1). Natural levels in groundwater are usually below 0.2 mg/L (WHO, 2011). Potential sources of ammonia include cement mortar pipe linings and bacterial, sewage or animal waste pollution (WHO, 2011).

Total iron concentrations in groundwater exceeded the PNG PHR and WHO (2011) aesthetically-based drinking water guidelines at numerous locations. At some locations, this may be attributable to the use of steel drums as well casings (Plate 7.7). Dissolved zinc concentrations

were also slightly above ANZECC/ARMCANZ (2000) criteria for freshwater ecosystem protection at five locations; however, concentrations were less than PNG PHR and WHO (2011) drinking water guidelines. The total arsenic concentration measured in the groundwater at Herd Base was equal to the WHO (2011) drinking water guideline but was less than the guideline value at all village springs and wells. Concentrations of all other metals were below the relevant screening criteria.

Plate 7.7 – Well With Steel Drum Used for Casing



Photo: SLR Consulting.

Concentrations of TPHs and PAHs were less than the limits of reporting in all groundwater samples. Concentrations of BTEX were also below reporting limits, except for toluene concentrations in all samples, which were just above the limit of reporting (2 µg/L) but over two orders of magnitude below the WHO (2011) drinking water guideline of 700 µg/L.

The microbiological water quality of the sampled wells and springs was found to be poor, with high coliform counts from 40 to 18,000 CFUs/100mL. This does not conform to either the PNG PHR and WHO (2011) drinking water guideline that coliforms should be less than 3 CFUs/100mL (PNG PHR) or 0 CFUs/100mL (WHO, 2011). This result is, however, not unexpected for Papua New Guinea, where people in rural areas, in particular, lack access to clean drinking water (WaterAid, 2017). All wells and springs at the village sampling locations were relatively open, allowing exposure to biological contamination. Potential sources of microbiological contamination include the well and spring users, direct contact with domestic and wild animals (e.g., animals drinking from water features and bird droppings in the water sources), subsurface migration of sewage-impacted water from pit latrines and informal toileting or windblown detritus. In addition, the well and spring construction method makes many of these structures susceptible to surface water inflows transporting contaminants and seawater inundation during tidal surges. While the village wells are not always the sole source of drinking water, as rainwater tanks are present in most locations, there is increased use of groundwater during extended dry periods and therefore the microbiological quality of water presents a human health concern (Part 16 of Volume 2)

Coliforms were also present in groundwater sampled at Herd Base. This bore has a basic cap at its headworks, and downhole contamination is possible from insects and amphibians that may gain access to the bore. The current water use from the bore is limited to vehicle and workshop washdown, and the water quality is considered suitable for this purpose.

Overall, the results of laboratory analyses on collected samples indicate that, apart from microbiological contamination, groundwater quality in the sampled systems within the study area is relatively good with no evidence of gross chemical contamination. These exceedances of water quality guidelines for chemical analytes are minor and are mostly related to aesthetic considerations, such as taste, to which the communities have likely become accustomed.

7.6 Freshwater and Estuarine Biodiversity

7.6.1 Regional Context

PRL-15 and the Purari River delta fall within the Papuan Gulf Foreland and the Papuan Gulf Coastal Lowlands ecoregions described by Polhemus et al. (2004). These ecoregions encompass the coastal lowlands in the southern part of central New Guinea, including the Purari, Fly, Digul and Kikori rivers. They are characterized by a high degree of endemism clustered around tectonic plates (Abell et al., 2008). The freshwater fauna of the ecoregions also has strong affinities with that of northern Australia, reflecting the recent geological connection between these land masses (Allen, 1991; Abell et al., 2008).

Papua New Guinea has high rainfall and high river discharges; and due to PNG's mountainous topography, its rivers tend to have high velocities in their upper reaches (Osborne, 1987). The riverine habitat types found in the study area are characteristic and representative of those found elsewhere in Papua New Guinea, i.e., fast-flowing, low-order streams in areas with steep topography, which widen and lose velocity at lower gradients and eventually form large turbid lowland river systems in the lowland environments.

The study area encompasses the Purari River and its tributaries, the tributaries of the Era and Pie rivers and the deltaic plains of the Purari River. The portion of the Purari River catchment in the study area is located downstream of Hathor Gorge (see Figure 7.10). As described in Section 7.3.1, the Hathor Gorge rapids represent a significant hydraulic and physical barrier and are a key control on aquatic fauna distribution patterns in the Purari River catchment (Haines, 1979).

The deltaic plains of the Purari River consist of a broad floodplain containing low-gradient floodplain channels and a range of freshwater wetland systems. The most extensive wetland types are lowland freshwater swamps (forested wetlands) and, to a lesser extent, marshes and lakes. The floodplain wetland types occurring along the Purari River are well represented throughout Papua New Guinea, e.g., in the Sepik River basin, Fly River basin, Kikori River basin and the numerous other river systems listed in Section 7.1 that discharge into the Gulf of Papua.

The Vaihua River estuary at Caution Bay is part of the Papua Peninsula ecoregion defined by Abell et al. (2008). This ecoregion encompasses the Papuan Peninsula and offshore islands including the Trobriand islands, D'Entrecasteaux islands and Louisiade Archipelago along the southeast coast of New Guinea. This ecoregion is also characterized by a high degree of endemism clustered around tectonic plates (Abell et al., 2008). The Papuan Peninsula ecoregion overlaps with the South Papuan Peninsula Foreland (Area 30) ecoregion, as defined by Polhemus et al. (2004).

7.6.2 Aquatic Habitats Baseline Characterization

7.6.2.1 Study Overview

Description of the existing freshwater and estuarine biodiversity in the study area is based on information from previous studies, the scientific literature and targeted field surveys of the study area. These surveys were undertaken in conjunction with the surface water and sediment quality

surveys described in Section 7.4 and were completed in June and July 2016 and January and February 2017 (Part 5 of Volume 2). Sampling was undertaken at the same sites as the surface water and sediment quality (see Figure 7.10).

The baseline characterization focused on the following:

- Description of different aquatic habitat types and features in the study area, including rivers, tributary streams and wetlands.
- Characterization of spatial and temporal patterns in the structure of fish and macroinvertebrate assemblages of the study area including benthic macroinvertebrates in estuarine areas.
- Identification of species listed as Threatened under the International Union for Conservation of Nature (IUCN) Red List, species listed as threatened or protected by the *Fauna (Protection and Control) Act 1996*, or species and habitats potentially relevant to a critical habitat assessment.
- Quantification of contaminants (i.e., metals, metalloids and PAHs) in aquatic biota.

Haines (1983) identified the following five key freshwater and estuarine habitat types in the study area:

- High- to moderate-gradient tributary streams.
- Low-gradient slow- to moderate-flowing tributary systems.
- Unconfined turbid major river systems and floodplain stream mouths.
- Freshwater floodplain wetlands and oxbow lagoons.
- Estuarine wetlands.

These are analogous to habitat types defined by Polhemus and Allen (2006). Further detail regarding the characteristics of each of these habitats is provided in Part 2 of Volume 2. The occurrence of each of these habitats in the study area is discussed in the following sections.

Estuarine areas of the Vaihua River are included in this section due to the close connectivity with the Caution Bay marine environment (Section 8.5), which is included in the upstream Project area at the southern end of the offshore export pipeline corridor.

7.6.2.2 PRL-15

High- to moderate-gradient tributary streams occur in steep valleys within PRL-15 in the vicinity of the gas field. These streams have confined or partially confined channels; clear, swift-flowing waters; substrate comprising predominantly bedrock, boulders and cobbles; and an absence of trailing vegetation and macrophytes. High- to moderate-gradient tributary streams that were surveyed in PRL-15 included sites 3B, 4, 5, 6, 9 and 10, which were located in tributary streams of the Era and Purari rivers (see Figure 7.10 and Plate 7.8). The riparian zone generally comprises intact, continuous lowland forest that forms a dense canopy over narrow streams.

Low-gradient slow- to moderate-flowing tributary streams were identified to occur in the southern region of PRL-15, with such locations including sites 1B (see Figure 7.10), located in an unnamed creek upstream of Herd Base, and site 2 (see Figure 7.10), located in Oyomo Creek near the proposed CPF area (Plate 7.9). These are a transitional zone between the swift-flowing, clear-water environments that characterize the high- to moderate-gradient tributary streams and the slow-flowing, unconfined turbid major river systems. They have substrates dominated by gravel, pebbles and sand; the common occurrence of gravel and sand bars; and hydraulic habitats including riffles, glides and runs with occasional pools. They usually have low turbidity, although

this is temporally variable and turbidity is higher in lower reaches. Woody debris, leaf litter, trailing vegetation and trailing roots are abundant, providing a high level of microhabitat complexity. Riparian vegetation is continuous lowland or alluvial forest, while aquatic macrophytes are absent, which is likely due to channel scour and shading by riparian vegetation.

Plate 7.8 – Example of High- to Moderate-Gradient Tributary Stream in PRL-15 at Site 4 (Boa Creek)



Photo: BMT WBM.

Plate 7.9 – Example of Low-Gradient Slow- to Moderate-Flowing Tributary Stream in PRL-15 at Site 1B



Photo: BMT WBM.

The Purari River below Hathor Gorge (see Figure 7.10) is classed as an unconfined turbid major river system. In places, the river consists of multiple braided channels that are highly unstable and subject to shifts in position. The river can also form a continuous meandering channel that is also unstable, migrating over time (see Plate 7.4, Section 7.2.4.3). Downstream of Herd Base, the river has an extensive floodplain and in-channel sediment deposits. The river is highly turbid, is up to 11 m deep in areas, and comprises a continuous run hydraulic habitat (Plate 7.10). Substrates vary depending on channel form and include gravel, sands and muds. Riparian vegetation consists of continuous forests but is semi-continuous to patchy adjacent to villages and gardens.

Plate 7.10 – Highly Turbid Purari River (Unconfined Turbid Major River System)



Photo: TEP PNG.

The tributary streams near their confluence with the Purari River, including sites 11, 12, 13, 14 and 15, are classed as floodplain stream mouths (e.g., Plate 7.11). The mouths of floodplain streams are strongly influenced by the Purari River and have similar physical/hydraulic habitat characteristics. Extensive sand and cobble bars are present at most river mouth sites, which are dynamic features that vary in response to flow conditions (e.g., sites 12 and 14).

Plate 7.11 – Confluence of Nea Creek to PRL-15 Oxbow Wetlands Tie Channel and the Purari River, Site 11



Photo: BMT WBM.

The Purari River has an extensive floodplain containing palustrine wetlands (swamps), flooded forests and oxbow lakes. The degree of inundation by overbank flooding of these wetland types varies seasonally in response to flooding of the Purari River. Freshwater floodplain wetlands and oxbow lagoons occur in the southwest of PRL-15, with vegetation including mixed swamp forests, herbaceous swamps and swamp woodlands. Further detail regarding the flora composition is provided in Section 7.7.

The PRL-15 oxbow wetlands (Plate 7.12) are located in the southwest of PRL-15 approximately 18 km downstream of Herd Base (see Figure 7.10). Such oxbow lakes form where meander bends have been separated from the main channel. The PRL-15 oxbow wetlands may connect

with the main channel of the Purari River during periods of high flow via the Nea Creek tie channel (see Plate 7.11). Aerial observations of the PRL-15 oxbow wetlands indicate submerged grasses and aquatic macrophytes occur along the littoral margins, with herbaceous swamp and swamp woodland vegetation dominating the surrounding area.

Plate 7.12 – PRL-15 Oxbow Wetlands



Photo: BMT WBM.

7.6.2.3 Purari River Delta

Downstream of Herd Base, the Purari River and other major distributaries within the delta, including the Urika-Ivo and Wame-Varoi rivers, are classified as unconfined turbid major river systems with an extensive floodplain (Plate 7.13).

Plate 7.13 – Unconfined Turbid Major River Systems, Wame-Varoi River



Photo: ERIAS Group.

The floodplain has large areas of floodplain forest containing palustrine wetlands and small off-river waterbodies (classed as freshwater floodplain wetlands and oxbow lakes). Section 7.7 describes the floristic characteristics of these wetlands, which include mixed swamp forests, herbaceous swamps and swamp woodlands. The low gradient of the Purari River has resulted in a gradual transition from forest to sago and nipa palms through tidal freshwater swamp forest to mangrove vegetation on the coast.

The Purari River delta estuary, including the Urika-Ivo and Wame-Varoi rivers, forms the transitional zone between freshwater environments and the Gulf of Papua. These major

distributaries are up to 6 m deep and hundreds of meters wide and have low sinuosity with mid-channel bars and islands. The distributaries and secondary and side channels that comprise the estuary are heavily influenced by freshwater inputs from the Purari River and small subcatchments feeding directly into the estuarine zone.

Estuarine wetlands are found in the southern extent of the Purari River delta and primarily comprise mangrove forests (Plate 7.14). This habitat is tidally influenced despite the large freshwater inputs from the Purari River. The small estuarine creeks surveyed (sites 20, 21 and 22) were narrow (10 to 40 m) and deep (3 to 10 m). The upper reaches of these creeks were poorly flushed, with high organic loads, resulting in low dissolved oxygen concentrations less than 60% saturation. Point bars and silt deposits were observed at most creek confluences throughout the delta.

Plate 7.14 – Purari River Delta Estuarine Wetlands – Mangroves (*Sonneratia lanceolata)* on Shallow Bank



Photo: BMT WBM.

Based on observations from the current study and consistent with previous studies by Cragg (1983), the mangrove species *Sonneratia* dominates low-energy environments (i.e., inside bends) within the estuary while *Avicennia* and *Sonneratia* species are most abundant in more coastal environments. Mangrove communities are interspersed with freshwater species, particularly in more landward locations. *Nypa fruticans* is dominant in higher-energy environments, including creeks and along the Purari River main channel to the freshwater/estuarine boundary (Plate 7.15). A high diversity of mangrove communities occur along more quiescent creek margins in the lower estuarine areas, with species of *Sonneratia, Rhizophora, Xylocarpus, Avicennia, Ceriops*, *Bruguiera* and *Nypa* observed. The flora found in the Purari River delta is further described in Section 7.7.

Plate 7.15 – Purari River Delta Estuarine Wetlands – Nipa Palm (*Nypa fruticans*) Along Steeper Banks



Photo: BMT WBM.

The floodplain wetland types occurring along the Purari River are well represented throughout Papua New Guinea, including the Sepik River basin, Fly River basin and the numerous other river systems including the Kikori, Turama, and Vailala rivers that discharge into the Gulf of Papua.

7.6.2.4 Vaihua River Estuary

The Vaihua River estuary at Caution Bay is another example of an estuarine wetland with mangrove forests as the primary vegetation type (Plate 7.16). Mangroves are found along much of the coastline in Caution Bay and within the Vaihua River estuary. Saltmarshes and salt flats are found on the landward margin beyond the mangrove forests.

Plate 7.16 – Mangroves in the Vaihua River Estuary, Caution Bay



Photo: BMT WBM.

CNS (2008) previously noted the spotted red mangrove (*Rhizophora stylosa*), the dominant species in the area, to occur between 300 and 900 m from the waters edge to the beginning of the salt flats and accounts for over 90% of all mangrove individuals present. Other species observed in the area include the grey mangrove (*Avicennia marina*), club mangrove (*Aegialitis*

annulata) and yellow mangrove (*Ceriops* sp.) (CNS, 2008). The survey undertaken in 2016 also found that *R. stylosa* is the dominant species in the Vaihua River estuary close to Caution Bay but is absent further inland at Site 29. Other species of *Rhizophora* and *Bruguiera*, the yellow mangrove (*Ceriops tagal*) and the myrtle mangrove (*Osbornia octodonta*) were also recorded in the Vaihua River estuary during the 2016 and 2017 survey.

7.6.3 Aquatic Fauna Baseline Characterization

This section provides information on aquatic macroinvertebrates, fish and crustaceans in the study area. Section 7.7.6 describes aquatic herpetofauna (i.e., turtles, crocodiles and frogs).

7.6.3.1 Aquatic Macroinvertebrates

Freshwater Environments (PRL-15 and Upper Purari River Delta)

Surveys of aquatic macroinvertebrate assemblages were conducted during the 2016 southeast trade wind season and 2017 northwest monsoon season in riffle, edge and pool hydraulic habitats.

Sixty-three aquatic macroinvertebrate families were identified during the surveys across both seasons. Assemblages across both survey periods were numerically dominated by mayfly (Ephemeroptera) families (Baetidae, Caenidae and Leptophlebiidae), which together accounted for 34% of the catch. Other abundant taxa were copepods, which accounted for approximately 19% of the catch; Hemiptera (true bugs), which accounted for over 17% of the catch; and non-biting midges from the subfamily Chironominae, representing approximately 17% of the catch. Other common fauna, occurring in lower abundance, were decapods (freshwater shrimp and prawns), Oligochaeta (worms) and Plecoptera (stoneflies).

Previous surveys in PRL-15 (DES, 2008, 2010) also found mayflies (Ephemeroptera) from the family Baetidae to be the most common macroinvertebrate. Atyidae shrimps were also widespread and abundant, while Caenidae mayflies and Philopotamidea caddisflies were widespread but not as abundant as Baetidae.

The following two endemic aquatic insect species, which Polhemus et al. (2004) found are restricted to the Papuan Gulf Coastal Lowlands ecoregion, are also expected to occur:

- The waterstrider *Ciliometra setosa* (family Gerridae).
- The waterstrider *Iobates ivimka* (family Gerridae).

The habitat requirements of these species are not well documented but are expected to mostly encompass quiescent freshwater environments (e.g., floodplain wetlands, backwaters and slow-flowing streams).

Estuarine Environments (Lower Purari River Delta)

Sampling at sites in the lower Purari River delta in 2016 identified 21 benthic macroinvertebrate taxa from at least 11 families. These comprised representatives from a range of common estuarine fauna groups, including mollusks, crustaceans (excluding macrocrustaceans) and polychaete worms. Polychaete worms were the dominant benthic macroinvertebrates, with species from the families Spionidae and Capitellidae accounting for approximately 70% of the total abundance. Bivalve mollusks accounted for around 8% of the total catch, while crustaceans, other than prawns, and gastropods accounted for 3% and 1% of the catch respectively.

Taxonomic richness and abundance varied greatly among sites, with poorly flushed environments in the upper reaches of brackish creeks having particularly depauperate assemblages. This observation is consistent with upper estuarine environments elsewhere that have fluctuating

salinity levels, have low dissolved oxygen levels and are poorly flushed and, as such, typically have low benthic macroinvertebrate species richness and abundance (Saenger et al., 1988; Alongi 1990).

Estuarine Environments (Vaihua River Estuary)

Although no sediment samples were collected in the Vaihua River estuary during the 2016 and 2017 surveys due to safety risks from unexploded ordnances, previous studies (Hydrobiology, 2008b) identified 17 major taxa, including 41 families. The most abundant families or taxa included Oligochaeta (Naididae), Polychaeta (Amphinomidae, Spionidae), Ostracoda and Cumacea (Leuconidae). Polychaeta and Spionidae were also found to be abundant in the lower Purari River delta.

Polhemus et al. (2004) identified five freshwater invertebrate species as endemic to the South Papuan Peninsula Foreland ecoregion. These are the Gerridae (water striders) *Ciliometra femorata* and *Ptilomera breddini* and the Naucoridae (creeping water bugs) *Aptinocoris fenneri*, *A. sogeri* and *Cavocoris ismayi*. The ecology and salinity tolerance of these insect species is poorly known, but they are most likely found only in freshwater habitats. Sampling by Hydrobiology (2008b) did not identify any of these species in the Vaihua River estuary. On this basis, the Vaihua River estuary is unlikely to represent an important habitat for any of these endemic freshwater insects.

7.6.3.2 Fish and Macrocrustaceans

PRL-15 and the Purari River Delta

A total of 1,123 individual fish were recorded from 31 families represented by 61 species during the sampling undertaken in the 2016 and 2017 surveys. An additional 14 species from nine additional families were identified in villager fish catches. Ariidae (ariid catfish) was the most specious family, represented by 12 species, while Eleotridae and Gobiidae were represented by six and five species respectively. The remaining 28 fish families were represented by only one to three species.

Six fish species comprised 58% of the catch: Goldie River rainbowfish (*Melanotaenia goldiei*), estuarine glass perchlet (*Ambassis macracanthus*), greenback mullet (*Liza subviridis*), spoon-snouted catfish (*Nedystoma novaeguineae*, formerly known as *Doiichthys novaeguineae*), nursery fish (*Kurtus gulliveri*) and freshwater anchovy (*Thryssa scratchleyi*) (Table 7.4). Thirteen of the remaining species each accounted for between 1% and 4% of the catch, while the remaining 42 species comprised less than 1% each.

With regards to macrocrustaceans, 1,151 individuals were recorded from seven families in the 2016 and 2017 surveys. This included river prawns (Palaemonidae), shrimps (Atyidae) and mud crabs (*Scylla serrate*) in estuarine areas. The results showed that the study area supports a rich and abundant macrocrustacean fauna. A full list of species recorded and the numbers caught in the various habitats is provided in Part 5 of Volume 2.

The highest species diversity was recorded in the estuarine areas of the Purari River delta (39 species). In comparison, 15 species were recorded in the freshwater reaches of the Purari River delta, 18 species in the Purari River at tributary mouths and 24 species in the clear-water tributaries within PRL-15. Fish assemblages in the Purari River delta were dominated by species that are tolerant of fast-flowing and turbid conditions. The most abundant species in the Purari River delta, at both freshwater and estuarine locations, were estuarine glass perchlet (*Ambassis macrocanthus*), spoon-snouted catfish (*Nedystoma novaeguineae*) and greenback mullet (*Liza subviridis*).

Table 7.4 – Numerically Dominant Fish Species in the 2016 and 2017 Surveys

Species	% of Catch	Occurrence	Photo
Goldie River rainbowfish *(Melanotaenia goldiei)*	18%	Exclusively in tributary streams. Dominant fish species at most tributary creek sites.	
Estuarine glass perchlet *(Ambassis macracanthus)*	10%	Present in the Purari River delta in freshwater and estuarine waters.	
Greenback mullet *(Liza subviridis)*	9%	Present in the Purari River delta in freshwater and estuarine waters.	
Spoon-snouted catfish (*Nedystoma novaeguineae*)	8%	Present in the Purari River delta in freshwater and estuarine waters.	
Nursery fish (*Kurtus gulliveri*)	7%	Present in the Purari River delta in freshwater and estuarine waters.	
Freshwater anchovy *(Thryssa scratchleyi*)	6%	Present in the Purari River delta in freshwater and estuarine waters, and the upper reaches of the Purari River main channel (near PRL-15).	

Photos: BMT WBM.

In the clear-water tributaries, the most abundant species were from the families Palaemonidae (freshwater prawns), Eleotridae (gudgeons), Gobiidae (gobies), Terapontidae (grunters) and Melanotaeniidae (rainbowfishes). Species of *Macrobrachium* prawns were the most abundant fauna in the clear-water tributaries.

The majority of fish species identified during the 2016 and 2017 surveys are able to occur across both estuarine and freshwater environments or occur only as estuarine specialists, while very few freshwater specialists were identified. This is consistent with Haines (1979) and Allen (1991), who found that the majority of fish species in the lower Purari River are of marine origin and occur across both estuarine and freshwater environments.

Most species recorded were widespread in the study area. The exceptions were one species of goby (*Awaous* sp.) (site 10), the Bengal eel (*Ophisternon bengalense*) (site 2) and freshwater crabs from the family Hymenosomatidae (site 5) that were recorded at only one location in tributary streams in PRL-15. *Awaous* species have been recorded elsewhere in southern New Guinea and northeastern Australia so are not limited in their distribution to the study area. Bengal eels have a widespread distribution but are infrequently reportedly, and the Hymenosomatidae crabs are found in other regions in Papua New Guinea and around Australia.

No introduced (non-native) species were caught during the surveys; however, a common carp (*Cyprinus carpio*) was incidentally observed in the fish catch of local villagers in the Purari River delta area near site 18 (see Figure 7.10 and Plate 7.17). Introduced species are further discussed in Section 7.6.5.

All freshwater and estuarine fauna determined likely to occur in the study area are listed in Part 5 of Volume 2, based on the 2016 and 2017 surveys, previous observations and inference from distribution and habitat information. Threatened or sensitive aquatic fauna species are described in Section 7.6.4.1.

Plate 7.17 – Common Carp (*Cyprinus carpio*) Caught by Local Villagers (Lali Village, near Site 18)



Photo: BMT WBM.

Vaihua River Estuary, Caution Bay

Thirty fish species and five macrocrustacean species have previously been recorded in the Vaihua River estuary and surrounding catchment (Hydrobiology, 2008b). These are described in Part 5 of Volume 2. One fish species not previously observed, the seven-spot archerfish (*Toxotes chatareus*), was recorded during the survey undertaken in 2017. Schools of mullet (Mugilidae), garfish (Hemiraamphidae) and baitfish were also observed during the 2017 survey. The fish observed were primarily juveniles of marine species and were observed close to the mangroves.

Sediment sampling for macroinvertebrate species was not undertaken during the 2016 or 2017 surveys due to risks from unexploded ordnances.

7.6.4 Sensitive Species, Ecosystems and Habitat Features

7.6.4.1 Sensitive Species

Table 7.5 identifies 14 sensitive aquatic species occurring in the freshwater and estuarine study area, considers the likelihood of occurrence of the species and categorizes the species as one or more of the following:

- Species listed under the *Fauna (Protection and Control) Act 1966*.
- Trade-restricted under the Convention on the International Trade in Endangered Species (CITES) of Wild Fauna and Flora or the *International Trade (Fauna and Flora) Act 1979*.
- Species with a 'Threatened' status under the IUCN Red List of Threatened Species.
- Endemic or restricted-range species.
- Migratory and congregatory species.

Alien and native invasive species are not considered sensitive fauna, even where they occur in one of the above categories. This reflects the negative impact such species have on the ecosystem.

Further details on the listed categories and the process of classifying species are provided in Part 5 of Volume 2.

In summary, the following groups of sensitive species are either known, likely, or considered possible to occur in the study area:[14]

- Three Critically Endangered species, consisting of two sawfish species (*Pristis pristis* and *P. zijsron*) and one river shark (*Glyphis garricki*).
- One mangrove species (*Bruguiera hainesii*). Ono et al. (2016) consider *B. hainesii* to be a hybrid between *B. cylindrica* and *B. gymnorhiza*. Hybrids are not assessed under the IUCN Red List of Threatened Species and it is therefore not considered further here.
- Two Endangered species, the narrow sawfish (*Anoxypristis cuspidata*) (Plate 7.18) and speartooth shark (*Glyphis glyphis*).
- Four Vulnerable species, consisting of two ray species (*Glaucostegus typus*, *Urogymnus granulatus*) and two dolphin species (*Sousa sahulensis*, *Orcaella heinsohni).*
- One Near Threatened species, the bull shark (*Carcharhinus leucas*).
- Two aquatic insect species (waterstriders – *Ciliometra setosa* and *Iobates ivimka*) not considered Threatened on the IUCN Red List but identified as endemic to the Papuan Gulf Coastal Lowlands ecoregion by Polhemus et al. (2004).

Further description of the sensitive species listed in Table 7.5 is provided in Part 5 of Volume 2.

14 The following changes have been made to the IUCN rankings of recorded or potentially occurring species since undertaking the freshwater and estuarine biodiversity baseline study (based on the 2018 IUCN Red List): the orange-spotted grouper (*Epinephelus coioides*) has had its status downgraded from Near Threatened to Least Concern, and the Australian snubfin dolphin (*Orcaella heinsohni*) has had its status upgraded from Near Threatened to Vulnerable. There are no changes to nationally Protected status.

Table 7.5 – Sensitive Freshwater and Estuarine Species Potentially Present in the Study Area

Species Name	Common Name	IUCN*	CITES #	Other	Occurrence within Biotopes†						
					1	2	3	4	5	6	7
Bruguiera hainesii	Haines orange mangrove	CR	-	-	Does not occur	Does not occur	Does not occur	Does not occur	Does not occur	Known	Does not occur
Pristis pristis	Longtooth sawfish	CR	I	Migratory	Unlikely	Unlikely	Likely	Likely	Likely	Likely	Likely
Pristis zijsron	Green sawfish	CR	I	-	Does not occur	Does not occur	Does not occur	Possible	Does not occur	Possible	Does not occur
Anoxypristis cuspidata	Narrow sawfish	EN	I	Migratory	Does not occur	Does not occur	Does not occur	Possible	Does not occur	Possible	Does not occur
Glyphis glyphis	Speartooth shark	EN	-	-	Unlikely	Unlikely	Likely	Likely	Possible	Likely	Possible
Glyphis garricki	Northern river shark	CR	-	-	Unlikely	Unlikely	Likely	Likely	Possible	Likely	Possible
Carcharhinus leucas	Bull shark	NT	-	-	Unlikely	Unlikely	Likely	Likely	Likely	Likely	Likely
Glaucostegus typus	Giant shovelnose ray	V	-	-	Unlikely	Unlikely	Possible	Likely	Possible	Likely	Possible
Urogymnus granulatus	Mangrove whipray	V	-	-	Unlikely	Unlikely	Unlikely	Likely	Unlikely	Likely	Unlikely
Orcaella heinsohni	Australian snubfin dolphin	V	I	Migratory	Unlikely	Unlikely	Possible	Likely	Does not occur	Likely	Unlikely
Sousa sahulensis	Australian humpback dolphin	V	I	Migratory	Unlikely	Unlikely	Possible	Likely	Does not occur	Likely	Unlikely
Ciliometra setosa	Water strider	-	-	Considered to be endemic and range restricted	Likely	Unlikely	Unlikely	Does not occur	Likely	Does not occur	Likely
Iobates ivimka	Water strider	-	-	Considered to be endemic and range restricted	Likely	Unlikely	Unlikely	Does not occur	Likely	Does not occur	Likely

* IUCN, where CR – Critically Endangered; EN – Endangered; V – Vulnerable; NT – Near Threatened.
CITES, where I refers to CITES Appendix I (species threatened with extinction).
† Biotopes are (1) tributary streams (high- to moderate-gradient), (2) tributary streams (low-gradient), (3) freshwater reaches of unconfined turbid major river systems, (4) estuarine reaches of unconfined turbid major river systems, (5) floodplain wetlands, (6) estuarine wetlands, and (7) oxbow wetlands and off-river waterbodies.

Plate 7.18 – Narrow Sawfish (*Anoxypristis cuspidata*) Observed in Villager Catch at Orokolo Bay



Photo: Ken Aplin.

7.6.4.2 Sensitive Ecosystems and Habitat Features

As described in Section 7.6.2, the study area contains a mosaic of upland, lowland and coastal landscapes and encompasses a wide diversity of aquatic biotope types, including tributary streams, floodplain and estuarine wetlands, and large river systems. These habitat features can be important in that they have unique aquatic biotope features in a regional or greater context, provide habitat for a high diversity of aquatic species or particular threatened species, or are areas that may promote species endemism.

The sensitivity rating of the various habitat types that occur in the study area is categorized in Table 7.6 and is based on an assessment of their vulnerability (i.e., the likelihood of a value being lost) and irreplaceability (i.e., the spatial limitation of a value). Further description of the method and criteria used in this assessment is provided in Part 5 of Volume 2[15].

Table 7.6 – Sensitivity Rating of Freshwater and Estuarine Habitats

Aquatic Habitat	Sensitivity Rating	Comments/Applicable Criteria
High- to moderate-gradient tributary streams	Low	Habitat type does not support specific life cycle functions of species with moderate, high or extreme vulnerability and is not considered to be unique.
Low-gradient slow- to moderate-flowing rivers and backwaters of large rivers	Low	Habitat type does not support specific life cycle functions of species with moderate, high or extreme vulnerability and is not considered to be unique.
Unconfined turbid major river systems (including the Purari, Urika-Ivo and Wame-Varoi rivers)	Moderate	Area potentially used by species with extreme vulnerability (*Pristis* and *Glyphis* spp.) for activities other than those critical to the life cycle of the species. Note: As the species occurrence in this habitat is currently unconfirmed, the sensitivity rating is moderate rather than high.
Freshwater floodplain wetlands on deltaic plains	Moderate	Area potentially used by species with moderate, high or extreme sensitivity (*Pristis pristis*, *Glyphis* spp. and *Glaucostegus typus*) for activities other than those critical to the life cycle of the species. Note: As the use of this habitat by these species is currently unconfirmed, the sensitivity rating is moderate rather than high or extreme.

15 Sensitivity is redefined in Chapter 11 consistent with ratings in Chapter 3. The different rating terminology used in baseline reflects the approach at the time the baseline was undertaken.

Table 7.6 – Sensitivity Rating of Freshwater and Estuarine Habitats (cont'd)

Aquatic Habitat	Sensitivity Rating	Comments/Applicable Criteria
Estuarine wetlands	High	Area used by species with moderate, high and extreme vulnerability (*Pristis pristis* and *G. typus*) that is critical to life cycle functions (i.e., spawning and nursery areas for a range of fish species).
B. hainesii stands	Extreme	Area supports species with extreme vulnerability.
Oxbow lakes (including the PRL-15 oxbow wetlands) and off-river water bodies	High	Area potentially supports unique assemblages of aquatic species and is a unique landscape feature within the lower Purari River catchment. Note: As it is uncertain whether oxbows actually support unique assemblages, the sensitivity rating of this habitat is high rather than extreme.
Mouth or delta of large river systems	Moderate	These areas represent a potential congregation point for various aquatic species that are able to move between marine and freshwater systems, including as part of life-cycle migrations. They have been given a moderate sensitivity rating because there are no distinctive migration routes of any species within the study area.
Plateaus	High	Area potentially supports unique assemblages of species due to isolation or discontinuity. Note: As it is uncertain whether plateaus actually support unique assemblages, the sensitivity rating of this habitat is high rather than extreme.
Crater Mountain Wildlife Management Area	High	Protected area.

The more sensitive environments of the study area include the estuarine wetlands and mangroves, which are used as nursery and spawning areas for a range of fish species. The mangrove forests of the Purari River catchment, together with the Kikori River and Omati River mangrove system, represent the largest contiguous mangrove forest system in Papua New Guinea and are among the largest in the Asia-Pacific region. These mangrove forests have among the highest number of mangrove species in the world, including the Critically Endangered *Bruguiera hainesii* (see Section 7.6.4.1).

Habitat areas potentially used by threatened species include turbid main river channels and floodplain wetlands. The main channel of the Purari River (including the Urika-Ivo and Wame-Varoi rivers) and large, semi-confined turbid tributaries in the Purari River delta provide suitable habitat for threatened river sharks (*Glyphis garricki* and *G. glyphis*), rays (*Glaucostegus typus*), sawfish (*Pristis pristis*) and dolphins (*Orcaella heinsohni* and *Sousa sahulensis*).

The freshwater wetlands, including the PRL-15 oxbow wetlands, also provide potential habitat for endemic aquatic insect species (*Ciliometra setosa* and *Iobates iyimka*). The western floodplain of the Purari River contains a wide diversity of wetland types, including palustrine (swamps), lacustrine (oxbow lake) and lotic (running stream) systems. Some of these wetland environments may contain peat wetlands. These are highly sensitive environments that support specialist aquatic fauna species that are adapted to the unique water chemistry of low pH, low nutrient levels and low turbidity. The distribution and extent of peat wetlands in Papua New Guinea is not well known, and it is therefore unknown whether they are well represented at a regional or national scale.

PRL-15 plateau catchments occurring north and south of PRL-15 (see Figure 7.10) support waterways that are separated from lowland environments by waterfalls. Isolation over geological

timescales is a key driver of speciation, and such environments can represent centers of local endemism. Thus, endemic species or other features of evolutionary significance could occur on these plateaus.

7.6.5 Introduced and Invasive Species

While not recorded during the freshwater and estuarine surveys, an aquatic weed species, the water hyacinth (*Eichhornia crassipes*), was noted during the terrestrial biodiversity surveys in Nea Creek, in the PRL-15 oxbow wetlands and at the Purari Airstrip (see Section 7.7.6.6 for other weed species identified in the study area).

Other aquatic weed species are known to occur in Papua New Guinea and, although not recorded, may be present in the study area. These include the giant salvina (*Salvina molesta*) and water cabbage (*Pistia stratiotes*). In addition, hydrilla (*Hydrilla verticillata*) is considered to pose a potential future threat in Papua New Guinea (Orapa, 2006).

No introduced or invasive alien fish species were captured during the 2016 and 2017 field surveys, but some species have been identified as occurring in the study area from consultations with local villagers. A common carp (*Cyprinus carpio*) was observed in one fish catch, and anecdotal evidence from local fishermen suggests this species and tilapia (*Oreochromis mossambica*) are found in lacustrine environments such as the PRL-15 oxbow wetlands. DES (2010) also reported these two species to be present in the PRL-15 oxbow wetlands. Tilapia is also known to occur in the Vaihua River catchment, having been previously recorded approximately 2.5 km northwest of the Vaihua River estuary (Hydrobiology, 2008b).

Small-bodied Poeciliidae invasive species such as the mosquitofish (*Gambusia affinis*) and guppy (*Poecilia reticulata*) are not known in the Purari River but could occur, especially in slower flowing streams and floodplain environments. The mosquitofish (*Gambusia affinis*) is of most concern. The mosquitofish (*Gambusia affinis*) was introduced to Papua New Guinea to control mosquito populations. It has now become an established invasive species and has been reported to compete with small surface-feeding native species, such as fish and frogs, for food resources. There are records for this species in Lake Kutubu about 200 km northwest of Wabo, but there is little existing information on the population status of this species in the study area.

Other introduced fish species known to occur in the Purari River upstream of Hathor Gorge (see Figure 7.10) include snakeheads (*Channa striata*), walking catfish (*Clarias batrachus*) and climbing perch (*Anabas testudineus*), all of which compete or prey upon native fauna (Haines, 1983). Furthermore, rainbow trout *(Oncorhynchus mykiss),* brown trout *(Salmo trutta),* green swordtails *(Xiphophorus helleri*), blue panchax (*Aplocheilus panchax*) and gourami (*Trichogaster pectoralis* or *Trichogaster trichopterus*) are present in Papua New Guinea (Polhemus et al., 2004) and could in time colonize study area waterways.

7.6.6 Metals and Polycyclic Aromatic Hydrocarbons in Aquatic Fauna

Tissue samples were taken of selected freshwater and estuarine fish (i.e., 97 individuals of 17 species from 12 sites) and *Macrobrachium* prawn species (hind body tissue and cephalothorax (head) of 51 individuals from 11 sites) caught during the 2016 and 2017 surveys for laboratory analysis of metals, metalloids and PAHs. The results are presented and described in Part 5 of Volume 2 and provide information on current concentrations in various species in the study area against which future comparisons can be made.

Metal and metalloid concentrations were compared to international food standards for benchmarking. This includes maximum levels for contaminants permitted in foods, based on the

consideration of risk to human consumers assuming a certain dietary intake, that have been developed by Food Standards Australia New Zealand (FSANZ) (ANZFA, 2015), the Food and Agriculture Organization of the United Nations/World Health Organization (FAO/WHO) (FAO/WHO, 2006) and the United States Food and Drug Administration (USFDA) (USFDA, 2000). Comparison was also undertaken with generally expected levels (GELs) provided by FSANZ (ANZFA, 2001), which represent ninetieth percentile metal concentration that have been measured in Australian fish and shellfish. The GELs do not, therefore, represent a guideline for assessing the health risk associated with consuming fish and shellfish; however, the GELs do provide a benchmark for typical contaminant levels in fish and shellfish.

Biota take up contaminants, such as metals, metalloids and hydrocarbons, from their surrounding environment to a varying extent. The degree of uptake in aquatic fauna tissues depends on the pollutant type, body part, fauna species and its contaminant excretion rate and trophic level, and the physicochemical properties of the waters. For this reason, there is not always a strong correlation between contaminant levels in biota and the ambient environment where the specimen is captured, particularly for mobile species.

Metals and metalloids were detected in aquatic biota, with copper, lead and zinc concentrations in individual specimens often greater than GELs. Copper and lead concentrations in prawns exceeded GELs at most sites and were typically higher in the cephalothorax than the hind body tissues. The health-based USFDA Guidance Level for lead was also exceeded in one prawn at site 15 in the Purari River near Wabo in 2016. The cephalothorax contains most of a prawn's organs and represents a site of metal processing and storage, hence higher metal concentrations occur in this body part.

Exceedances of GELs in fish tissue for copper and zinc occurred at most sites for most fish species. Furthermore, lead concentrations in one specimen of *Nedystoma novaeguineae* at site 22b in the Purari River delta estuary in 2016 and one specimen of *Valamugil buchanani* at site 14 in the Purari River upstream of Herd Base in 2017 exceeded the health-based FAO/WHO (2006) CODEX food standard. All other metal or metalloid concentrations were below guideline values or guideline values were not available. No other studies to date have examined metal and metalloid pathways in aquatic biota tissues in the study area.

Polycyclic aromatic hydrocarbon concentrations in all aquatic biota specimens were below detection limits.

7.7 Terrestrial Biodiversity

The information in this section has been drawn and synthesized from the Upstream Terrestrial Biodiversity Baseline Report (Part 6 of Volume 2) and the Upstream Deforestation Baseline Report (Part 7 of Volume 2). More detailed information, including full field data results, is contained in those baseline reports and supporting annexes. Information on natural resource use is provided in Chapter 9.

7.7.1 Study Overview

The purpose of the terrestrial biodiversity study was to characterize the terrestrial biodiversity values of the Project area. This was undertaken at the three different scales of biological organization:

- Regional level – values associated with the national and broader regional biodiversity setting at a scale larger than that of the study area landscape.

- Ecosystems, habitats and focal sites – values include the composition and conservation value of the study area and its component landscape features, including ecosystems, protected areas, and 'focal sites',[16] and detailed vegetation mapping.
- Species level – values include the results of the baseline studies, with summaries for conservation-listed species, scientifically undescribed species, endemic and restricted-range[17] species, migratory and congregatory species, and invasive alien species. Seven major taxonomic groups were selected for focus at the species level: vascular plants, non-volant (non-flying) mammals, bats, birds, reptiles, amphibians and insects (represented by odonates). The individual taxonomic group studies are reported as Annex 1 (A to D) to Annex 6 in Part 6 of Volume 2. The vegetation and flora supporting studies include four individual studies on flora (A), vegetation communities and condition (B), weeds (C) and forestry (logging activities) (D). In addition, a separate deforestation baseline modeling study (Part 7 of Volume 2) has contributed to an analysis of anthropogenic effects on forests in the Project area.

Field surveys were undertaken for vegetation, flora and fauna over two seasons in 2016, i.e., the northwest monsoon season and the southeast trade wind season, at 14 sites (Figure 7.16), 13 of which were entirely within the Project area of influence (PAOI). Part 23 of Volume 2 has further information on field surveys.

The information presented in this section draws on the results of these field surveys, the review of existing data sources and expert opinion. These forms of assessment were supplemented with information provided by local community representatives, some of whom were assigned to assist with the terrestrial biodiversity field surveys.

7.7.2 Study Area

The upstream terrestrial biodiversity study area (hereafter 'study area') encompasses and expands on the ecosystems and habitats present in the upstream PAOI and is considered likely to support viable populations of most or all resident species whose distributions overlap Project components. Its boundaries are based on physical landscape features that influence the composition and distribution of terrestrial biotic communities, such as landform, substrate, elevation and watersheds. Figure 7.17 shows the study area. Covering approximately 7,292 km^2, it is bounded:

- In the north by the 500-m contour.
- In the west, from north to south, by the volcanic landforms of Mount Favenc, by the Era and Pie rivers and by Port Romilly.
- In the east, from north to south, by the Aure Scarp and the Vailala River.
- In the south by the Gulf Province coast, extended offshore to include intertidal habitats (e.g., mudflats) as determined by recent aerial and satellite imagery.

16 Various localized terrain and habitat features upon which multiple species or multiple individuals of one or more species are ecologically dependent.

17 Restricted-range species are defined as those that occur over an area less than 50,000 km^2.